

GAMOW-TELLER BETA DECAYS
IN 1S-OD SHELL NUCLEI

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Abstract

We have examined the β^+ decays of eight 1s-0d shell nuclei (^{26}Si , ^{30}P , ^{30}S , ^{31}S , ^{33}Cl , ^{34}Cl , ^{35}Ar and ^{38}Ca) by measuring the relative intensities of daughter γ rays with a large-volume high-resolution Ge (Li) detector. This work revealed the existence of seven previously unreported branches to excited states and established new limits for twenty-seven others. For ^{31}S , ^{33}Cl and ^{35}Ar , as well as for ^{25}Al , measurements of the absolute intensities of the excited state branches were made by normalizing γ -ray intensities to the intensity of 511-keV positron-annihilation radiation. Precise measurements of the half-lives of ^{26}Si , ^{30}S and ^{38}Ca were also made and, combined with the results of the CVC theory, this provided an absolute normalization for the γ -ray intensities in these nuclei. In each case, the experimentally determined Gamow-Teller strengths are compared to the results of recent large-basis shell-model calculations. A general comparison of experimental and shell-model Gamow-Teller strengths for 1s-0d shell nuclei is made.

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I. INTRODUCTION AND THEORY

This thesis reports on the measurements of the β decay rates in nine light and intermediate mass nuclei. These measurements provide useful nuclear structure information because the theory of the weak interaction shows how to relate the β decay rate between two nuclear states to the wavefunctions of these states. Because of the slowness of β decays, it is fairly straightforward to measure the transition rates between states with precision in the order of a few percent, so β rate measurements can provide a reliable, stringent test of nuclear wavefunction calculations. As we shall see later, the β decay rate is sensitive to small details of the wavefunction and for this reason it is frequently too stringent a test of a calculation. The situation for allowed β decay may be compared with the experimental difficulties involved in measuring M1 and E2 γ ray lifetimes, where precisions better than 10% are rare.

In this chapter, the relation between nuclear wavefunctions and β decay rates is developed and a few remarks are made about shell-model calculations which are tested by β rate measurements.

1. The connection between β decay and nuclear structure.

The relation between nuclear wavefunctions and β decay rates is discussed in most texts on nuclear physics (e.g., deShalit and Feshbach, 1974; Preston, 1962) and only a brief outline is given here. We start with the current-current form of the weak interaction:

$$\mathcal{H}(r) = \frac{G}{\sqrt{2}} (J_{\mu}^{\dagger} L_{\mu} + J_{\mu}^{\dagger} L_{\mu})$$

This is the amplitude for a proton at r to decay into a neutron, a neutrino and a positron. L_{μ} and J_{μ} are the lepton and nucleon currents comprised of a mixture of vector and axial vector:

$$L_{\mu} = \bar{\psi}_{\nu} \gamma_{\mu} (1 + \gamma_5) \psi_e$$

Note that we use the Bjorken and Drell (1964) notation for Dirac matrices. The nucleon current is more complicated because the strong interactions "induce" terms in addition to the basic terms appearing in the lepton currents.

$$J_{\mu} = V_{\mu} + A_{\mu}$$

$$V_{\mu} = \bar{\psi}_n (g_V \gamma_{\mu} + i \frac{1}{2Mc} g_W \sigma_{\mu\nu} q^{\nu} + \frac{1}{2Mc} g_S q_{\mu}) \tau^{-} \psi_p$$

$$A_{\mu} = \bar{\psi}_n (g_A \gamma_{\mu} \gamma_5 + \frac{1}{2Mc} g_P \gamma_5 q_{\mu} + i \frac{1}{2Mc} g_T \sigma_{\mu\nu} \gamma_5 q^{\nu}) \tau^{-} \psi_p$$

(Here M is the nucleon mass and q_{μ} is the 4-momentum transferred to the neutrino-positron pair.) The third component of the vector current, the scalar term, and the third component in the axial current, the tensor term, are known as the second class currents because they have opposite G -parity to the other terms. Recent measurements of the angular distribution of β particles emitted in the decays of several light nuclei are

consistent with the Conserved Vector Current (CVC) theory (which requires $g_S=0$) and with the absence of a tensor term ($g_T=0$) (Brändle et al., 1978; Calaprice and Alburger, 1978; Tribble and May, 1978; Behrens et al., 1978; Genz et al., 1976; Bowles and Garvey, 1978). Therefore, we may ignore the second class currents. The Partially Conserved Axial Current (PCAC) theory gives $g_P \sim 180 g_A$ for the coupling constant of the induced pseudoscalar component of the axial current (momentum transfer $< 10 \text{ MeV}/c$). Making the non-relativistic reduction for the γ_5 matrix, $\gamma_5 \sim \vec{\sigma} \cdot \vec{q}/2Mc$, shows that the magnitude of the induced pseudoscalar term is $< 5 \times 10^{-3}$ of the dominant axial vector term $g_A \gamma_\mu \gamma_5$. The coupling constant g_W for the second component of the vector current is given by the CVC theory as $g_W = 3.71$ = the difference between the proton and neutron anomalous magnetic moments. While this term has a relatively large magnitude (up to a few percent of the axial vector term), Wu and Moszkowski (1966) and Holstein (1974) show that it does not contribute significantly to the total Gamow-Teller β decay rate. Therefore, in what follows, we consider only the first term in each current and write for the total nucleon weak current

$$J_\mu = \bar{\psi}_n \gamma_\mu (g_V + g_A \gamma_5) \tau^- \psi_p$$

The next step is to obtain an expression for the total transition amplitude by integrating the expression $\mathcal{H}(r)$ over all space and by substituting the sum of the individual nucleon currents for the total nuclear current.

$$\begin{aligned} \langle \Psi_f; p_e, s_e; p_\nu, s_\nu | H | \Psi_i \rangle &= \frac{G}{\sqrt{2}} \sum_{n=1}^A \int d^3 r_1 d^3 r_2 \cdots d^3 r_A \\ &\times \{ \bar{\Psi}_f \gamma^\mu(n) (g_V + g_A \gamma_5(n)) \tau^-(n) \Psi_i \} \\ &\times \{ \bar{\psi}_\nu(r_n) \gamma_\mu (1 + \gamma_5) \psi_{e^+}(r_n) \} \end{aligned}$$

This expression is valid for positron decay. p_e, s_e and p_ν, s_ν refer to the momenta and spin projections of the positron and neutrino. Ψ_i and Ψ_f are the initial and final wavefunctions for the nucleus (which contains A nucleons). The integration also includes sums over spin and isospin coordinates.

Note that this step assumes that the nuclear wavefunction can be described entirely in nucleon coordinates and that the A nucleons in the nucleus have the same β decay properties as free nucleons. For the vector current this is correct (it follows from the CVC theory), but for the axial current it is not. A recent calculation by Towner and Khanna (1979) shows that the corrections due to non-nucleonic components of the wavefunction are $\sim \pm 5\%$ of the dominant axial vector term in five nuclei with closed LS shells plus (or minus) one nucleon. This number is the result of several larger cancelling contributions, so in some nuclei it could be much larger.

To separate this expression into nuclear and leptonic parts, we note that the wavelength of the positron and neutrino in nuclear β decay is much larger than the radius of the decaying nucleus. Therefore, to

order $|p_e + p_\nu|^2 R^2 / \hbar^2$ ($\leq 6\%$ for $A < 40$, $|p_e + p_\nu| < 10$ MeV/c), the neutrino and positron wavefunctions may be replaced by their values at the nuclear surface:

$$\psi_\nu = u(p_\nu, s_\nu)$$

$$\psi_e = v(p_e, s_e) \sqrt{F(-Z, E_e)}$$

where the Fermi function, $F(-Z, E_e)$, is given by many references (see, for example, Bahcall, 1966). Z is the charge of the daughter nucleus and u and v are the usual Dirac spinors for particles and antiparticles.

Inside the nucleus, the nucleons are moving slowly compared with c , so we make non-relativistic reductions for the nucleon spinors and Dirac matrices (see, for example, deShalit and Feshbach, 1974) and obtain

$$\bar{\psi}_n \gamma^0 \psi_p = \phi_n^*(r) u_n^+ u_p \phi_p(r)$$

$$\bar{\psi}_n \gamma^j \psi_p = \phi_n^*(r) u_n^+ \left(\frac{\vec{p} + \vec{p} + i\sigma \times (\vec{p} - \vec{p})}{2Mc} \right)_j u_p \phi_p(r) \quad j=1,2,3$$

$$\bar{\psi}_n \gamma^0 \gamma^5 \psi_p = \phi_n^*(r) u_n^+ \left(\frac{-\sigma \cdot \vec{p} - \sigma \cdot \vec{p}}{2Mc} \right) u_p \phi_p(r)$$

$$\bar{\psi}_n \gamma^j \gamma^5 \psi_p = \phi_n^*(r) u_n^+ \sigma_j u_p \phi_p(r) \quad j=1,2,3$$

Here u_p and u_n are the 2-component spin wavefunctions of the proton and neutron and ϕ_p and ϕ_n are the spatial wavefunctions. The operators σ_j are the usual two dimensional Pauli spin matrices. The first correction term in these expressions is of order $\frac{p^2}{4M^2c^2}$ times the leading term. In a nucleus, the kinetic energy of a nucleon at the top of the Fermi sea is ~ 40 MeV, so the error made in the non-relativistic approximation is $\sim 2\%$. Barroso and Blin-Stoyle (1975) quote values for the relativistic correction for the nuclei with a closed LS shell plus or minus one nucleon, and conclude that it is a reduction of ~ 2.5 to 5.0% . Finally, we note that the two terms of order $\frac{p}{2Mc}$ connect nuclear states with different parity while the large ("allowed") terms γ^0 and $\gamma_5\gamma^j$ do not change the parity. Consequently the terms γ^j and $\gamma^0\gamma^5$ do not interfere with the allowed terms.

By ignoring terms in the transition amplitude of order $\frac{p^2 R^2}{2\pi}$ and $\frac{p^2}{M^2 c^2}$ we have completed the "allowed approximation." The transition amplitude can now be written in the much simpler form

$$\begin{aligned} \langle \psi_f; p_e, s_e; p_\nu, s_\nu | H | \psi_i \rangle &= g_V \frac{G}{\sqrt{2}} M_F \bar{u}(p_\nu, s_\nu) \gamma_0 (1 + \gamma_5) v(p_e, s_e) \sqrt{F(-Z, E_e)} \\ &+ g_A \frac{G}{\sqrt{2}} M_{GT} \bar{u}(p_\nu, s_\nu) \underline{\gamma} (1 + \gamma_5) v(p_e, s_e) \sqrt{F(-Z, E_e)} \end{aligned}$$

with

$$\begin{aligned} M_F &= \text{Fermi matrix element} = \langle \psi_f | \sum_{n=1}^A \tau^-(n) | \psi_i \rangle \\ M_{GT} &= \text{Gamow-Teller matrix element} = \langle \psi_f | \sum_{n=1}^A \underline{\sigma}(n) \tau^-(n) | \psi_i \rangle \end{aligned}$$

Note that in the allowed approximation, β decays occur only between states with the same spin, parity and isospin, for which M_F is not zero, and between states with the same parity but differing by one unit of angular momentum ($\Delta J=1$) and isospin ($\Delta T=1$ or 0), where M_{GT} is not zero.

The decay rate is obtained from Fermi's Golden Rule:

$$d\lambda = \frac{2\pi}{\hbar} |\langle \Psi_f; p_e, s_e; p_\nu, s_\nu | H | \Psi_i \rangle|^2 \frac{d^3 p_e}{(2\pi\hbar)^3} \frac{d^3 p_\nu}{(2\pi\hbar)^3} \delta(E_0 - E_e - E_\nu)$$

This is only the rate for decaying into a positron with momentum p_e and spin s_e and a neutrino with momentum p_ν and spin s_ν . E_0 is the total energy difference between the initial and final nuclear states and the kinetic energy of the recoiling nucleus has been neglected. To obtain a total decay rate, for comparison with those measured in these experiments, this expression must be summed over magnetic substates in the final nucleus and lepton spins and integrated over lepton momenta. Using the trace algebra of Dirac matrices and performing the phase-space integral gives

$$\lambda = \frac{\ln 2}{\tau_{1/2}} = \frac{m_e^5 c^4}{2\pi^3 \hbar^7} G^2 \{ g_V^2 |M_F|^2 + g_A^2 |M_{GT}|^2 \} f(-Z, E_0)$$

with $f(-Z, E_0)$ = phase-space factor = $\frac{1}{m_e^5 c^9} \int_{m_e c^2}^{E_0} dE F(-Z, E) p E (E_0 - E)^2$.

Measurements of the 0^+ , $T=1$ to 0^+ , $T=1$ pure Fermi decays, where $|M_F|^2=2$ to high accuracy, such as ^{14}O , ^{26}Al and ^{54}Co , fix the value of $(g_V G)^2$

(Hardy and Towner, 1975, Raman et al., 1975). Studies of the β^- decay of free neutrons show that $g_A/g_V = 1.250 \pm 0.009$ (Kropf and Paul, 1974). Substituting the measured values of the coupling constants gives the following expression for the total rate of a β transition:

$$f(-Z, E_0) \tau_{1/2} = \frac{6163.4 \pm 3.8 \text{ sec}}{|M_F|^2 + (1.562 \pm 0.023) |M_{GT}|^2}$$

We have chosen to use the coupling constant given by Hardy and Towner (1975) for this expression. This is the central expression for allowed β decay connecting the phase-space factor f , the half life and the matrix elements. All of the theory outlined here also applies to electron (β^-) decay simply by replacing $-Z$ by Z in the expression for F and by changing γ_5 to $-\gamma_5$ in the matrix elements.

A few corrections to the formula still remain. A more accurate calculation of the statistical rate function or phase-space factor can be made if positron wavefunctions, calculated by solving the Dirac equation for a finite nucleus, are used instead of the point charge Coulomb wavefunctions evaluated at the nuclear radius. This is the approach used by Hardy and Towner (1975), Raman et al. (1975) and Raman et al. (1978), but it requires certain assumptions about the wavefunctions of the decaying nucleus as it amounts to calculating some of the second forbidden (order $\frac{p^2}{4M_c^2}$) corrections. We used the f values tabulated by Gove and Martin (1971) which were calculated using the simple expression

given above. Comparisons with more accurate calculations show that the error is small and almost always less than the $\pm 1.2\%$ accuracy of the numbers given by Gove and Martin. A second correction concerns the interaction of the positron with the charge of the decaying nucleon. This is called the radiative correction and a simple scheme for calculating it is given by Hardy and Towner (1975) and Wilkinson and Macefield (1970). For nuclei with $Z=10$ to 20 , this radiative correction increases f by 1% to 2% . Finally, in addition to emitting a positron, a nucleus can capture an orbital electron. The same physical interaction and nuclear matrix elements govern the process as β^+ decay, so it can be handled in the same manner. The essential information in this case, corresponding to the factor $F(Z,E)$, is the electron density at the nucleus. Atomic wavefunction calculations give this quantity so the electron capture rate can be calculated. In measurements such as ours, where we do not look for the outgoing positron, the orbital electron capture can be included by modifying $f(-Z, E_0)$.

Before continuing, it must be emphasized that, while the simple form of the total decay rate in the allowed approximation is a consequence of the V-A theory of weak interactions, it cannot be used as evidence for the V-A theory. This is because other forms of the weak interaction would yield the same non-relativistic matrix elements (a scalar current gives the Fermi matrix element and a tensor current gives the same Gamow-Teller). Also, the total decay rate is insensitive to the presence of pseudoscalar terms formed by contracting a vector with an axial vector. The true form

of the interaction can be studied only by examining the β particle and neutrino angular correlations and distributions and by observing the polarization of the emitted β particles. Such experiments were pursued vigorously about twenty years ago (see Preston, 1962; and Wu and Moszkowski, 1966, for a review).

2. Nuclear Structure Calculations

The single-particle nature of the β decay operators means that wavefunctions required in order to calculate the matrix elements must be expressed in single-particle coordinates; i.e., we need shell-model wavefunctions. The nuclear shell model is discussed in detail in most nuclear physics texts (e.g., deShalit and Feshbach, 1974, and Preston, 1962) and we do not go into great depth here.

The shell model is an independent-particle model of the nucleus in which the individual nucleons move (almost) freely in a potential well defined by the presence of the other nucleons in the nucleus. The Schrödinger equation can be solved for this potential well yielding a set of single particle wavefunctions describing the states within the assumed potential well. Nuclear states are constructed by assigning protons and neutrons to the single-particle states. Because of the strong interactions between nucleons it might be expected that they would scatter out of the single-particle states making the concept of single-particle quantum numbers meaningless. But this does not happen so quickly because of "Pauli blocking": nucleons are fermions, so in order to scatter they must scatter into unoccupied states. Conservation of energy requires that the final states in the scattering have about the same energy as the initial state, but these states are already occupied in the low-lying states of a nucleus. Consequently the interactions are reduced and the particles are expected to stay in their single particle orbits for times long compared to orbital "periods" in the nucleus.

Any nuclear wavefunction may be expanded in these single-particle wavefunctions, but if significant correlations exist in the true nuclear wavefunction the number of terms required becomes enormous. Thus the shell model is not easily applicable to highly deformed nuclei.

The motion of the individual nucleons is not entirely independent of the others and this remaining weak interaction is included in the calculation of the nuclear wavefunctions. To obtain the nuclear wavefunctions, one must solve the Schrödinger equation

$$\begin{aligned} H\Psi &= \sum_{i=1}^N \left[-\frac{\hbar^2}{2M} \nabla_i^2 + U(i) \right] \Psi(1,2,\dots,N) \\ &\quad + \sum_{i \neq j} V(i,j) \Psi(1,2,\dots,N) \\ &= E\Psi \end{aligned}$$

$U(j)$ is the potential well created by the other nucleons, Ψ is the nuclear N -particle wavefunction, E is the energy of the state and $V(i,j)$ is the two-body potential. Note that the spin and isospin coordinates are also to be included in this expression. N is not necessarily the number of nucleons in the nucleus being described. For example, in describing an $A=20$ nucleus, one might assume that 16 of the particles give a closed ^{16}O core, so that the Schrödinger equation above describes a system of only 4 "active" particles in which case $N=4$.

At this point we have defined a shell model. It consists basically of a spherical potential well U , a Hilbert space in which the state

eigenfunction Ψ exists and a 2-body potential $V(1,2)$ which describes the interactions of two particles in this space. Consequently in discussing a shell model calculation, one always refers to the basis (Hilbert space) and to the effective interaction (1+2 body potential) used.

In 1s-0d shell calculations, the shell model basis used generally consists, at most, of a closed ^{16}O core and no explicit account is taken of particle-hole excitations into the 0f-1p shell. Various techniques have been used for obtaining matrix elements of the two body potential $V(1,2)$. Either a simple form is assumed for the two body interaction, such as a surface delta interaction (e.g., Wildenthal et al., 1971b), or else the two body matrix elements are derived from a "realistic interaction," such as the Hamada-Johnston potential, which describes nucleon scattering (e.g., Wildenthal et al., 1971a). As a final step, the two-body matrix elements thus derived are sometimes adjusted iteratively to improve the agreement between calculated and measured excitation energies (e.g., Meurders et al., 1976, and McGrory and Wildenthal, 1971).

Several shell-model calculations of the wavefunctions of the 1s-0d shell nuclei have been made in the past 10 years with varying degrees of success in explaining observed nuclear properties. Until recently, all of these calculations have suffered from the problem that they could not use the full 1s-0d space for nuclei between $A=23$ and $A=34$, and consequently the model wavefunctions calculated have omitted

part of the "true" $1s-0d$ component of the nuclear state. This truncation was required because of the enormous number of shell-model configurations in the full basis, and the consequent problems of constructing and diagonalizing Hamiltonian matrices of extremely large dimension. (As an example, there are 853776 $1s-0d$ shell configurations for ^{28}Si with J ranging from 0 to 14 and isospin T ranging from 0 to 6.) Because these calculations are usually designed to reproduce energy spectra (at least when the effective interaction is adjusted to fit the spectra) agreement between observed and calculated energies is not a very good test of the accuracy of the calculation. β decay and $M1 \gamma$ decay matrix elements, which are usually not included in the fit for the Hamiltonian, are more sensitive to configuration mixing and the details of the wavefunctions involved. Because of the restricted shell-model space used, many of the small components are necessarily omitted from the model wavefunctions and therefore it is not surprising that predictions of β decay rates using a truncated shell-model basis have been quite poor.

Recently, however, Wildenthal and his collaborators have performed shell-model calculations throughout the $1s-0d$ shell using an un-truncated $1s-0d$ basis (Brown et al., 1978). This calculation used an effective interaction in which realistic 2-body matrix elements were adjusted to improve the agreement with experiment. Where possible, we will always include their results in comparison with our experimental results. We note in advance that the agreement between even this calculation and

experiment is not spectacular and that Brown et al. do not include components in the wavefunction from polarization of the ^{16}O core, nor do they include excitations into the 0f-1p and higher shells.

In most shell-model calculations, including all of the ones quoted in this thesis, isospin is assumed to be a good quantum number. Since the Fermi matrix element is just the matrix element of the isospin-lowering ladder operator, it is zero for all β^+ transitions to non-analog states, and it is $[T(T+1)-T_{3i}(T_{3i}-1)]^{1/2}$ between analog states where $T_{3i} = (Z-N)/2$ for the parent nucleus. Thus the Fermi matrix element is insensitive to the details of the nuclear wavefunctions and in making comparisons between model calculations and experiment we always quote only Gamow-Teller strength. In the cases of the transitions between ground states of mirror nuclei where both matrix elements contribute, the Gamow-Teller part is separated from the Fermi by assuming that the Fermi matrix element between $T=1/2$ analogs is 1. Finally, it is noted that these comments do not apply to calculations of Fermi transitions where pure isospin is not assumed (see the discussion by Hardy and Towner (1975) of Coulomb corrections to Fermi matrix elements and the measurements and theoretical references in Ingalls et al. (1977), Del Vecchio and Daehnick (1978), Dickey et al. (1978) and Alburger and Warburton (1979)).

Frequently theoretical references have used a value of the axial coupling constant g_A that has been adjusted to make calculated Gamow-Teller rates agree better with experiment. We do not use these values

as they simply obscure the fact that shell-model calculations of Gamow-Teller strengths do not agree well with experiment and they make no distinction among the errors resulting from an incorrect effective interaction, shell-model space truncation and mesonic effects. The theoretical values quoted here are always the ft values calculated by the authors, or recalculated using the free nucleon values.

II. EXPERIMENTAL METHODS

1. Introduction

The general type of radioactive decay being studied is illustrated in Figure 1 where a parent nucleus (mass A and atomic number Z+1) decays to the various states of its daughter nucleus (mass A and atomic number Z; this is a positron decay). The vertical displacement of each level is proportional to its atomic energy relative to the ground state of the daughter nucleus. In positron decays, the decaying state of the parent atom must have at least enough energy to make the final state in the daughter atom plus a positron and a neutrino (total lepton rest mass energy = $m_e c^2 = 511 \text{ keV}$) plus an extra electron (left over from the atom with charge Z+1). Thus the total kinetic energy available for the neutrino and positron is the atomic mass difference less 1022 keV ($= 2m_e c^2$) (neglecting the small kinetic energy of the recoiling atom). The 1022 keV not available for positron and neutrino kinetic energy is depicted by the short vertical bar in the figure. In addition, electron-capture decays may proceed to any level in the daughter atom with a total atomic energy less than that of the parent atom. Electron-capture decays are indicated in the figure by lines connecting the parent atomic level (in this case the ground state) directly to the final state.

The purpose of an experimental investigation of such a β decay is to determine the Fermi and Gamow-Teller matrix elements controlling the decay rates to each final state in the daughter (see the discussion of the connection between decay rates and the nuclear matrix elements in the preceding chapter). The experimental problems are to measure (1) the absolute intensities of the decays to the various possible final

states, (2) the half life of the parent nucleus and (3) the total energy difference between the initial and final atomic states. The first two measurements determine the half life for the decay to a particular final state (τ_j = half life for the parent state to decay to state j of the daughter = $\frac{\text{half life of parent}}{\text{probability of decay to state } j}$) while the third determines the phase space factor f . Together these determine the matrix elements $|M_F|^2$ and $|M_{GT}|^2$, governing the decay rate through the relation, derived in the last chapter,

$$f\tau_j = \frac{6163.4 \pm 3.8 \text{ sec}}{|M_F|^2 + 1.562 \pm 0.023 |M_{GT}|^2}$$

The constant 6163.4 ± 3.8 sec is derived by Hardy and Towner (1975) from an analysis of $0^+ \rightarrow 0^+$ Fermi β decays in light and intermediate mass nuclei. An analysis of the same data by Raman et al. (1975) gives 6177.2 ± 4.2 sec because they use slightly different Fermi matrix elements. The difference of 0.2% is negligible.

f is a very strong function of the energy released in a decay, varying roughly as $(E_{\text{parent}} - E_{\text{daughter}})^5$ for β^+ and β^- decays and as $(E_{\text{parent}} - E_{\text{daughter}})^2$ for electron captures. Thus the decay rate to a highly excited daughter state may be two or more orders of magnitude smaller than the rate to a low-lying daughter state even though the decays have equal matrix elements.

In this thesis, we report on several positron decays in intermediate-mass nuclei near the "valley of β stability." The choice of these decays is dictated by several considerations:

- (1) in positron decay, the Coulomb repulsion of the protons raises

the energy of the parent nucleus relative to the daughter making more states in the daughter available for β^+ decay than in the mirror β^- decay;

(2) most of the reactions available for producing intense relatively pure activities in intermediate and light nuclei make positron activities. (The principal exception to this is the (d,p) reaction);

(3) it is difficult to make intense, relatively pure activities more than one nucleus from $N=Z$ in s-d shell nuclei using a low-energy beam such as that available from the tandem accelerator.

Near the bottom of the "valley of β stability", the accessible states of the daughter nuclei are bound with respect to emission of protons, neutrons and alpha particles, so these excited nuclei must decay by emitting γ rays. Thus the problem of determining the absolute intensities of the various branches in the decay is really one of measuring the intensities of γ rays relative to the total number of positron decays. The nice feature of positron decays is that each decay produces a positron which annihilates with an electron producing two 511-keV γ rays with a calculable detection efficiency. Consequently, a single γ -ray detector serves to measure both the number of decays to excited states and the total number of decays. This situation may be contrasted with the cases of β^- decay and delayed proton emission where a second detector must be used to measure either the ground-state branch intensity or the total number of decays.

The γ ray detector used is usually a large volume Ge(Li) which combines high resolution (required if one is to detect weak γ rays in the presence of the background always present in positron decays) and reasonable efficiency. Because Ge(Li) detectors are damaged by neutrons,

the Ge(Li) detector is placed a fairly long distance from the bombarding station (10 to 20 meters in our experiments) and is shielded from the neutrons.

An experiment consists, then, of producing the radioactivity in a target at the bombarding station, transporting it by a shuttle system ("rabbit") to the detector (or by hand if the half life is long), and then returning it to the bombarding station after the radioactivity being studied has decayed. This cycle is repeated. The various steps required to perform the experiments, the equipment used and the methods of data reduction are described in the remainder of this chapter.

2. Experimental Procedures

(i) Measurement of branching ratios.

As noted earlier, this is one of three measurements required to determine the nuclear matrix elements governing a β decay, the other two being Q value and half life.

The branching ratios are generally all we measure and report in this thesis because the half lives and Q values of the decays studied are already known to fairly high precision ($<0.5\%$ in Q value and $<1\%$ in half life except for ^{31}S and ^{38}Ca). The half lives were measured only in the cases where the total half life of a nucleus could be combined with the known partial half life for a Fermi superallowed transition to determine the absolute intensity of one branch in the decay. We also measured the half life of ^{31}S since it is known only within an error of 2.4%.

The measurement of the absolute branch intensities was divided into two parts: in the first, the relative intensities of the daughter γ rays were measured while, in the second, the absolute intensity of one or more of the γ rays or else the absolute intensity of one of the branches was determined. Some experiments do not require both parts, either because there are no known high energy γ rays to which intensities may be compared (for example, ^{19}Ne β^+ decay studied by Mann and Kavanagh, 1974) or because the absolute intensity of one high energy γ ray is known so well that it may be used as a measure of the total number of β decays (for example, ^{14}O decay studied by Wilson and Kavanagh, 1978).

(a) Relative γ Ray Intensities

For the first part of the measurement, we usually wanted to look for high-energy γ rays and to be relatively insensitive to the intense 511

keV annihilation radiation which always accompanies positron decay. Therefore, these measurements (with the exception of the ^{38}Ca experiment to be described later) were made with lead absorbers ranging from 1.9 to 4.4 cm in thickness which decreased the detector's absolute total efficiency for 511-keV radiation by factors of ~15 to ~400 while reducing the photopeak efficiency for higher energy γ rays by a much smaller factor. This made it possible to use very intense radioactive sources without seriously affecting the Ge(Li) detector and amplifier system with too high a count rate.

During the relative-intensity phase of the experiment, data were always recorded in two sequential 4096 channel spectra (groups) each lasting about a half life of the radioactivity being studied. This allowed a rough half life measurement of weak γ rays seen, while the high dispersion available with a 4096 channel spectrum did not seriously reduce the energy resolution of the detector-amplifier-ADC system (with a 4096 channel spectrum, we were able to use 1.0 to 1.5 keV/channel dispersions when looking for high-energy γ rays). An additional advantage of using two groups is that it permits separation of a γ ray peak area into short- and long-lifetime components when a contaminant γ ray with a long half life occurs at about the same energy as a γ ray originating in the decay being studied (this technique was used in the study of the ^{33}Cl decay to measure the area of the 841-keV γ ray peak which could not be separated completely from the 844-keV γ ray due to ^{27}Mg decay).

The instruments used to collect the spectra and to direct the data to the correct region of the computer memory are described in the equipment section of this chapter.

The relative detection efficiencies necessary to convert peak areas to relative γ ray intensities were measured with sources which emit several strong γ rays with well known relative intensities. Generally, the sources were mounted in a rabbit and counted in the experimental geometry. Small differences from experimental geometries were taken into account by calculating the photon absorption in the various materials surrounding the sources in the calibration and experimental geometries using the attenuation coefficients given by Grodstein (1957). In cases where the calibration source could not be mounted in the rabbit system, special care was taken to correct the measured relative efficiencies for extra absorbers. It should be noted that relative efficiencies are quite insensitive to the position of a source whereas the absolute efficiencies are very sensitive, scaling approximately as $\frac{1}{r^2}$ where r is the mean source-to-detector distance. For this reason, we did not use absolute efficiencies except in the measurement of the γ ray intensities in ^{38}Ca decay where a source connecting the 0.3 MeV region of the γ ray spectrum to the 1 to 2 MeV region was not available.

There are many sources with several intense γ rays which may be used in the relative efficiency calibration of Ge(Li) detectors, most of which are listed in Appendix II of Lederer and Shirley (eds.), Table of Isotopes, Seventh Edition (1978). The γ ray sources used in this work and the references for relative intensities are listed below:

- (1) ^{182}Ta Ref.: R.A. Meyer, quoted in Table of Isotopes, Seventh Edition (1978).

- (2) ^{133}Ba Refs: (i) Gehrke et al., 1975, Nucl. Inst. Meth. 147, 405.
(ii) Schötzig et al., 1977, Int. J. Appl. Rad. Isotopes 28, 503.
(iii) Henry, 1974, Nuclear Data Sheets B11, 495.
- (3) ^{207}Bi Refs: (i) Donnelly et al., 1967, Nucl. Inst. Meth. 57, 219.
(ii) Jardine 1975, Phys. Rev. C11, 1385.
(iii) Schmorak, 1977, Nuclear Data Sheets B22, 487.
- (4) ^{56}Co Refs: (i) Camp and Meredith, 1971, Nucl. Phys. A166, 349.
(ii) McCallum and Coote, 1975, Nucl. Inst. Meth. 124, 309.
- (5) ^{66}Ga Refs: (i) Camp and Meredith, 1971, Nucl. Phys. A166, 349.
(ii) McCallum and Coote, 1975, Nucl. Inst. Meth. 124, 309.

The ^{182}Ta source was made in 6.4 μm Ta foil by $^{181}\text{Ta}(\text{n},\gamma)^{182}\text{Ta}$ at the UCLA reactor. Very thin Ta was used in order to reduce the absorption of the low-energy γ rays in the source. ^{133}Ba has only a few strong γ rays and, apart from the 81-keV γ ray, they all lie between 276 and 384 keV, so it is not normally useful for relative efficiency calibrations. As part of the ^{38}Ca experiment, a calibrated ^{133}Ba source was used with calibrated ^{60}Co and ^{22}Na sources to connect the 0.3 MeV region to the region to the

region of the spectrum covered by ^{56}Co (0.84 to 3.5 MeV). ^{207}Bi source has strong lines at 570 keV, 1064 keV and 1770 keV which makes it useful for extending relative efficiency calibrations down in energy from the region spanned by ^{56}Co and ^{66}Ga . ^{56}Co was our most commonly used source because of its long half life (79 days), its convenience (it is made via $^{56}\text{Fe} (p,n) ^{56}\text{Co}$ in readily available iron) and its broad range of non-interfering γ rays (0.847 MeV to 3.55 MeV with no cases of escape peaks interfering with photopeaks of other γ rays). There is one difficulty with ^{56}Co that we have noticed: in high-efficiency geometries summing between the 847 keV photopeak and the annihilation radiation photopeak (511 keV) interferes with the 1360 keV photopeak. ^{66}Ga is not as good as ^{56}Co because it has a short half life (9.4 hr) and because it has so many γ rays that measuring the areas of many of the photopeaks is made difficult by the presence of nearby single- and double-escape peaks. The only advantage of ^{66}Ga is that it has strong isolated γ rays at 4.09, 4.46 and 4.81 MeV. It must be emphasized that the relative intensities for ^{56}Co and ^{66}Ga given by Camp and Meredith (1971) are in error for γ ray intensities above 2.8 MeV as was first noted by McCallum and Coote (1975) who also provided a formula for correcting Camp and Meredith's results.

Because of the uncertainty in the ^{56}Co and ^{66}Ga relative intensities, we also extended our relative-efficiency measurements to higher energies by using the resonant capture reaction $^{14}\text{N}(p,\gamma)^{15}\text{O}$ at $E_p = 1.058$ MeV. This reaction produces two γ rays in a cascade (at 3.043 and 5.240 MeV) and an 8.282 MeV γ ray with a less well known relative intensity (Evans, Brown, and Marion, 1966). These γ rays are known to have almost isotropic

angular distributions. The $^{14}\text{N}(p,\gamma)^{15}\text{O}$ calibration measurements were made using targets of TiN on a 0.25 mm W backing in a glass tee. The detector was placed at 55° from the beam direction in order to eliminate the small $P_2(\cos \theta)$ component of the angular distributions. Several calibrations were made using Pb absorbers ranging in thickness from 0.64 cm to 2.54 cm. Our conclusion is that the McCallum and Coote formula for correcting the Camp and Meredith relative intensities is correct (within our experimental error of about $\pm 5\%$).

If two or more photons are emitted simultaneously in a decay, then more than one photon may interact in the Ge(Li) detector, the detector seeing only the sum of the energies deposited by the two (or more) photons. This has the effect of reducing a γ ray's photopeak area by the factor $(1 - \text{probability of at least one other photon interacting in detector})$. This is called the summing correction and it depends on the absolute total efficiency for detecting anything in the Ge(Li) when a γ ray is emitted by the source, the angular correlations of the coincident γ rays and the number of γ rays coincident with the γ ray being measured. Absolute total efficiencies were measured at ~ 1.25 and 0.66 MeV using calibrated ^{60}Co and ^{137}Cs γ -ray sources in a geometry similar to the experimental geometry. Neglecting scattering and pair production in the materials around the Ge(Li) detector, the absolute total efficiencies for photons is given by the following expression:

$$\epsilon(E_\gamma) = \frac{1}{4\pi} \int_{\text{detector}} d\theta d\phi \sin\theta \left[1 - e^{-\mu\lambda(\theta\phi)} \right] T(\theta, \phi)$$

where μ is the absorption coefficient for photons with energy E_γ in the

detector material (Ge in this case), $\ell(\theta, \phi)$ is the path length in the detector at angles θ and ϕ and $T(\theta, \phi)$ is the probability that a photon with energy E_γ emitted in direction (θ, ϕ) reaches the detector. For a simple cylindrical Ge(Li) detector with a negligibly small dead volume in the center, with the source on the axis of the detector and with slab absorbers with a total transmission T_0 for a photon emitted toward the detector along its axis, this expression becomes

$$\epsilon(E_\gamma) = \frac{1}{2} \int_{\text{detector}} d\theta \sin\theta \left[1 - e^{-\mu\ell(\theta)} \right] T_0 \frac{1}{\cos\theta}$$

A computer program was written to evaluate this integral for the geometries encountered in these experiments where the simplifications listed above were valid. Absorption coefficients, μ , were taken from Grodstein (1957). The absolute total efficiencies used to make the summing corrections were obtained by multiplying the output of the computer program by a single, energy-independent correction factor which made the efficiencies match the measured efficiencies at 0.66 and 1.25 MeV. The approximate validity of this procedure for taking scattering into account is demonstrated by the fact that the correction factors for 0.66 MeV and for 1.25 MeV differed by no more than 10%. An error of 20% was assigned to the summing correction to take angular correlations, energy dependent scattering, source strength uncertainties and errors in the positions of the source and of the Ge(Li) crystal inside its Al can. Because summing corrections were always less than 10% and usually less than 3% in this work, only a negligible uncertainty in the results was introduced with the summing correction.

Summing corrections were made to all calibration source spectra, where the multiplicity of γ ray lines is usually the result of a complicated cascade scheme, and to experimental data in the cases where cascading occurred in the daughter nucleus. Summing with 511-keV photons was not considered because all γ rays are coincident with a positron and therefore have the same summing correction (except for small effects due to different positron energies). This is untrue only when some of the daughter γ rays originate from electron-capture decays (as in ^{34m}Cl decay) or when one is observing the 511-keV radiation as a means of measuring the total number of radioactive decays.

Many of the weak branches in these decays are expected to populate highly excited states in the daughter nucleus which then emit high-energy γ rays, so we were very sensitive to several sources of high-energy background which are described below. Each β^+ decay produces a positron with an average kinetic energy of about half of the energy difference between the parent level and the daughter (i.e., ~1 to ~3 MeV) and ranging up to twice the average. Most of these positrons slow down in the material surrounding the target and annihilate at rest with an electron producing two 511-keV γ rays. Occasionally the positron annihilates with an electron before stopping (in-flight-annihilation) or creates bremsstrahlung in an inelastic collision with an atomic nucleus. These effects produce a background of γ rays ranging up to the highest energy that can be produced by the de-exciting daughter nucleus. Since the total production of bremsstrahlung by a positron while slowing down varies roughly as Z , the atomic number of the stopping medium, the problem of bremsstrahlung can be minimized by using low Z materials in the target wherever possible (e.g.,

lucite, beryllium, and aluminum). In-flight annihilation proceeds by two mechanisms: (i) the positron and electron annihilate producing two photons (two quantum annihilation) and (ii) they annihilate in the field of an atomic nucleus producing only one real photon (one-quantum annihilation). Two-quantum annihilation dominates in-flight annihilation and is independent of Z . Since the total stopping rate per electron in matter is also almost independent of Z , this means that the total in-flight annihilation probability for a positron is only weakly dependent on the stopping material.

A third source of high-energy background is pulse pileup where two or more non-coincident γ rays are detected in the Ge(Li) in such a short period of time that the output pulses from the linear shaping amplifier are not separated from each other. The ADC then sees a sum of pulses and records a count in the high-energy region of the spectrum that is not due to a high energy γ ray. This problem can be reduced, but not eliminated entirely, by a pileup-rejection system which uses fast electronics to determine when a pileup has occurred and to disable the ADC system before the slow linear shaping amplifier has processed the pulses. For more on pileup rejection, see the section on electronics later in this chapter. Note also that the pileup rate is proportional to the square of the pulse rate (for two-pulse pileup), so that the fraction of the spectrum lost to pileup is proportional to the count rate. Consequently, the pileup problem can be reduced by lowering the count rate, and counting longer in order to obtain the necessary statistics. For two-pulse pileup, the loss of statistical precision due to low count rate is balanced by the reduction in background due to reduced pileup and there is no gain in the precision of measured branch intensities when the count rate is changed.

Finally, all of the sources of high-energy background discussed here are also sources of low-energy background, but at low energies the background contributed by Compton scattering of higher-energy photons is dominant. Consequently pileup rejection and reduction of the background due to high-energy positrons will cause only a small increase in the statistical precision of measured peak areas.

(b) Absolute Measurements

After measuring the relative intensities of the γ rays emitted in a decay and deducing the relative excited-state branching ratios, a second experiment usually must be performed to measure the absolute intensity of one of the γ rays or branches. This may be done by comparing γ ray intensities to the 511-keV intensity (which is a measure of positron production) or, where the partial half life of one of the branches is known because it is a $0^+ \rightarrow 0^+$ superallowed Fermi transition, by measuring the total half life precisely. The half life technique is described following the discussion of the γ ray method.

The method of measuring the γ ray absolute intensity by comparing its intensity to the 511-keV intensity is complicated by the fact that positrons are not very well behaved. There are four principal factors that must be considered in the interpretation of the spectra: (1) All positron emitters produce 511-keV annihilation radiation, so the 511-keV counts from the activity being studied can be identified only by half life, (2) The positrons are emitted with high kinetic energies (up to 5.5 MeV endpoint in these experiments), so the source of the 511-keV radiation is distributed over a finite volume, unlike the γ rays from the source, (3) The positrons may annihilate in flight, reducing the area of the 511-keV peak and (4) 511-keV photons are also produced following pair production in the Pb absorber and shields near the detector by high energy γ rays and in-flight annihilation photons. These complications are discussed in order.

The solution to the first problem is to measure the activity in several consecutive spectra and then to fit the decay curve of the 511-keV

peak with a sum of exponentials with the half lives of the various positron emitters in the target. This procedure requires at least two groups but should normally be performed with four or more in order to have surplus data which allow the quality of the fit to be checked by the χ^2 criterion. In the four cases where we measured positron intensities, we used between four and sixteen groups, each group lasting 0.5 to 1.0 half lives of the radioactivity being studied. Because the count rate, and thus the pileup and dead time, changed by typically a factor of 2 to 4 between the first and last groups, it was necessary to measure the peak losses in each group. This was done by feeding a pulser with a known frequency into the Ge(Li) preamp and measuring the area of the pulser peak in the spectra or by using a γ ray peak of known half life as a normalizer. For details of the χ^2 fitting, see the section of this chapter on data analysis. The multi-spectral scaler which allowed us to use up to 16 groups in our experiments is described in the equipment section.

A computer program was written to calculate the spatial distribution of stopped positrons taking into account their initial energy distribution and details of the structure of the rabbit and rabbit hutch. Ranges were calculated for each energy and direction by computing the reciprocal-stopping-power ranges. The stopping power was calculated using the method of Nelms (1956) for the electronic stopping power but also including the density effect correction of Sternheimer (1956), and the radiative stopping power was calculated from the bremsstrahlung cross section $3BN$ given by Koch and Motz (1959). Scattering was not included in the calculation of the stopping position of the positrons, but multiplying all ranges

by a factor of 0.7 did not affect the results significantly. Measurements of the relative efficiency for detection of 511-keV radiation as a function of position in the rabbit hutch were made using an Al-jacketed ^{22}Na source. These relative efficiency data were fed into the computer program which integrated the 511-keV relative efficiency over the distribution of stopped positrons and calculated the relative efficiency per emitted positron for detecting a 511-keV photon. The in-flight annihilation was also calculated by the program for each positron trajectory and angle, using the formulas presented by Azuelos and Kitching (1976), and this was included in the integral over 511-keV source density. Because both one- and two-quantum annihilation cross sections were calculated, small effects due to different stopping materials were included. We found that the effect of the distributed source was negligible compared to the in-flight annihilation which reduced 511-keV efficiencies by up to 7.5% for ^{41}Sc positrons (endpoint kinetic energy = 5.5 MeV).

The final correction, that for pair production by high energy photons was very small in our experiments. In the four cases where we measured the positron intensity, the absolute intensity of daughter γ rays was less than 1.7%, implying a contribution to the 511-keV area from this source of less than 0.3% of the total. The contribution from high-energy in-flight-annihilation photons was also estimated roughly and this turned out to be very small, being about 0.3% for ^{25}Al decay (endpoint kinetic energy = 3.26 MeV) and about 1.6% for ^{41}Sc decay (endpoint = 5.47 MeV). In all cases, this contribution was less than a third of the estimated uncertainty in the absolute intensity derived from the measurement.

The absolute intensity of the γ ray was calculated in the following way: First, the relative 511-keV efficiencies for the radioactive decay being studied and for ^{22}Na were calculated in the experimental and calibration geometries respectively. These two geometries were made as similar as possible. Then a ^{22}Na source was measured, relating the efficiency for 511-keV detection to the efficiency for detecting 1275-keV photons. A ^{56}Co relative efficiency calibration related the 1275-keV efficiency to the efficiency for detecting the γ ray produced by the radioactivity under investigation. The absolute intensity of the γ ray was then given by the following equation:

$$\begin{aligned} \text{absolute intensity} = & 2 \times \frac{\text{area}(\gamma \text{ ray peak})}{\text{area}(511, \text{activity})} \times \frac{\text{Rel. eff. (511, activity)}}{\text{Rel. eff. (511, } ^{22}\text{Na)}} \\ & \times \frac{\text{Rel. eff. (511, } ^{22}\text{Na)}}{\text{Rel. eff. (1275)}} \times \frac{\text{Rel. eff. (1275)}}{\text{Rel. eff. } (\gamma \text{ ray})} \end{aligned}$$

An alternative method for measuring absolute branches was used in the studies of ^{26}Si , ^{30}S and ^{38}Ca decays. The β^+ decays of these nuclei are dominated by a superallowed Fermi branch connecting the 0^+ , $T=1$ ground state of the parent to the 0^+ , $T=1$ analog state in the daughter. The strength of these superallowed pure Fermi transitions is usually characterized by the quantity $\mathcal{F}t_\beta$ defined by the relation $\mathcal{F}t_\beta = (1+\delta_R)(1-\delta_C)f_\beta t_\beta$ (Towner and Hardy, 1975) where now t_β is the partial half life for β^+ decay (and not including electron capture decay), δ_R is the radiative correction due to the interaction of the positron with the proton that emitted it, and δ_C is the Coulomb correction to the Fermi matrix element given by $|M_F|^2 = |\langle \psi_f | T^- | \psi_i \rangle|^2 = 2(1-\delta_C)$. The three corrections

listed above are all small, the largest, δ_R , being less than 2%. Because of the inclusion of $(1-\delta_C)$, $\mathfrak{F}t_\beta$ is a function only of the vector coupling constant in β decay. Very precise measurements of $\mathfrak{F}t_\beta$ have been made for 0^+ to 0^+ Fermi decays for many light and intermediate mass nuclei in the $4N+2$ series and they show that $\mathfrak{F}t_\beta$ is a constant ($\pm 0.7\%$) at least for $10 \leq A \leq 54$. This verifies the CVC theory prediction that the vector coupling constant in β decay is independent of nuclear structure, and that the Fermi matrix element between members of an isobaric multiplet deviates very little from the value $|\langle \psi_f; T, T_3-1 | T^- | \psi_i; T, T_3 \rangle|^2 = T(T+1) - T_3(T_3-1)$ predicted by assuming that isospin is a good quantum number, at least for $A \leq 54$. It can be added that the deviation from isospin purity, δ_C , is small and that calculations of δ_C are reliable because the values of $\mathfrak{F}t$ do not show fluctuations of the order of δ_C .

The conclusion to be drawn from this is that the partial half lives for the superallowed $0^+ \rightarrow 0^+$ Fermi decays in ^{26}Si , ^{30}S and ^{38}Ca can be calculated reliably to high precision. We did this using the relation between $\mathfrak{F}t_\beta$ and the partial half lives of the various transitions and the values for δ_C , δ_R and the electron-capture rates quoted by Hardy and Towner (1975) and Raman et al. (1975). We used their values for f_β , which are somewhat more precise than the table of Gove and Martin (1971) and which involve more sophisticated positron and atomic wavefunctions, but corrected them for the more accurate Q values measured since these review articles were completed in 1975. Because of slight differences in the approaches used in the two papers we calculated partial half lives using both sets of data and combined the final results.

Because the three decays studied were accompanied by γ rays, we were able to measure the half lives by observing the decay of the intense γ ray with time. The experiment was then straightforward. A "leaky integrator" was constructed from the Ortec 459 current digitizer by shunting the integration capacitor with a large capacitor and a resistor so that the time constant of the parallel R and C was $RC = \text{mean life of radioactivity being studied}$. The beam current was amplified by the current integrator and was then fed to the Ortec 459 which thus measured

$$Q = \int_{-\infty}^t I(\tau) e^{-(t-\tau)/RC} d\tau$$

where Q is proportional to the amount of radioactivity with mean life RC in the target at time t . When the desired amount of radioactivity had been made, the Ortec 459 issued a pulse, resetting the sequence timer and returning the rabbit to the detector for a counting cycle. This technique ensured that the same amount of the activity being studied was counted on each cycle. Data were collected in either 8 or 16 consecutive spectra, each spectrum lasting 0.3 to 0.6 half lives. The cycle was repeated typically 200 to 300 times in a run. Several runs were made for each nucleus varying the count rate from run to run. A pulser was fed into the spectra in order to allow a correction for dead time and pileup losses. Data analysis consisted of two least-squares fits for each run: first a simple three-parameter fit was made to the area of the pulser peak in the 8 or 16 spectra in order to know the pileup and dead time losses as a function of time. Then a two parameter

exponential (Ae^{-Bn}) was fit to the areas of the γ ray in sequential groups, taking into account the peak loss function determined from the pulser data. Details of the fitting procedure are given in the section on data analysis.

3. Equipment Used

(i) Ge(Li) Detector

With the exception of an early run in the ^{34}Cl experiment, all of the measurements reported in this thesis were made with the 100 cc Ge (Li) detector manufactured by Princeton Gamma Tech, Inc. This is a closed-end coaxial detector with a drift depth of 2.4 cm, a diameter of 5.0 cm and an efficiency of 19% at 1.33 MeV and 25 cm source-to-detector distance, relative to a 7.6 cm x 7.6 cm NaI(Tl) detector. The overall resolution of the Ge(Li) amplifier and ADC system was 1.8 keV FWHM at 1.33 MeV when the detector was new. This deteriorated slightly to about 2.0 keV after three years of use. The chief advantage of this detector over the Ge(Li)'s used previously in this laboratory was that it was never exposed to neutrons so it kept its good resolution and peak shape, especially at high energies where we usually wanted to look for weak γ rays. Because of the large volume, the ratio of photopeak efficiency to total efficiency was high for this detector which meant that for a given count rate, shorter times were required to achieve a particular statistical precision in peak areas. The higher absolute efficiency was no real advantage because we were not limited by the amount of radioactivity that could be made but rather by the maximum count rate that the pulse height analysis system could tolerate without a serious reduction in resolution.

(ii) Sequence Timer

The data collection for these measurements was always controlled by a crystal-oscillator sequence timer which controlled the valves on the rabbit system, the accumulation of data in the ND812-ND4420 analyzer system and the chopping of the accelerator beam. For details on this instrument,

see Fred Mann's thesis (1975).

(iii) Multispectral Scaler

The multispectral scaler was built in order to send pulse height spectra from a single ADC into several (up to 16) consecutive regions of memory. The device is very simple and works by adding high order bits to the output of the ADC, thus generating an address in the desired region of memory. The group size (i.e., the number of channels that the scaler steps each time it is incremented) can be varied from 256 channels to 4096 channels in powers of 2 by a rotary switch which connects the address lines from the ADC to the appropriate bits in the scaler. The scaler switches from one group to the next when it receives a positive 5V pulse at least 1 μ s long. A reset input is also included so the device may be restarted in group 1.

The sequence timer raises and lowers the voltage on the outputs but it does not issue narrow pulses, so an edge-to-spike converter was built to allow the sequence timer to drive the multispectral scaler. There are presently five identical parallel inputs to the edge-to-spike converter; more could be added if desired. The power for this device is provided by the sequence timer.

(iv) Rabbit System

Because the Ge(Li) detector had to be removed from the bombarding area to prevent neutron damage, a fast shuttle system was used to transport the radioactivity from the target area to the detector. The system used here (see Figure 2) is the rabbit system built by D.R. Goosman and R.W. Kavanagh and described in F. Mann's thesis (1975). Only the

modifications made for these experiments are described here.

At the detector, the rabbits stopped in a block of low Z material (the "hutch," see Figure 2) which confined the positrons to the volume around the source. Most of the work used a large lucite hutch but an aluminum hutch was used in a few cases because it confined the high energy positrons to a smaller volume. The aluminum hutch was made from 3.18 cm square material and like the lucite hutch, had a 0.87 cm hole in the center where the rabbit stopped.

The beam-end hutch and solenoid valves were also modified. Previously the beam-end valves had worked in the same way as the detector-end valves and this had required that several slits be cut in the side of the beam-end hutch so the flow of pusher gas would not be impeded when the rabbit was being transported to the detector. Consequently, the rabbit could not seal the region between the exit foil and the hutch which caused a high pusher-gas pressure in this region. The beam made contaminant radioactivities in the gas and the lack of sealing resulted in more pusher (air or argon) being pumped through the vacuum pump which operates the system. The modification was to remove the slits in the beam-end hutch and to add a third solenoid valve which admitted pusher gas to the system 8 cm behind the hutch. To ensure that the rabbit was not trapped in the hutch, the extra valve was opened about 0.1 sec after the first valve.

We used a variety of rabbit designs in these experiments. Details of their construction are given in the next chapter where the individual experiments are described.

(v) Pileup-Rejection System

The system is shown in Figure 3. Each time a γ ray deposits energy in the detector, the linear shaping amplifier (Canberra 2010 in the figure) sends a unipolar pulse, 8 to 16 μ s wide to the ADC (this corresponds to a shaping time of 2 to 4 μ s). Assuming 8 μ s wide pulses, if a second γ ray is detected within the interval of 4 μ s following another γ ray, then the second pulse from the shaping amplifier is added to the first pulse before the first pulse reaches its maximum. When this occurs, the ADC sees a pulse height between the height of the first pulse and the sum of the pulses and adds a background count to the spectrum.

The pileup rejection system is intended to disable the ADC when two pulses occur within a given period of time, thus preventing storage of a bad count. The system is very simple. A fast shaping amplifier (Ortec 454 in this case) produces an output ~ 150 ns wide, proportional in height to the input pulse from the preamp. Whenever the output pulse is large enough, the fast discriminator (EG&G T105/N here) produces a fast logic pulse which is fed to the Ortec 404 pileup inspector. The pileup inspector blocks the ADC if two signals are sent to it within the inspect interval (4 μ s in this case).

If the two preamp pulses occur within ~ 150 ns they will pileup in the fast shaping amplifier and will not be rejected because the discriminator fires only once in this situation. Also, pileup between a small pulse (typically $\lesssim 100$ keV) and a large pulse will not be rejected because the discriminator will not fire at all on the small pulse. It is necessary to accept these pileup events in order to ensure that the system does not reject good photopeak events and distort the spectrum.

This distortion is a serious problem and when doing precise work it is necessary to make sure that photopeak rejection does not occur. We used two methods. In the first, calibration runs were made with the ADC gate switched from anticoincidence to coincidence so the rejected spectrum could be examined for photopeaks. In the second method, we took advantage of the fact that the distortion of the spectrum by a pileup-rejection system is count-rate dependent, so a comparison of data taken at different count rates gives a measure of the distortion. In this analysis, we plotted area γ ray (high count rate)/area γ ray (low count rate) against γ ray energy and looked for deviations from a constant.

Pileup rejection was used only in the ^{34}Cl and ^{31}S experiments.

4. Data Analysis Techniques

This section is a description of the methods used to extract branch intensities and half lives from pulse-height spectra.

(i) Ge(Li) Peak Areas

Analysis of the Ge(Li) data consisted of calculating the areas of peaks in the pulse-height spectrum. Examination of a large peak with a small background (Figure 4) shows the difficulties involved even in defining the peak area:

(1) All Ge(Li) detectors are imperfect in the sense that some of the charge carriers, particularly the holes, are trapped in defects in the crystal. This results in a "tail" in the pulse height spectrum on the low-energy side of the peaks.

(2) To achieve good energy resolution, long time constants ($2\ \mu\text{s}$ or $4\ \mu\text{s}$) must be used on the shaping amplifier. This enhances pulse pileup which puts a tail on the high-energy side of the peaks.

(3) There is a "step" in the background beneath the peak which results in the low-energy "background" being higher than the high-energy "background." The enhancement in the low-energy background is due to γ rays which Compton scatter in the Ge(Li) detector two or more times but which are not finally absorbed in a photoelectric event.

Many authors solve these problems by fitting the peaks in the pulse height spectra with Gaussians, or Gaussians with exponential tails, and step functions (or arctangents or arccosines) plus quadratics or cubics for the background using a non-linear least squares fitting program (for an example, see Robinson, 1970). In these cases the area is one parameter calculated in the fit. While this is a more powerful approach, we have

not found it necessary to use a system with such complexity. Except where the background was strongly curved, we used the following simple method which could be used on the ND812-ND4420 computer system in the tandem accelerator laboratory:

(1) The computer produced an estimate of the FWHM (Full Width at Half Maximum) in channels for the peaks in the spectrum. If pulse pile-up was not important (less than a few percent of the peak area), then a window width of 2.2 to 2.5 x FWHM for each peak was used. Where a pile-up due to a high count rate was a problem, a single window width at least 2xFWHM of the widest peak in the spectrum was used in the analysis of all the peaks. This ensured that the fraction of the counts that would have appeared in the peak in the absence of pileup that actually appeared in the peak window and in the high-energy-background window did not change from peak to peak (see below for definitions of the windows).

(2) A region of one window width centered on the peak was integrated (call this area A).

(3) Two regions with the same width but separated from the peak window by one channel were integrated to provide estimates of the background above and below the peak (areas B_1 and B_2).

(4) The area of the peak was calculated with the formula

$$\text{area} = [A - \frac{1}{2}(B_1 + B_2)] \pm \sqrt{A + \frac{1}{4}(B_1 + B_2)}$$

Modifications were made whenever another peak interfered with the background estimates and for some small peaks wider background windows were used. A choice of 2.2 to ~2.5 x FWHM means that 98.6 to 99.7% of the peak is included if we assume a Gaussian peak shape.

Where the background was more complex, linear least squares fitting was used to produce a function describing the background (but not the peak). This function was then evaluated in the peak region and the counts above background summed to obtain the area. In the case where the simpler method and the background-fitting method were compared, the peak areas calculated differed by less than 2% and the peak area ratios were in agreement.

As long as a consistent method is used to calculate peak area, the degree of sophistication should be only a minor source of error in the extracted area ratios. In our case, whatever small errors are made in peak areas in the β decay spectra are also made in the calibration spectra, so the relative efficiencies measured are really the relative efficiencies when peak areas are measured this way. We estimate that errors $<1\%$ were incurred from this source.

(ii) Least Squares Fitting

Least-squares fitting of decay-curve data was required to decompose the decay curve for the 511-keV-peak area into a sum of components with various half lives and also to extract half lives from γ ray decay data.

The basic techniques used were matrix inversion for linear least squares fits and iterations for the non-linear fits (see, for example, Bevington (1969) for mathematical details). The only unusual aspect of the fitting was our treatment of the dead time and pileup losses which distort a decay curve.

If the analyzer is dead for a time δ each time it converts a pulse height to a number and pileup occurs whenever two pulses occur within a

time ϵ of each other, then it can be shown that for a total pulse rate A , the fraction of pulses in a peak actually appearing in the spectrum produced by the ADC is

$$\alpha = \frac{1}{e^{A\epsilon} + A\delta}.$$

The next step in our analysis was to assume that the true pulse rate could be represented by a constant plus a short lived part with mean life $1/\mu$:

$$A(t) = A_0 + A_1 e^{-\mu t}$$

Since we always worked at relatively low count rates where the total loss rate was ~10% to 20% at the start of counting, it was felt that an expansion of the loss rate, α , to second order in the count rate would be adequate. After a little algebra, then, α can be cast in the form

$$\alpha(t) = h_0 + h_1 e^{-\mu t} + h_2 e^{-2\mu t}$$

At first glance the error in this expression would appear to be $\sim A_1^3(\epsilon+\delta)^3$. In fact the parameters h_1 and h_2 can be adjusted so the maximum error is $\sim 0.05 A_1^3(\epsilon+\delta)^3$ (i.e., a quadratic function can approximate a cubic function over a small interval with a small error).

In our experiments, a pulser with a known frequency was fed into the detector preamp and then the pulser peak was collected in the sequential spectra, each lasting a dwell time Δt . If P is the number of pulses sent to the preamp from the pulser during each group, then, according to the preceding analysis, the pulser peak area in group n , P_n , can be fit by the function

$$P_n = P(f_0 + f_1 e^{-n\mu\Delta t} + f_2 e^{-2n\mu\Delta t}).$$

The parameters f_v are related simply to the parameters h_v . We now use the parameters f_v to calculate dead time and pileup corrections to the areas of the other peaks in the spectrum. This approach helps to smooth variations in the area of the pulser peak and allows corrections to be made for the fact that the count-rate-dependent losses can change substantially within a group when the dwell time is comparable to the half life of the dominant short lived radioactivity and that peaks with different decay rates therefore show different fractional losses. It has the disadvantage that, because the parameters f_v have statistical uncertainties, peak areas corrected for dead time and pileup are no longer statistically independent quantities. The small correlations introduced this way were taken into account by the fitting programs.

III. EXPERIMENTAL RESULTS

In this chapter we discuss the features of each experiment that were not included in the previous chapter, summarize the results of our experiments, and compare these results to previously reported measurements and to theoretical calculations. Results are reported for the Gamow-Teller β decays of ^{25}Al , ^{26}Si , ^{30}S , ^{31}S , ^{33}Cl , ^{34}Cl and $^{34\text{m}}\text{Cl}$, ^{35}Ar , and ^{38}Ca . Because ^{30}S decays to ^{30}P , we are also able to report new upper limits on three branches in ^{30}P decay.

1. ^{25}Al Decay

This decay, illustrated in Figure 5, was studied in this laboratory in 1974 and reported by Mann et al. (1976) who measured the intensities of the daughter γ rays relative to the 1612-keV intensity, but did not measure the absolute intensity of this γ ray. In order to obtain absolute intensities, they used the value $(8.4 \pm 0.7) \times 10^{-3}$ for the absolute intensity of the 1612-keV γ ray which had been reported by Jundt et al. (1971).

We have measured the absolute intensity of the 1612-keV γ ray by measuring the decay of the 511-keV radiation in 8 consecutive groups each lasting 5 seconds and comparing the 7.183-second component to the 1612-keV γ ray. The technique is described in detail in the previous chapter. The ^{25}Al was produced by the $^{24}\text{Mg}(d,n)^{25}\text{Al}$ reaction in targets of 99.96% enriched ^{24}Mg metal evaporated on 0.25 mm Ta backings. These targets were mounted in Be rabbits. Enriched ^{24}Mg was chosen as the target material to prevent the production of ^{26}Al which has almost the same half life as ^{25}Al , and would have complicated the extraction of the component of the 511-keV radiation with the ^{25}Al half life (7.183 ± 0.012 sec, Endt and Van der Leun, 1978).

Five measurements were made of the absolute intensity of the 1612-keV γ ray, three using a large lucite hutch to stop the ^{25}Al positrons plus a 0.64 cm Pb absorber, one run using an aluminum hutch plus 0.64 cm Pb and one using the aluminum hutch plus the Pb and an extra 1.90 cm of lucite between the Pb and the detector. The results obtained in the three geometries were in good agreement with each other, giving a weighted average of $(7.76 \pm 0.28) \times 10^{-3}$ for the absolute intensity of the 1612-keV

γ ray. We were careful to separate errors that were common to all of our measurements from the independent errors and to average only the independent errors. The common errors were the uncertainty in the relative intensities of γ rays from ^{56}Co (used to measure relative efficiencies) and the uncertainty in positron efficiencies introduced by positron scattering from the Ta target backings. Table 1 lists the measurements of the absolute intensity of the 1612-keV γ ray that have been reported and the weighted average. Table 2 shows the results of Mann et al. but calculated with the new value of the branch to the 1612-keV level. The error in the relative intensities of ^{56}Co γ rays given by Camp and Meredith (1971) has been taken into account by applying the correction formula suggested by McCallum and Coote (1975). The experimental results are compared to the shell-model calculations of Brown et al. (1978) and Timmer et al. (1978). Results for both calculations were obtained using the free nucleon value for the axial coupling constant, $g_A/g_V = 1.250 \pm 0.009$, and the vector coupling constant deduced from superallowed pure Fermi decays by Hardy and Towner (1975). Note that we have extracted the value of $\log ft$ for the Gamow-Teller part of the ground-state transition, taking advantage of the well-known Fermi matrix element between $T=1/2$ isobaric analog states ($|M_F|^2 = 1$), in order to facilitate a significant comparison with theoretical calculations.

Both calculations used a large shell-model basis and an effective Hamiltonian obtained by adjusting the matrix elements of the residual interaction so that the calculated energy levels of s-d shell nuclei matched the experimental spectra as well as possible. Consequently, the agreement between the two calculations is not surprising. The agreement

with experiment in both cases is quite good. We have not used the values of $\log ft$ calculated by both groups in which the value of g_A/g_V was changed in order to improve agreement with experiment, as we wish to emphasize any errors arising from the use of the multiparticle shell model and an unrenormalized axial coupling constant.

2. ^{26}Si Decay

The ^{26}Si was made in a solid natural magnesium rabbit by the ^{24}Mg (^3He , n) ^{26}Si reaction. In the first part of the experiment, the intensities of the ^{26}Al γ rays were measured relative to the sum of all ^{26}Al γ rays. Because we were looking only for high energy γ rays and because the ^3He bombardment of natural magnesium copiously produces positron emitters other than ^{26}Si (via the reactions $^{24}\text{Mg}(^3\text{He}, \alpha)^{23}\text{Mg}$, $^{24}\text{Mg}(^3\text{He}, p)^{26}\text{Al}$, $^{24}\text{Mg}(^3\text{He}, pn)^{25}\text{Al}$, $^{25}\text{Mg}(^3\text{He}, n)^{27}\text{Si}$), we used a 3.2 cm Pb absorber between the Ge(Li) detector and the radioactivity. The decay is illustrated schematically in Figure 6 and Ge(Li) spectra from this experiment are shown in Figures 7 and 8.

Unlike previous workers, we were not interested in verifying the CVC predictions of the decay rate for the superallowed Fermi transition connecting the 0^+ ground state of ^{26}Si to the 0^+ state at 228 keV in ^{26}Al . We therefore followed the program described in the previous chapter which assumes the CVC theory and purity of isospin and measured the half life of ^{26}Si by analyzing the decay of the intensity of the strong 829 keV γ ray. By using a leaky integrator to control the termination of the bombardment period, we were able to ensure that the same amount of ^{26}Si was observed by the detector in each cycle. Following the return of the rabbit to the detector, data were accumulated in sixteen consecutive groups, each lasting 0.8000 ± 0.0003 sec (or about one third of a half life of ^{26}Si). A pulser and frequency meter were used to measure the group dwell time. We made five runs at slightly different count rates and analyzed them separately. The data from one of the runs are shown in Figure 9. The five independent results for the half life of ^{26}Si showed

good agreement with each other so the error quoted for the half life of ^{26}Si is just the "internal error." Our final result for the half life of ^{26}Si , namely the weighted average of the results of five independent measurements, is 2.240 ± 0.010 sec. Table 3 lists the previously measured values of the ^{26}Si half life, and the "best value" that is deduced from them. The value of 2.2345 ± 0.0090 sec was used in further calculations. The partial half life for the superallowed Fermi branch to the 228 keV state in ^{26}Al was calculated to be 2.978 ± 0.014 sec using the radiative and Coulomb corrections presented by Hardy and Towner (1975) and by Raman et al. (1975) and correcting the values of f_β in these papers to take into account the improved Q values available in 1979.

The relative intensities of daughter γ rays measured in the first part of the experiment are shown in Table 4 along with the relative intensities from Hardy et al. (1975), Moss et al. (1971) and Kavanagh (1969). We include an error in the normalizing 829 keV γ ray in order to maintain independent errors in the other relative intensities. Our upper limits are 2σ confidence intervals (98% confidence).

The absolute branches deduced from the relative intensities and the values of $\log ft$ are presented in Table 5. Where a γ ray was not observed and only an upper limit could be given for its intensity, we assumed it was zero and did not increase the uncertainties in the other branches to take it into account.

The branches in Table 5 are based only on our work. In spite of the difference between our relative intensity for the 1622-keV γ ray and that given by Hardy et al. (1975), we choose to adopt our value alone.

Measurement of the peak area of the 1622 keV γ ray is complicated in our experiment by the 1612 keV γ ray due to ^{25}Al formed in the target, presumably by $^{24}\text{Mg}(^3\text{He},\text{np})^{25}\text{Al}$ and $^{25}\text{Mg}(^3\text{He},\text{t})^{25}\text{Al}$, and by the curved background due to Compton scattering of 1778 keV γ rays from ^{28}Al β^- decay. We were very careful to take these effects into consideration. Because our high-energy data were collected in two groups of 2.3 sec, we were able to make two independent measurements of the ratio of the area of the 1622 keV peak to the area of the 829 keV peak. For group 1, the area ratio was 0.2380 ± 0.0012 while for group 2 it was 0.2348 ± 0.0020 . For comparison, an area ratio of 0.255 would correspond to a relative intensity of 0.134, as reported by Hardy et al., for the 1622 keV γ ray. The 1622 keV photopeak is illustrated in Figure 8.

The values of $\log ft$ given in Table 5 are based on the $\log f$ tables of Gove and Martin (1971) and include the radiative corrections recommended by Hardy and Towner (1975). We emphasize again that the absolute branch to the 228 keV state was not measured directly, but rather that the CVC value for the partial half life of the analog transition was used to normalize the absolute intensities of the excited state branches.

The theoretical references quoted in Table 5 are the references already cited for ^{25}Al decay. The same comments apply here as were made in the section on ^{25}Al . Both calculations use a large shell-model basis: Timmer et al. (1978) used a basis of the 300 pure s-d shell configurations believed to lie lowest in energy while Brown et al. (1978) did not truncate the shell-model basis at all. The agreement between the two calculations is not as good as it was for ^{25}Al , but both calculations predict about the right strength for the two intense Gamow-Teller transitions.

Again, we have used the unrenormalized values of the axial coupling constant to recalculate values of $\log ft$ of Timmer et al. and we have used the unrenormalized calculations of Brown et al.

3. ^{30}S Decay

This decay is illustrated in Figure 10. The radioactivity was made by ^3He bombardment of natural silicon targets mounted in aluminum rabbits. The experiment was performed in the same manner as the ^{26}Si experiment described in the previous section.

In the first part of the experiment, the intensities of the daughter γ rays were measured relative to the intense 677 keV γ ray following the superallowed Fermi branch in the decay. For this part of the measurement, 1.9 cm of Pb absorber was used to attenuate the intense 511 keV radiation emitted by the various positron activities in the target. Spectra were collected in two consecutive groups of 1.3 and 1.4 sec. Efficiency calibrations for this experiment were done with ^{56}Co and ^{207}Bi sources. A $^{14}\text{N}(p,\gamma)^{15}\text{O}$ calibration using 1.9 cm of Pb extended the relative efficiency to 5.24 MeV. The references used for the relative γ ray intensities for these sources are given in the previous chapter.

Because of the thick Pb absorber, the calculation of the relative photopeak efficiencies for the 677 and 709 keV γ rays, emitted in the decay of ^{30}S , presented some difficulties. The interpolation of the relative efficiencies was carried out assuming that the relative efficiency of the shielded detector for photons with energy E_γ was given by the following expression:

$$\text{eff}(E_\gamma) = \frac{A}{E_\gamma^\alpha} \int_{\text{detector}} T_0^{1/\cos\theta} (1 - e^{-\lambda(\theta)\mu}) \sin\theta \, d\theta$$

The integral on the right hand side of this expression is just the integral evaluated in calculating absolute total efficiencies: T_0 is the total transmission probability for a photon travelling toward the

detector along the detector's axis, $\ell(\theta)$ is the thickness of germanium seen by a photon emitted at an angle θ to the detector's axis and μ is the attenuation coefficient of photons with energy E_γ in germanium. The constants A and α were adjusted to match the measured relative efficiencies of 570 and 847 keV. Extrapolation to 1 MeV gave good agreement with the measured relative efficiency so we had confidence in this expression's ability to predict the 677 and 709 keV relative efficiencies.

Figure 11 shows a spectrum collected in this experiment. We have identified all of the peaks in the spectrum with the exception of a small peak appearing at 456 keV. Figure 12 shows detailed spectra of some of the ^{30}S peaks. The relative intensities of the daughter γ rays are presented in Table 6.

The ground state branch in the γ decay of the 3019 keV state of ^{30}P was detected in this experiment. The contribution to the photopeak from summing of 677 keV and 2341 keV photons has been subtracted (this was a small correction because the absolute photopeak efficiency at 677 keV with 1.9 cm of Pb absorber is only $(6.4 \pm 0.6) \times 10^{-4}$).

We calculated γ ray intensities for only those β transitions which Endt and Van der Leun (1978) show to be allowed or where they make no firm spin-parity assignment for the final ^{30}P state. We discuss differences with earlier work below.

The absolute intensity of the superallowed Fermi branch to the 0^+ state at 677 keV was determined by measuring the half life of ^{30}S following the procedures discussed in the previous chapter. For the half life measurement, data were collected in 16 consecutive groups of 0.4000 ± 0.0001 sec ($\sim 1/3$ of a ^{30}S half life). Dead time and pileup

losses were monitored by including in the spectra a pulser with a known frequency.

The half life was extracted from the data by correcting the areas of the 677 keV peak for dead time and pileup losses and then fitting to an exponential. Five runs were made with only slight differences (up to 30%) in count rate and a sixth run was taken at about twice the count rate of the other five (see Figure 13). The internal agreement of the six results for the ^{30}S half life was reasonably good, with the weighted average of 1.1783 ± 0.0039 sec. having $\chi^2 = 6.65$ for 5 degrees of freedom. Because the probability of $\chi^2 \geq 6.65$ is only 25%, we increase the uncertainty by a factor of $\sqrt{6.65/4.35}$ where 4.35 is the 50% point of the χ^2 distribution for 5 degrees of freedom. We therefore conclude that our data indicate a half life of 1.1783 ± 0.0048 sec. Table 7 lists this value, the previously reported values and the adopted "best value."

The partial half life of 1.5485 ± 0.0067 sec for the superallowed Fermi branch was calculated from the data given by Hardy and Towner (1975) and Raman et al. (1975), with small corrections to the phase space factor f_{β} due to the use of a more recent Q-value.

Table 8 lists the absolute branches deduced from the γ -ray relative intensities and the ^{30}S half life. Where a γ ray was not observed and only an upper limit could be given for its intensity, we assumed it was zero and did not increase the uncertainties in the other branches to take it into account. Where necessary, γ ray branching ratios were taken from Endt and Van der Leun (1978). We also list $\log ft$ values and the predictions of several shell-model calculations.

Our work shows real disagreement on some points with the results of most previous experiments. The relative intensity of the 709 keV γ ray in the experiment is almost a factor of 2 lower than the relative intensity reported by Kavanagh (1969) and the difference between the two values, $(3.5 \pm 2.3) \times 10^{-3}$ is likely to occur by chance less than 14% of the time. We display the large peaks in the spectra in Figure 12. These data show no need for a curved background in the region from channel 556 to channel 577 which was used to determine the net area of the 709 keV peak. Because our results are much more precise, we have used only our result in calculating the absolute branch.

Similar comments apply to the relative intensity of the 2341 keV γ ray emitted in the γ decay of 3019 keV state in ^{30}P . Here we agree with Kavanagh (1969) but disagree with Moss et al. (1971). Again we use the result of the present work only because it is much more precise than previous results.

One potential source of systematic error is the relative efficiency calibration of the Ge(Li) detector. We have already discussed our procedures in detail. In particular, we point out that the use of the ^{207}Bi source with its 570 keV γ ray allows us to interpolate in order to obtain the relative efficiency at 677 and 709 keV. Moss et al. give no details on the procedures used to calibrate their detector, but they state that they used only ^{56}Co and ^{66}Ga sources. In this case they would have had to extrapolate the relative efficiency from 847 keV which is the lowest-energy intense γ ray emitted by ^{56}Co . Their spectra suggest that very little absorber was used to reduce the intensity of the 511 keV radiation, so the relative efficiency probably had not departed very much from a

simple power law in E_γ , but an error of 5-10% is quite reasonable. An error of this magnitude would bring their results into agreement with this work.

The third large disagreement concerns the half life of ^{30}S (see Table 7). We begin by ignoring the results of Johnson et al. (1960), Robinson et al. (1961) and Frick et al. (1963) because of their large errors and the difficulties involved in these early experiments. Barker et al. (1967) and Moss et al. (1971) show good agreement with the remaining high precision measurements. Of the three high precision measurements, Kavanagh (1969) is in serious disagreement with the results of this work and of Schmeing et al. (1974). It seems unlikely that we would have made exactly the same systematic error as Schmeing et al. or that systematic errors would be largely count rate independent (we varied the count rate a factor of two). We therefore reject Kavanagh's result and use the weighted average of this work and Schmeing et al.

We note that this work disagrees with the measurement of Frick et al. (1963) for the relative intensities of the ground state and 677-keV branches. Using the same equipment and techniques, these authors also underestimated the intensity of the ^{26}Si branch to the 228 keV level in ^{26}Al relative to the branch to the 1058 keV level by several standard deviations (their result was $(\text{intensity } 228 \text{ keV branch})/(\text{intensity } 1058 \text{ keV branch}) = 1.94^{+0.09}_{-0.31}$ compared to the more recent values 3.44 ± 0.15 (Endt and Van der Leun, 1978) and 3.43 ± 0.07 (this work)). Therefore we conclude that this disagreement is neither an argument for nor against our results.

If isospin symmetry were perfect in the A=30 nuclei then the 0^+ ground states of ^{30}Si and ^{30}S would be perfect analogs of each other and the Gamow-Teller strengths connecting these states to the 1^+ ground state of ^{30}P would be identical apart from a statistical spin factor of $2J_f + 1$. I.e., log ft value for the transition $^{30}\text{P}(\beta^+)^{30}\text{Si}(\text{gs})$ would be related to log ft for the transition $^{30}\text{S}(\beta^+)^{30}\text{P}(\text{gs})$ by

$$\log ft (^{30}\text{P} \rightarrow ^{30}\text{Si}) = \log ft (^{30}\text{S} \rightarrow ^{30}\text{P}) + \log 3.$$

If the half life reported by Kavanagh (1969) and the branching ratio reported by Frick et al. (1963) are used to deduce log ft values, then the Fermi branch to the 677 keV state is in agreement with CVC and the Gamow-Teller branch to the ground state shows mirror (i.e., isospin) symmetry with the branch to the ground state of ^{30}Si from ^{30}P . Using our half life and the CVC value for the partial half life of the superallowed Fermi branch, we obtain $\log ft = 4.327 \pm 0.012$ for the branch to $^{30}\text{P}(\text{gs})$. If isospin symmetry holds, then the Gamow-Teller branch to the ground state of ^{30}Si should have $\log ft = 4.804 \pm 0.012$. The measured value for this branch using the data in Endt and Van der Leun (1978) is $\log ft = 4.840 \pm 0.006$ which is $8.7 \pm 3.4\%$ slower than mirror symmetry requires. Actually this is not unreasonable given the departure from isospin symmetry expected in the A=30 nuclei (see δ_C calculated by Hardy and Towner (1975) and Raman et al. (1975)), and the weakness of this decay ($|M_{GT}|^2 = 0.063$).

The agreement between experimental values of log ft and the predictions of shell-model calculations is quite poor for this decay (see Table 8), although the excitation energies of the daughter states

were predicted with reasonable success in all three cases. Glaudemans et al. (1971) and Lanford and Wildenthal (1973) used shell-model wavefunctions calculated by Wildenthal et al. (1971a) who studied the $A=30-35$ nuclei using a shell-model space consisting of all configurations of the form $(0d_{5/2})^{n_1}(1s_{1/2})^{n_2}(0d_{3/2})^{n_3}$ with $n_1 \geq 10$ (i.e., up to two holes were allowed in a "closed" ^{28}Si core). Two sets of wavefunctions were calculated by Wildenthal et al. using slightly different 2-body interactions.

The first set of wavefunctions, used by Glaudemans et al., was obtained using an effective interaction derived from a modified surface-delta interaction (MSDI). The second set (used by Lanford and Wildenthal) was obtained by adjusting the matrix elements of the effective interaction calculated with the MSDI to improve agreement with experiment (this was labelled the free-parameter surface-delta interaction or FPSDI). It is thus not surprising that the two calculations agree quite well with each other. Also, it should be added here that M1 and E2 γ -transition rates calculated with these wavefunctions also fail to agree with experiment.

More surprising is the failure of Brown et al. (1978) to show better agreement with experiment. They used a full $1s-0d$ model space and an effective interaction obtained by adjusting all 63 matrix elements defining the $1s-0d$ shell 2 particle interaction to obtain best agreement with excitation energies in the heavier half of the $1s-0d$ shell.

The results of Engelbertink and Brussaard (1966) which assumed a closed ^{28}Si core have not been included here.

Our limits on transition rates to states above 3.9 MeV in ^{30}P do

not provide any really useful constraints on the Gamow-Teller matrix elements except to say they are weaker than the very strong branch to the 3019 keV level.

4. ^{30}P Decay

The reaction of ^3He with natural silicon also produces ^{30}P via the reactions $^{28}\text{Si}(^3\text{He},\text{p})^{30}\text{P}$, $^{30}\text{Si}(^3\text{He},\text{t})^{30}\text{P}$ and by the β^+ decay of ^{30}S . Therefore the spectra taken in the study of the relative intensities of ^{30}S γ rays were also analyzed to obtain the relative intensities of γ rays emitted in ^{30}P β^+ decay. It appears that this is the first study of this decay in which an intense source of ^{30}P made possible a search for electron capture transitions to ^{30}Si states above 2.3 MeV.

Figure 14 is a level diagram illustrating this decay. Table 9 lists the relative intensities of the ^{30}P γ rays and Table 10 lists the absolute intensities of the branches to all of the accessible states in ^{30}Si . We did not measure the absolute intensity of the branch to the 2235 keV 2^+ state but, rather, used the value of $(6.9 \pm 1.2) \times 10^{-4}$ given by Endt and Van der Leun (1978).

The agreement between the theoretical values for $\log ft$ and the experiments is, as for ^{30}S decay, poor. The references quoted are the same ones quoted for ^{30}S decay in the previous section. We have ignored an earlier shell-model calculation which used a model space which allowed no holes in the ^{28}Si core (Engelbertink and Brussaard, 1966).

5. ^{31}S Decay

The decay is illustrated in Figure 15. We were searching for the electron-capture branches to states at 4.26 and 4.59 MeV which would be detectable only if they were very strong.

The radioactivity was made by the $^{31}\text{P}(\text{p},\text{n})^{31}\text{S}$ reaction with 11.0 MeV protons in targets of MnP powder wrapped in 25 μm Ta foil and mounted in Be rabbits. A Pb absorber 1.9 cm thick attenuated the 511 keV radiation. Data were collected in two consecutive 4096-channel spectra each lasting 2.5 sec. The sum of all spectra taken in the first 2.5 sec group is shown in Figure 16 and detailed spectra of the ^{31}S γ ray peaks are shown in Figure 17. A preliminary run showed that the major source of high-energy background was two-pulse pileup in the shaping amplifier so a pileup-rejection system was used for these measurements (see the previous chapter for a description of this system). We were careful to adjust the discriminator threshold so that no peaks appeared in the spectrum of rejected pulses. Also, two calibrations were made with a ^{66}Ga source at count rates differing by a factor of two. From these data, the ratio of peak area in the high-count-rate calibration to peak area in the low-count-rate spectrum was calculated for each strong peak in the ^{66}Ga spectrum. The ratios, shown in Figure 18, for 14 peaks from 1039 to 4807 keV were consistent with a constant independent of pulse height ($\chi^2 = 12.7$ for 13 degrees of freedom). Therefore we conclude that the pileup-rejection system did not seriously distort the relative efficiencies in a count-rate-dependent way.

The relative-efficiency calibrations were made using a ^{66}Ga source produced in a target of ZnP identical to the targets used in the experiment.

Relative intensities for the ^{66}Ga γ rays were taken from Camp and Meredith (1971) applying the correction factor given by McCallum and Coote (1975). Also a $^{14}\text{N}(\text{p},\gamma)^{15}\text{O}$ efficiency calibration was performed with 1.9 cm of Pb to extend the relative photopeak efficiency to 5.24 MeV and 8.28 MeV. Relative intensities for the ^{15}O γ rays were taken from Evans et al. (1966).

The relative γ ray intensities measured in our experiment are listed in Table 11. They show good agreement with the previous results of Détraz et al. (1971).

The absolute intensity of the 1266-keV γ ray was also measured by comparing the intensities of the 1266-keV γ ray and the positron annihilation. As in the relative intensity measurement, the ^{31}S activity was made by the $^{31}\text{P}(\text{p},\text{n})^{31}\text{S}$ reaction in targets of MnP powder mounted in beryllium rabbits. The detector geometry consisted of a large block of lucite which slowed and trapped the positrons escaping from the rabbit and 0.64 cm of Pb which absorbed about 60% of the annihilation radiation. By collecting spectra in several consecutive groups using the multispectral scaler, the component of the 511-keV peak due to the short-lived ^{31}S (~2.6 sec half life) activity could be separated from longer lived contaminants such as ^{11}C , ^{13}N , and ^{14}O . Two cycles were used to collect data: three runs were made with eight consecutive groups each lasting 2.000 sec and two runs were made with sixteen groups each lasting 2.400 sec. Analysis of the last two runs also permitted a determination of the ^{31}S half life (see the discussion of the half life below). A pulser sent 100 pulses per second to the preamp in order to

allow corrections for analyzer dead time and pileup in the shaping amplifier. We used only one detector geometry in this experiment but varied the count rates by a factor of 1.6. The ratio of the 1266-keV peak area to the ^{31}S component of the 511-keV peak area was calculated separately for each of the five runs, and, because the half life of ^{31}S is not well known, for each run the peak area ratio was also calculated for three choices of ^{31}S half life: 2.605 sec, 2.564 sec and 2.543 sec. It was found that the fits to the 511-keV peak area assuming a 2.605 sec half life were poor for all choices of long lived background half lives and for all runs (the best fit obtained had $\chi^2 = 35.3$ for 6 degrees of freedom). It was assumed that the long lived background consisted of 1223 sec ^{11}C , 598.7 sec ^{13}N or 70.6 sec ^{14}O or a combination of these activities since these are the long lived activities made by proton bombardments of C, N and O. The fits assuming that the half life is 2.543 sec were much better, but only one of the fits to the data yielded a χ^2 value small enough that one would expect to exceed it by chance more than 15% of the time. Finally, with the exception of one of the eight group runs, the fits to the 511-keV peak assuming a ^{31}S half life of 2.564 sec were all acceptable (i.e., probability of χ^2 exceeding the values calculated was greater than 25%). One run had $\chi^2 = 21.6$ for 6 degrees of freedom when a 2.564 sec ^{31}S half life was used (probability less than 0.5%). The same run was fit well assuming that the ^{31}S half life is 2.543 sec ($\chi^2 = 5.26$), so these data were retained for further analysis. However, we note that rejecting this run would make a difference of less than 0.5% in the final result.

The ratios calculated for the five runs were in good agreement. It was found that changing the assumed half life of ^{31}S from 2.564 to 2.543 sec changed the ratio of the 1266-keV peak area to the 511-keV peak area from $(5.324 \pm 0.051) \times 10^{-3}$ to $(5.341 \pm 0.052) \times 10^{-3}$. This is a small difference and further calculations use $(5.324 \pm 0.069) \times 10^{-3}$ for the ratio.

The annihilation radiation efficiency relative to the 1266-keV γ ray efficiency was determined using a ^{22}Na source. The effects on the 511-keV intensity of distributed source, in-flight annihilation and absorption of annihilation radiation in the various parts of the lucite positron stopper and rabbit were calculated by a computer program as described in the previous chapter. Small corrections were also made for summing of annihilation radiation with the 1266-keV radiation and electron-positron pair production by high energy in-flight-annihilation photons (the latter was estimated to be $0.5 \pm 0.3\%$). From these calculations and the measured ratio of peak areas it is concluded that the absolute intensity of the 1266-keV γ ray emitted in the decay of ^{31}S is $(1.087 \pm 0.021) \times 10^{-2}$.

The intensity of the 1266-keV γ ray has been measured several times and previous results are listed in Table 12. All of the measurements agree with each other except for those reported by Alburger (1974) and this work which differ by 2.6 standard deviations. The probability that a difference this large or larger would occur by chance in a sample of four measurements is only 6.2% so it is quite likely that either Alburger or we have made a systematic error. The weighted average of the four measurements included in Table 12 is $(1.103 \pm 0.019) \times 10^{-2}$ with

$\chi^2 = 6.96$ for 3 degrees of freedom. Since a value of χ^2 this large or larger is expected less than 8% of the time, the uncertainty in the final value has been increased by a factor $\sqrt{6.96/2.37}$ where $\chi^2 = 2.37$ is the 50% point of the χ^2 distribution for 3 degrees of freedom. Consequently, we adopt the value $(1.103 \pm 0.033) \times 10^{-2}$ for the absolute intensity of the 1266-keV γ ray. A fifth measurement of the absolute intensity has been reported by Détraz et al. (1971). Their value of $(0.8 \pm 0.4) \times 10^{-2}$ was given as a rough value only and they did not use it in further calculations in their paper.

The areas of the 511-keV peak in the two runs taken with sixteen groups of 2.400 sec were also analyzed to determine the half life of ^{31}S . Since the group length is comparable to the half life, we were very careful to take into account the effects of the change in count rate dependent losses within each group. A leaky integrator was not used to ensure that the same amount of activity was made on each bombardment of the target, but we did monitor the count rate and because the beam intensity was stable, the count rate varied less than $\pm 15\%$ from cycle to cycle. The ^{31}S activity was quite pure, accounting for 99.4% of the area of the 511-keV peak in the first 2.4 sec group in the first run and 99.1% in the second. As a result, we were unable to determine the half life of the long lived background since the decay was followed for only 14 half lives. To overcome this problem, the half life of the ^{31}S component of the 511-keV peak was calculated four times for each run assuming that the background was due to (1) ^{11}C (1223 sec half life), (2) ^{13}N (599 sec), (3) ^{14}O (70.6 sec) or (4) ^{11}C and ^{14}O . These are the only intense activities likely to be made on C, N and O contaminants in the target. Poor fits

for both runs were obtained with the ^{14}O background but the other three yielded good fits and, not surprisingly, the same value for the half life of ^{31}S . Also, the possibility that other short lived activities were contributing to the 511-keV radiation was investigated by fitting both runs with a ^{13}N background (599 sec half life) and one of ^{35}Ar (1.773 sec), ^{27}Si (4.16 sec), ^{23}Mg (11.317 sec) or ^{19}Ne (17.219 sec) and then determining the value of the ^{31}S half life giving the best fit. By applying the F-test to the best fit values of χ^2 with and without the extra short lived component (Bevington, 1969; p. 195), it was determined that including a ^{35}Ar component in the first run and a 4 to 20 second half life component in the second run gave marginally significant improvements in the fits. Because no single component improved both fits, it was concluded that significant amounts of short lived activities other than ^{31}S were absent. The first run was done at an average count rate of 10500 pulses per second at the start of the first group while the count rate was reduced to 8000 per second in the second run in order to see if there was a strong count rate dependence in the results. The half life of ^{31}S deduced from the higher-count-rate run is 2.562 ± 0.008 sec and from the lower-count-rate data 2.562 ± 0.010 sec. Thus our data indicate a half life of 2.562 ± 0.007 sec for ^{31}S .

Ten values of the half life of ^{31}S have been published in the past 30 years and they are summarized by Endt and Van der Leun (1978). The notable point is the very poor agreement of the measurements, implying significant systematic errors. We reviewed all of these measurements before calculating a "best" value for the half life, accepting five of the values which are included in Table 13 along with the result of this work and rejecting five others for the following reasons. Haslam et al.

(1952) reported a half life of 2.66 ± 0.03 sec but did not discuss the measurement in detail except to outline the method of dead time corrections. We reject this measurement because the count rate was so high at the start of the counting sequence that dead time corrections of ~100% had to be applied. This is a poor procedure generally, but it was made worse because they calibrated the high count rate response of their apparatus with a ^{62}Cu source which they believed had a half life of 10.1 minutes rather than the best estimate presently available of 9.73 ± 0.02 min. Since the true count rate in the calibration run was calculated from the intensity of the source after it had decayed to a much lower count rate where the dead time effects were negligible, the error in the half life of ^{62}Cu means that they certainly underestimated the magnitude of the dead time correction in their system. The results of Cline and Chagnon (1958), Mihailović and Povh (1958), Jänecke (1960) and Wallace and Welch (1960) were rejected because, in each case, the authors had measured at least seven other positron half lives with the same equipment and techniques and these other half lives differed significantly from the best estimates available in 1979. (See Endt and Van der Leun, 1978, and Tables of Isotopes, Seventh Edition, Lederer (ed.), 1978.) To be specific, Cline and Chagnon reported seven other half lives, one of which, ^{38}Ca was in error by a factor of 1.52 ± 0.12 , but could be explained by $^{38\text{m}}\text{K}$ and ^{39}Ca contamination in the target. The other six had a root-mean-square error of 3.3 standard deviations. Mihailović and Povh reported an additional seven half lives with an rms error of 6.8 standard deviations. Jänecke's extra fifteen measurements had an

rms error of 4.0 standard deviations and Wallace and Welch's additional ten measurements had an rms error of 1.67 standard deviations. Wallace and Welch also reported a half life of 0.87 ± 0.05 sec for ^{41}Sc (the present best estimate is 0.5963 ± 0.0017 sec (Endt and Van der Leun, 1978)), but this could be due to $^{38\text{m}}\text{K}$ contamination in their source. As shown in Table 13, the weighted average of the measurements is 2.5617 ± 0.0048 with $\chi^2=24.8$ for 5 degrees of freedom which has a probability of $<0.5\%$ of occurring by chance. The scatter is taken into account by multiplying the error on the weighted average by $\sqrt{24.8/4.35}$ where the probability of $\chi^2>4.35$ is 50% for 5 degrees of freedom. Consequently, the weighted average of the six measurements of the ^{31}S half life is taken to be 2.562 ± 0.012 sec.

Table 14 lists the absolute intensities and log ft values for the six allowed β^+ and electron-capture branches in this decay and compares to theoretical values predicted by shell-model calculations. Again, because of the higher precision of this work, only our relative γ ray intensities are used to calculate absolute branch intensities to the state above 1266 keV. Only the values of log ft calculated with the unrenormalized axial coupling constant are quoted and the values tabulated by Glaudemans et al. (1971) and by Lanford and Wildenthal (1973) have been recalculated using the coupling constants available in 1979. The references quoted here are the references cited in the discussion of $^{30}\text{S}(\beta^+ \gamma)^{30}\text{P}$ and here, too, agreement between experiment and theory is

not good for Glaudemans et al. and for Lanford and Wildenthal who used a restricted model space and slightly different interactions. It is interesting to note that the full s-d shell calculation of Brown et al., which used an interaction adjusted to match energy levels yields a good prediction for the Gamow-Teller strength to the ground state but that this calculation overestimates the strength of the 3506 keV branch by a factor of 3.2. One final note on this nucleus: in a pure single-particle shell model, the ground states of ^{31}S and ^{31}P would be described as $s_{1/2}$ holes in a ^{32}S closed shell and the Gamow-Teller transition connecting them would have $\log ft=3.12$. Similarly, in this extreme shell model, the Gamow-Teller transition connecting the $1/2^+$ ground state and the $3/2^+$ excited states would be ℓ -forbidden ($s_{1/2}$ to $d_{3/2}$ involves a change of ℓ of two, which cannot be accomplished by the Gamow-Teller operator). Thus the fact that there are large fractional errors in the shell-model predictions must be balanced against the fact that the quantities being measured are very small and are the result of cancellations of several contributions of larger magnitude but with varying sign. In this light, the agreement between experiment and shell-model calculations does not appear to be so poor.

6. ^{33}Cl Decay

This decay is illustrated in Figure 19. Our purpose in performing this experiment was to measure the intensities of several allowed, but previously unreported, branches to excited states in ^{33}Cl above 2 MeV. We also remeasured the absolute intensities of the branches to the 1966-keV and 2866-keV states in a separate experiment.

The relative intensities of the ^{33}S γ rays were measured using intense sources of ^{33}Cl produced by 11 MeV deuterons via the $^{32}\text{S}(d,n)^{33}\text{Cl}$ reaction in thick targets of natural sulfur. Preliminary runs with targets of melted sulfur powder wrapped in 25 μm Ta foil and mounted in Be rabbits were unsuccessful because the sulfur tended to evaporate and to leave the target when bombarded. Therefore gas-tight rabbits in which a 25 μm Ta entrance foil was sealed to the rabbit body were used (see Figure 20). These targets worked very well with the entrance foils lasting for many hundreds of cycles. The only problem was the production of ^{27}Mg and ^{28}Al activities in the 2024-aluminum alloy body of the rabbits by (d,p), (n,p), and (n, γ) reactions.

Data were recorded in two consecutive groups of 2.5 sec each and this made it possible to separate the area of the 840.3 keV peak due to ^{33}Cl from the 843.8 keV peak due to the decay of the ^{27}Mg activity made in the body of the rabbit. For this part of the experiment, the Ge(Li) detector was shielded from the source by a 4.5 cm layer of Pb which absorbed or scattered about 99.9% of the intense annihilation radiation emitted by the source. The relative efficiency calibration was done using a ^{56}Co source mounted in an Al rabbit. Small differences between the

source rabbit and the sulfur rabbit were taken into account in calculating the relative photopeak efficiencies. The ^{56}Co relative intensities were taken from Camp and Meredith (1971) making the correction recommended by McCallum and Coote (1975). Also, the high-energy relative efficiency of the detector had been measured with a 2.54 cm Pb absorber using the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction at a bombarding energy of 1.06 MeV and the relative intensities of Evans et al. (1966). This calibration was adapted to the present geometry by calculating the attenuation of 3.04, 5.24, and 8.28 MeV γ rays in an extra 1.90 cm of Pb using the attenuation coefficients of Grodstein (1957).

The results of the relative intensity measurement are presented in Table 15 and compared to the previous results reported by Bardin et al. (1970). The origin of the discrepancies for the 841-keV and 1472-keV intensities is not clear. Because of the higher precision of this work, only the results of this work are used to calculate the relative intensities of the ^{33}Cl γ rays. Figure 21 shows the 4096-channel spectrum accumulated in group 1 (0.0 to 2.5 sec) and Figure 22 shows detailed spectra of the ^{33}Cl γ rays reported here for the first time. Attention must be drawn to the two especially weak γ rays at 4053 keV and 4746 keV for which values rather than upper limits are given. The evidence for these peaks is weak because distinct photopeaks are not seen. Nevertheless, the net area calculated using a linear background is more than 3.4 standard deviations from zero in both cases and therefore the probability of this happening by chance in these particular regions of the spectrum is less than 0.1% for each peak. Further, the areas in the two groups do not

disagree with each other (i.e., we are not seeing an anomalous bump in one group only). Finally, the centroids of the "peaks" were calculated and they are in agreement with the positrons calculated from the energy calibration and the known energy levels of ^{33}S (note that the last argument is valid only if it is initially assumed that a peak is present, but that it might be due to some other γ ray).

The 2312 keV γ ray also appears in the β^+ decay of ^{14}O (half life = 70.6 sec) which could be made by a low-energy deuteron beam only by the $^{14}\text{N}(\text{d},2\text{n})^{14}\text{O}$ reaction. Experimental cross sections for this reaction have not been reported in the literature, but it has a Q value of -8.15 MeV while the center-of-mass energy of an 11.0 MeV deuteron and a ^{14}N nucleus is only 9.63 MeV. In the presence of other channels available with much larger Q values ($^{14}\text{N}(\text{d},\text{n})^{15}\text{O}$, $Q=5.07$ MeV; $^{14}\text{N}(\text{d},\text{p})^{15}\text{N}$, $Q=8.61$ MeV; $^{14}\text{N}(\text{d},\alpha)^{12}\text{C}$, $Q=13.57$ MeV; $^{14}\text{N}(\text{d},\text{pn})^{14}\text{N}$, $Q=-2.25$ MeV; $^{14}\text{N}(\text{d},2\text{p})^{14}\text{C}$, $Q=-1.60$ MeV; and $^{14}\text{N}(\text{d},\alpha\text{n})^{11}\text{C}$, $Q=-5.14$ MeV) it seems that only a miniscule probability exists for the $^{14}\text{N}(\text{d},2\text{n})^{14}\text{O}$ reaction. Because it was unlikely that the ^{14}O contamination was a significant problem, the relative intensity for the 2312 keV γ ray given in Table 15 was deduced from the data assuming that there was no contribution from ^{14}O decay. A separate analysis of the data, taking advantage of the fact that the spectra were collected in two groups of 2.5 sec, showed that, if a ^{14}O contamination were allowed to contribute to the 2312-keV peak area, then the measured intensity of the 2312-keV γ ray from ^{33}Cl decay relative to the 2866-keV γ ray would be changed to 0.0212 ± 0.0033 from 0.0231 ± 0.0014 . The component of the 2312-keV intensity due to ^{14}O was consistent with

zero in this analysis. Because the de-excitation of the 2312-keV level in ^{33}S is dominated by the cascade through the 841-keV level, emitting a 1472-keV γ ray, the effect of including ^{14}O in the analysis was to reduce the calculated intensity of the branch to the 2312-keV level by $(2.3 \pm 5.6)\%$.

The absolute intensities of the 1966-keV and 2866-keV γ rays were measured in exactly the same way as the absolute intensity of the 1612-keV γ ray in ^{25}Al and as described in the previous chapter. Natural PbS was evaporated onto 0.38 mm thick discs of Ta and then these targets were mounted in Be rabbits, and the ^{33}Cl activity was made by the ^{32}S (d,n) ^{33}Cl reaction. Data were collected in 8 consecutive 1024-channel spectra each lasting 1.8 sec. Because we wanted to be sensitive to the annihilation radiation, only 0.64 cm of Pb absorber was used between the source and the Ge(Li) detector. Three runs were made using the Al hutch and a further run was made with 1.90 cm of lucite placed between the Pb and the detector in order to reduce the effect of the distributed source. The decay curve of the 511-keV peak was fit with components of 2.511 sec (^{33}Cl), 64.6 sec (^{17}F) and 149.9 sec (^{30}P). Of the first three runs, one was rejected because the least squares fit to the decay curve of the 511-keV peak yielded a large value of χ^2 ($\chi^2 = 36$ for 5 degrees of freedom). No systematic trend could be observed in the residuals of the rejected fit so we did not feel that it indicated the presence of some unknown contaminant. The remaining two and the fourth run taken with the extra lucite were then analyzed separately and the absolute intensities of the 1966-keV and 2866-keV γ rays were calculated. Again, analysis of the

841-keV peak was made difficult due to a contaminant peak at 846 keV from the decay of ^{56}Mn produced in the beam-end rabbit hutch. The three results were averaged with care being taken not to average errors common to two or three of the measurements. A rough estimate of the total production of ^{34}Cl (1.58 sec half life) due to $^{33}\text{S}(d,n)^{34}\text{Cl}$ was made and we concluded that it was less than 3.0% of the ^{33}Cl . Assuming 50% errors in all tabulated spectroscopic factors, this could be as much as 70% higher, so the contribution of the ^{34}Cl decay to the 511-keV peak area was fixed as $(2.6 \pm 2.6)\%$ of the ^{33}Cl , and the absolute branches in ^{33}Cl decay were increased by this amount.

The results of this work do not agree very well with the published results of Bardin et al. (1970). They explicitly ignore the reduction in the 511-keV intensity due to in-flight-annihilation of the ^{33}Cl positrons, but our calculations show that 0.9% of the ^{22}Na positrons and 7.0% of the ^{33}Cl positrons annihilated in flight. Taking the relative intensity of the 2866-keV γ ray as 1, this means that their factor for converting relative intensities to absolute intensities should be reduced from $(5.60 \pm 0.59) \times 10^{-3}$ to $(5.26 \pm 0.55) \times 10^{-3}$ (the in-flight-annihilation probability for ^{33}Cl was taken to be $(7.0 \pm 0.5)\%$). Our factor, derived from the 1966- and 2866-keV γ rays is $(4.20 \pm 0.24) \times 10^{-3}$ where, again, care was taken not to add common errors in quadrature nor to include common errors in weighted averages. The weighted average of Bardin et al. and this work is $(4.37 \pm 0.22) \times 10^{-3}$ with a χ^2 of 3.12 for one degree of freedom. The probability of this happening by chance is only 8%, so the uncertainty in the weighted average was multiplied by

$\sqrt{3.12}$ (i.e., if all estimated uncertainties were multiplied by $\sqrt{3.12}$, then χ^2 would be 1 which corresponds to a probability of 32%). Thus the relative intensities in Table 13 are multiplied by $(4.37 \pm 0.39) \times 10^{-3}$ in order to obtain absolute intensities.

Measurements of the half life of ^{33}Cl are reported by Muller et al. (1958), Jänecke (1960), Scanlon and Crabtree (1970), Tanihata et al. (1973) and Azuelos et al. (1977). Muller et al. report a half life of 2.53 ± 0.02 sec for ^{33}Cl but the half lives for $^{26\text{m}}\text{Al}$ and ^{25}Al which were also reported in this paper and which were used as evidence for the corrections of the techniques used in the ^{33}Cl measurement show a root-mean-square error of 1.8 standard deviations from the 1979 adopted values. Therefore we rejected this measurement as unreliable. Jänecke's results have already been discussed and rejected for the same reason. (See the discussion of ^{31}S half life on page 71 of this thesis). The weighted average of the values reported by the remaining three groups (2.47 ± 0.02 sec, 2.513 ± 0.004 sec, and 2.507 ± 0.008 sec respectively) is 2.511 ± 0.004 sec which we use to calculate partial half lives for this decay.

The absolute branch intensities and log ft values for ^{33}Cl decay are shown in Table 16 and are compared to the results of shell-model calculations. Where necessary, γ -ray branching ratios taken from Endt and Van der Leun (1978) were used to calculate β -branch intensities from the γ -ray intensities. When a sum included an intensity for which only an upper limit could be given, the upper limit was replaced by zero and the uncertainty in the sum did not include the uncertainty in the unseen branch. For example, in calculating the total excited-state relative

intensity, the uncertainty in the sum did not include the uncertainties in the branches to the levels at 3832, 3935, 4144, 4375 and 4424 keV.

The agreement between the shell-model estimates and the measured values for the Gamow-Teller rates is surprisingly good. These are the same references quoted in the β decays of ^{30}S , ^{30}P and ^{31}S . First note that the $\log ft$ value for a pure $d_{3/2}$ to $d_{3/2}$ Gamow-Teller transition is 3.82 and for a pure $d_{3/2}$ to $d_{5/2}$ transition it is 3.22, so the observed rates in this nucleus are all reduced at least a factor of 10 from the pure single-particle estimates. Thus the observed matrix elements are the result of a large amount of configuration mixing and one might not expect high accuracy in this case. In fact, the results of Brown et al. (1978) predict the two strong transitions quite well although they miss the transition to the 1966-keV level, which has a Gamow-Teller matrix element of $|M_{\text{GT}}|^2 = 0.041$, by more than a factor of 100 (but the absolute error in $|M_{\text{GT}}|$ is still only 0.188).

The allowed branch to the level at 4746 keV restricts the spin and parity of this state to $1/2^+$, $3/2^+$ or $5/2^+$. There is a $5/2^+$ state in ^{33}Cl at an excitation of 4746 keV (Endt and Van der Leun, 1978) whose isobaric analog in ^{33}S has not been identified previously. Since there are no other candidates for a $5/2^+$ state within 400 keV of the 4746-keV level in ^{33}S , we believe that this makes an identification of the two levels as isobaric analogs correct. In this case, the spin and parity of the 4746-keV level in ^{33}S is $5/2^+$.

7. ^{34}Cl and $^{34\text{m}}\text{Cl}$ decay

These decays are illustrated in Figure 23. Our first purpose in examining these radioactivities was to search for the Gamow-Teller branch from the ground state of ^{34}Cl (0^+ ; $T=1$) to the 1^+ state at 4074 keV in ^{34}S . The data were also analyzed to search for the weak electron-capture branches, seen previously by Van Driel et al. (1975), in the decay of $^{34\text{m}}\text{Cl}$ (3^+ ; $T=0$) to several states in ^{34}S near 4.8 MeV.

The radioactivity was made by the $^{31}\text{P}(\alpha, n)^{34}\text{Cl}$ reaction on targets of MnP powder pressed into 0.64 cm holes in Be, Zr and Al target holders. These targets were bombarded by α beams of 10 to 11 MeV in a glass tee and were transported to the detector by hand (this was possible because of the 32 min half life of $^{34\text{m}}\text{Cl}$). Thick Pb absorbers (usually 2.5 cm) were used to reduce the intense 511-keV radiation in most runs and a stopping thickness of lucite or beryllium was used to stop the positrons with a minimum of bremsstrahlung.

The principal source of high-energy background in this experiment was pileup in the shaping amplifier, so a pileup-rejection system was used which reduced the background by a factor of 3-4. In most of our runs, we were interested primarily in measuring the intensity of the 4074-keV γ ray from $^{34}\text{Cl}(\text{g.s.})$ decay relative to the intensity of the 4114-keV γ ray emitted in $^{34\text{m}}\text{Cl}$ decay, so questions of relative photo-peak efficiency and count-rate-dependent distortion of the spectrum by the pileup-rejection system were unimportant. However, the areas of all $^{34\text{m}}\text{Cl}$ γ rays were measured in one set of data and here these energy-dependent effects were important; in this case it was necessary

to verify that there was no count-rate-dependent distortion of the spectrum. To check this, (peak area group 1)/(peak area group 2) was calculated for the four intense γ rays emitted in ^{34m}Cl decay (1176, 2127, 3303, and 4114 keV). The ratios are plotted in Figure 24. Since the ratio is constant within statistical errors, it was concluded that there is no significant count-rate dependence in the relative-efficiency calibration.

The relative-efficiency calibration was made with a ^{56}Co source mounted in the same geometry as the ^{34m}Cl sources and the ^{56}Co relative γ ray intensities were taken from Camp and Meredith (1971) applying the correction recommended by McCallum and Coote (1975). The $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction at $E_p = 1.058$ MeV was used to extend the relative efficiency calibration to 5.24 and 8.28 MeV and the relative γ -ray intensities were taken from Evans et al. (1966).

Several runs were made with no absorbers in order to measure the relative intensity of the 146-keV γ ray emitted in the M3 γ decay of ^{34m}Cl to $^{34}\text{Cl}(\text{g.s.})$. In these cases, the source was positioned 12.0 cm from the detector where the detector, with a diameter of 5.0 cm, subtends 1.1% of a sphere. Thus the summing correction due to positrons entering the detector because of the absence of a β stopper was small and could be made with confidence.

Relative-efficiency calibrations for this phase of the experiment were performed using a ^{182}Ta source (made by thermal-neutron capture in a 6.4 μm thick Ta foil), ^{56}Co , ^{66}Ga , and $^{14}\text{N}(p,\gamma)^{15}\text{O}$ at $E_p = 1.058$ MeV using the relative intensities of Meyer (1978), Camp and Meredith (1971) and corrected by McCallum and Coote (1975), and Evans et al. (1966).

Our measurements of the relative intensities of all γ rays emitted following the decay of ^{34m}Cl are summarized in Table 17. γ rays are not tabulated if they can be emitted only in β decays that are forbidden according to the compilation of Endt and Van der Leun (1978). The results of the earlier measurement by Van Driel et al. (1975) are also included for comparison. Because Van Driel et al. used the relative intensities for ^{56}Co given by Camp and Meredith without applying the correction of McCallum and Coote, their relative intensities above 2.8 MeV have been multiplied by a factor $1.053 - 0.079 E_{\gamma} + 0.026 E_{\gamma}^2$ in Table 17. Also, the relative intensity of the 146-keV γ ray reported by Van Driel et al. was adjusted to correct for the difference between the relative intensities of the 152- and 156-keV γ rays in ^{182}Ta given by White et al. (1970) and the more precise relative intensities given by Meyer (1978) which we used. γ ray spectra collected with 2.5 cm Pb absorber are shown in Figures 25 and 26.

The agreement between this work and the previous results is excellent. Generally our results are more precise for the intense γ rays because we had greater confidence in the relative-efficiency calibration, while Van Driel et al. are more precise for the weak γ rays because they used Compton suppression on their Ge(Li) detector to remove most of the background in the spectrum.

Determining the branching of ^{34m}Cl is now straight-forward if the internal-conversion coefficient for the M3 γ transition to $^{34}\text{Cl(g.s.)}$ is known accurately. Ward and Kuroda (1971) report the measured value 0.100 ± 0.009 , in sharp disagreement with the calculations of Band et al.

(1976) which yield an internal-conversion coefficient of 0.172 ± 0.005 for this transition. Normally, internal-conversion-coefficient calculations are quite reliable, particularly in light nuclei such as ^{34}Cl , and we checked the results of Band et al. by comparing with the measured internal-conversion coefficients for the M3 γ decays of $^{58\text{m}}\text{Co}$ and $^{60\text{m}}\text{Co}$. Since they agreed, it was concluded that Band et al. calculated the M3 conversion coefficients correctly. However, note that the strength of the M3 transition in ^{34}Cl is only 1.6×10^{-6} W.u. while it is 1.4×10^{-5} W.u. in ^{58}Co and 2.9×10^{-4} W.u. in ^{60}Co . The conversion of electrons penetrating the nucleus is determined by a different matrix element than the M3 matrix element which controls the conversion of electrons outside the nucleus (this is the penetration matrix element; see Church and Weneser (1960) and Green and Rose (1958) for a discussion of the penetration effect). If the M3 matrix element is sufficiently small, then the conversion of electrons inside the nucleus may make a significant contribution to the total conversion rate. From the tables given by Green and Rose, we can estimate that the required penetration matrix element is 250 ± 50 times the M3 γ -ray matrix element. This is not impossible in view of the weakness of the M3 matrix element for the ^{34}Cl decay, so the value of 0.100 ± 0.009 for the internal-conversion coefficient is not unreasonable and it is used to calculate the $^{34\text{m}}\text{Cl}$ branching intensities.

Precise measurements of the half life of $^{34\text{m}}\text{Cl}$ have been reported in several papers and they show poor mutual agreement. Green and Richardson (1956) report a half life of 32.40 ± 0.04 min while Ebrey and Gray (1965) report 31.99 ± 0.05 min and Van Driel et al. (1975) give $32.06 \pm$

0.08 min. It is unlikely that the last two groups made the same systematic error since they used different techniques, so we conclude that Green and Richardson are wrong and adopt 32.01 ± 0.04 min as the half life of ^{34m}Cl .

Table 18 shows the absolute branch intensities and the log ft values calculated from the relative γ -ray intensities measured in this work (i.e., not averaged with Van Driel et al.) and using the γ ray branching information in Endt and Van der Leun (1978) where necessary. The results are compared to the results of the shell-model calculations of Glaudemans et al. (1971), Lanford and Wildenthal (1973) and Brown et al. (1978). The same comments apply here as in the discussion of the ^{33}Cl decay. Glaudemans et al. and Lanford and Wildenthal used only slightly different effective interactions and obtained quite different results for the weak transitions showing the sensitivity of weak Gamow-Teller transitions to small changes in the wavefunctions. Both calculations overestimate the strength of the branch to the 3303-keV level in ^{34}S by a factor of about 2, but the errors in the branches to the state at 2127 keV and 4114 keV amount to less than 0.032 in $|M_{\text{GT}}|^2$. Brown et al. who used a full s-d model space do quite well predicting Gamow-Teller strengths: this calculation correctly gives approximately equal strengths to the branches to the ^{34}S levels at 3303 keV and 4114 keV and the only large differences between experiments and theory amount to errors in $|M_{\text{GT}}|^2$ of less than 0.041. The effect of configuration mixing may be seen by noting that the simplest 2-particle shell model with no polarization of the ^{32}S "core" predicts $\log ft=4.21$ for a Gamow-Teller decay from the

3^+ ; T=0 state to the 2^+ ; T=1 state in the $(d_{3/2})^2$ configuration.

8. ^{35}Ar Decay

The branching in this decay is illustrated in Figure 27. A preliminary report of this work is given by Wilson and Kavanagh (1976); the branch intensities reported there are superseded by the results presented here.

This experiment was essentially the same as the ^{33}Cl experiment. In the first part of the experiment, the relative intensities of the γ rays following ^{35}Ar β decay were measured using the 100 cc Ge(Li) detector and a 2.5 cm Pb absorber to attenuate the intense 511-keV radiation. The radioactivity was made by the $^{35}\text{Cl}(p,n)^{35}\text{Ar}$ reaction in targets of LiCl or PbCl_2 powders wrapped in 25 μm Ta foil and mounted in Be rabbits. The 11-MeV proton beam lost less than 1.1 MeV in the rabbit system's exit foil and in the Ta foil surrounding the target material. Data were collected in two consecutive 4096-channel groups of 1.8 sec each in order to permit a rough determination of the half lives of weak γ rays seen in this part of the experiment. Figure 28 shows the spectrum accumulated in group 1 (0.0-1.8 sec) and Figure 29 shows detailed spectra of some of the γ rays emitted in the decay of ^{35}Ar . The Ge(Li) detector's relative photopeak efficiency was calibrated using a ^{56}Co source and also using the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction at $E_p = 1.058$ MeV to extend the calibration to 5.24 MeV. Relative γ ray intensities for these sources were taken from Camp and Meredith (1971) with corrections from McCallum and Coote (1975) for ^{56}Co and from Evans et al. (1966) for $^{14}\text{N}(p,\gamma)^{15}\text{O}$. The effects of small differences between the experimental and calibration geometries were calculated using the attenuation coefficients given by Grodstein (1957).

Table 19 shows the relative intensities of the daughter γ rays in ^{35}Ar decay and compares this work with previous studies of this radio-activity.

We also measured the absolute intensity of the 1219 keV γ ray by comparing to the short-lived 511-keV intensity. For this part of the experiment, only 0.64 cm of Pb absorber was used so the detector would be sensitive to annihilation radiation. The same PbCl_2 targets were used for this part of the ^{35}Ar experiment as for the measurement of relative γ ray intensities. This time the spectra were accumulated in four consecutive 2048-channel groups each lasting 1.0 sec. To extract the part of the 511-keV peak due to the ^{35}Ar decay, the ratio (area 511)/(area 1219) in group n was fit with the two parameter expression $A_0 + \beta^n A_1$ where $\beta = 2^{1.000 \text{ sec}/1.773 \text{ sec}} = 1.478$ is the decay constant for the ^{35}Ar radiation. Then A_0 is the ratio of the ^{35}Ar 511-keV peak area to the 1219-keV peak area.

Two runs were made in slightly different geometries, an extra 1.4 cm of lucite being inserted between the source and the detector in the second run. In both cases the two-parameter fits to the four-point decay curves gave acceptable values of χ^2 (2.0 in run 1 and 2.5 in run 2, both for 2 degrees of freedom), which indicated that other short-lived activities made only negligible contributions to the total 511-keV radiation. A computer program calculated the effect of the distributed source of annihilation radiation and in-flight-annihilation. Small corrections were made for pair production by the high-energy photons produced by in-flight-annihilation and summing between 511-keV radiation

and the 1219-keV photons. Efficiency calibrations were made with ^{22}Na and ^{56}Co sources using the relative intensities given in Endt and Van der Leun (1978) and Camp and Meredith (1971).

The values of the absolute intensity of the 1219-keV γ ray obtained from the two runs were in agreement with each other ($(1.191 \pm 0.042) \times 10^{-2}$ in run 1 and $(1.256 \pm 0.038) \times 10^{-2}$ in run 2 with a common systematic error of $\pm 0.014 \times 10^{-2}$; the weighted average is $(1.228 \pm 0.030) \times 10^{-2}$). Table 20 lists the results reported previously. The agreement between this work and other measurements is generally good with the exception of the result reported by Azuelos et al. (1977). The weighted average of the five results has $\chi^2=6.11$ for four degrees of freedom (probability of $\chi^2 \geq 6.11$ is 20%). The uncertainty in the adopted weighted average has been increased to take account of this scatter.

High-precision measurements of the half life of ^{35}Ar have been reported by Jänecke (1960), Wick et al. (1969), Geiger and Hooton (1971) and Azuelos et al. (1977). Because of the previously noted discrepancies in the results reported by Jänecke, this value is not used in calculating a "best value" for the half life (see the discussion of the ^{31}S half life on page 71). Geiger and Hooton report a value of 1.787 ± 0.012 sec but the consistency of the 8 measurements used to derive the reported value is poor: a weighted average of the separate values has a χ^2 of 29.3 for 7 degrees of freedom (probability $\ll 0.1\%$). Therefore this value was rejected also. Wick et al. and Azuelos et al. report

1.770 ± 0.006 and 1.774 ± 0.003 sec respectively, which are combined to give the adopted ^{35}Ar half life of 1.773 ± 0.003 sec.

The absolute β branches and the log ft values for the decay of ^{35}Ar are listed in Table 19. Relative intensities were taken from this work alone while the absolute intensity of the 1219-keV γ ray is the weighted average of several measurements (see Table 18). The reports of Lanford and Wildenthal (1973) and Brown et al. (1978) give the only large-basis shell-model calculations of β rates available. Both calculations used a complete s-d shell basis. Lanford and Wildenthal used wavefunctions calculated with a "realistic" interaction based on the Hamada-Johnston scattering potential while Brown et al. used an effective interaction in which the 2-particle matrix elements were adjusted to reproduce energy levels of s-d shell nuclei. The agreement with experiment is not spectacular; the calculation of Brown et al. with the fitted 2-particle matrix elements does somewhat better. The most serious discrepancy in both cases is in the branch to the 3003-keV level where Lanford and Wildenthal predict $|M_{GT}| = 0.53$ and Brown et al. predict $|M_{GT}| = 0.42$ compared to the measured matrix element $|M_{GT}| = 0.20$.

9. ^{38}Ca Decay

A level diagram illustrating this decay is shown in Figure 30. ^{38}K states populated in allowed β transitions γ decay almost exclusively to the 130-keV level. When this work was started, the allowed Gamow-Teller branch to the 1^+ state at 459 keV in ^{38}K had not been observed and the primary purpose of this experiment was to measure its intensity. We also remeasured the half life of ^{38}Ca and the intensities of branches to the excited states at 1698 keV and 3342 keV.

As in previous studies of this decay (Kavanagh et al., 1968, and Gallmann et al., 1969), the ^{38}Ca activity was made by the reaction $^{36}\text{Ar}(^3\text{He},n)^{38}\text{Ca}$, in this case in gas rabbits designed for this experiment (see Figure 31). The ^{36}Ar gas was sealed in the rabbits by a rubber plug and by a 6.4 μm Ta foil bonded to the rabbit body with epoxy. ^3He beams of 12 to 15 MeV entered the rabbit through the Ta foil losing less than 1.5 MeV in the foil. These targets had to be particularly rugged because the short half life of ^{38}Ca meant that the rabbit had to travel the 10 meters to the detector in ~ 0.3 sec, resulting in considerable shock when it stopped.

The first experiment measured the intensity of the 328-keV γ ray emitted following β^+ decay to the 459-keV level of ^{38}K relative to the intensity of the 1568-keV γ ray from the strong branch to the 1698-keV level. For these runs, no absorber was used to shield the Ge(Li) detector except lucite to stop the positrons. The real difficulty in this measurement is the intense background near 328 keV produced principally by Compton scattering of 511-keV photons in the Ge(Li) detector

(see Figures 32 and 33 for sample spectra). This experiment was performed in two separate runs. In the first run, a 12.7 cm diameter by 10.2 cm thick NaI(Tl) detector was used to suppress the 511-keV Compton background. This system made use of the fact that the two 511-keV photons produced by annihilation of a stopped positron are emitted at 180° to each other. Thus, a second detector placed in the opposite side of the source from the Ge(Li) detector is hit by a 511-keV photon whenever the Ge(Li) detector is hit and a coincidence between the detectors is a signal that the photon hitting the Ge(Li) is an annihilation quantum. Consequently, the Ge(Li) spectrum in anticoincidence with the NaI(Tl) detector has a reduced 511-keV peak and Compton background. In a real detector system, the anticoincidence is not 100% efficient, there is absorption and scattering of the 511-keV radiation in the source and positron stopper and the source of annihilation radiation is distributed so that a 511-keV photon can hit the Ge(Li) without a veto from the NaI. In test runs with a ^{22}Na source, in the same geometry used in the experiment, the anticoincidence system reduced the 511-keV area by a factor of 3.3 but in the ^{38}Ca experiment this ratio fell to 2.4 and background in the vicinity of the 328-keV peak was reduced by a factor of only 1.7. It was felt that this did not justify the effort required to set up the system, so the second run measuring the 328-keV γ ray did not use the anticoincidence system. In analyzing the data from the first run, the possibility of a bias in the spectrum, due to differences in the vetoing of the 328-keV and 1568-keV γ rays because of different energy distribution of the coincident positrons, was included in the

calculated uncertainty in the relative intensity.

Because the laboratory did not have a multiple-line source to connect the 330 keV region of the spectrum to the region spanned by ^{56}Co , the relative efficiency calibration in this case was performed by measuring the absolute efficiencies with calibrated ^{133}Ba , ^{137}Cs , ^{60}Co and ^{22}Na sources. As expected from previous experience, in a geometry with no absorbers, the efficiency followed a simple power law from 300 keV to 2000 keV (efficiency $\sim E_{\gamma}^{-0.90}$). Corrections for absorption in the Ta and Al of the rabbit were applied later, as were corrections for the 0.051 cm Sn and 0.025 cm Nb X-ray absorber used in the second run. Photon attenuation coefficients were taken from Grodstein (1957). The spectrum accumulated in group 1 (0.00-0.45 sec) in the second run (without NaI veto) to measure the 328-keV γ ray is shown in Figure 32 and detailed spectra of the 328-keV and 1568-keV peaks are shown in Figure 33. The measurements of the intensity of the 328-keV γ ray, relative to the 1568-keV γ ray, were 0.116 ± 0.023 (first run), 0.135 ± 0.021 (second run) and 0.126 ± 0.016 (weighted average).

In the second part of the ^{38}Ca measurement, a 1.9 cm Pb absorber was placed in front of the detector to reduce dead time by absorbing most of the 511-keV radiation, and spectra were taken up to 5.0 MeV. In addition, the spectra taken in the half-life measurement (see below) were analyzed because they included the 3211-keV γ ray emitted following Gamow-Teller decays to the 1^+ state at 3343 keV and previously reported by Gallmann et al. (1969). Here the relative photopeak-efficiency calibration was performed in the same manner as in previous experiments

using ^{56}Co and the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction at $E_p=1.058$ MeV. The Ge(Li) spectrum taken in group 1 (0.00-0.45 sec) of this phase of the experiment is shown in Figure 34 and Figure 35 displays detailed spectra of the 1568- and 3211-keV peaks emitted in the branches to the 1698- and 3343-keV states.

Table 22 summarizes the results of both relative-intensity measurements and compares with previous work. We do not disagree with the measurements of Kavanagh et al. (1968) or Gallmann et al. (1969).

The third part of the ^{38}Ca study was the measurement of the half life. This was performed in exactly the same way as the half-life measurements of ^{26}Si and ^{30}S described previously. Eight consecutive groups of 0.26 sec each were collected after the rabbit returned to the detector. A leaky integrator triggering the sequence timer ensured that the same amount of ^{38}Ca activity was produced in each cycle provided that the ^{36}Ar pressure in the rabbit did not change, and a pulser at the high-energy end of the spectrum monitored dead-time and pileup losses. The area of the 1567-keV peak, corrected for dead time and pileup, was fit with a single exponential (two-parameter fit) as described in the discussion of ^{26}Si and ^{30}S decays. Figure 36 shows the data and fit from one of four separate runs. Table 23 shows the results of this measurement and compares to a previous measurement. The internal agreement of our four runs is not good, but since the scatter is expected to be this bad or worse about 20% of the time, these results were not rejected. However, the uncertainty in the weighted average was multiplied by 1.42 (if the errors on all of our measurements were multiplied by 1.42,

then the value of χ^2 would be 2.37, the 50% point of the χ^2 distribution for 3 degrees of freedom). The adopted "best" value for the half life of ^{38}Ca , combining this work and the results of Gallmann et al. (1969), is 0.435 ± 0.009 sec. We did not include the measurements reported by Kavanagh et al. (1968) because of a known systematic error (Kavanagh, 1979) and by Zioni et al. (1972) because of their large uncertainty.

Using the radiative corrections and Coulomb mixing given by Hardy and Towner (1975) and by Raman et al. (1975) and using the 1979 Q value for ^{38}Ca decay to correct their phase-space factors f , the partial half life for the 0^+ to 0^+ superallowed Fermi transition to the 130-keV level is calculated to be 0.5716 ± 0.0049 sec. Combining this with the measured total half life of ^{38}Ca gives the result that the partial half life for the sum of Gamow-Teller decays is 1.83 ± 0.17 sec, and that the branching ratio for the $0^+ \rightarrow 0^+$ decay is 0.761 ± 0.017 .

Table 24 lists the absolute branch intensities and $\log ft$ values derived from the half-life and relative-intensity measurements. The agreement between the measured Gamow-Teller strengths and those calculated by Lanford and Wildenthal (1973), Brown et al. (1978), Engelbertink and Glaudemans (1969) and Dieperink and Brussaard (1969) is quite poor apart from the fact that the first three calculations predict that the strongest Gamow-Teller decay will be to the second excited 1^+ state in ^{38}K . With the exception of Engelbertink and Glaudemans, all groups used a full $1s-0d$ shell and allowed no $0f-1p$ shell components in the model wavefunctions. Thus these calculations differed only in their choices of Hamiltonians. Lanford and Wildenthal used the wavefunctions

calculated by Wildenthal et al. (1971a) using a "realistic" interaction derived from the Hamada-Johnston potential which fits nucleon-nucleon scattering data. Brown et al. (1978) started with a similar effective interaction and then adjusted the two-body matrix elements to improve the agreement between experimental and model excitation energies for s-d shell nuclei. Dieperink and Brussaard used the Tabakin interaction to derive the two-body matrix elements. The Tabakin interaction is a soft-core non-local potential derived to fit nucleon-nucleon scattering data. Not surprisingly, then, considering their similarity, these three calculations predict comparable strengths for the strong Gamow-Teller transition to the 1698-keV 1^+ state and they all predict a greatly reduced strength to the first excited 1^+ state at 459 keV. The calculation of Engelbertink and Glaudemans (1969) used a modified surface-delta interaction and allowed holes in only the $1s_{1/2}$ and $0d_{3/2}$ subshells (i.e., they assumed a closed ^{28}Si core). Since the weakness of the transition to the 1^+ state at 459 keV is the result of an accidental cancellation of larger matrix elements due to mixing with $d_{5/2}$ configurations, the calculation would be expected to fail in this case. Finally, note that there will be non-negligible admixtures to the low-lying states of the A=38 nuclei from configurations with two particles excited into the 0f-1p shell and this will reduce further the accuracy of the 1s-0d shell-model calculations discussed here. The pairing-vibration calculation of Bouyssy and Vinh Mau (1974) indicates that f-p shell configurations comprise about 6% of the ^{38}Ca ground state and ~16% of the first 1^+ state in ^{38}K .

IV. CONCLUSIONS

As was emphasized in the last chapter when the experimental results were compared to shell-model calculations, the general trend of the Gamow-Teller rates is usually reproduced by the models but the calculations cannot reliably predict even the strongest rates with better than factor-of-two accuracy.

Before presenting summaries of the measured Gamow-Teller strengths in the s-d shell, we discuss the interpretation of deviations between shell-model calculations and experiment. If the mesonic effects mentioned in the first chapter are present, we would expect that the rates for all transitions would be affected, but that the quenching might be A-dependent or might depend on the specific j and l values of the decaying nucleons. (This effect is discussed by Blin-Stoyle (1978) and Khanna, Towner and Lee (1978)). The most recent microscopic calculation of the mesonic effects on G-T decays by Towner and Khanna (1979) shows an A-dependence in the total mesonic correction (as opposed to core-polarization correction) in closed-shell plus (or minus) one nucleon, that the mesonic correction contributes from -13% to +4% to the rate, and that this is the result of summing several larger cancelling contributions.

Several authors (Azuelos and Kitching, 1977, Wilkinson, 1974, and Raman et al., 1978) have attempted to calculate the effect of mesonic corrections on the Gamow-Teller transitions connecting the ground states of mirror nuclei ($T=1/2$ to $T=1/2$ transitions). The

program followed by these authors is outlined here: the correction to the isoscalar magnetic moment due to one pion exchange in the nucleus is zero (Blin-Stoyle, 1978). Consequently the sum of the magnetic moments of a mirror pair of nuclei should be a good estimate of the σ_3 operator in the ground state $|\psi, M_J = J\rangle$ of the nuclei:

$$\langle \psi | \sigma_3 | \psi \rangle = \frac{2\mu_0 - J}{\mu_p + \mu_n - 1/2} - \frac{2\mu_x}{\mu_p + \mu_n - 1/2}$$

where μ_x is the (presumably) small correction due to the exchange of heavier mesons and two or more pions and μ_0 is the isoscalar magnetic moment of the pair. Wilkinson (1974) points out that the operator $\sigma_3(1-\tau_3)$ should be small in $T_3 > 0$ nuclei ($\sigma_3(1+\tau_3)$ is small in $T_3 < 0$ nuclei) because this operator vanishes in the extreme single-particle shell model. Thus these authors calculate the Gamow-Teller matrix element from the isoscalar magnetic moment via the relation (valid for $T=1/2$ states)

$$\langle \psi | \sigma_3 \tau_3 | \psi \rangle = \langle \psi | \sigma_3 | \psi \rangle - \langle \psi | \sigma_3 (1-\tau_3) | \psi \rangle = \left(\frac{J}{J+1}\right)^{1/2} |M_{GT}|$$

The latest results of Raman et al. (1978) (see Table C of their paper) indicate that the mesonic effects vary from nucleus to nucleus in the s-d shell or that the assumptions regarding μ_x , the mesonic correction to the isoscalar magnetic moment, are wrong, or that the shell-model calculations of $\langle \psi | \sigma_3 (1-\tau_3) | \psi \rangle$ in the ground state of the $T=1/2$ nuclei are seriously in error, or a combination of these effects. The conclusion

is that the situation is not well understood but that the purely mesonic effects reduce Gamow-Teller strengths by ~10% in s-d shell nuclei. As was seen in the last chapter, this is much smaller than the typical difference between shell-model calculations and experiment.

If the effective interaction used in a shell-model calculation is incorrect or if the s-d space is seriously truncated, then the wavefunctions obtained are incorrect and good agreement between calculated and measured Gamow-Teller rates cannot be expected. It is not possible to make any general statements about the result of an incorrect effective interaction because it can produce several changes. In particular, incorrect single-particle energies for the $d_{5/2}$, $s_{1/2}$ and $d_{3/2}$ orbitals have the effect of truncating the model space by changing the importance of the orbitals in the low-lying states where G-T transitions can be measured. Small random errors in the two-particle interaction would be expected to cause a random change in the calculated rates. Exclusion of a tensor force has been shown to result in significant errors in the p shell nuclei, in particular in mass 14 (Rose, Häusser and Warburton, 1968) and it should be expected that a similar situation would occur in the s-d shell.

The effect of truncating the shell-model space has been studied by McGrory (1970) who examined the systematic errors arising from the exclusion of the $d_{3/2}$ orbitals in shell-model calculations in the A=17 to A=21 region. Essentially, because intermediate mass nuclei do not show complete jj coupling, $d_{3/2}$ orbitals contribute significantly even to low-lying states in the light s-d shell nuclei. McGrory interprets

the results of his calculations as indicating the presence of super-multiplet structure in the s-d shell and exclusion of one member of a spin-orbit pair in jj coupling wavefunctions destroys this symmetry. Breaking this structure by truncating the space is expected to reduce the calculated strengths for strong transitions and to increase them for the weak transitions which would be forbidden in the pure super-multiplet model.

Exclusion of configurations with holes in the 0p shell (polarization of the ^{16}O core) or with particles in the 0f-1p and higher shells must lead to further errors in the calculated Gamow-Teller rates. If it is assumed that the Gamow-Teller matrix elements connecting the configurations outside the model space are neither very large nor extremely small, then the result will be a reduction in the matrix elements of strong s-d shell transitions and a more-or-less random contribution to weak decays.

Finally, it must be remembered that the mesonic effects, the errors in the model space and the errors in the effective interaction are not independent because they all arise from the strong interactions of nucleons. The shell-model calculations explicitly ignore the details of these effects so one should not be surprised when errors are made.

The results of the full s-d shell model calculation of Brown, Chung and Wildenthal (1978) are compared to measured Gamow-Teller strengths in Figures 37 to 42. The work reported in this thesis is included in the first three figures ($T=1/2$ to $T=1/2$, and $T=1$ to $T=0$ decays). The choice of which quantity to plot in order best to compare theory and experiment is somewhat arbitrary; we choose $|M_{GT}| = \sqrt{3945 \text{ sec/ft}}$. The disadvantage

with $|M_{GT}|$ is that it is strongly dependent on the orbit of the decaying nucleon so it does not measure directly the error in the initial and final model wavefunctions (for example, $|M_{GT}| = \sqrt{3}$ for an $s_{1/2}$ to $s_{1/2}$ decay but only $\sqrt{3/5}$ for $d_{3/2}$ to $d_{3/2}$). This error could be remedied by dividing theoretical and experimental values of $|M_{GT}|$ by the extreme single-particle shell-model matrix elements but this could not be applied in the cases where $|M_{GT}|$ is the sum of two or more matrix elements of comparable magnitude or where the large components of the wavefunctions are not connected by the Gamow-Teller operator. Plots were also made to compare the calculated and measured reduced Gamow-Teller matrix elements $B^{1/2}$, where B is defined by the Wigner-Eckart theorem:

$$|M_{GT}|^2 = \frac{1}{2J_i+1} \begin{pmatrix} T_f & 1 & T_i \\ -T_{3f} & \Delta T_3 & T_{3i} \end{pmatrix}^2 B(GT)$$

B has a different dependence on initial and final spins and isospins but plots of $\sqrt{B(GT)(theory)}$ against $\sqrt{B(GT)(experiment)}$ are not qualitatively different from Figures 37 to 42.

Because of the large number of β transitions in the s-d shell a single plot would be very cluttered, so the comparison of theory and experiment is presented separately for each combination of isospins: $T=1/2$ to $T=1/2$ decays are displayed in Figure 37, 0^+ ; $T=1$ to 1^+ ; $T=0$ in Figure 38, other $T=1$ to $T=0$ transitions in Figure 39, $T=3/2$ to $T=1/2$ in Figure 40, $T=2$ to $T=1$ in Figure 41, and $T=5/2$ to $T=3/2$ in Figure 42. This also makes it easy to see whether the shell-model calculations do a better job with states of higher isospin.

Before discussing the figures, a few systematic biases must be noted. Because these are displays of $|M_{GT}|$ rather than a true matrix element including phase, the region with $|M_{GT}|(\text{theory}) - |M_{GT}|(\text{exp}) < -|M_{GT}|(\text{exp})$ is unoccupied. This tends to increase the number of points with $|M_{GT}|(\text{theory}) - |M_{GT}|(\text{exp}) > 0$ for low $|M_{GT}|(\text{exp})$. Experimental observability is, of course, biased in favor of decays with large matrix elements. This would tend to deplete the plots in the region with small $|M_{GT}|(\text{exp})$, but by plotting upper limits at the point $|M_{GT}|(\text{exp}) = \text{upper limit}/2$ and $|M_{GT}|(\text{theory}) - \text{upper limit}/2$ this effect is diminished. A few cases in which the experimental limit on the matrix element was much larger than the theoretical estimate were not included in the plots. Also, points are plotted in Figures 37 to 42 for only those transitions for which Brown, Chung and Wildenthal have calculated Gamow-Teller matrix elements, so several transitions to highly excited states reported in this thesis have been omitted.

Examination of these plots shows that whatever systematic trends are present are less significant than the general random error in the calculated Gamow-Teller matrix element. It is apparent that the errors in the $T=3/2$ to $T=1/2$, $T=2$ to $T=1$, and $T=5/2$ to $T=3/2$ transitions are generally smaller than the errors in the $T=1$ to $T=0$ and $T=1/2$ to $T=1/2$ transitions. However, these results are not good enough to conclude that this is because jj coupling is a better approximation for high-isospin states as suggested by Elliot and Lane (1957). The comparison of the experiment and theory for the lower-isospin transitions indicates that the theoretical rates are systematically high. Whether this is

predominantly due to the mesonic effects mentioned earlier or to errors in the wavefunctions resulting from configurations outside the s-d shell and errors in the effective interaction (or both) cannot be determined for the strong transitions. The fact that the absolute errors in the weak transitions are almost as large as for the strong transitions shows that the nuclear-structure calculations are making large errors apart from errors arising from the exclusion of non-nucleonic components in shell-model wavefunctions.

A final comment is to note that the very large errors in a few cases, for example ^{28}Mg , ^{30}S , ^{37}K and ^{38}Ca show that occasionally the effective interaction used mixes up the large components of the wavefunctions. One would not expect such large errors to result from an admixture of a small amount of 0f-1p shell or 0p shell configurations. Perhaps the only way to remedy this situation is to adjust the matrix elements of the effective interaction used in shell-model calculations to fit the transition data as well as the energies of the excited states of the 1s-0d shell nuclei.

Note added :

After this thesis was completed, we learned of a new measurement of the neutron half life (Bondarenko et al. 1978, Sov. Phys.-JETP Lett. 38, 303). If this value of the neutron half life, 10.13 ± 0.09 min, is used, then $g_A/g_V = 1.273 \pm 0.006$. This will increase theoretical Gamow-Teller rates by 3.7% and will not substantially affect the results and conclusions presented here.

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Table 1. Absolute Intensity of 1612 keV γ ray in $^{25}\text{Al}(\beta^+ \gamma) ^{25}\text{Mg}$.

<u>Reference</u>	<u>Absolute Intensity</u>
Makela et al. (1969)	$(9 \pm 2) \times 10^{-3}$
Bardin et al. (1970)	$(7 \pm 2) \times 10^{-3}$
Jundt et al. (1971)	$(8.4 \pm 0.7) \times 10^{-3}$
Azuelos et al. (1977)	$(7.94 \pm 0.35) \times 10^{-3}$
This work	$(7.76 \pm 0.28) \times 10^{-3}$
Weighted average of all results	$(7.88 \pm 0.21) \times 10^{-3}$

Table 2. Branch intensities and log ft values for ^{25}Al decay.

Final ^{25}Mg State E_x (keV) J^π	Absolute (a) Intensity	log ft	Theoretical log ft (b)	(c)
0 $5/2^+$	0.99168 ± 0.00022	3.574 ± 0.006		
975 $3/2^+$	$(4.4 \pm 0.5) \times 10^{-4}$	3.981 ± 0.015 (G-T)	3.80 (G-T)	3.73 ± 0.06 (G-T)
1612 $7/2^+$	$(7.88 \pm 0.21) \times 10^{-3}$	6.245 ± 0.050	6.22	6.42
1965 $5/2^+$	$< 2.1 \times 10^{-5}$	4.373 ± 0.012	4.23	4.16 ± 0.05
2738 $7/2^+$	$< 4.3 \times 10^{-5}$	> 6.50	8.24	
2801 $3/2^+$	$< 1.0 \times 10^{-5}$	> 4.64	7.35	
3908 $5/2^+$	$< 3.1 \times 10^{-6}$	> 5.10	5.11	
		> 3.85		

(a) Relative branch intensities taken from Mann et al. (1976).

(b) Brown et al. (1978).

(c) Timmer et al. (1978). The log ft values given there have been recalculated using the free-nucleon axial coupling constant ($g_A/g_V = 1.250 \pm 0.009$).

Table 3. Half life measurements of ^{26}Si .

<u>Reference</u>	<u>Half life (sec)</u>
Robinson and Johnson (1960)	2.1 ± 0.3
Frick et al. (1963)	2.1 ± 0.1
Kavanagh (1969)	2.31 ± 0.02
Moss et al. (1971)	2.1 ± 0.2
Hardy et al. (1975)	2.210 ± 0.021
This work	2.240 ± 0.010
Weighted average of Hardy et al. and this work	2.2345 ± 0.0090

Table 4. Relative intensities of daughter γ rays in $^{26}\text{Si}(\beta^+\gamma)^{26}\text{Al}$.

E_γ (keV)	Transition		Relative intensity			
	initial state	final state	this work ^(d)	(a)	(b)	(c)
792	1850	1058	< 2.7			
829	1058	228	1000.0 ± 5.2	1000	1000	1000
889	2739	1850	< 2.0			
980	2739	1759	< 1.6			
1014	2072	1058	(e)			
1342	1759	417	< 0.98		< 7	< 20
1434	1850	417	< 0.96			
1622	1850	228	124.5 ± 2.3	134 ± 5	149 ± 16	127 ± 7
1655	2072	417	1.45 ± 0.32			
1682	2739	1058	< 0.58			
1843	2072	228	11.79 ± 0.27	16 ± 3	13 ± 3	12 ± 2
1873	3723	1850	< 0.41			
1964	3723	1759	< 0.38			
2322	2739	417	< 0.28			
2511	2739	228	2.82 ± 0.10		< 5	4.5 ± 1.5
2666	3723	1058	< 0.15			
3306	3723	417	< 0.064			
3495	3723	228	< 0.045		< 5	

(a) Hardy et al. (1975)

(b) Moss et al. (1971)

(c) Kavanagh (1969)

(d) Upper limits are 2σ confidence intervals (98% confidence).

(e) Obscured by the 1014-keV γ ray due to $^{27}\text{Mg} \beta^-$ decay.

Table 5. Absolute branch intensities and log ft for $^{26}\text{Si}(\beta^+ \gamma)^{26}\text{Al}$.

final ^{26}Al state (keV)	J^π	absolute branch intensity	log ft	Theoretical Values (a)	(b)
228	0^+	0.7503 ± 0.0046			
1058	1^+	0.2189 ± 0.0041	3.550 ± 0.011	$3.46^{+0.11}$	3.37
1850	1^+	$(2.726 \pm 0.070) \times 10^{-2}$	3.855 ± 0.013	$3.57^{+0.17}$	3.87
2072	1^+	$(2.90 \pm 0.11) \times 10^{-3}$	4.629 ± 0.018	4.2	3.80
2739	1^+	$(6.18 \pm 0.25) \times 10^{-4}$	4.539 ± 0.019		4.29
3723	1^+	$< 1.3 \times 10^{-5}$ (c)	> 4.15 (c)		4.04

(a) Timmer et al. (1978)

(b) Brown et al. (1978)

(c) 2σ limit (98% confidence)

Table 6. Relative intensities of daughter γ rays in $^{30}\text{S}(\beta^+\gamma)^{30}\text{P}$.

E_γ (keV)	transition (a)		Relative intensity		
	initial state	final state	this work (b)	(c)	(d)
677	677	0	1000 ± 12	1000	1000
709	709	0	3.74 ± 0.88	6 ± 3	7.2 ± 2.1
745	1454	709	< 1.6		
990	3927	2938	< 0.94		
1454	1454	0	< 0.56		
1484	2938	1454	< 0.47		
1565	3019	1454	< 0.44		
1850	3304	1454	< 0.47		
2261	2938	677	< 0.30		
2277	3731	1454	< 0.30		
2310	3019	709	(e)		
2341	3019	677	29.00 ± 0.55	33 ± 2	27.5 ± 2.0
2370	4343	1973	< 0.28	< 0.65	
2473	3927	1454	< 0.49		
2595	3304	709	< 0.44		
2627	3304	677	< 0.30		
2781	4235	1454	< 0.44		
3019	3019	0	0.125 ± 0.061		
3022	3731	709	< 0.26		
3047	4501	1454	< 0.18		
3054	3731	677	< 0.27		
3218	3827	709	< 0.13		

Table 6 (cont.)

E_{γ} (keV)	transition ^(a)		Relative intensity		
	initial state	final state	this work ^(b)	(c)	(d)
3250	3927	677	< 0.11		
3304	3304	0	< 0.15		
3526	4235	709	< 0.079		
3558	4235	677	< 0.13		
3731	3731	0	< 0.065	< 0.55	
3759	4468	709	< 0.073 (f)		
3792	4501	709	< 0.061		
3824	4501	677	< 0.059		
3927	3927	0	< 0.057		
4235	4235	0	< 0.045		
4343	4343	0	< 0.038		
4468	4468	0	< 0.043 (f)	< 2.7	
4501	4501	0	< 0.042	< 2.7	

(a) Level energies are taken from Endt and Van der Leun (1978).

(b) 2σ upper limits (98% confidence).

(c) Moss et al. (1971).

(d) Kavanagh (1969).

(e) Obscured by ^{14}O γ ray at 2313.

(f) Isospin-forbidden Fermi transition.

Table 7. Measurements of ^{30}S half life.

<u>Reference</u>	<u>Half life (sec)</u>
Johnson et al. (1960)	1.5 ± 0.1
Robinson et al. (1961)	1.35 ± 0.10
Frick et al. (1963)	1.4 ± 0.1
Barker et al. (1967)	1.18 ± 0.04
Kavanagh (1969)	1.210 ± 0.010
Moss et al. (1971)	1.22 ± 0.03
Schmeing et al. (1974)	1.181 ± 0.013
This work	1.1783 ± 0.0048
Weighted average of Schmeing et al. and this work	1.1786 ± 0.0045 sec (adopted value)

If Kavanagh's result is included, the weighted average becomes 1.1839 ± 0.0041 sec with $\chi^2=8.2$. The probability of $\chi^2 \geq 8.2$ for 2 degrees of freedom is ~2%.

Table 8. Absolute branch intensities and log ft values for $^{30}\text{S}(\beta^+ \gamma) ^{30}\text{P}$.

final ^{30}P state $E_x(\text{keV})$ $J^\pi; T$	absolute branch intensity (b)	log ft (c)	theoretical log ft (d), (f) (e), (f) (g)
0 1^+	0.2131 ± 0.0046	4.327 ± 0.012	3.34 3.34 5.06
677 0^+	0.7611 ± 0.0044		
709 1^+	$(2.93 \pm 0.69) \times 10^{-3}$	5.91 ± 0.11	4.85 5.32 4.54
3019 1^+	$(2.283 \pm 0.054) \times 10^{-2}$	3.562 ± 0.012	3.95
3304 (h) $(0^+, 1^+)$	$< 7.5 \times 10^{-4}$	> 4.76	
3731 1^+	$< 1.1 \times 10^{-4}$	> 5.10	
3927 $(1^+, 2^-, 3^+)$	$< 7.4 \times 10^{-4}$	> 4.01	
4235	$< 4.8 \times 10^{-4}$	> 3.67	
4343 $\pi = \text{unnat.}$	$< 2.1 \times 10^{-4}$	> 3.81	
4501 $1^+; 1$	$< 7.3 \times 10^{-5}$	> 3.92	4.62

- (a) Level energies and spin-parity assignments are taken from Endt and Van der Leun (1978).
- (b) Branch intensities are based on the relative γ -ray intensities from this work only. The half life of ^{30}S is taken to be 1.1786 ± 0.0045 sec. Limits are 2σ confidence intervals (98% confidence).
- (c) Log f is calculated from the tables of Gove and Martin (1971) and radiative corrections have been applied following Hardy and Towner (1975).
- (d) Glaudemans et al. (1971).
- (e) Lanford and Wildenthal (1973).
- (f) These theoretical log ft values have been recalculated using the axial coupling constant given by $g_A/g_V = 1.250 \pm 0.009$.
- (g) Brown et al. (1978).
- (h) This state has been seen only in the $^{29}\text{Si}(^3\text{He}, d)^{30}\text{P}$ reaction (Endt and Van der Leun, 1978).

Table 9. Relative intensities of γ rays emitted in ^{30}P decay.

E_{γ} (keV)	transition		relative intensity ^(a)
	initial state	final state	
1534.3	3770	2235	< 0.068
1552.5	3788	2235	< 0.11
2235.4	2235	0	1
3498.7	3499	0	< 0.021
3769.7	3770	0	< 8.3×10^{-3}

(a) Upper limits are 2σ confidence intervals (98% confidence).

(b) Obscured by contaminant ^{29}P γ ray at 1273.5 keV.

Table 10. Absolute branch intensities and log ft values for $^{30}\text{P}(\beta^+ \gamma)^{30}\text{Si}$.

final E_x (keV)	^{30}Si state J^π	absolute branch intensity ^(b)	log ft ^(c)	theoretical log ft	
				(d), (f)	(e), (f) (g)
0	0^+	0.99931 ± 0.00012	4.840 ± 0.006	3.82	3.82 5.53
2235	2^+	$(6.9 \pm 1.2) \times 10^{-4}$ (a)	5.784 ± 0.076	4.89	4.59 4.83
3499	2^+	$< 3.4 \times 10^{-5}$	> 4.91		4.34
3770	1^+	$< 1.3 \times 10^{-5}$	> 4.90		5.09
3788	0^+	$< 7.6 \times 10^{-5}$	> 4.13		4.51

(a) Level energies, spin-parity assignments and branch to the 2235-keV level taken from Endt and Van der Leun (1978).

(b) 2σ upper limits (98% confidence).

(c) Log f is calculated from the tables of Gove and Martin (1971) and radiative corrections have been applied following Hardy and Towner (1975).

(d) Glaudemans et al. (1971).

(e) Lanford and Wildenthal (1973).

(f) The theoretical log ft values have been recalculated using the axial coupling constant given by $g_A/g_V = 1.250 \pm 0.009$.

(g) Brown et al. (1978).

Table 11. Relative intensities of γ rays emitted in $^{31}\text{S}(\beta^+\gamma)^{31}\text{P}$.

E_γ (keV)	transition ^(a)		relative intensity	
	initial state	final state	this work ^(b)	(c)
1266	1266	0	1000 ± 20	1000
1868	3134	1266	< 1.7	
2234	2234	0	< 0.64	< 7
2240	3506	1266	4.35 ± 0.69	
2360	4594	2234	< 0.74	
2995	4261	1266	(d)	
3134	3134	0	28.80 ± 0.81	28 ± 4
3327	4594	1266	< 0.56	
3506	3506	0	6.62 ± 0.44	10 ± 3
4261	4261	0	< 0.18	
4594	4594	0	< 0.051	

(a) Level energies are taken from Endt and Van der Leun (1978).

(b) 2σ upper limits (98% confidence). The uncertainty in the 1266-keV relative efficiency is included only in the relative intensity of the 1266-keV γ ray.

(c) Détraz et al. (1971).

(d) Obscured by the single-escape peak of the 3506-keV γ ray.

Table 12. Absolute intensity of 1266-keV γ ray in ^{31}S decay.

<u>Reference</u>	<u>Absolute intensity (%)</u>
Talbert and Stewart (1960)	1.1 ± 0.1
Alburger (1974)	1.25 ± 0.06
Azuelos et al. (1977)	0.98 ± 0.20
This work	1.087 ± 0.021
Weighted average of all results	1.103 ± 0.019
	$\chi^2=6.96$ (Probability < 8%)
Adopted value	1.103 ± 0.033

(error increased by a factor $\sqrt{6.96/2.37}$ where 2.37 is the 50% point of the χ^2 distribution for 3 degrees of freedom)

Table 13. Half life of ^{31}S .

<u>Reference</u>	<u>Half life (sec)</u>
Hunt et al. (1954)	2.40 ± 0.07
Lindenberger and Scheer (1960)	2.61 ± 0.05
Nelson et al. (1963)	2.56 ± 0.10
Alburger (1974)	2.605 ± 0.012
Azuelos et al. (1977)	2.543 ± 0.008
This work	2.562 ± 0.007
Weighted average	2.5617 ± 0.0048
	$\chi^2=24.8$ (probability $\ll 0.5\%$)
Adopted value	2.562 ± 0.012 sec

(error increased by a factor of $\sqrt{24.8/4.35}$ where 4.35 is the 50% point of the χ^2 distribution for 5 degrees of freedom).

Table 14. Absolute branch intensities and log ft values for $^{31}\text{S}(\beta^+ \gamma) ^{31}\text{P}$

final ^{31}P E_x (keV)	state J^π	absolute branch (a)	log ft (b)	theoretical log ft		
				(c), (f)	(d), (f)	(e)
0	$1/2^+$	0.9886 ± 0.0004	3.682 ± 0.007			
1266	$3/2^+$	$(1.097 \pm 0.033) \times 10^{-2}$	4.341 ± 0.033 (GT)	3.70 (GT)	3.69 (GT)	4.32 (GT)
3134	$1/2^+$	$(3.26 \pm 0.16) \times 10^{-4}$	4.966 ± 0.015	4.72	4.77	4.97
3506	$3/2^+$	$(1.21 \pm 0.10) \times 10^{-4}$	4.770 ± 0.023		4.10	4.47
4261	$3/2^+$	$(1.21 \pm 0.10) \times 10^{-4}$	4.538 ± 0.038		4.55	4.03
4594	$3/2^+$	$< 2.8 \times 10^{-6}$	> 4.71			5.12
	$3/2^+$	$< 2.5 \times 10^{-6}$	> 4.45			6.40

- (a) Limits are 2σ confidence intervals (98% confidence). The branch to the 1266-keV level is determined from the measurements shown in Table 12.
- (b) Log f values calculated from the tables of Gove and Martin (1971). The half life adopted is 2.562 ± 0.012 sec. Radiative corrections have been applied following Hardy and Towner (1975).
- (c) Claudemans et al. (1971).
- (d) Lanford and Wildenthal (1973).
- (e) Brown et al. (1978).
- (f) Log ft values tabulated in this reference were recalculated using the axial vector coupling constant $g_A/g_V = 1.250 \pm 0.009$.

Table 15. Relative intensities of daughter γ rays in $^{33}\text{Cl}(\beta^+\gamma)^{33}\text{S}$.

E_γ (keV)	transition		relative intensity	
	initial state	final state	this work ^(b)	(c)
841	841	0	1186 ± 36	960 ± 120
1125	1966	841	13.8 ± 3.4	
1472	2312	841	57.9 ± 3.3	< 44
1519	3832	2312	< 5.2	
1966	1966	0	1042 ± 16	1000 ± 70
2026	2866	841	15.4 ± 1.9	
2312	2312	0	23.1 ± 1.4 (d)	
2409	4375	1966	< 3.6	
2866	2866	0	1000 ± 18	1000 ± 70
3094	3935	841	< 3.0	
3212	4053	841	< 1.3	
3534	4375	841	< 0.96	
3584	4424	841	< 0.90	
3832	3832	0	< 1.2	
3905	4746	841	< 0.68	
3935	3935	0	< 0.95	
4053	4053	0	1.08 ± 0.31	
4144	4144	0	< 0.58	
4375	4375	0	< 0.99	
4424	4424	0	< 0.67	
4746	4746	0	0.85 ± 0.23	

(a) Level energies taken from Endt and Van der Leun (1978).

(b) 2σ upper limits (98% confidence).

(c) Bardin et al. (1970).

(d) We assume that there is no contamination from ^{14}O decay. See the discussion on page 76 of the text.

Table 16. Absolute branch intensities and log ft values for $^{33}\text{Cl}(\beta^+ \gamma)^{33}\text{S}$.

final ^{33}Cl state E_x (keV)	J^π	absolute branch (a)	log ft (b)	theoretical log ft		
				(c), (e)	(d), (e)	(f)
0	$3/2^+$	0.9858 ± 0.0013	3.755 ± 0.007			
			4.88 ± 0.10 (GT)	4.15 (GT)	4.17 (GT)	5.06 (GT)
840.9	$1/2^+$	$(4.80 \pm 0.46) \times 10^{-3}$	5.664 ± 0.043	5.13	4.92	5.17
1966.3	$5/2^+$	$(4.61 \pm 0.42) \times 10^{-3}$	4.979 ± 0.040		4.27	7.19
2312.5	$3/2^+$	$(3.54 \pm 0.36) \times 10^{-4}$	5.825 ± 0.045		4.88	4.90
2866.4	$5/2^+$	$(4.44 \pm 0.41) \times 10^{-3}$	4.191 ± 0.041		4.33	3.88
3831.6	$5/2^+$	$< 9.2 \times 10^{-6}$	> 5.40			
3934.6	$3/2^+$	$< 7.0 \times 10^{-6}$	> 5.30			
4053.0	$1/2^+$	$(4.7 \pm 1.5) \times 10^{-6}$	5.24 ± 0.15			
4143.7	$(3/2^+, 5/2)$	$< 2.5 \times 10^{-6}$	> 5.28			
4374.9	$1/2^+$	$< 4.4 \times 10^{-6}$	> 4.65			
4424.5	$(1/2^+, 3/2)$	$< 5.7 \times 10^{-6}$	> 4.49			
4746		$(4.1 \pm 1.2) \times 10^{-6}$	4.37 ± 0.14			

(a) The branches to the 1966-keV and 2866-keV states used the results of this work combined with the results of Bardin et al. (1970). The remaining relative intensities were taken from this work only (Table 15). Limits are 2σ confidence intervals.

(b) Log f values are taken from the table of Gove and Martin (1971) and radiative corrections have been applied following Hardy and Towner (1975).

(c) Glaudemans et al. (1971).

(d) Lanford and Wildenthal (1973).

Table 16. (cont.)

- (e) The results of this calculation have been recalculated using the 1979 value of the axial coupling constant ($g_A/g_V=1.250\pm0.009$).
- (f) Brown et al. (1978).

Table 17. Relative intensities of γ rays in ^{34m}Cl decay.

E_{γ} (keV)	transition		relative intensities	
	initial state	final state	this work ^(b)	(c)
146	^{34m}Cl	$^{34}\text{Cl}(0)$	944 ± 14	956 ± 19
1176	3303	2127	329.0 ± 2.8	322 ± 10
1385	4688	3303	< 0.21	
1573	4876	3303	0.37 ± 0.12	0.26 ± 0.05
1586	4889	3303	< 0.18	< 0.15
1987	4114	2127	4.31 ± 0.15	4.09 ± 0.11
2127	2127	0	1000 ± 11	1000
2560	4688	2127	0.783 ± 0.067	0.72 ± 0.14
2748	4876	2127	0.521 ± 0.066	0.49 ± 0.05
2762	4889	2127	< 0.11	
3303	3303	0	287.3 ± 3.1	273 ± 9
4074	4074	0	< 0.0081 (d)	< 0.023
4114	4114	0	6.37 ± 0.14	6.1 ± 0.4
4876	4876	0	< 0.0076	< 0.010
4889	4889	0	< 0.015	< 0.010

(a) Level energies taken from Endt and Van der Leun (1978). Except for the 146-keV γ ray, the transitions are between ^{34}S states.

(b) 2σ upper limits (98% confidence). The uncertainty in the 2127-keV relative efficiency is included only in the relative intensity of the 2127-keV γ ray.

(c) Van Driel et al. (1975) used Camp and Meredith (1971) for ^{56}Co relative intensities and White et al. (1970) for ^{182}Ta intensities. The relative intensities of the 146-keV γ ray and the γ rays above 2800 keV have been recalculated using Meyer (1978) for ^{182}Ta and applying the correction factor of McCallum and Coote (1975) for ^{56}Co .

(d) The relative intensity of the 4074-keV γ ray is the result of three experiments.

Table 18. ^{34m}Cl and ^{34}Cl β^+ and electron-capture decays.

Parent State	final E_x	^{34}S state J^π (a)	absolute branch (b)	log ft (c)	theoretical log ft (d), (f) (e), (f) (g)		
^{34m}Cl	2127.3	2^+	0.2853 ± 0.0052	5.994 ± 0.010	7.13	5.86	7.53
	3303.2	2^+	0.2642 ± 0.0029	4.831 ± 0.008	4.36	4.24	4.77
	4114.1	2^+	$(4.58 \pm 0.10) \times 10^{-3}$	5.089 ± 0.012	5.15	8.12	4.71
	4687.6	4^+	$(3.36 \pm 0.29) \times 10^{-4}$	5.431 ± 0.039		6.46	5.49
	4875.8	3^+	$(3.82 \pm 0.60) \times 10^{-4}$	5.190 ± 0.071	4.91		4.76
	4889.3	2^+	$< 1.3 \times 10^{-5}$	> 6.64			4.99
^{34}Cl	0	0^+	1				
	4072	1^+	$< 7.8 \times 10^{-6}$	> 4.53		4.44	

(a) Excitation energies and spin-parity assignments are taken from Endt and Van der Leun (1978).

(b) The absolute branch to $^{34}\text{Cl}(\text{g.s.})$ is 0.4453 ± 0.0049 (γ emission plus internal conversion).

(c) Log f is taken from the tables of Gove and Martin (1971) and radiative corrections are applied following Hardy and Towner (1975).

(d) Glaudemans et al. (1971).

(e) Lanford and Wildenthal (1973).

(f) The log ft value has been adjusted using the axial coupling constant available in 1979 ($g_A/g_V = 1.250 \pm 0.009$).

(g) Brown et al. (1978).

Table 19. Relative intensities of daughter γ rays in $^{35}\text{Ar}(\beta^+\gamma)^{35}\text{Cl}$.

E_γ (keV)	transition ^(a)		relative intensity			
	initial state	final state	this work ^(b)	(c)	(d)	(e)
916	3918	3003	(f)			
930	2694	1763	11.3 ± 2.6			
965	3968	3003	< 8.7			
1219	1219	0	1000 ± 15	1000	1000	1000
1225	3918	2694	(f)			
1239	3003	1763	< 3.0			
1274	3968	2694	< 4.2			
1474	2694	1219	8.27 ± 1.27			
1763	1763	0	230.8 ± 3.7	234 ± 13	200 ± 27	180 ± 20
1783	3003	1219	< 3.9			
1931	4624	2694	< 2.1			
2155	3918	1763	< 2.2			
2204	3968	1763	< 2.7			
2645	2645	0	< 1.2			(e)
2694	2694	0	109.6 ± 1.8		102 ± 15	(e)
2699	3918	1219	< 3.3			
2748	3968	1219	4.80 ± 0.62			
2861	4624	1763	< 0.99			
3003	3003	0	72.4 ± 1.4		90 ± 15	58 ± 15
3405	4624	1219	(f)			
3918	3918	0	5.21 ± 0.32			
3968	3968	0	1.06 ± 0.25			
4624	4624	0	< 0.35			

(a) Level energies are taken from Endt and Van der Leun (1978).

(b) Upper limits are 2σ confidence intervals (98% confidence).

(c) Wick et al. (1969).

(d) Geiger et al. (1971).

(e) Detraz et al. (1971). These authors did not report relative γ -ray intensities and they did not quote a reference for γ -ray branching

Table 19. (cont.)

in ^{35}Cl . They give an upper limit of 25 for the relative intensity of the 2645-keV branch and a relative intensity of 160^{+20} for the 2694-keV branch.

(f) Peak obscured by another peak.

Table 20. Absolute intensity of 1219-keV γ ray in $^{35}\text{Ar } \beta^+$ decay.

<u>Reference</u>	<u>Absolute Intensity (%)</u>
Wick et al. (1969)	1.223 ± 0.046
Geiger and Hooten (1971)	1.22 ± 0.20
Azuelos et al. (1977)	1.55 ± 0.15
Hagberg et al. (1979)	1.34 ± 0.08
This work	1.228 ± 0.030
Weighted average	1.244 ± 0.024 ($\chi^2 = 6.11$)
The probability of $\chi^2 \geq 6.11$ for 4 degrees of freedom is only 20%, so we increase the uncertainty on the weighted average.	
Adopted average	1.244 ± 0.033

Table 21. Absolute branch intensities and log ft values for $^{35}\text{Ar } \beta^+$ decay.

final ^{35}Cl state E_x (keV)	(a) J^π	absolute branch (b)	log ft (c)	theoretical log ft (d)	(e)
0	$3/2^+$	0.98235 ± 0.00052	3.760 ± 0.006		
1219.3	$1/2^+$	0.01228 ± 0.00034	4.95 ± 0.10 (GT)	4.73 ± 0.05	4.71
1763.2	$5/2^+$	$(2.72 \pm 0.10) \times 10^{-3}$	5.100 ± 0.014	4.47	4.83
2693.6	$3/2^+$	$(1.606 \pm 0.065) \times 10^{-3}$	5.444 ± 0.017	5.82	7.91
3002.6	$5/2^+$	$(9.01 \pm 0.33) \times 10^{-4}$	5.006 ± 0.019	4.27	4.66
3918.4	$3/2^+$	$(7.90 \pm 0.52) \times 10^{-5}$	4.975 ± 0.017	4.14	4.35
3967.5	$1/2^+$	$(7.44 \pm 0.87) \times 10^{-5}$	4.880 ± 0.030	4.53	4.43
4624	$(3/2, 5/2^+)$	$< 4.4 \times 10^{-6}$	4.825 ± 0.053		4.67
			> 4.75		

(a) Excitation energies and spin-parity assignments are taken from Endt and Van der Leun (1978).

(b) The absolute intensity of the 1219-keV γ ray is taken from Table 20. The relative intensities of the γ rays are taken from this work only.

(c) Log f values were taken from the table of Gove and Martin (1971) and radiative corrections were made following Hardy and Towner (1975).

(d) Lanford and Wildenthal (1973). Their values of log ft have been recalculated with the 1979 value of the axial coupling constant.

(e) Brown et al. (1978).

Table 22. Relative intensities of γ rays in $^{38}\text{Ca}(\beta^+ \gamma)^{38}\text{K}$.

E_γ (keV)	transition		relative intensities		
	initial	final	this work ^(b)	(c)	(d)
328	459	130	0.126 ± 0.016	< 0.16	< 0.14
1240	1698	459	< 0.010	< 0.04	< 0.02
1568	1698	130	1	1	1
1643	3342	1698	< 0.010		
1698	1698	0	< 0.0082	< 0.06	< 0.02
1944	2402	459	< 0.011	< 0.16	
2646	2646	0	< 0.0046		
2883	3342	459	< 0.0033		
3185	3316	130	< 0.0029		
3211	3342	130	0.0139 ± 0.0015		0.024 ± 0.008
3316	3316	0	< 0.0027		
3342	3342	0	< 0.0024		
3519	3978	459	< 0.0042		
3710	3841	130	< 0.0059		
3716	4175	459	< 0.0045		
3726	3857	130	< 0.0036		
3739	3739	0	< 0.0036		
3848	3978	130	< 0.0081		
4084	4214	130	< 0.0029		
4318	4318	0	< 0.0019		
4395	4395	0	< 0.0037		

(a) Energies of ^{38}K levels taken from Endt and Van der Leun (1978).

(b) Upper limits for this work are 2σ confidence intervals (98% confidence). References (c) and (d) do not say what confidence may be assigned to their upper limits.

(c) Kavanagh et al. (1968).

(d) Gallmann et al. (1969).

Table 23. Half-life measurements for $^{38}\text{Ca}(\beta^+ \gamma) ^{38}\text{K}$.

(i) This work:

Run	Half life (sec)
1	0.4099 ± 0.0175
2	0.4173 ± 0.0163
4	0.4596 ± 0.0183
7	0.4375 ± 0.0163

Weighted
average 0.4302 ± 0.0085

$\chi^2 = 4.75$ (20% probability for 3 degrees of freedom)

Adopted
average 0.430 ± 0.012 sec

(ii) Average with previous result:

Source	Half life (sec)
Gallmann et al. (1969)	0.439 ± 0.012
This work	0.430 ± 0.012
Adopted value	0.435 ± 0.009

Table 24. Absolute branch intensities and log ft values for ^{38}Ca β^+ decay.

final ^{38}K state $E_x(\text{keV})$	(a) J^π	(b) absolute branch	(c) log ft	theoretical log ft		
				(d)	(e)	(f) (g)
130.4	0^+	$0.761^{+0.017}$				
458.7	1^+	$(2.66 \pm 0.35) \times 10^{-2}$	4.827 ± 0.062	6.18	3.85	3.85 5.58
1698.3	1^+	0.210 ± 0.016	3.398 ± 0.038	3.03	3.07	4.44 3.25
3316	$(1^+, 2^-, 3^+)$	$< 1.3 \times 10^{-3}$	> 4.58			
3342	1^+	$(2.91^{+0.38}) \times 10^{-3}$	4.227 ± 0.060		3.97	
3702	(0^+-4^+)	$< 2.5 \times 10^{-3}$	> 3.97			
3739	(1^+-5^+)	$< 7.5 \times 10^{-4}$	> 4.46			
3841	$\pi=\text{unnat.}$	$< 1.0 \times 10^{-3}$	> 4.24			
3857	1^+	$< 7.5 \times 10^{-4}$	> 4.34			
3978	1^+	$< 2.3 \times 10^{-3}$	> 3.74			
4214	(0^+-2^+)	$< 8.6 \times 10^{-4}$	> 3.89			
4318	(1^+-5^+)	$< 4.0 \times 10^{-4}$	> 4.09			
4395	(1^+-5^+)	$< 7.8 \times 10^{-4}$	> 3.70			

(a) Excitation energies and spin-parity assignments are taken from Endt and Van der Leun (1978).

(b) Relative γ ray intensities are taken from this work only. The absolute branch to the ground state is calculated from the measured half life ($0.435^{+0.009}$ sec, the combined result of Gallmann et al. (1969) and this work) and the known partial half life for the superallowed Fermi transition to the 0^+ state at 130 keV. Limits are 2σ confidence intervals.

(c) Log f values are taken from the table of Gove and Martin (1971) and small radiative corrections have

Table 24. (cont.)

- been applied following Hardy and Townner (1975).
- (d) Lanford and Wildenthal (1973). Log ft values recalculated using the axial coupling constant given by $g_A/g_V = 1.250^{+0.009}$.
 - (e) Brown et al. (1978).
 - (f) Englebertink and Glaudemans (1969).
 - (g) Dieperink and Brussaard (1969).

Table 25. T=1/2 to T=1/2 Gamow-Teller transitions in 1s-0d shell nuclei.

Parent		Daughter		J ^π	log ft (exp) ^(a) (G-T part only)	log ft(theory) (G-T part only)	
	J ^π		E _x (keV)			(d)	(e)
(a)	¹⁷ F 5/2 ⁺	¹⁷ O	0	5/2 ⁺	3.788 [±] 0.002	3.45	3.45
(a)	¹⁹ Ne 1/2 ⁺	¹⁹ F	0	1/2 ⁺	3.380 [±] 0.002	3.14	3.15
			1554	3/2 ⁺	5.742 [±] 0.063	6.96	10.5
(b)	²¹ Na 3/2 ⁺	²¹ Ne	0	3/2 ⁺	4.095 [±] 0.021	3.89	3.92
			351	5/2 ⁺	4.599 [±] 0.018	4.36	4.52
			2796	1/2 ⁺		4.95	4.32
(b)	²³ Mg 3/2 ⁺	²³ Na	0	3/2 ⁺	4.327 [±] 0.031	4.14	4.33
			440	5/2 ⁺	4.422 [±] 0.018	4.26	4.68
			2391	1/2 ⁺	4.993 [±] 0.058	4.46	4.69
			2982	3/2 ⁺	> 4.66	3.99	
(c)	²⁵ Al 5/2 ⁺	²⁵ Mg	0	5/2 ⁺	3.981 [±] 0.015	3.80	3.73 [±] 0.06
			975	3/2 ⁺	6.245 [±] 0.050	6.22	6.42
			1612	7/2 ⁺	4.373 [±] 0.012	4.23	4.16 [±] 0.05
			1965	5/2 ⁺	> 6.50	8.24	
			2738	7/2 ⁺	> 4.64	7.35	
			2801	3/2 ⁺	> 5.10	5.11	
			3908	5/2 ⁺	> 3.85		

Table 25. (cont.)

Parent			Daughter		log ft (exp) (G-T part only)	log ft (theory)		
	J^π		$E_x(\text{keV})$	J^π		(G-T part only)		
						(d)	(f)	
(b)	^{27}Si	$5/2^+$	^{27}Al	0	$5/2^+$	4.117 ± 0.022	3.96	3.62 ± 0.04
				1014	$3/2^+$	7.37 ± 0.24		5.7 ± 0.3
				2211	$7/2^+$	4.689 ± 0.032		4.67 ± 0.11
				2735	$5/2^+$	5.024 ± 0.049		5.0 ± 0.4
				2981	$3/2^+$	4.340 ± 0.041		4.14 ± 0.04
						(d)	(e)	
(b)	^{29}P	$1/2^+$	^{29}Si	0	$1/2^+$	4.360 ± 0.038	4.50	4.05
				1273	$3/2^+$	4.880 ± 0.081		4.64
				2426	$3/2^+$	$4.242 \pm 0.082^{(g)}$		4.05
						(d)	(e)	(h)
(c)	^{31}S	$1/2^+$	^{31}P	0	$1/2^+$	4.341 ± 0.033	4.32	3.69 3.70
				1266	$3/2^+$	4.966 ± 0.015	4.97	4.77 4.72
				3134	$1/2^+$	4.770 ± 0.023	4.47	4.10
				3506	$3/2^+$	4.538 ± 0.038	4.03	4.55
				4261	$3/2^+$	> 4.71	5.12	
				4594	$3/2^+$	> 4.45	6.40	

Table 25. (cont.)

Parent			Daughter		log ft (exp)	log ft (theory)			
J^π			$E_x(\text{keV})$	J^π	(G-T part only)	(G-T part only)			
						(d)	(e)	(h)	
(c)	^{33}Cl	$3/2^+$	^{33}S	0	$3/2^+$	$4.88^{+0.10}_{-0.10}$	5.06	4.17	4.15
				841	$1/2^+$	$5.664^{+0.043}_{-0.043}$	5.17	4.92	5.13
				1966	$5/2^+$	$4.979^{+0.040}_{-0.040}$	7.19	4.27	
				2312	$3/2^+$	$5.825^{+0.045}_{-0.045}$	4.90	4.88	
				2866	$5/2^+$	$4.191^{+0.041}_{-0.041}$	3.88	4.33	
				2832	$5/2^+$	> 5.40			
				3935	$3/2^+$	> 5.30			
				4053	$1/2^+$	$5.24^{+0.15}_{-0.15}$			
				4144	$(3/2^+, 5/2)$	> 5.28			
				4375	$1/2^+$	> 4.65			
				4424	$(1/2^+, 3/2)$	> 4.49			
				4746		$4.37^{+0.14}_{-0.14}$			
						(d)	(e)		
(c)	^{35}Ar	$3/2^+$	^{35}Cl	0	$3/2^+$	$4.95^{+0.10}_{-0.10}$	4.71	$4.73^{+0.05}_{-0.05}$	
				1219	$1/2^+$	$5.100^{+0.014}_{-0.014}$	4.83	4.47	
				1763	$5/2^+$	$5.444^{+0.017}_{-0.017}$	7.91	5.82	
				2694	$3/2^+$	$5.006^{+0.019}_{-0.019}$	4.66	4.27	
				3003	$5/2^+$	$4.975^{+0.017}_{-0.017}$	4.35	4.14	
				3918	$3/2^+$	$4.880^{+0.030}_{-0.030}$	4.43	4.53	
				3968	$1/2^+$	$4.825^{+0.053}_{-0.053}$	4.67		
				4624	$(3/2, 5/2^+)$	> 4.75			

Table 25. (cont.)

Parent			Daughter		log ft (exp)	log ft (theory)			
J^π			$E_x(\text{keV})$	J^π	(G-T part only)	(G-T part only)			
						(d)	(e)	(h)	
(b)	^{37}K	$3/2^+$	^{33}Ar	0	$3/2^+$	$4.260^{+0.032}$	3.94	3.85	3.92
				1410	$1/2^+$	> 6.71	6.40	6.30	7.6
				2796	$5/2^+$	$3.859^{+0.074}$	3.55	3.78	3.49
				3171	$5/2^+$	> 6.00	3.91	5.27	
				3602	$3/2^+$	$5.039^{+0.070}$	4.52		
						(d)	(e)	(i)	
(b)	^{39}Ca	$3/2^+$	^{39}K	0	$3/2^+$	$4.159^{+0.024}$	3.82	3.83	3.85
				2522	$1/2^+$	> 6.41			
				3939	$3/2^+$	> 5.59			
				4095	$1/2^+$	> 5.00			

(a) Results from Lederer (ed.), Table of Isotopes, 7th edition.

(b) Experimental results taken from Endt and Van der Leun (1978).

(c) Experimental results taken from this thesis.

(d) Brown et al. (1978).

(e) Lanford and Wildenthal (1973).

(f) Timmer et al. (1978).

(g) Wilson and Kavanagh, unpublished result (1979).

(h) Glaudemans et al. (1971).

(i) Dieperink and Brussaard (1969).

Table 26. 0^+ ; T=1 to 1^+ ; T=0 Gamow-Teller transitions in 1s-0d shell nuclei.

Parent			Daughter		log ft (exp)	log ft (theory)			
J^π			$E_x(\text{keV})$	J^π		(d)	(e)		
(a)	^{18}Ne	0^+	^{18}F	0	1^+	$3.099^{+0.007}_{-0.007}$	2.86	2.87	
				1701	1^+	$4.392^{+0.058}_{-0.058}$			
(b)	^{22}Mg	0^+	^{22}Na	583	1^+	$3.650^{+0.012}_{-0.012}$	3.40	3.50	
				1937	1^+	$3.427^{+0.016}_{-0.016}$	3.23	3.28	
				3944	1^+		3.97	3.59	
				4319	1^+		5.24		
(c)	^{26}Si	0^+	^{26}Al	1058	1^+	$3.550^{+0.011}_{-0.011}$	3.37	$3.46^{+0.11}_{-0.11}$	
				1850	1^+	$3.855^{+0.013}_{-0.013}$	3.87	$3.57^{+0.17}_{-0.17}$	
				2072	1^+	$4.629^{+0.018}_{-0.018}$	3.80	4.2	
				2739	1^+	$4.539^{+0.019}_{-0.019}$	4.29		
				3723	1^+	> 4.15			
(c)	^{30}S	0^+	^{30}P	0	1^+	$4.327^{+0.012}_{-0.012}$	5.06	3.34	3.34
				709	1^+	$5.91^{+0.11}_{-0.11}$	4.54	5.32	4.85
				3019	1^+	$3.562^{+0.012}_{-0.012}$	3.95	4.23	
				3731	1^+	> 5.10			

Table 26. (cont.)

Parent			Daughter		log ft (exp)	log ft (theory)			
	J^π		E_x (keV)	J^π		(d)	(e)	(g)	
(b)	^{34}Ar	0^+	^{34}Cl	461	1^+	$5.317^{+0.049}_{-0.049}$	4.91	3.62	3.72
				666	1^+	$4.786^{+0.022}_{-0.022}$	5.73	4.27	4.08
				2580	1^+	$4.110^{+0.035}_{-0.035}$	3.77		
				3129	1^+	$3.462^{+0.031}_{-0.031}$	3.18		
						(d)	(e)	(h)	
(c)	^{38}Ca	0^+	^{38}K	459	1^+	$4.827^{+0.062}_{-0.062}$	3.85	6.16	5.58
				1698	1^+	$3.398^{+0.038}_{-0.038}$	3.07	3.01	3.25
				3343	1^+	$4.227^{+0.060}_{-0.060}$	3.97		
				3857	1^+	> 4.34			
				3978	1^+	> 3.74			

(a) Experimental data from Lederer (ed.), Table of Isotopes, 7th edition, and Ajzenberg-Selove (1978).

(b) Experimental data from Endt and Van der Leun (1978).

(c) Experimental data from this thesis.

(d) Brown et al. (1978).

(e) Lanford and Wildenthal (1973).

(f) Timmer et al. (1978).

(g) Glaudemans et al. (1971).

(h) Dieperink and Brussaard (1969).

Table 27.^(a) Gamow-Teller transitions between 1s-0d shell T=1 and T=0 nuclei. (Transitions included in Table 26 and their mirrors are excluded from this table.)

Parent		Daughter		J^π	log ft (exp.)	log ft (theory)	
J^π		E_x (keV)				(b)	(d)
^{20}F	2^+	^{20}Ne	1633	2^+	$4.973^{+0.001}$	4.85	4.96
^{20}Na	2^+	^{20}Ne	1633	2^+	$4.988^{+0.009}$	(b) 4.85	(d) 4.96
			7415	2^+	$4.184^{+0.034}$	4.21	4.11
			7826	2^+	$5.416^{+0.037}$		4.94
			8820		$6.281^{+0.092}$		
			9481	2^+	$5.061^{+0.037}$		
			9873	3^+	$5.84^{+0.25}$	5.00	4.88
			10584	2^+	$4.754^{+0.048}$		
			10848	2^+	$4.170^{+0.039}$		3.51
			11320	2^+	$4.406^{+0.054}$		
			11856	2^+	$5.00^{+0.12}$		
^{22}Na	3^+	^{22}Ne	1275	2^+	$7.407^{+0.006}$	(b) 9.39	(d) 6.59
^{24}Na	4^+	^{24}Mg	4123	4^+	$6.119^{+0.006}$	(b) 5.79	(c) 5.5
			5236	3^+	$6.765^{+0.034}$	6.18	$6.1^{+0.4}$

Table 27. (cont.)

Parent		Daughter		log ft (exp)	log ft (theory)	
	J ^π		E _x (keV) J ^π		(b)	(c)
²⁴ Al	4 ⁺	²⁴ Mg	4123 4 ⁺	6.27±0.34	5.79	5.5
			5236 3 ⁺	6.55±0.23	6.18	6.1±0.4
			6010 4 ⁺	6.49±0.32	5.96	3.5±0.2
			8437 (3,4) ⁺	3.947±0.056	3.89	4.7
			9298 (3,4) ⁺	4.825±0.093	4.40	
			11217 4 ⁺	6.58±0.11		
			11694 4 ⁺	5.406±0.082		
			12049 4 ⁺	6.756±0.089		
			12125±30	6.01±0.14		
			12159 4 ⁺	6.04±0.12		
^{24m} Al	1 ⁺	²⁴ Mg	0 0 ⁺	6.01±0.15	5.70	4.1±0.2
			1369 2 ⁺	6.18±0.15	5.94	4.26±0.15
			4238 2 ⁺	6.07±0.15	5.74	5.4±0.7
²⁸ Al	3 ⁺	²⁸ Si	1779 2 ⁺	4.869±0.006	4.7±0.4	4.40

Table 27. (cont.)

Parent			Daughter		log ft (exp)	log ft (theory)		
J^π			E_x (keV)	J^π		(c)	(d)	
^{28}P	3^+	^{28}Si	1779	2^+	$4.854^{+0.019}_{-0.019}$	$4.7^{+0.4}_{-0.4}$	4.40	
			4617	4^+	$5.816^{+0.035}_{-0.035}$	$5.9^{+0.2}_{-0.2}$	5.49	
			6276	3^+	$4.792^{+0.043}_{-0.043}$	$4.10^{+0.08}_{-0.08}$	4.04	
			6888	4^+	> 6.47			
			7417	2^+	> 6.18			
			7799	3^+	$4.733^{+0.037}_{-0.037}$	$4.01^{+0.09}_{-0.09}$		
			7933	2^+	$4.737^{+0.042}_{-0.042}$			
			8259	2^+	$5.21^{+0.12}_{-0.12}$			
			8589	3^+	$4.319^{+0.034}_{-0.034}$			
			9480	2^+	$5.45^{+0.14}_{-0.14}$			
			10669	3^+	$4.633^{+0.075}_{-0.075}$			
^{30}P	1^+	^{30}Si	2235	2^+	$5.784^{+0.076}_{-0.076}$	4.83	4.59	4.89
			3499	2^+	> 4.91		4.34	
			3770	1^+	> 4.90		5.09	
			3788	0^+	> 4.13		4.51	
^{32}P	1^+	^{32}S	0	0^+	$7.909^{+0.006}_{-0.006}$	5.38	4.63	4.99

Table 27. (cont.)

Parent			Daughter		log ft (exp)	log ft (theory)		
J^π			E_x (keV)	J^π		(b)	(e)	
^{32}Cl	1^+	^{32}S	0	0^+	$6.74^{+0.15}_{-0.15}$	5.38	4.99	
			2230		$4.525^{+0.029}_{-0.029}$	4.46	3.80	
			3778	0^+	$5.54^{+0.14}_{-0.14}$	5.52	4.92	
			4282	2^+	$5.315^{+0.057}_{-0.057}$	5.56	5.38	
			4695	1^+	$4.791^{+0.052}_{-0.052}$	5.22	4.19	
			5549	2^+	$4.804^{+0.054}_{-0.054}$	4.83		
			6666	2^+	$4.77^{+0.13}_{-0.13}$	4.43		
			7190	1^+	$4.830^{+0.050}_{-0.050}$	6.32		
^{34m}Cl	3^+	^{34}S	2127	2^+	$5.994^{+0.010}_{-0.010}$	7.53	5.86	7.13
			3303	2^+	$4.831^{+0.008}_{-0.008}$	4.77	4.24	4.36
			4114	2^+	$5.089^{+0.012}_{-0.012}$	4.71	8.12	5.15
			4688	4^+	$5.431^{+0.039}_{-0.039}$	5.49	6.46	
			4876	3^+	$5.190^{+0.071}_{-0.071}$	4.76	4.91	
			4889	2^+	> 6.64	4.99		
						(b)	(d)	(e)
^{36}K	2^+	^{36}Ar	1970	2^+	$4.788^{+0.051}_{-0.051}$	4.60	4.79	4.85
			4440	2^+	$4.914^{+0.051}_{-0.051}$	4.52	4.76	
			4951	2^+	$6.44^{+0.14}_{-0.14}$			
			6730	2^+	$5.117^{+0.060}_{-0.060}$			
			6867	$(1,2)^+$	$5.35^{+0.11}_{-0.11}$			
			7140	3^+	$5.065^{+0.060}_{-0.060}$			
			7178	$(1,2)^+$	$5.053^{+0.069}_{-0.069}$			

Table 27. (cont.)

Parent			Daughter		log ft (exp)	log ft (theory)		
J^π			$E_x(\text{keV})$	J^π		(b)	(d)	(f)
^{38}K	3^+	^{38}Ar	2168	2^+	4.982 ± 0.007	4.90	4.97	4.75
			3937	2^+	5.889 ± 0.036	6.69	5.76	
			4565	2^+	> 6.40			
			5157	2^+	> 5.70			
			5350	4^+	> 5.57			

(a) Experimental data from Endt and Van der Leun (1978) and the references given there, and from this thesis for ^{30}P and $^{34\text{m}}\text{Cl}$.

(b) Brown et al. (1978).

(c) Timmer et al. (1978). ($g_A/g_V = 1.250 \pm 0.009$)

(d) Lanford and Wildenthal (1973). ($g_A/g_V = 1.250 \pm 0.009$)

(e) Glaudemans et al. (1971).

(f) Dieperink and Brussaard (1969).

Table 28. 1s-0d Gamow-Teller transitions between T=3/2 and T=1/2 states.

Parent		Daughter		log ft (exp) ^(a)		log ft (theory)	
	J ^π		E _x (keV)	J ^π		(b)	(c)
¹⁹ O	5/2 ⁺	¹⁹ F	197	5/2 ⁺	5.437 [±] 0.045	5.92	5.60
			1554	3/2 ⁺	4.579 [±] 0.030	4.48	4.59
			4378	7/2 ⁺	3.651 [±] 0.048	3.69	3.81
						(b)	(c)
²¹ F	5/2 ⁺	²¹ Ne	0	3/2 ⁺	5.218 [±] 0.092	5.60	5.53
			351	5/2 ⁺	4.743 [±] 0.043	4.73	4.68
			1746	7/2 ⁺	5.066 [±] 0.059	4.68	4.78
						(b)	(d)
(d) ²¹ Mg	5/2 ⁺	²¹ Na	0	3/2 ⁺		5.60	5.55
			332	5/2 ⁺		4.73	4.70
			1716	7/2 ⁺		4.68	4.80
			3544	5/2 ⁺	6.09 [±] 0.06	7.69	8.34
			4294	5/2 ⁺	4.82 [±] 0.02		5.21
			4468	3/2 ⁺	4.48 [±] 0.02	5.66	4.44
			5022	(5/2 ⁺ , 3/2 ⁺)	4.95 [±] 0.04		4.67
+ 11 branches to higher states including							
			8816		3.73 [±] 0.04		

Table 28. (cont.)

Parent		Daughter		log ft (exp)		log ft (theory)	
	J^π		E_x (keV)	J^π		(b)	(c)
^{23}Ne	$5/2^+$	^{23}Na	0	$3/2^+$	5.270 ± 0.010	5.51	5.00
			440	$5/2^+$	5.388 ± 0.016	5.53	4.74
			2076	$7/2^+$	5.835 ± 0.019	6.93	5.42
			2982	$3/2^+$	6.142 ± 0.023	5.63	5.55
			3915	$5/2^+$		6.73	6.76
			4776	$7/2^+$		6.30	5.24
^{23}Al		^{23}Mg	Not yet studied experimentally				
^{25}Na	$5/2^+$	^{25}Mg	0	$5/2^+$	5.260 ± 0.017	5.16	4.5 ± 0.2
			975	$3/2^+$	5.056 ± 0.025	5.04	4.8 ± 0.2
			1612	$7/2^+$	5.039 ± 0.030	5.06	4.6 ± 0.2
			1965	$5/2^+$	6.004 ± 0.072	5.61	5.7
			2738	$7/2^+$	> 6.44	7.39	
			2801	$3/2^+$	5.196 ± 0.081	4.98	$5.4^{+1.4}_{-0.5}$
^{25}Si		^{25}Al	Not yet known accurately				
^{27}Mg	$1/2^+$	^{27}Al	844	$1/2^+$	4.734 ± 0.007	4.01	7.0
			1014	$3/2^+$	4.940 ± 0.009	4.16	4.7 ± 0.2
^{27}P		^{27}Si	Not yet studied experimentally				

Table 28. (cont.)

Parent		Daughter		log ft (exp)		log ft (theory)			
J^π		E_x (keV) J^π							
							(c)		
^{29}Al	$5/2^+$	^{29}Si	1273	$3/2^+$	5.055 ± 0.009	4.32			
			2028	$5/2^+$	5.726 ± 0.029	4.60			
			2426	$3/2^+$	5.012 ± 0.027	4.19			
			3067	$5/2^+$	6.24 ± 0.19	4.56			
							(f)		
(f) ^{29}S	$5/2^+$	^{29}P	1383	$3/2^+$		4.77			
			1954	$5/2^+$		5.46			
			2423	$3/2^+$		4.63			
			3106	$5/2^+$		7.28			
			4080	$7/2^+$	> 6.2	7.18			
			4954	$5/2^+$	4.65 ± 0.02	4.44			
			5293	$7/2^+$	5.04 ± 0.04	4.47			
			5826		4.88 ± 0.05	4.92			
			5967	$3/2^+$	6.17 ± 0.06	5.43			
+ 17 branches to higher states including									
			8532	$(3/2,5/2)^+$	4.43 ± 0.04				
			9390		4.40 ± 0.12				
							(b)	(c)	(g)
^{31}Si	$3/2^+$	^{31}P	0	$1/2^+$	5.528 ± 0.007	4.92	4.92	5.10	
			1266	$3/2^+$		5.21	5.26	5.04	
^{31}Cl		^{31}S	Not yet studied experimentally						
							(b)	(c)	(g)
^{33}P	$1/2^+$	^{33}S	0	$3/2^+$	5.029 ± 0.010	4.74	4.62	4.78	

Table 28. (cont.)

Parent		Daughter		log ft (exp)		log ft (theory)			
	J ^π		E _x (keV)	J ^π		(b)	(c)		
(h) ³³ Ar	1/2 ⁺	³³ Cl	0	3/2 ⁺		4.74	4.62		
			810	1/2 ⁺	4.44 [±] 0.03	4.32	3.29		
			2352	3/2 ⁺		5.34	4.54		
			3972	3/2 ⁺	5.71 [±] 0.05	7.09			
			4099	1/2 ⁺	5.64 [±] 0.05	6.27	4.36		
			4113	3/2 ⁺		6.74			
			4438	1/2 ⁺	4.76 [±] 0.05	4.50			
			4463	3/2 ⁺					
			4832	3/2 ⁺	5.54 [±] 0.05				
			5105	3/2 ⁺	6.03 [±] 0.07				
			5450	1/2 ⁺	5.05 [±] 0.05	4.98			
			+ 14 T=3/2 to T=1/2 branches to higher states, including						
					7475 [±] 18		4.35 [±] 0.06		
					8183 [±] 25		4.2 [±] 0.3		
						(b)	(c)		
³⁵ S	3/2 ⁺	³⁵ Cl	0	3/2 ⁺	5.014 [±] 0.007	4.74	5.01		
³⁵ K		³⁵ Ar	Not yet studied experimentally						
						(b)	(c)	(i)	
³⁷ Ar	3/2 ⁺	³⁷ Cl	0	3/2 ⁺	5.104 [±] 0.007	5.13	5.53	5.12	

Table 28. (cont.)

Parent		Daughter		log ft (exp)	log ft (theory)		
J^π		E_x (keV)	J^π		(b)	(c)	(i)
^{37}Ca	$3/2^+$	^{37}K	0 $3/2^+$		5.13	5.53	5.12
		1369	$1/2^+$			6.35	
		2750	$(5/2^+)$	$4.87^{+0.05}$		4.52	
+ 10 branches to higher $T=1/2$ states, including							
		5122^{+6}	$1/2^+$	$4.17^{+0.04}$		3.69	

- (a) Experimental data from Ajzenberg-Selove (1978) and Endt and Van der Leun (1978) except where noted.
- (b) Brown et al. (1978).
- (c) Lanford and Wildenthal (1973). Their log ft values have been recalculated using the axial coupling constant given by $(g_A/g_V) = 1.250^{+0.009}$.
- (d) Sextro et al. (1973). The theoretical calculations given in this reference are from a private communication from Lanford and Wildenthal.
- (e) Timmer et al. (1978). Their log ft values have been recalculated using the axial coupling constant given by $(g_A/g_V) = 1.250^{+0.009}$.
- (f) Vieira et al. (1979). These results are normalized to the theoretical strength for the mixed Fermi and Gamow-Teller transition to the isobaric analog of the ground state of ^{29}S . The theoretical calculations quoted in this reference are from a private communication from Chung and Wildenthal.
- (g) Glaudemans et al. (1971). Their log ft values have been recalculated using the axial coupling constant given by $(g_A/g_V) = 1.250^{+0.009}$.
- (h) Hardy et al. (1971).
- (i) Dieperink and Brussaard (1969).

Table 29. Gamow-Teller transitions from T=2 to T=1 ls-0d shell nuclei.

Parent		Daughter		log ft (exp) ^(a)		log ft (theory)	
	J ^π		E _x (keV)	J ^π		(b)	(c)
²⁰ O	0 ⁺	²⁰ F	1057	1 ⁺	3.736 [±] 0.009	3.78	3.86
²² F(d)	4 ⁺	²² Ne	3357	4 ⁺	6.80 [±] 0.25	6.40	
			5523	4 ⁺	4.802 [±] 0.016	4.65	
			5641	3 ⁺	5.274 [±] 0.022	5.25	
			6345	4 ⁺	5.355 [±] 0.022	5.65	
			7341	(3,4) ⁺	5.633 [±] 0.068	5.96 ^(e)	
			7424	5 ⁺	4.725 [±] 0.025	4.65	
²⁴ Ne	0 ⁺	²⁴ Na	472	1 ⁺	4.373 [±] 0.013	4.64	4.27
			1346	1 ⁺	4.401 [±] 0.024	4.16	4.28
²⁶ Na(f)	3 ⁺	²⁶ Mg	1809	2 ⁺	4.717 [±] 0.010	4.60	
			2938	2 ⁺	> 6.71	6.40	
			3940	3 ⁺	5.775 [±] 0.056		
			4318	4 ⁺	6.143 [±] 0.090		
			4332	2 ⁺	5.600 [±] 0.054	5.67	
			4350	3 ⁺	5.073 [±] 0.034		
			4834	2 ⁺	5.202 [±] 0.036	5.10	
			4900	4 ⁺	6.14 [±] 0.16		
			5291	2 ⁺	> 6.10		
			5474	4 ⁺	> 6.71		
			5710	4 ⁺	5.345 [±] 0.064		
			6125	(2,3) ⁺	4.723 [±] 0.055		

Table 29. (cont.)

Parent		Daughter		log ft (exp)		log ft (theory)	
	J^π		E_x (keV)	J^π		(b)	(c)
^{28}Mg	0^+	^{28}Al	1372	1^+	4.464 ± 0.011	6.48	3.76
			1620	1^+	4.572 ± 0.090	3.92	
$^{30}\text{Al}(\text{g})$	3^+	^{30}Si	2235	2^+	5.610 ± 0.029	5.10	6.08
			3499	2^+	4.566 ± 0.020	4.58	4.36
			4809	2^+	5.043 ± 0.026	4.75	5.29
			4831	3^+	4.970 ± 0.022		4.44
			5231	3^+	5.162 ± 0.036		7.54
			5280	4^+	> 6.40		4.84
			5613	2^+	5.869 ± 0.094	5.45	
			5950	4^+	5.92 ± 0.15		
^{32}Si	0^+	^{32}P	0	1^+	8.45 ± 0.07		(c) 3.87
$^{34}\text{P}(\text{h})$	1^+	^{34}S	0	0^+	5.163 ± 0.015	5.08	5.49
			2127	2^+	4.929 ± 0.061	4.86	4.23
			3304	2^+	> 6.66	7.28	5.31
			3914	0^+	6.01 ± 0.17	5.44	6.40
			4074	1^+	5.387 ± 0.097	4.95	4.84
			4114	2^+	4.863 ± 0.084	4.56	
			4688	4^+	> 5.19		
			4876	3^+	> 3.29		
			4889	2^+	> 4.34	5.29	
^{36}Ca		^{36}K	Not yet studied experimentally				

Table 29. (cont.)

- (a) Experimental data are from Ajzenberg-Selove (1978) and Endt and Van der Leun (1978) except as noted.
- (b) Brown et al. (1978).
- (c) Lanford and Wildenthal (1973). Their log ft values have been recalculated using the axial coupling constant given by $g_A/g_V = 1.250^{+0.009}$.
- (d) Davids et al. (1974). Lanford and Wildenthal calculated log ft values for this decay but used $J=3$ for the ^{22}F ground state.
- (e) Brown et al. (1978) assume $J=3$ for this level.
- (f) Alburger et al. (1973) and Klotz et al. (1973). We use Alburger's value for the branch to the 4350-keV level in ^{26}Mg .
- (g) Alburger and Goosman (1974) and Klotz and Walter (1974).
- (h) Goosman et al. (1973c).

Table 30. Gamow-Teller transitions from T=5/2 to T=3/2 1s-0d shell nuclei.

Parent		Daughter		log ft (exp)	log ft (theory)
	J^π	$E_x(\text{keV})$	J^π		
^{23}F		^{23}Ne	Ground-state branch not yet known		
					(b)
(a) ^{25}Ne	$(1/2, 3/2)^+$	^{25}Na	0 $5/2^+$	> 5.00	
			90 $3/2^+$	4.387 ± 0.034	4.34
			1069 $1/2^+$	4.695 ± 0.072	4.63
			2201 $3/2^+$	5.18 ± 0.12	5.30
			2417	> 5.88	
			2788	> 5.81	
			2914 $(3/2, 5/2)^+$	> 5.65	
			3353	> 5.34	
			3688 $(1/2-5/2)^+$	4.82 ± 0.14	5.05
			4289 $1/2^+$	4.81 ± 0.16	4.72
^{27}Na		^{27}Mg	Studied by Détraz et al. No theoretical calculations are available.		
^{29}Mg		^{29}Al	Studied by Détraz et al. No theoretical calculations are available.		
					(b), (d)
(d) ^{31}Al	$(3/2, 5/2)^+$	^{31}Si	0 $3/2^+$	4.728 ± 0.057	4.48
			752 $1/2^+$	> 5.8	
			1695 $5/2^+$	5.21 ± 0.21	4.60
			2317 $3/2^+$	4.42 ± 0.11	4.25
			2788 $(3/2, 5/2)^+$	> 5.5	6.46

Table 30. (cont.)

Parent		Daughter		log ft (exp)	log ft (theory)		
	J^π		$E_x(\text{keV})$	J^π			
^{33}Si		^{33}P	Ground-state branch not yet known.				
					(b), (e)	(c), (e)	
(e) ^{35}P	$(1/2, 3/2)^+$	^{35}S	0	$3/2^+$	> 6.08	7.89	6.32
			1572	$1/2^+$	$4.055^{+0.058}$	4.09	4.17
			2718	$5/2^+$	> 4.00		
			2939	$(3/2, 5/2)^+$	> 3.59	5.54	

(a) Experimental values from Goosman et al. (1973a).

(b) Brown et al. (1978).

(c) Lanford and Wildenthal (1973). Their log ft values have been recalculated using the axial coupling constant given by $g_A/g_V = 1.250 \pm 0.009$.

(d) Experimental data from Détraz et al. (1979). The strength of the branch to the 2788-keV level in ^{31}Si is taken from Goosman and Alburger (1973b). Brown et al. (1978) assume that the ground state of ^{31}Al is $5/2^+$.

(e) Experimental data from Endt and Van der Leun (1978) and references quoted by them. Brown et al. and Lanford and Wildenthal assume that the ground state of ^{35}P is $1/2^+$.

Figure 1.

Schematic illustration of a positron decay. Atomic energies are plotted and the short vertical line from the parent state indicates the 1022 keV ($= 2 mc^2$) not available for positron and neutrino kinetic energy. The arrows from the end of the vertical line indicate positron decays and the arrows directly from the ground state of the parent nucleus indicate electron-capture decays. See page 17 of the text.

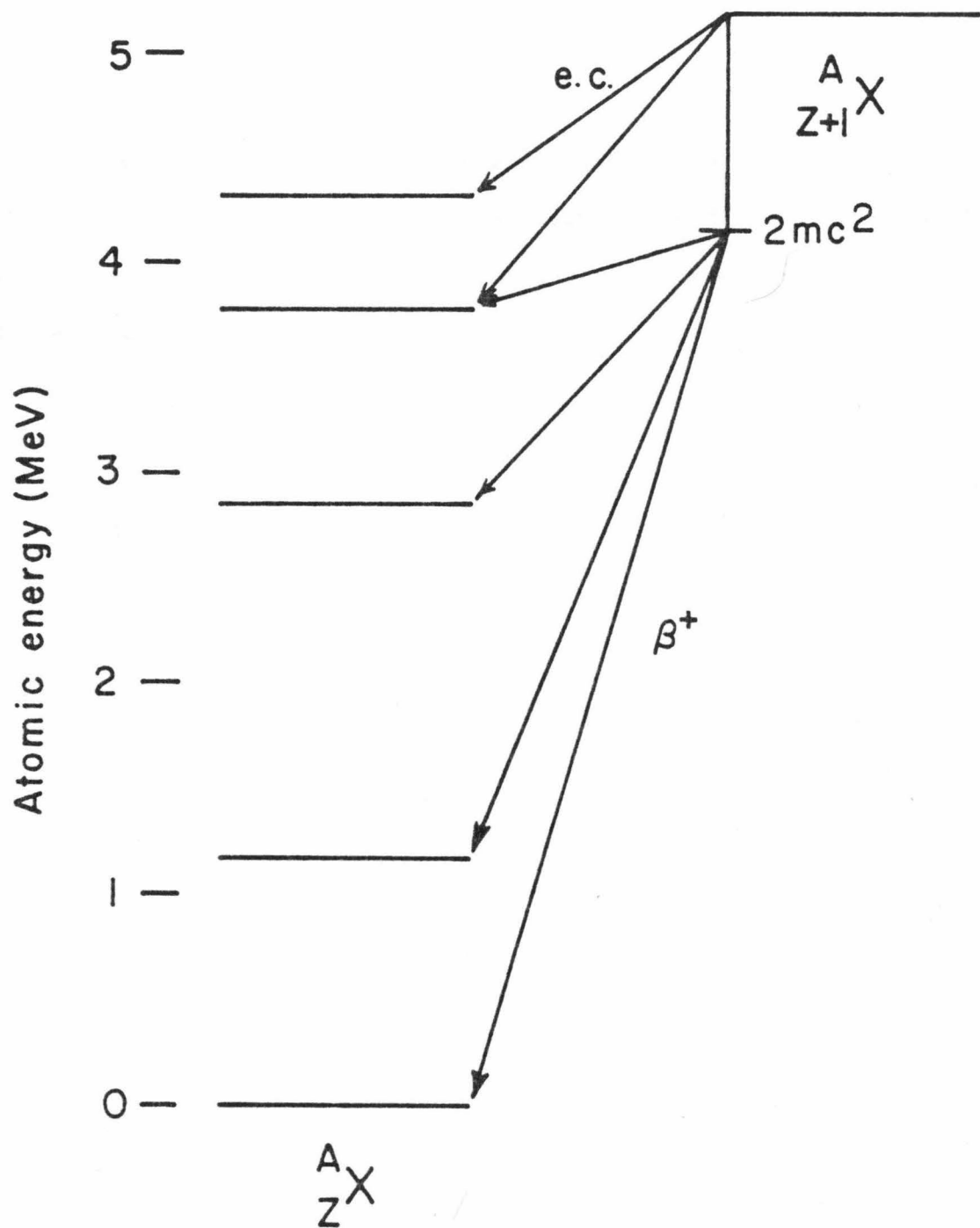


Figure 1

Schematic β^+ decay

Figure 2.

Schematic diagram of the pneumatic shuttle (rabbit system). The rabbit travels from the bombardment station to the detector in as little as 0.35 sec. The exit foil was 25 μm Al or 2.5 μm Havar. See page 39 of the text.

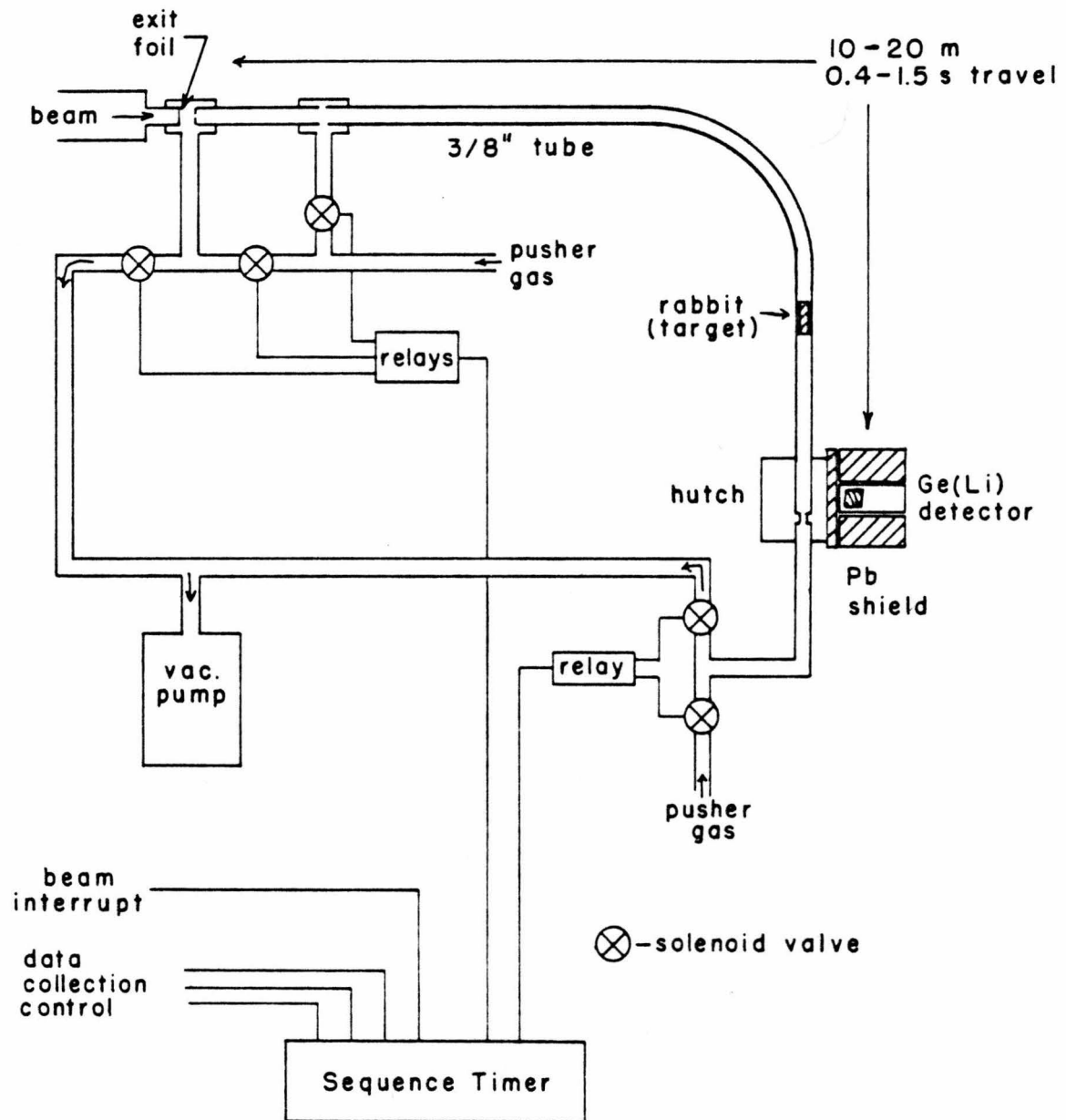
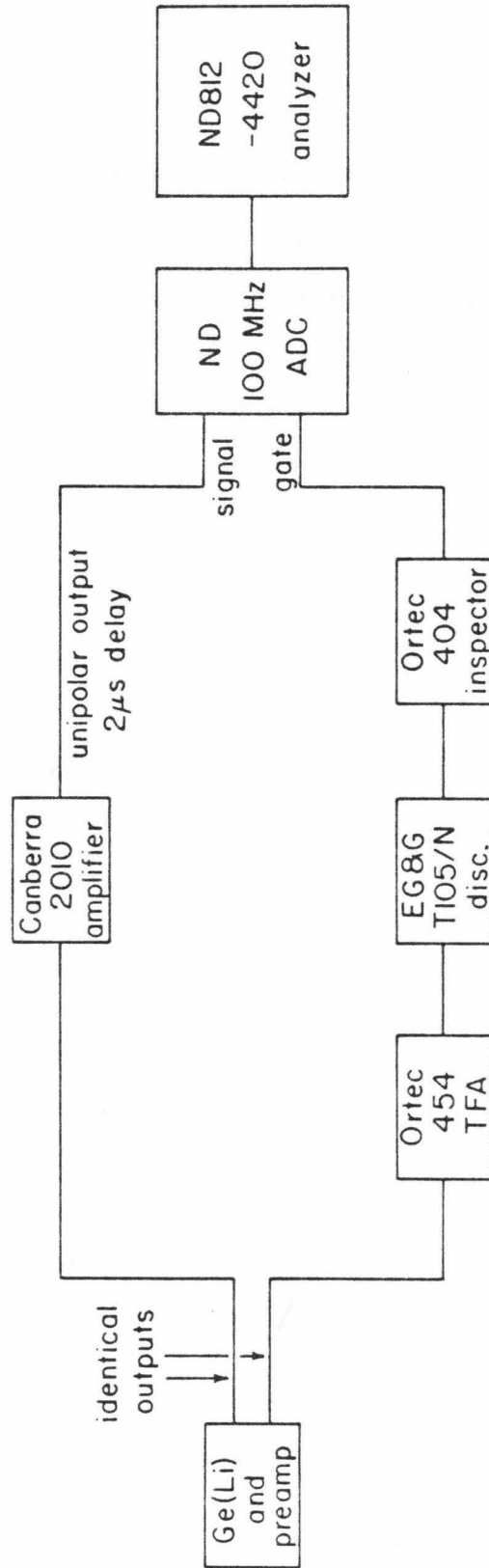


Figure 2

Figure 3.

The pileup rejection system used in the ^{31}S and ^{34}Cl experiments. The Ortec 454 TFA (Timing Filter Amplifier) is a fast shaping amplifier. When the Ortec 404 inspector receives two pulses from the discriminator within the inspect interval of 4 μs , it issues a signal which blocks the ADC. See page 41 of the text.



Pileup rejection system

Figure 3

Figure 4.

A large peak in a Ge(Li) spectrum. This is the 2313 keV peak emitted in the β^+ decay of ^{14}O . It is shown with two vertical scales in order to make the tails on the peak visible. See page 43 of the text.

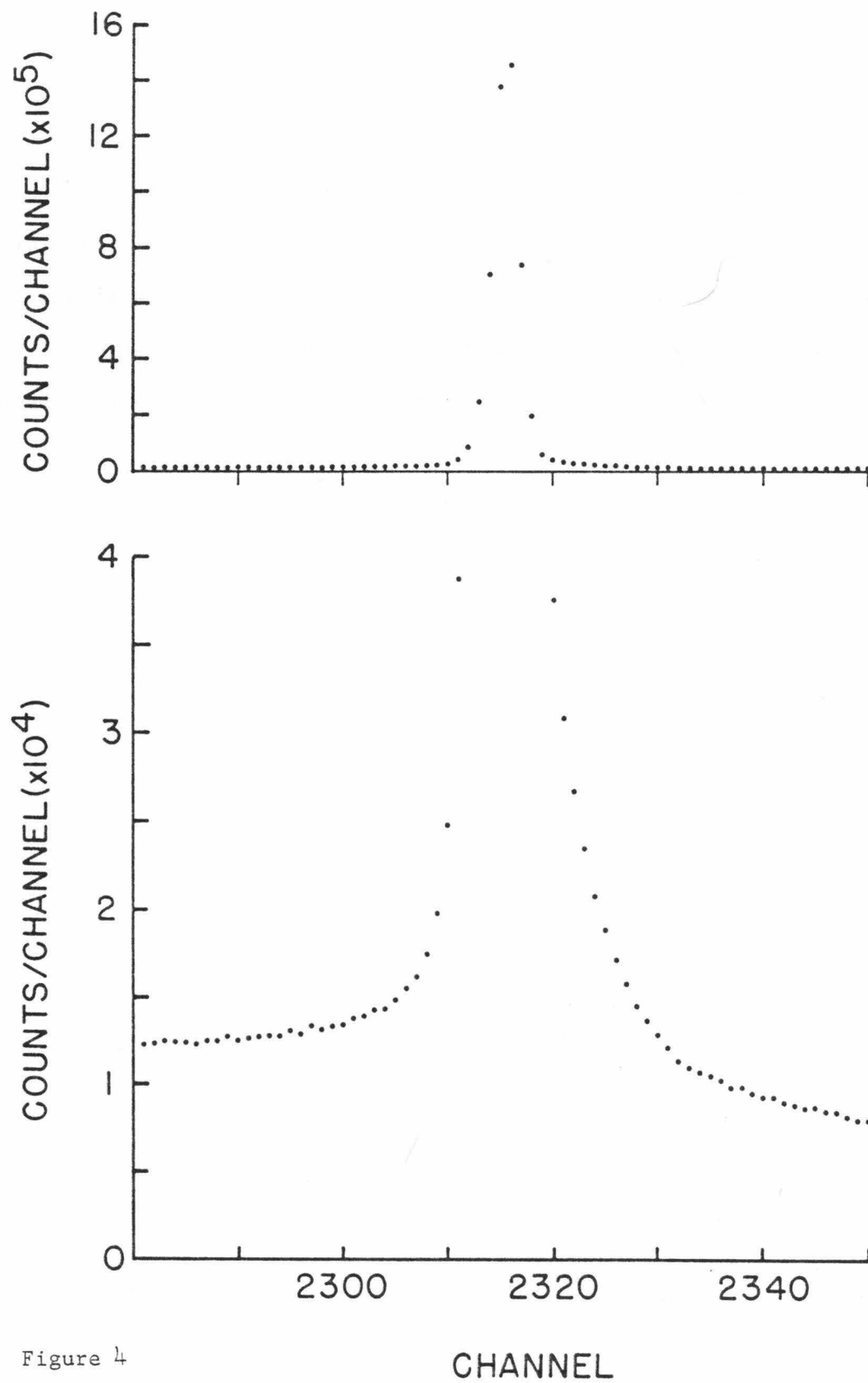


Figure 4

Figure 5.

Level diagram illustrating the β^+ decay of ^{25}Al . All energies are in keV. Observed branches are indicated by the arrows, and the remaining daughter states for allowed but not observed decays are shown. The diagram has been simplified by omitting most levels not involved in allowed decays. ^{25}Al decay is discussed on page 49 of the text.

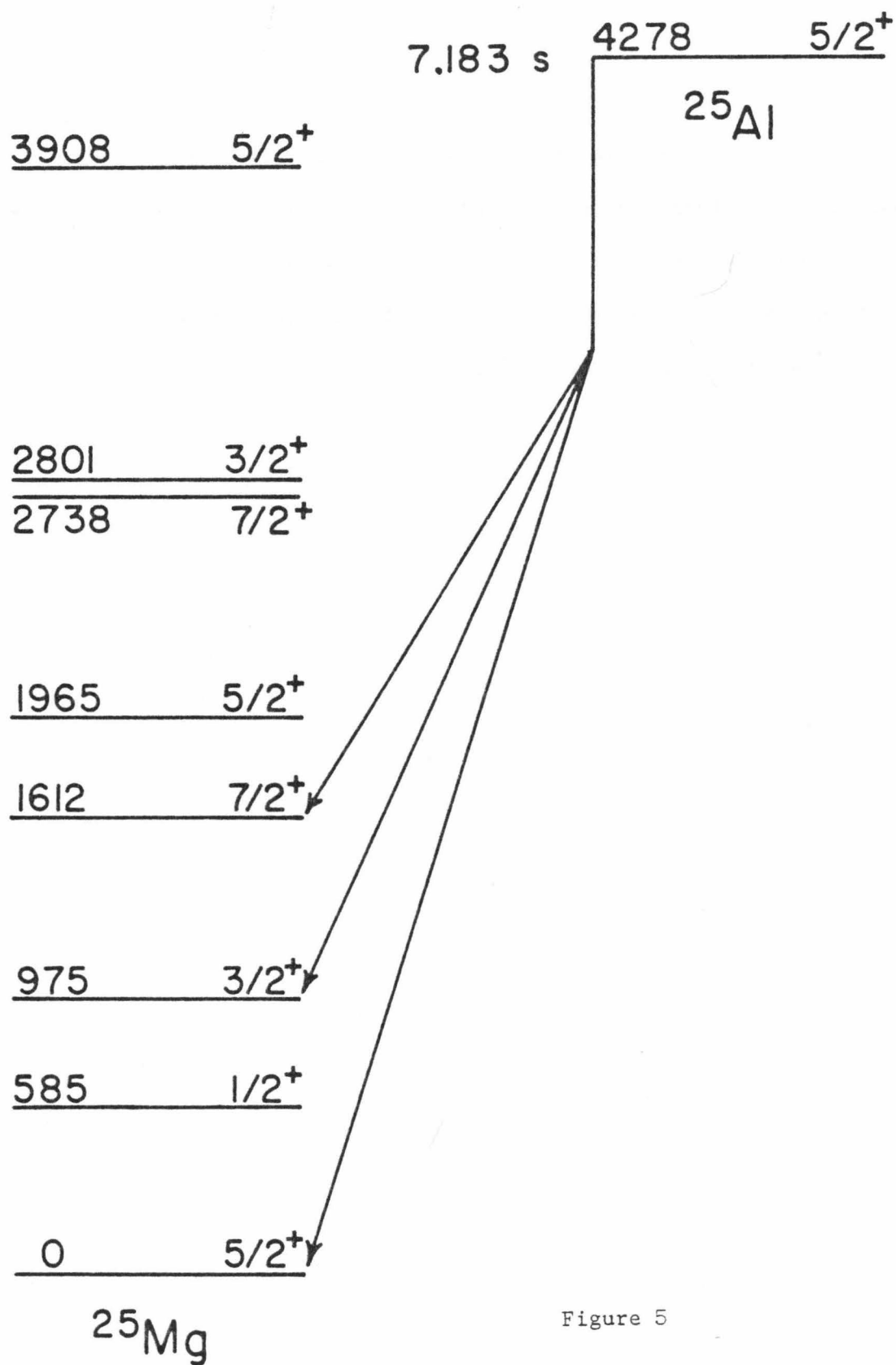


Figure 5

Figure 6.

Level diagram illustrating the β^+ decay of ^{26}Si . The diagram has been simplified by omitting most of the levels not involved in allowed β^+ decays of ^{26}Si . Observed transitions are indicated by arrows. A more detailed level diagram and γ ray branching ratios are given by Endt and Van der Leun (1978). The decay of ^{26}Si is discussed on pages 52 to 55 of the text.

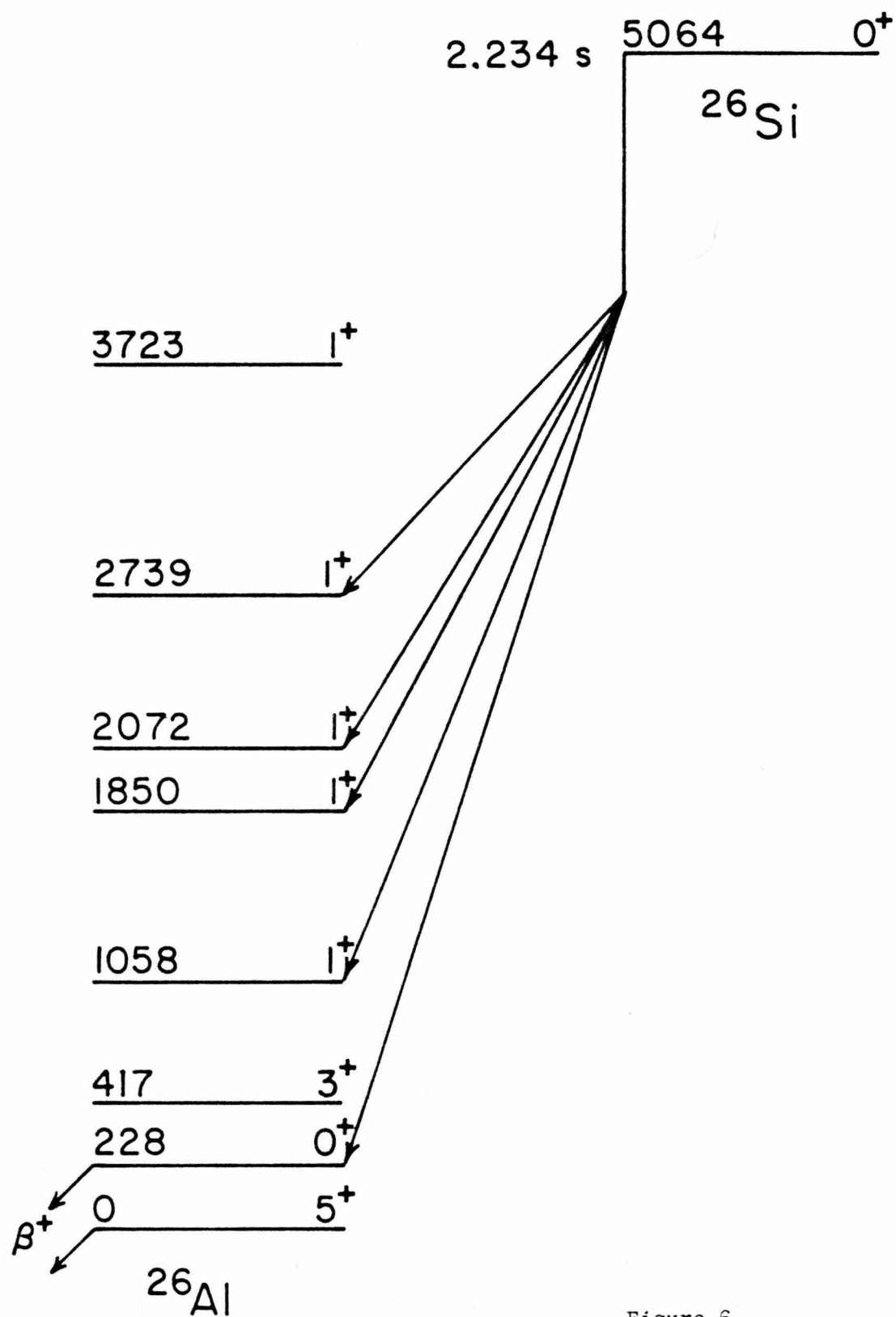


Figure 6

Figure 7.

A Ge(Li) spectrum accumulated in the study of ^{26}Si decay with a dispersion of 1.251 keV/channel. These data are from the first group (0.0 to 2.3 sec). Peaks are labelled in keV. We have identified all of the peaks in the spectrum. The 1779 keV peak is due to ^{28}Al decay and the 2313 to ^{14}O ; the other labelled peaks are due to ^{26}Si . Detailed spectra of the γ -ray peaks due to ^{26}Si β^+ decay are shown in Figure 8. The decay of ^{26}Si is discussed on pages 52 to 55 of the text.

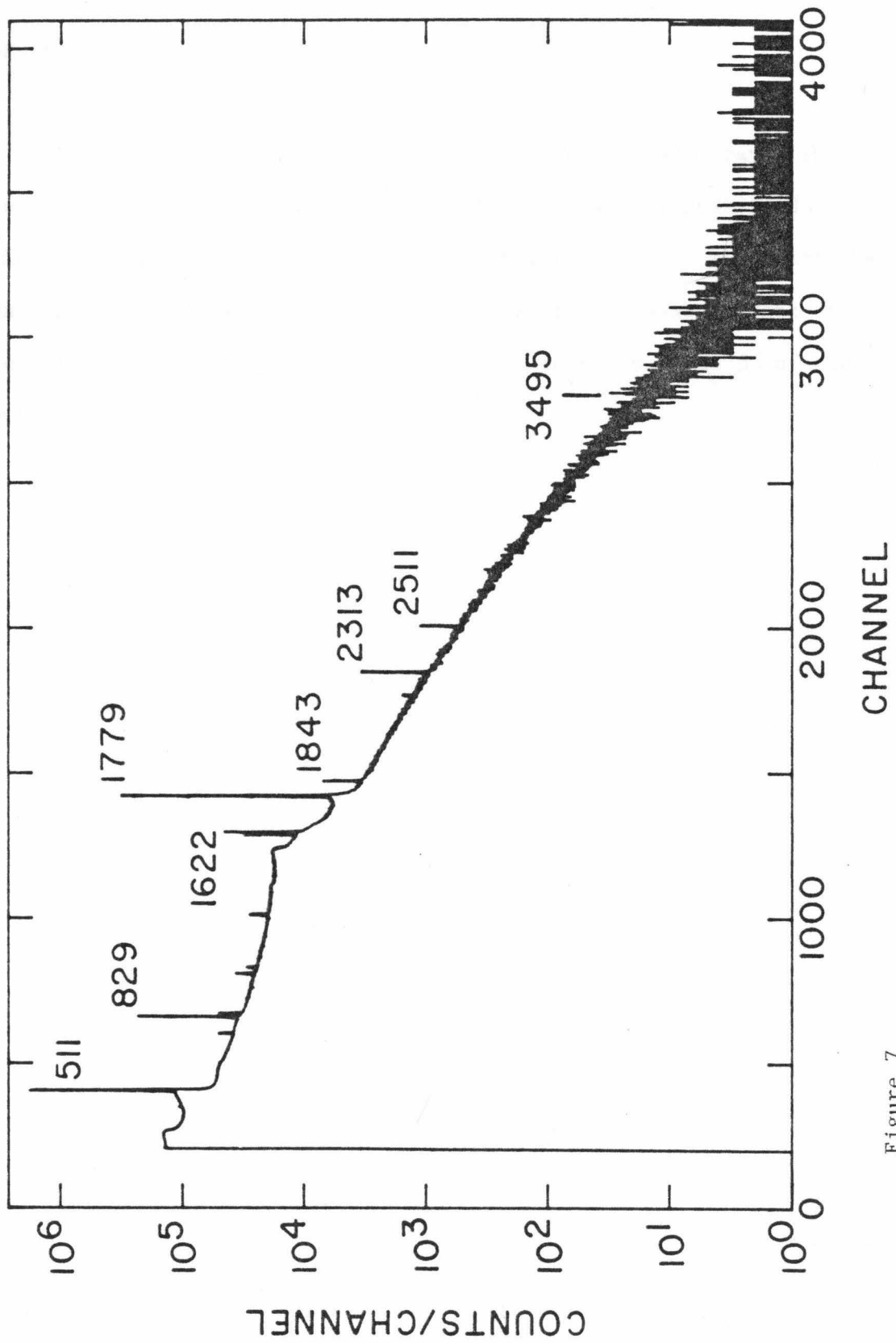


Figure 7

Figure 8.

Detailed Ge(Li) spectra of the peaks due to ^{26}Si decay. The energy calibration is 1.251 keV/channel. The 844-keV peak is due to ^{27}Mg decay and the 1612 keV peak originates from ^{25}Al . We assign the small peak at 1655 keV to the γ ray emitted in the weak γ branch from the 2072- to the 417-keV levels in ^{26}Al . See pages 52 to 55 of the text.

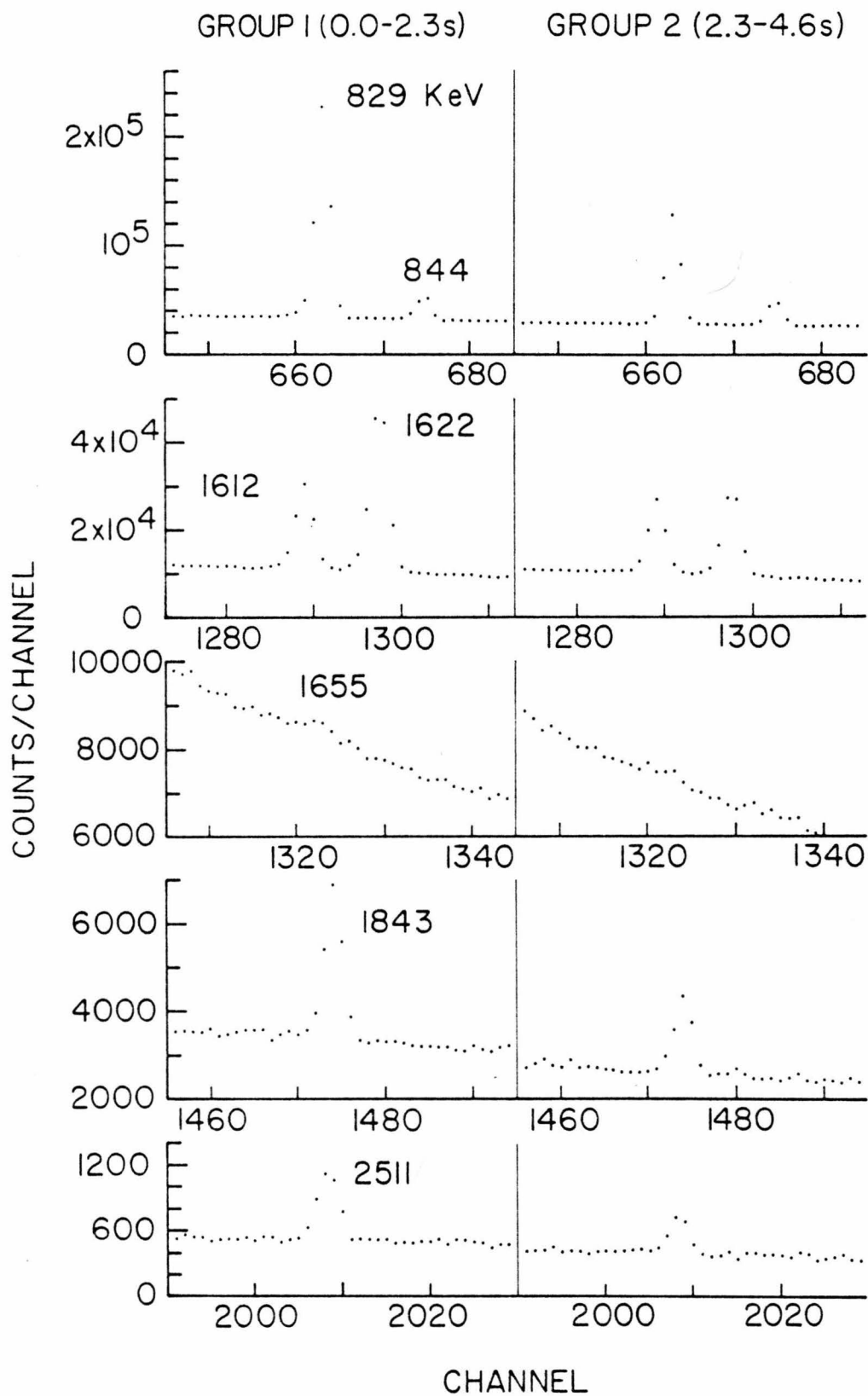


Figure 8

Figure 9.

The data and exponential fit for one of five runs to measure the half life of ^{26}Si . The 829-keV peak area was normalized by the area of a pulser peak in order to correct for dead time and pileup effects. The errors are purely statistical. The weighted average of 5 runs was 2.240 ± 0.010 sec. A χ^2 of 10.7 or greater for 14 degrees of freedom has a probability of 71%. See page 52 of the text.

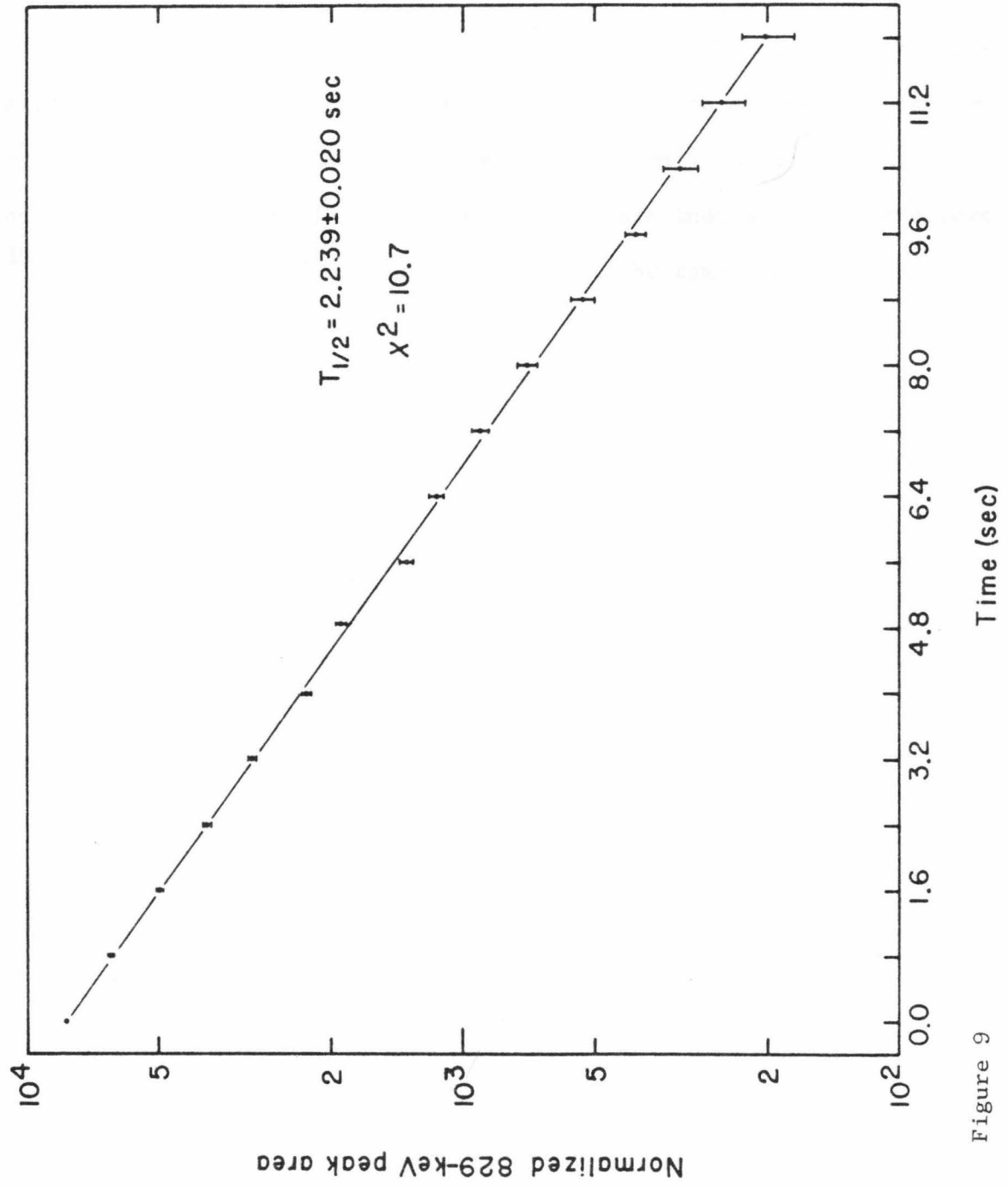


Figure 9

Figure 10.

Level diagram showing the β^+ decay of ^{30}S . The diagram has been simplified by displaying only those levels to which allowed β decays may proceed. The 3304 keV level has been seen in only one experiment (Endt and Van der Leun, 1978). Observed branches are indicated by the arrows. ^{30}S decay is discussed on pages 56 to 63 of the text.

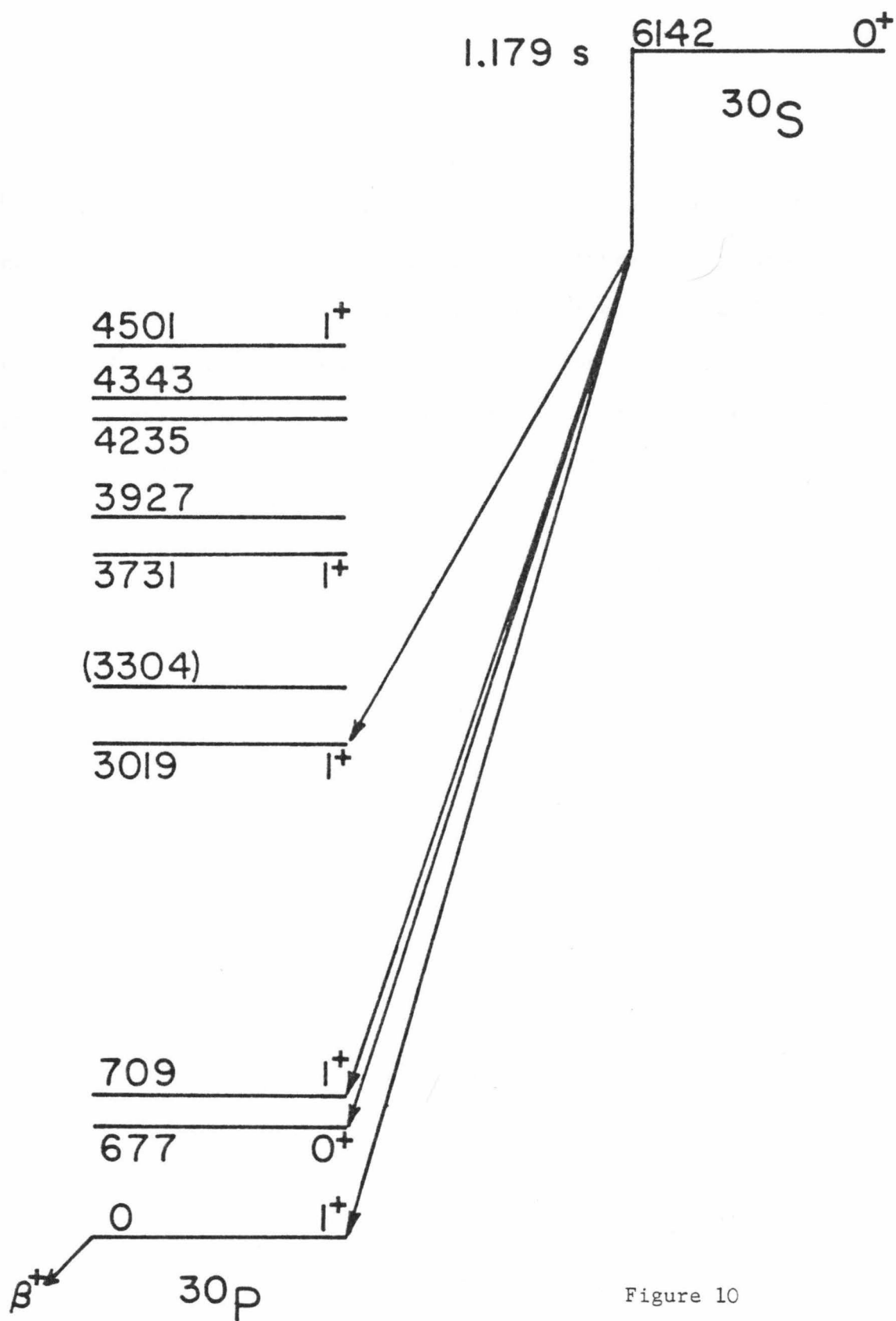


Figure 10

Figure 11.

The Ge(Li) spectrum collected in group 1 (0.0-1.3 sec) in the ^{30}S experiment. The energy calibration is 1.250 keV/channel. Peak energies are in keV. We have identified all of the peaks except for a small peak at 456 keV. The peaks at 1274 keV and at 2426 keV are due to ^{29}P decay and the peak at 2981 keV is due to ^{27}Si . Detailed spectra of the peaks due to ^{30}S decay are given in Figure 12. ^{30}S decay is discussed on pages 56 to 63 of the text.

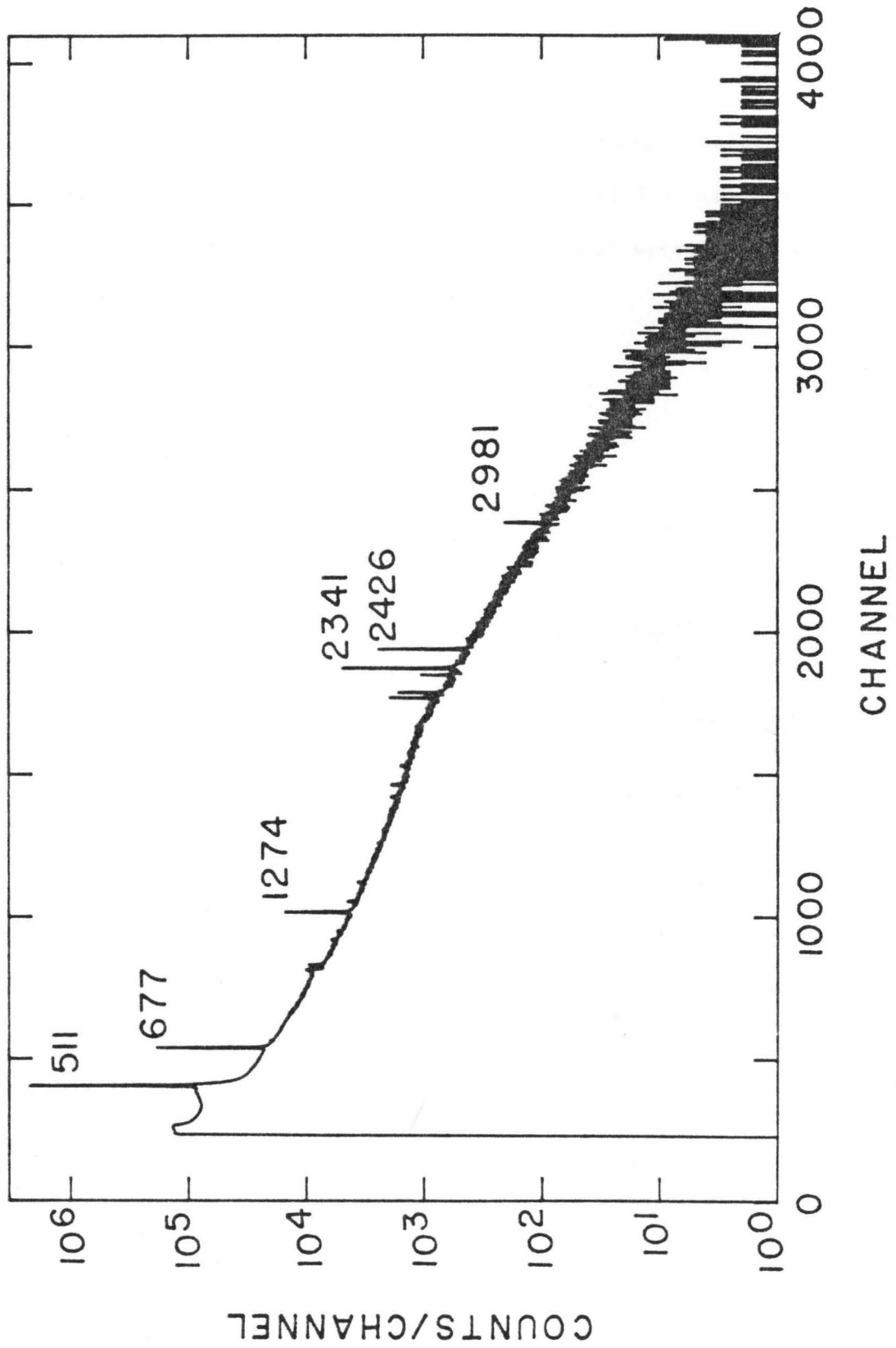


Figure 11

Figure 12.

Detailed spectra of the ^{30}S γ rays. The energy calibration is 1.250 keV/channel and the spectra of the 3019 and 3731 keV peaks are the sum of groups 1 and 2. The arrow on the 3731 keV spectrum shows where the peak should be. See page 57 of the text.

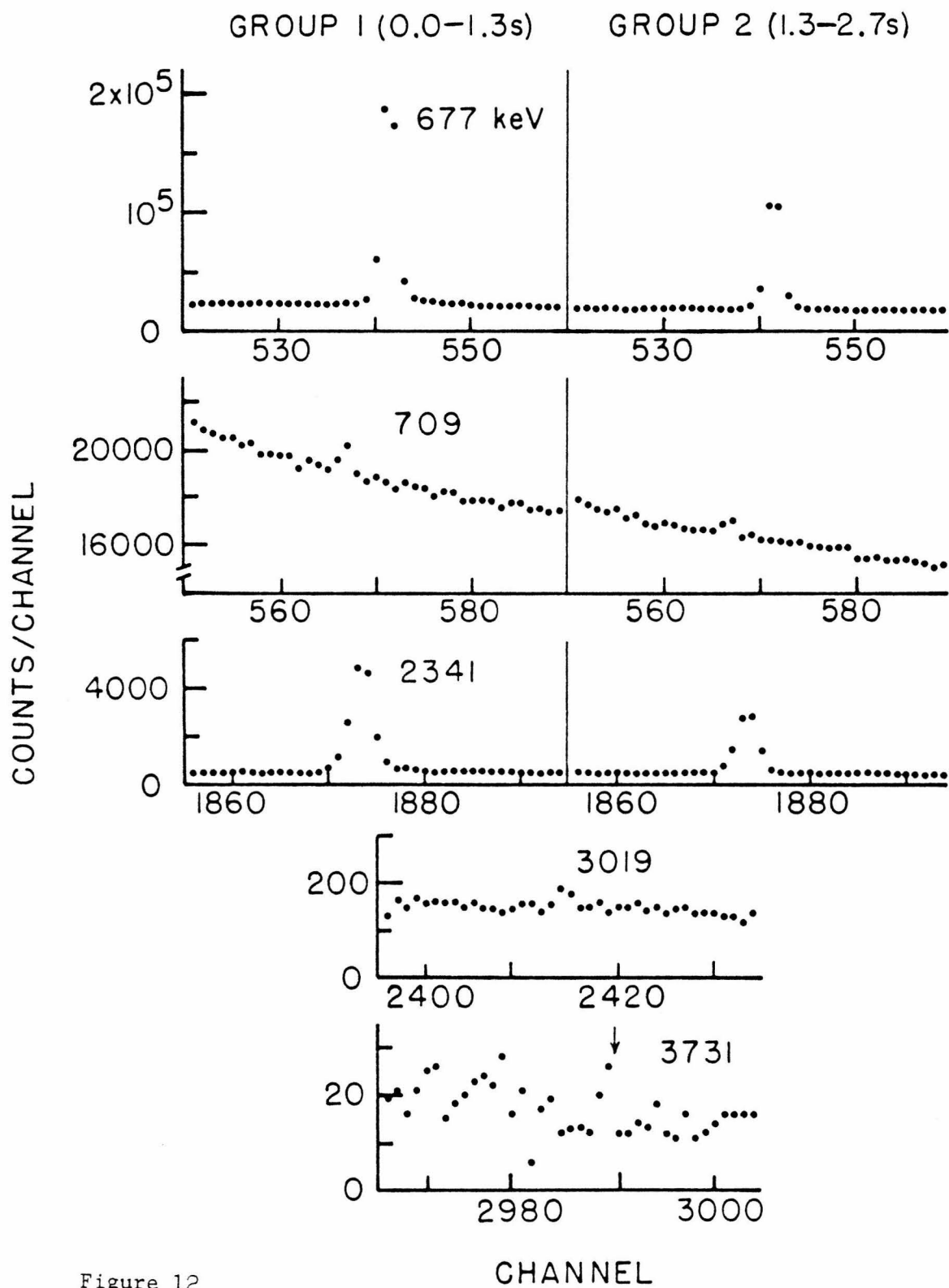


Figure 12

Figure 13.

The data and the exponential fit for one of six runs made in the measurement of the half life of ^{30}S . The 677-keV peak area was normalized by dividing by the dead time and pileup losses determined from the pulser peak area. The errors shown are purely statistical. The weighted average of the six runs was 1.1783 ± 0.0048 sec. The measurement of the ^{30}S half life is discussed on pages 57 and 58 of the text.

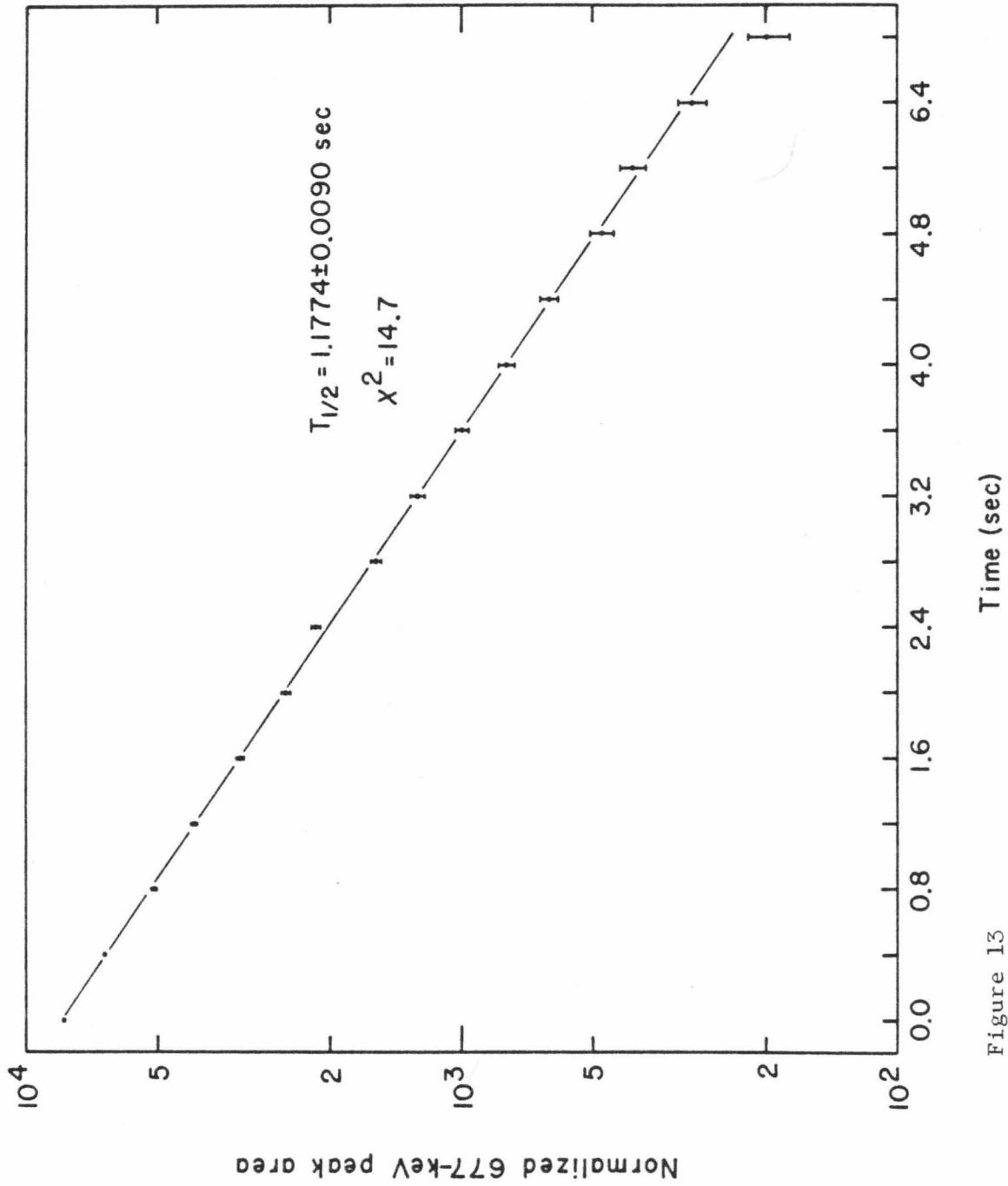


Figure 13

Figure 14.

Level diagram illustrating the β^+ decay of ^{30}P . The two observed transitions are indicated by the arrows; we were searching for weak branches to the three highest states. This decay is discussed on page 64 of the text.

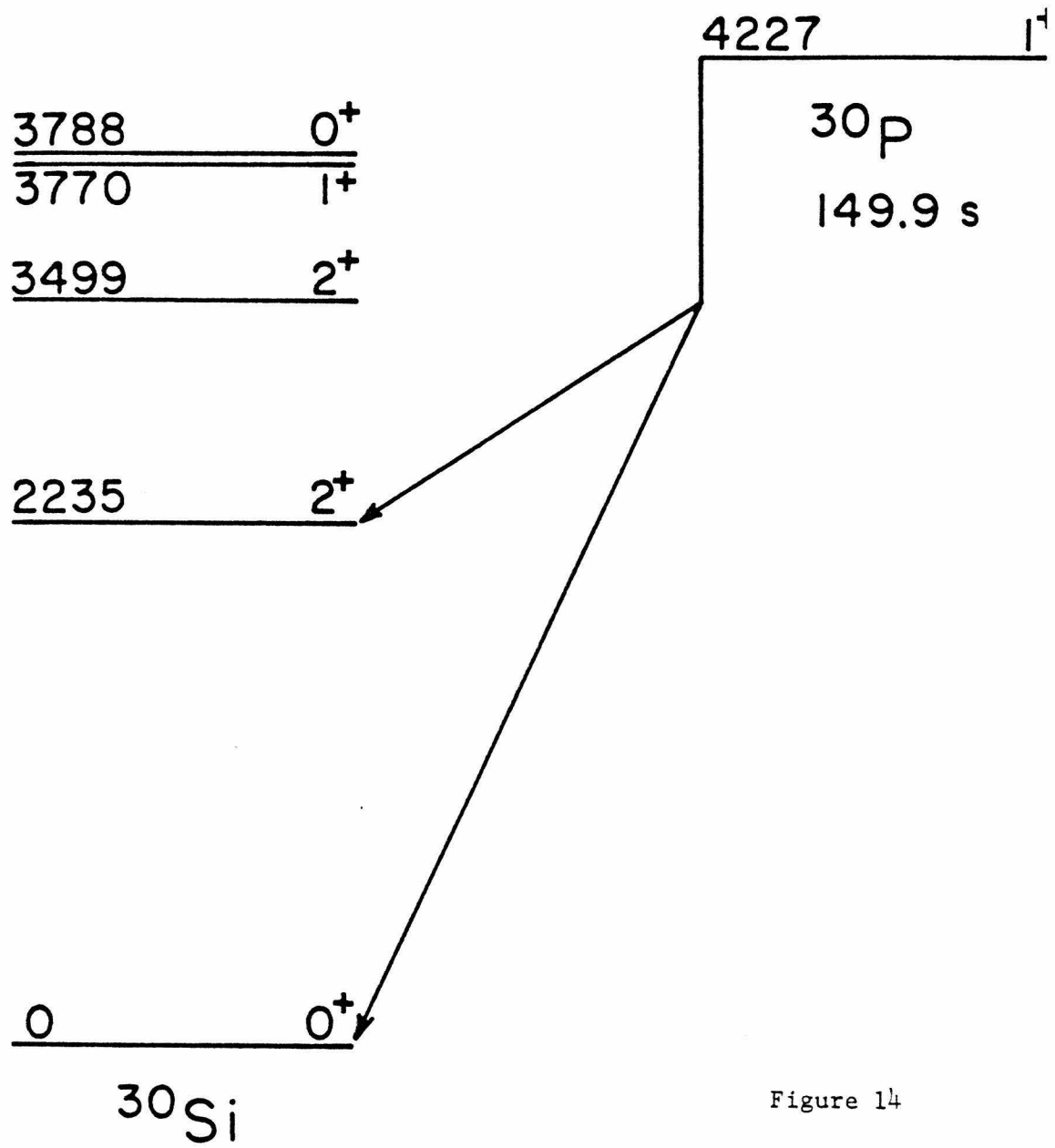


Figure 14

Figure 15.

Level diagram illustrating the decay of ^{31}S . Energies are in keV and observed branches are indicated by the arrows. The diagram has been simplified by removing most of the states that are not involved in allowed branches. More detailed information on the structure of ^{31}P is available in Endt and Van der Leun (1978). ^{31}S decay is discussed on pages 65 to 73.

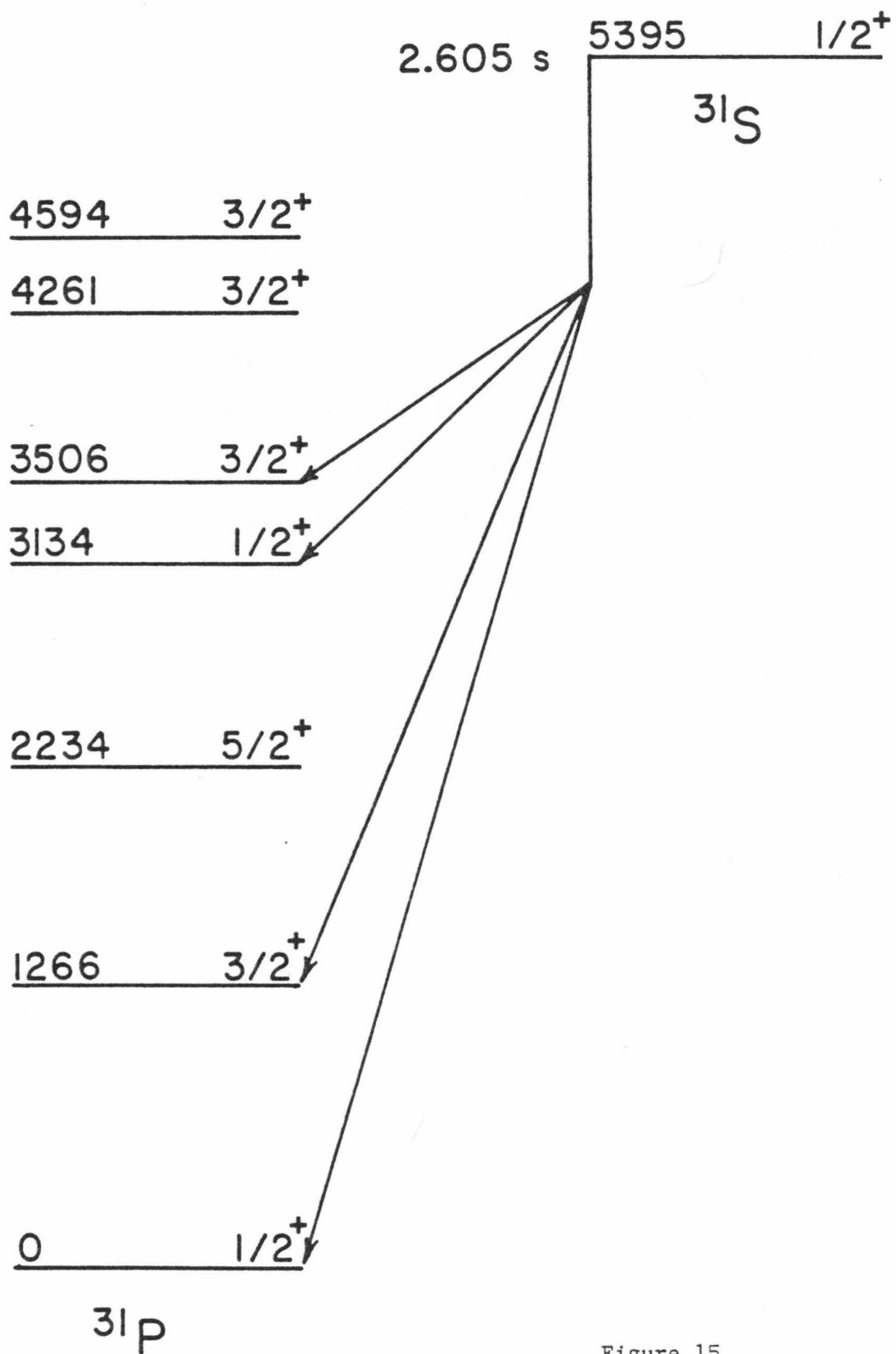


Figure 15

Figure 16.

The sum of all spectra taken in the first 2.5 sec group in the measurement of ^{31}S decay. The energy calibration is 1.252 keV/channel and peak energies are indicated in keV. We have identified all peaks in this spectrum except for a small peak at 1157 keV with a half life >2.6 sec. The 2313 keV peak is due to ^{14}O produced by the reaction $^{14}\text{N}(p,n)^{14}\text{O}$ in the air propellant used to drive the rabbit system. Detailed spectra of the ^{31}S peaks are shown in Figure 17. The decay of ^{31}S is discussed on pages 65 to 73 of the text.

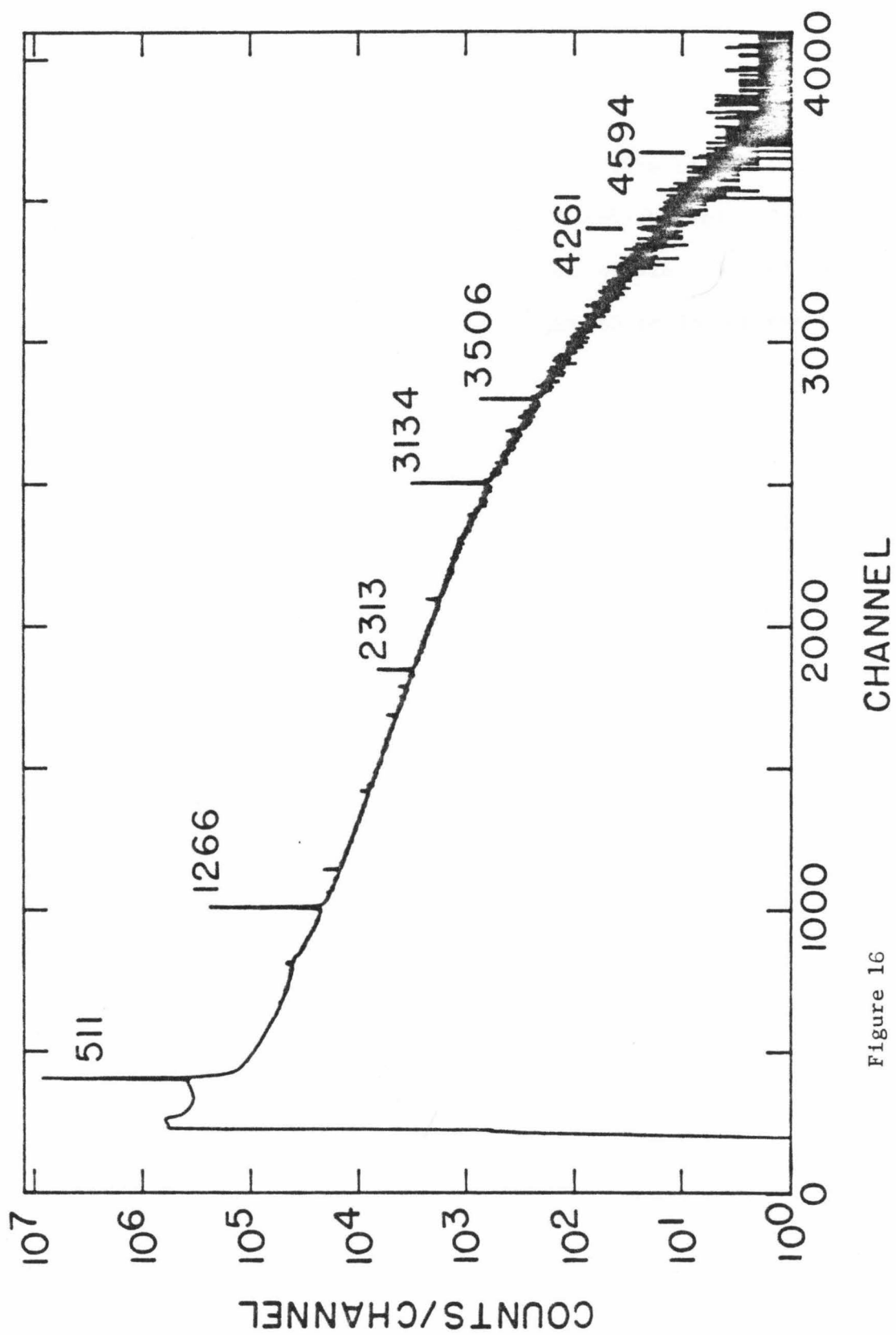


Figure 16

Figure 17.

Detailed spectra of the ^{31}S γ ray peaks. This is the sum of all of our data. The energy calibration is 1.252 keV/channel. The arrows in the spectra indicate the expected positions of 4261 keV and 4594 keV peaks. The decay of ^{31}S is discussed on pages 65 to 73 of the text.

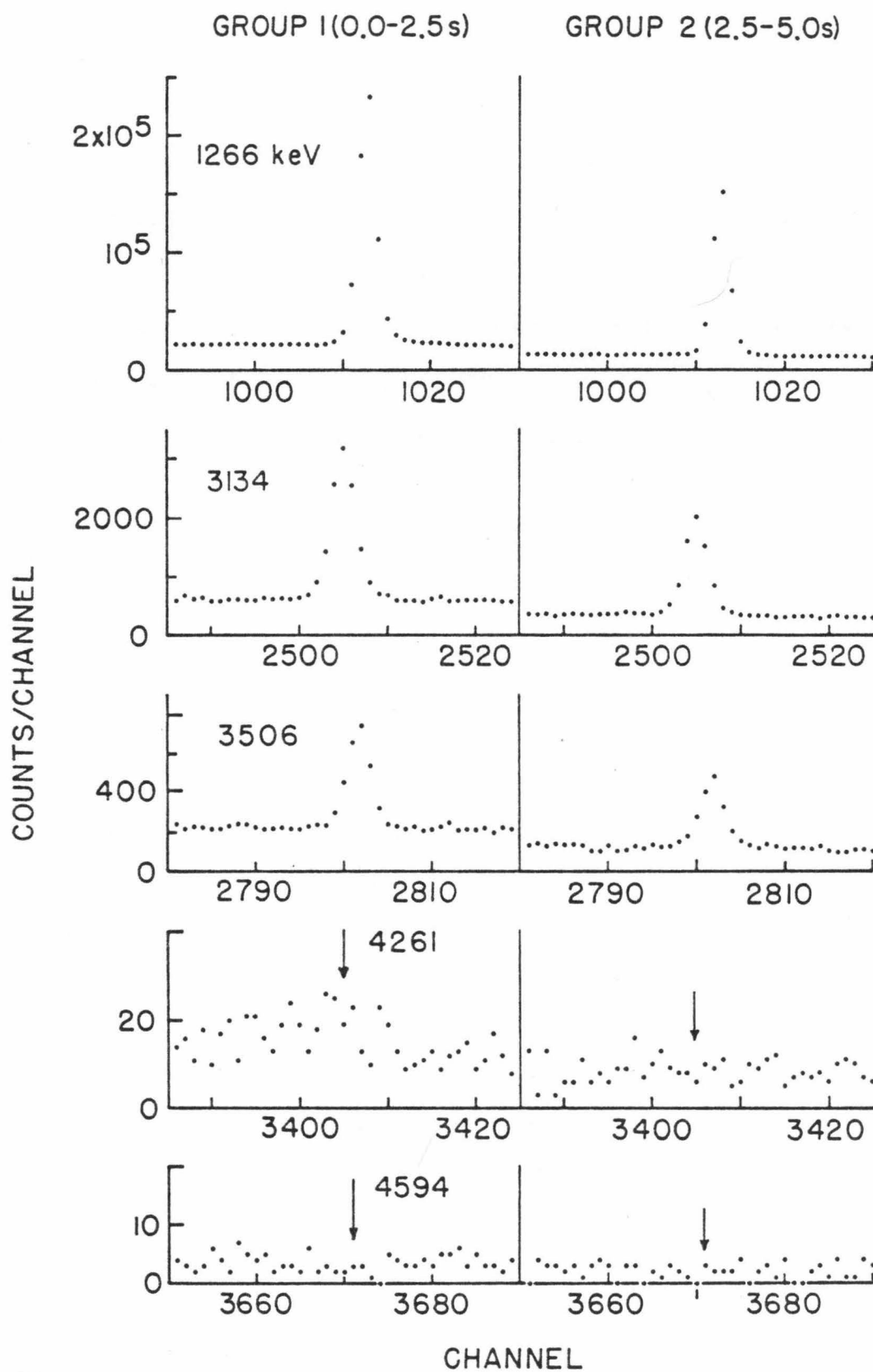


Figure 17

Figure 18.

The peak-area ratio is the area of a peak in the high-count-rate ^{66}Ga calibration spectrum divided by the area of the same peak in the low-count-rate spectrum. The good value of χ^2 (12.7 for 13 degrees of freedom) indicates that the data are consistent with the peak-area ratio being independent of pulse height. The pileup rejection in the ^{31}S experiment is discussed on page 65 of the text.

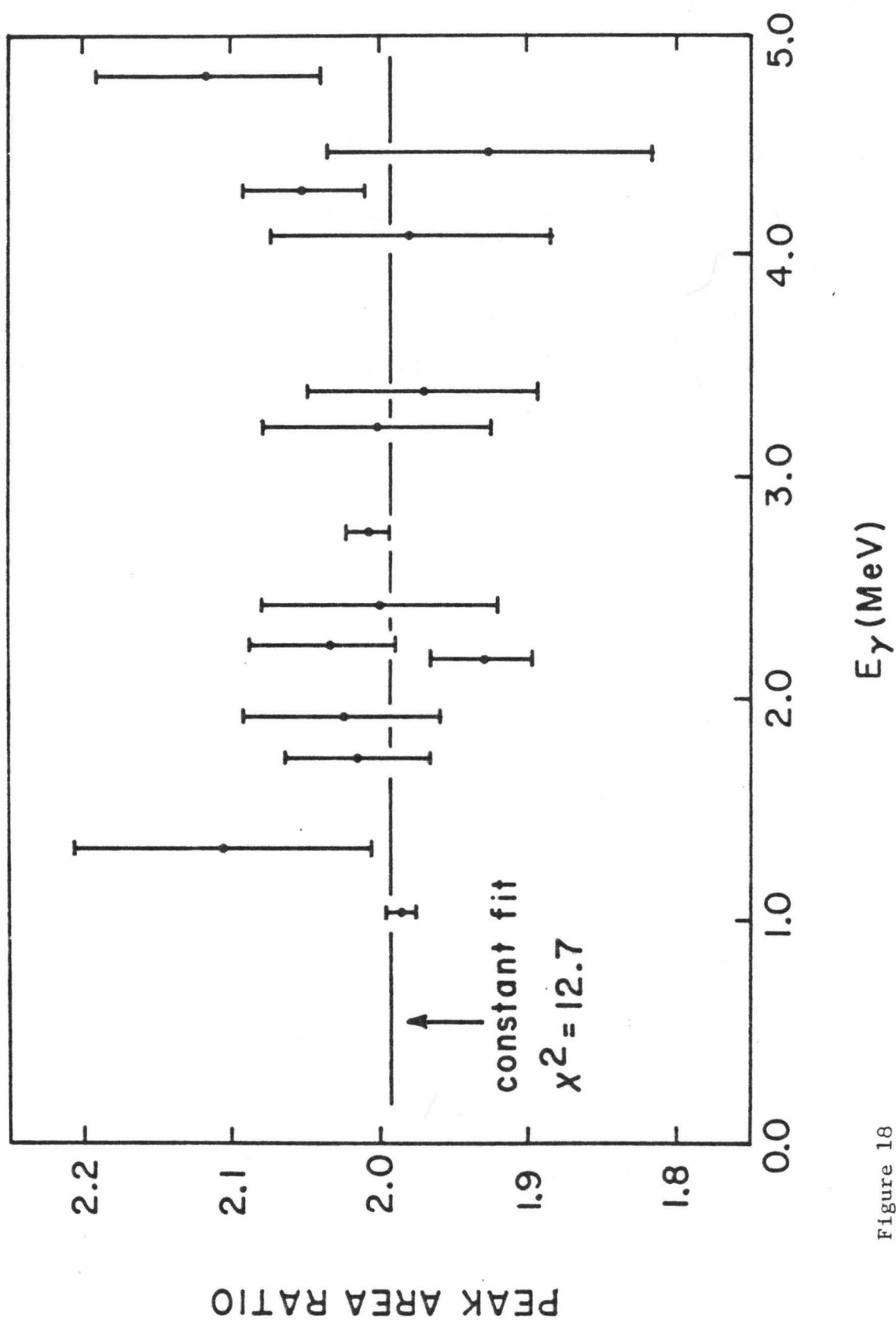


Figure 18

Figure 19.

Level diagram illustrating the decay of ^{33}Cl . Excitation energies, in keV, and spin-parity assignments are taken from Endt and Van der Leun (1978). Observed branches are indicated by the arrows. The diagram has been simplified by the omission of states which cannot participate in allowed β decay. ^{33}Cl decay is discussed on pages 74 to 80 of the text.

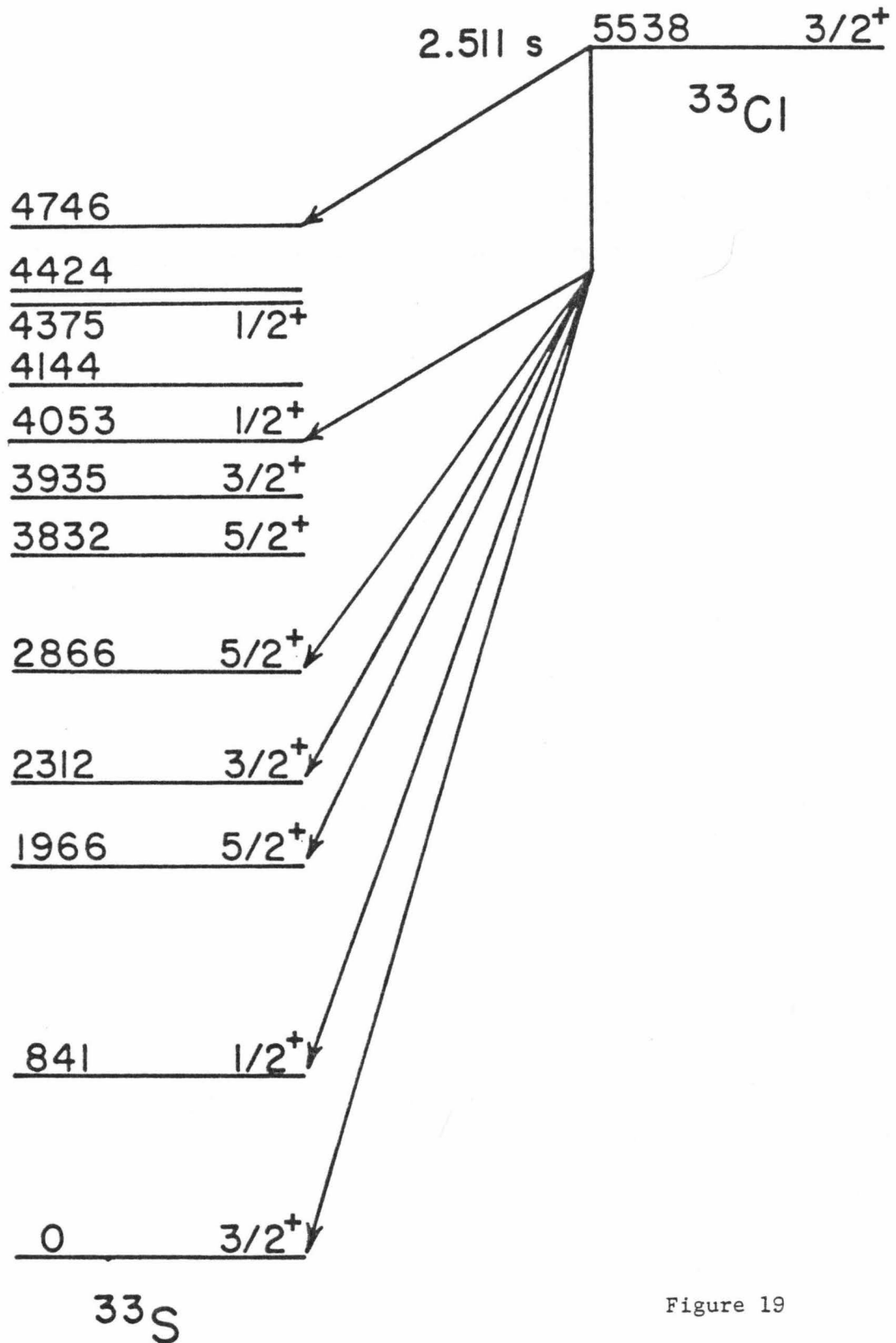
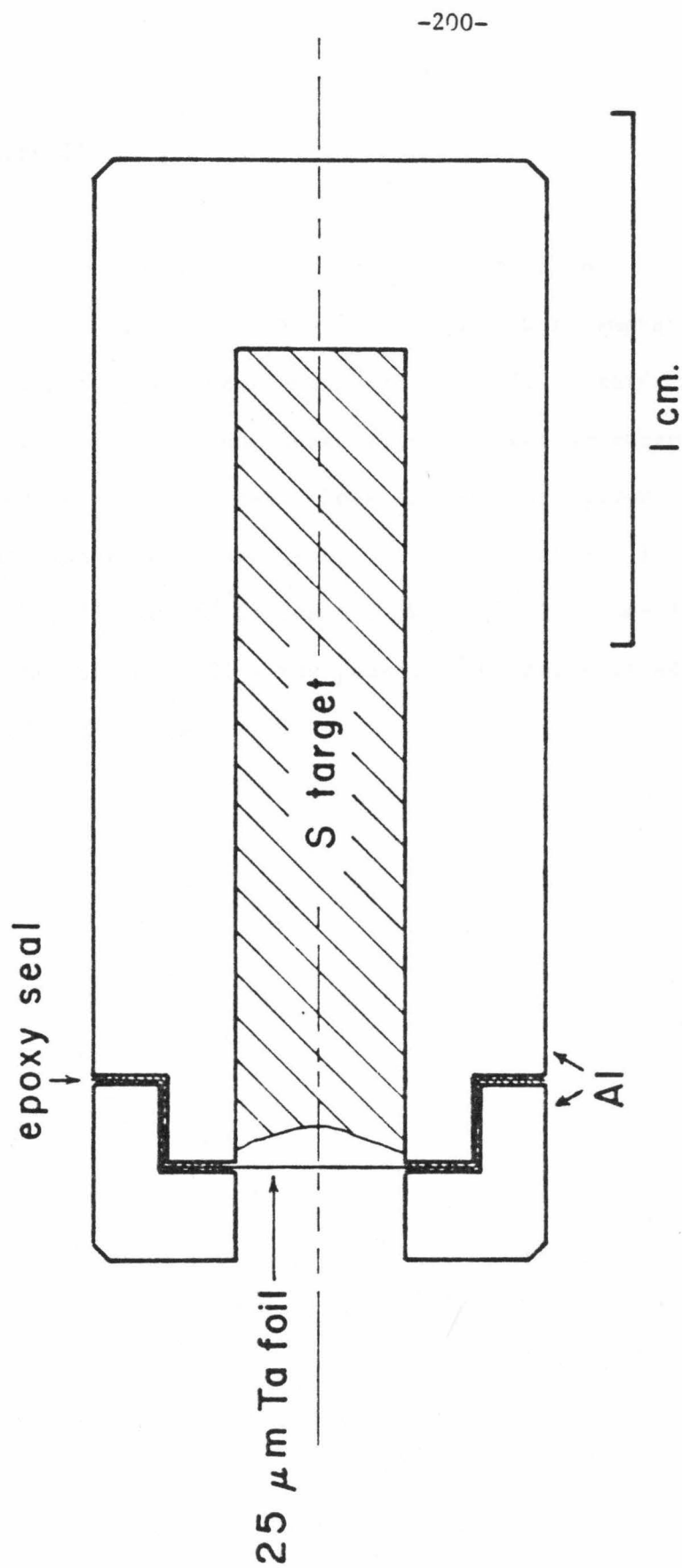


Figure 19

Figure 20.

Gas-tight sulfur rabbit used in the ^{33}Cl experiments. The 11 MeV deuteron beam lost about 1.2 MeV in the 25 μm Ta entrance foil. The decay of ^{33}Cl is discussed on pages 74 to 80 of the text.



Sulfur rabbit

Figure 20

Figure 21.

The Ge(Li) spectrum collected in group 1 (0.0 to 2.5 sec) in the study of ^{33}Cl decay. A 4.5 cm Pb absorber removed most of the 511 keV radiation. The energy calibration is 1.200 keV/channel. We have identified all of the peaks in this spectrum except for a small long-lived peak at 2025 keV. Peak energies are given in keV. The following contaminant peaks are labelled in the figure: 1779 keV (^{28}Al), 2235 keV (^{30}P), 3103 keV (^{37}S) and 3303 keV ($^{34\text{m}}\text{Cl}$). See Figure 22 for detailed spectra of the ^{33}Cl γ ray peaks. ^{33}Cl decay is discussed on pages 74 to 80 of the text.

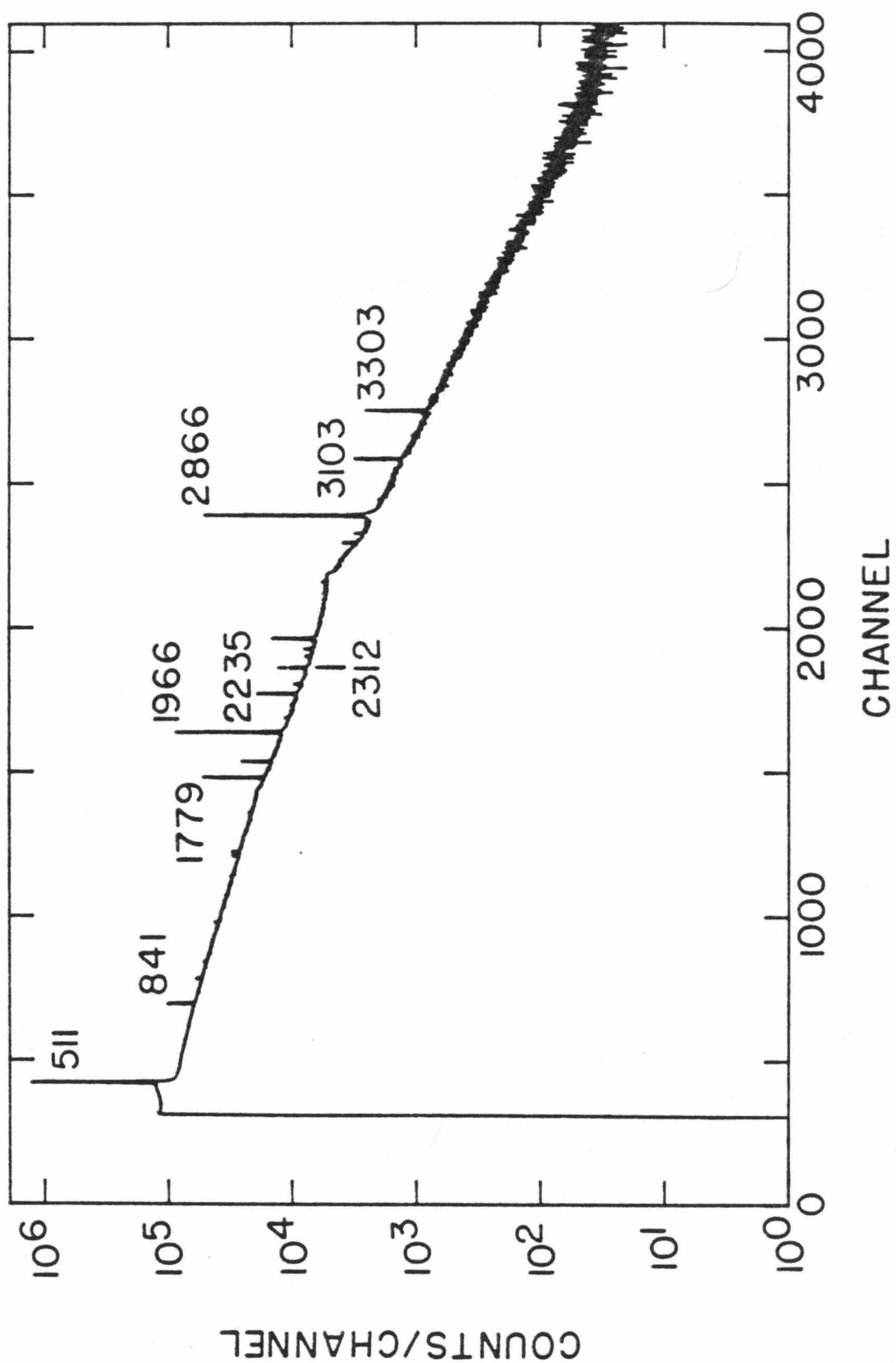


Figure 21

Figure 22.

Detailed spectra of γ -ray peaks due to ^{33}Cl decay. The arrows indicate the positions of the 4053- and 4746-keV peaks calculated from the energy calibration and the solid lines indicate linear backgrounds. The decay of ^{33}Cl is discussed on pages 74 to 80 of the text.

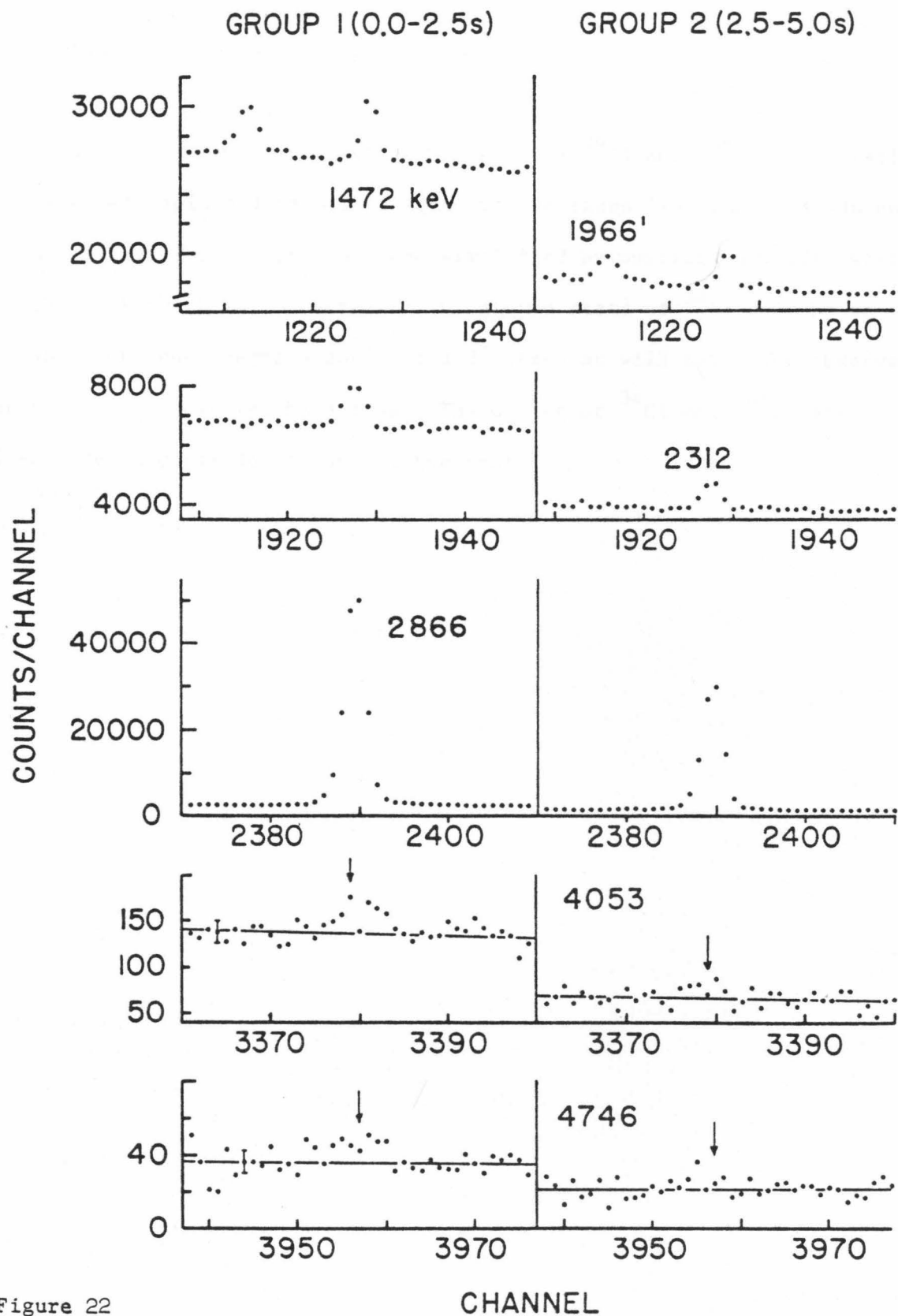


Figure 22

Figure 23.

Level diagram illustrating the decay of ^{34}Cl and $^{34\text{m}}\text{Cl}$. Excitation energies and spin and parity assignments are taken from Endt and Van der Leun (1978). The diagram has been simplified by omitting a $0^+; T=1$ state at 3914 keV which is connected to the ground state of ^{34}Cl only by an isospin forbidden Fermi branch and a 3^- state at 4623 keV. The observed branches are indicated by arrows. The decays of ^{34}Cl and $^{34\text{m}}\text{Cl}$ are discussed on pages 81 to 86 of the text.

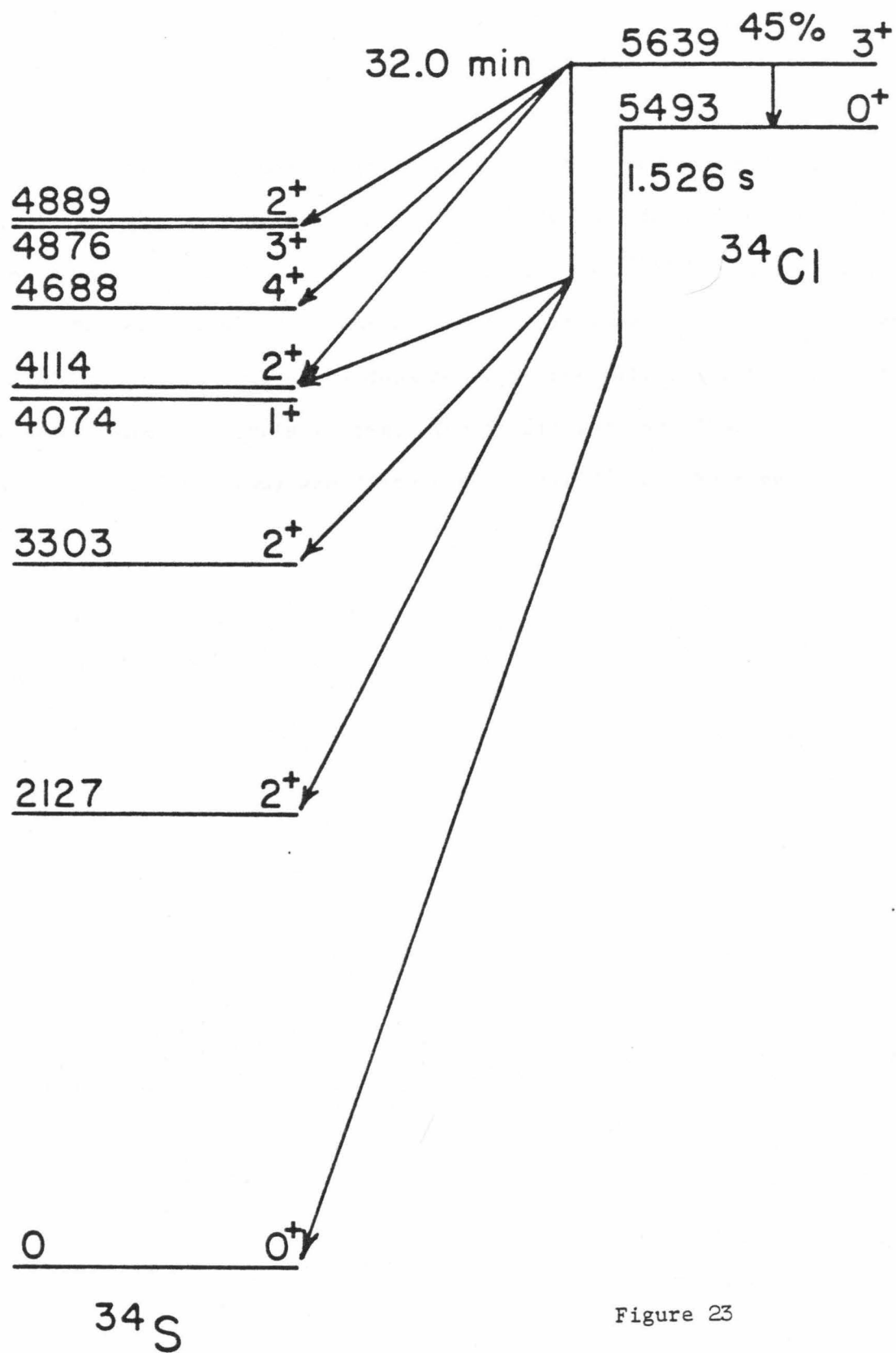


Figure 23

Figure 24.

Ratio of peak areas in group 1 (0-1500 sec) and group 2 (1500-3000 sec). The only difference between the groups is a reduction in the count rate by a factor of 1.72 (the half life of ^{34m}Cl is 32.01 ± 0.04 min). The good value of χ^2 for a constant fit shows that these data are consistent with no count-rate dependence in the relative efficiency of the pulse-height-analysis system. The figure and the pileup-rejection system in the ^{34}Cl study are discussed on page 82 of the text.

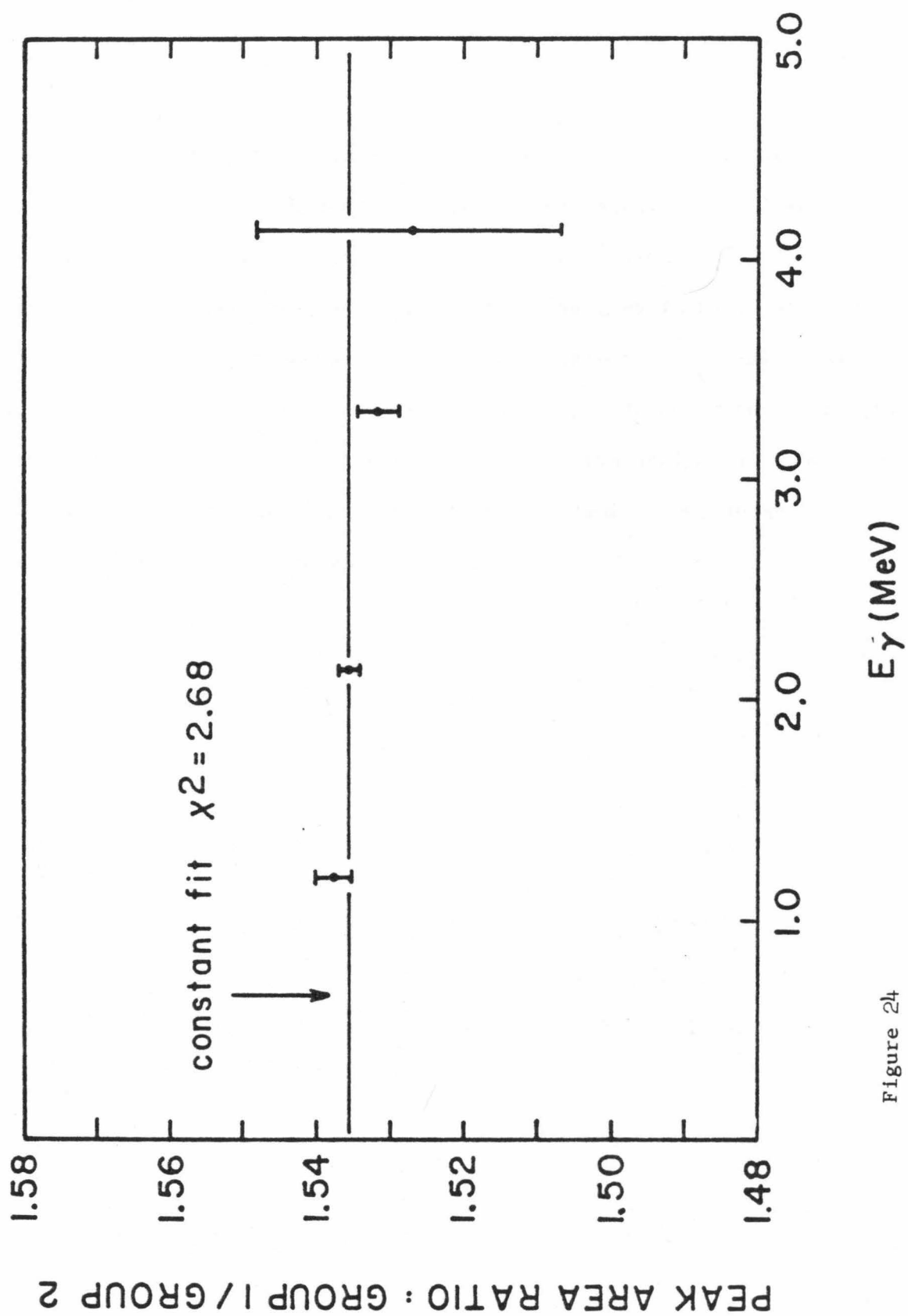


Figure 24

Figure 25.

Ge(Li) spectrum collected in group 1 (0-1500 sec) in the ^{34}Cl experiment. A 2.5 cm Pb absorber reduced the intensity of 511-keV radiation. The energy calibration is 1.252 keV/channel, and the prominent photopeaks are labelled by their energies in keV. We have identified all of the peaks in the spectrum except for a small peak at 4407 keV. The 811-keV peak is due to ^{58}Co produced by the $^{55}\text{Mn}(\alpha, n)^{58}\text{Co}$ reaction. The pileup-rejection system allows the accidental summing of two 2127 keV photopeak events to appear as a peak. ^{34}Cl decay is discussed on pages 81 to 86 of the text.

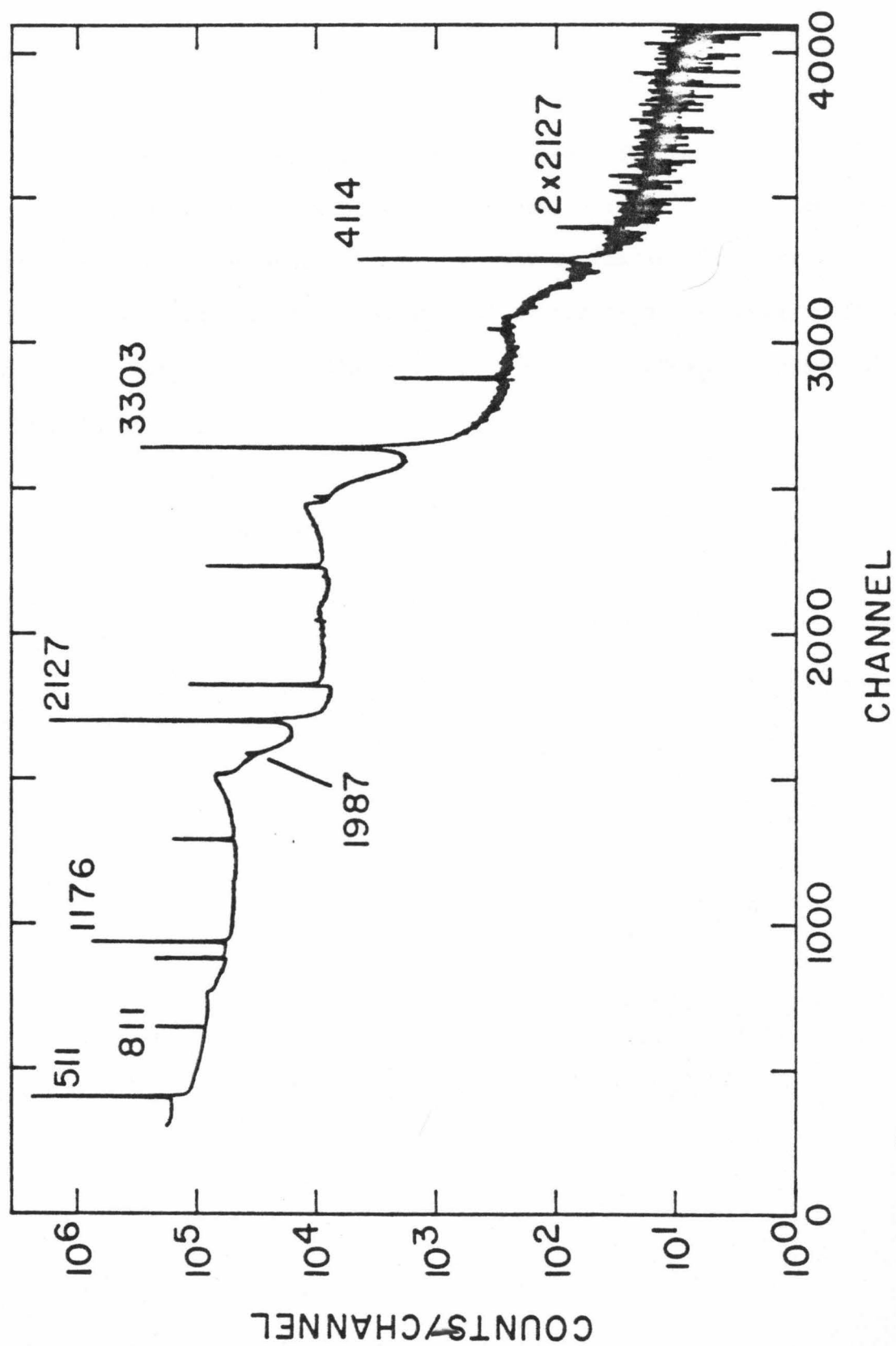


Figure 25

Figure 26.

Detailed spectra of some of the weak peaks due to ^{34m}Cl and ^{34}Cl γ rays. The 2560-keV and 2748-keV photopeaks are due to the electron-capture decays to the 4688-keV and 4876-keV states in ^{34}S . Arrows indicate the positions of photopeaks calculated from the energy calibration (1.252 keV/channel). The decay of ^{34}Cl is discussed on pages 81 to 86 of the text.

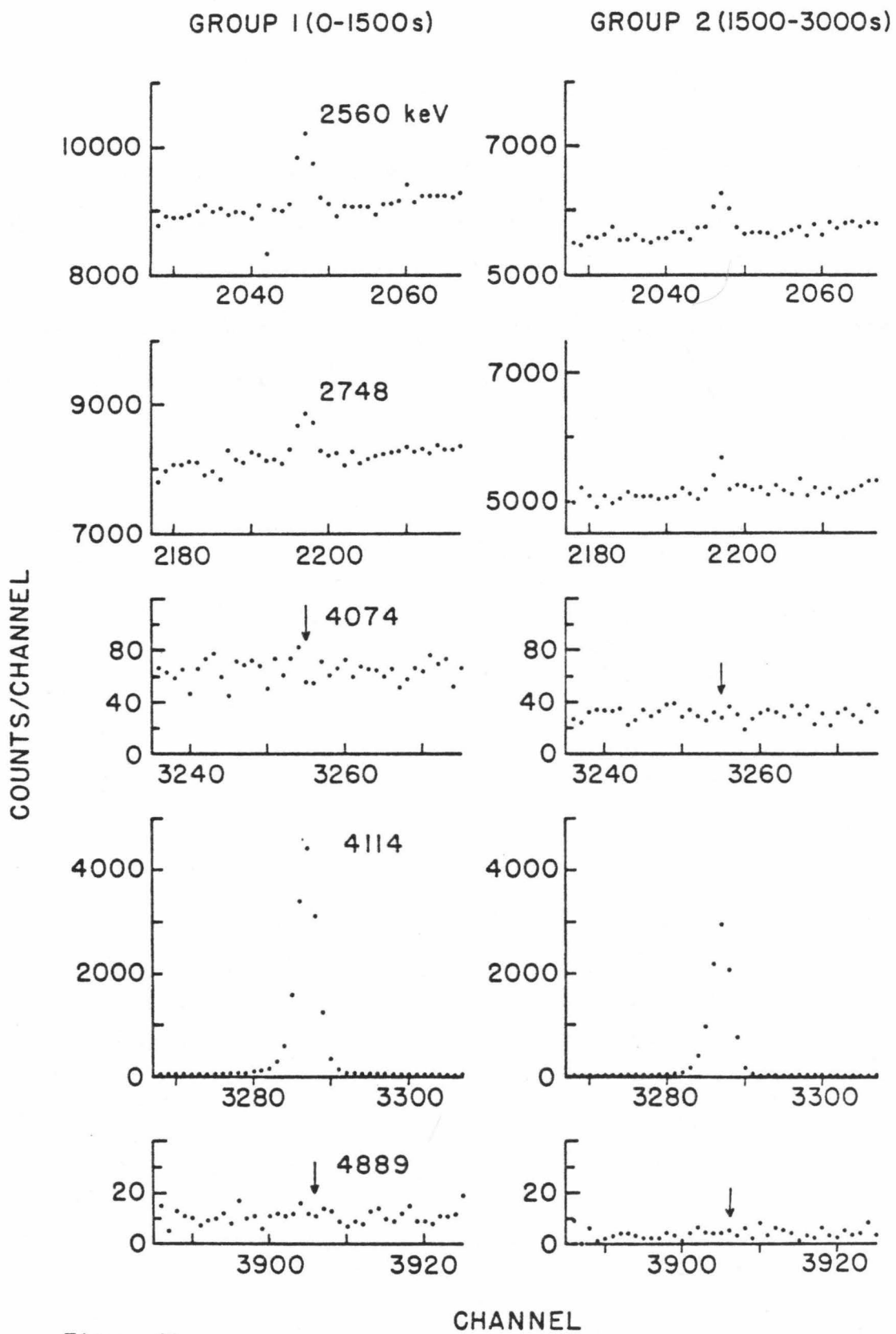


Figure 26

Figure 27.

Level diagram illustrating the decay of ^{35}Ar . Excitation energies and spin-parity assignments are taken from Endt and Van der Leun (1978). The diagram has been simplified to show only those levels to which allowed β decays can proceed. The decay of ^{35}Ar is discussed on pages 87 to 90 of the text.

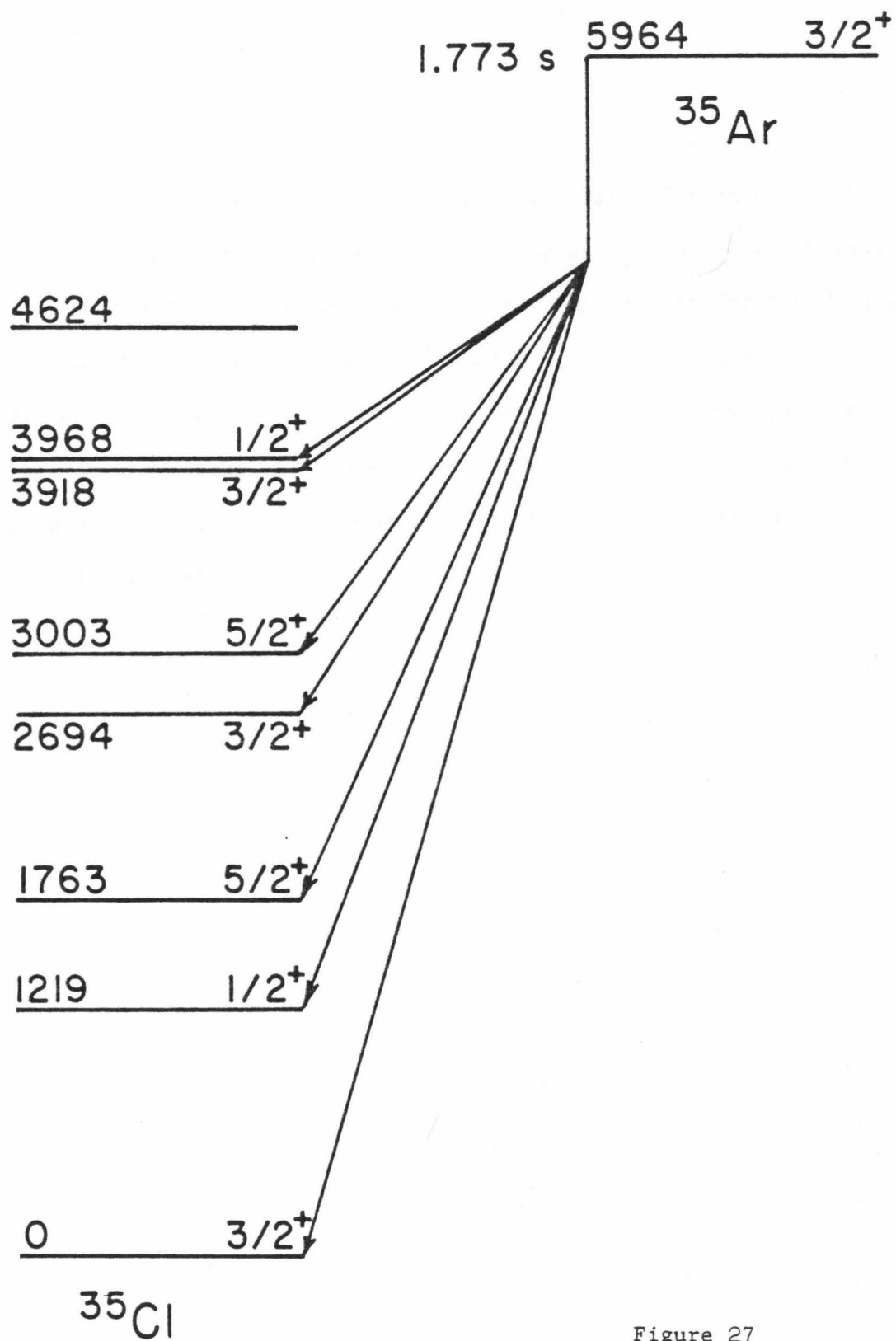


Figure 27

Figure 28.

The Ge(Li) spectrum accumulated in group 1 (0.0-1.8 sec) in the ^{35}Ar experiment. The energy calibration is 1.225 keV/channel. A 2.5 cm Pb absorber was used to reduce the intensity of the annihilation radiation. All of the labelled peaks are due to ^{35}Ar γ rays except for the 2313-keV peak from ^{14}O produced by $^{14}\text{N}(\text{p},\text{n})^{14}\text{O}$ in the air pusher gas in the rabbit system. We have identified all of the peaks in the spectrum except for weak peaks at 1158 keV and 1483 keV. Figure 29 shows detailed spectra of some of the ^{35}Ar peaks. ^{35}Ar decay is discussed on pages 87 to 90 of the text.

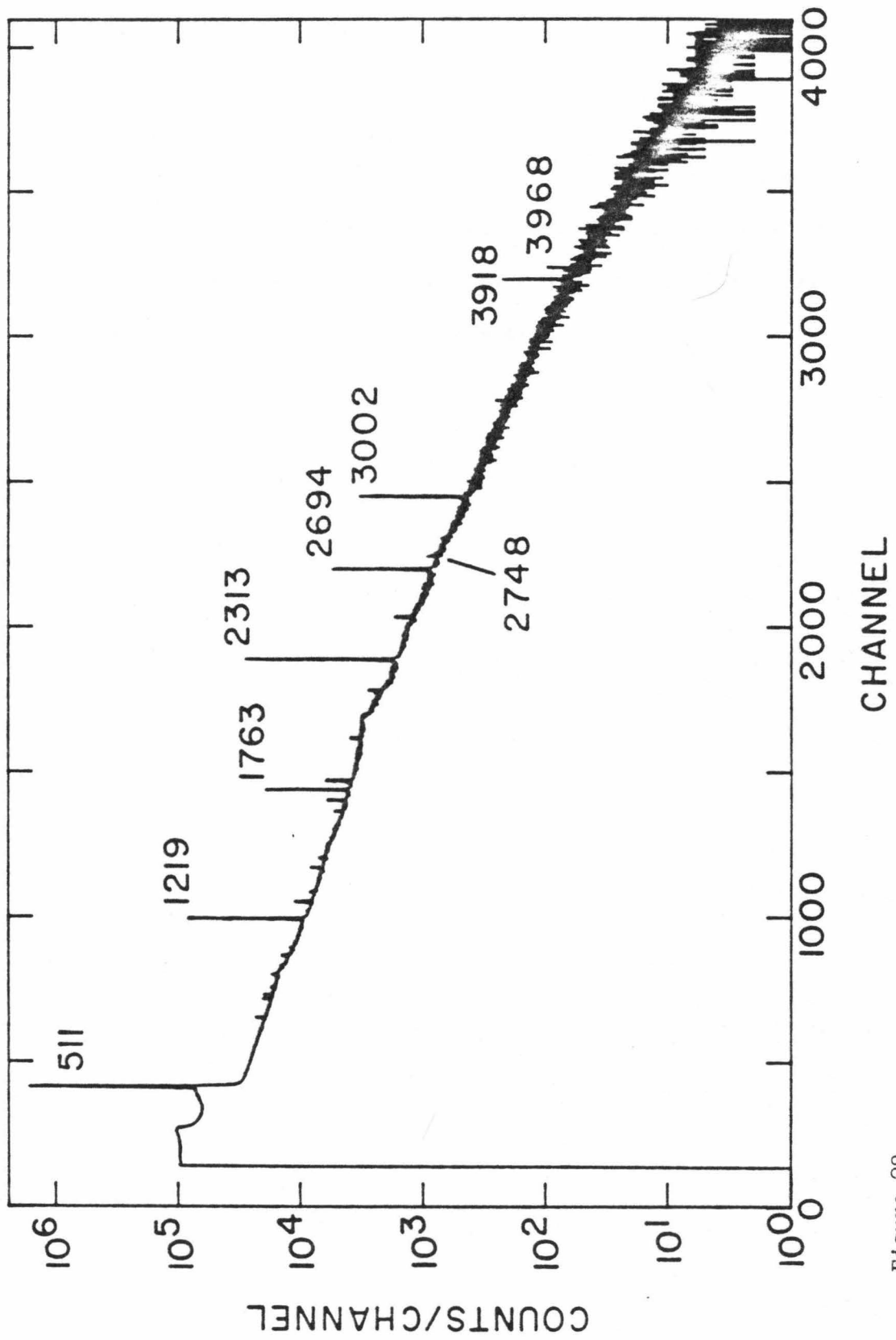


Figure 28

Figure 29.

Detailed spectra of some of the peaks due to ^{35}Ar γ rays. The energy calibration is 1.225 keV/channel. Arrows indicate the positions of photopeaks calculated from the energy calibration. The decay of ^{35}Ar is discussed on pages 87 to 90 of the text.

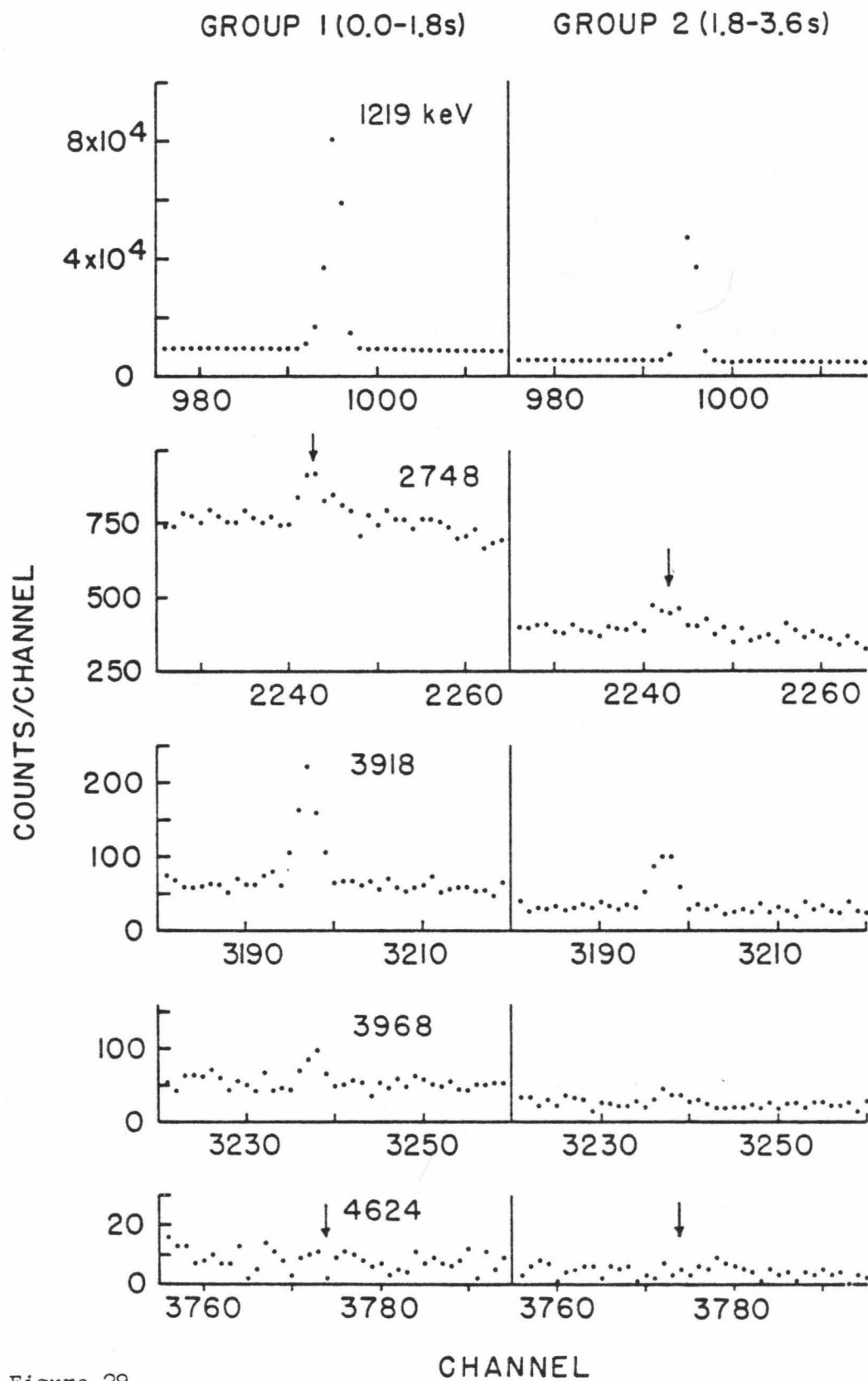


Figure 29

Figure 30.

Level diagram illustrating the decay of ^{38}Ca . Excitation energies and spin-parity assignments have been taken from Endt and Van der Leun (1978). The diagram has been simplified by omitting most of the states not involved in allowed β decays. The observed transitions are indicated by arrows. The decay of ^{38}Ca is discussed on pages 91 to 97 of the text.

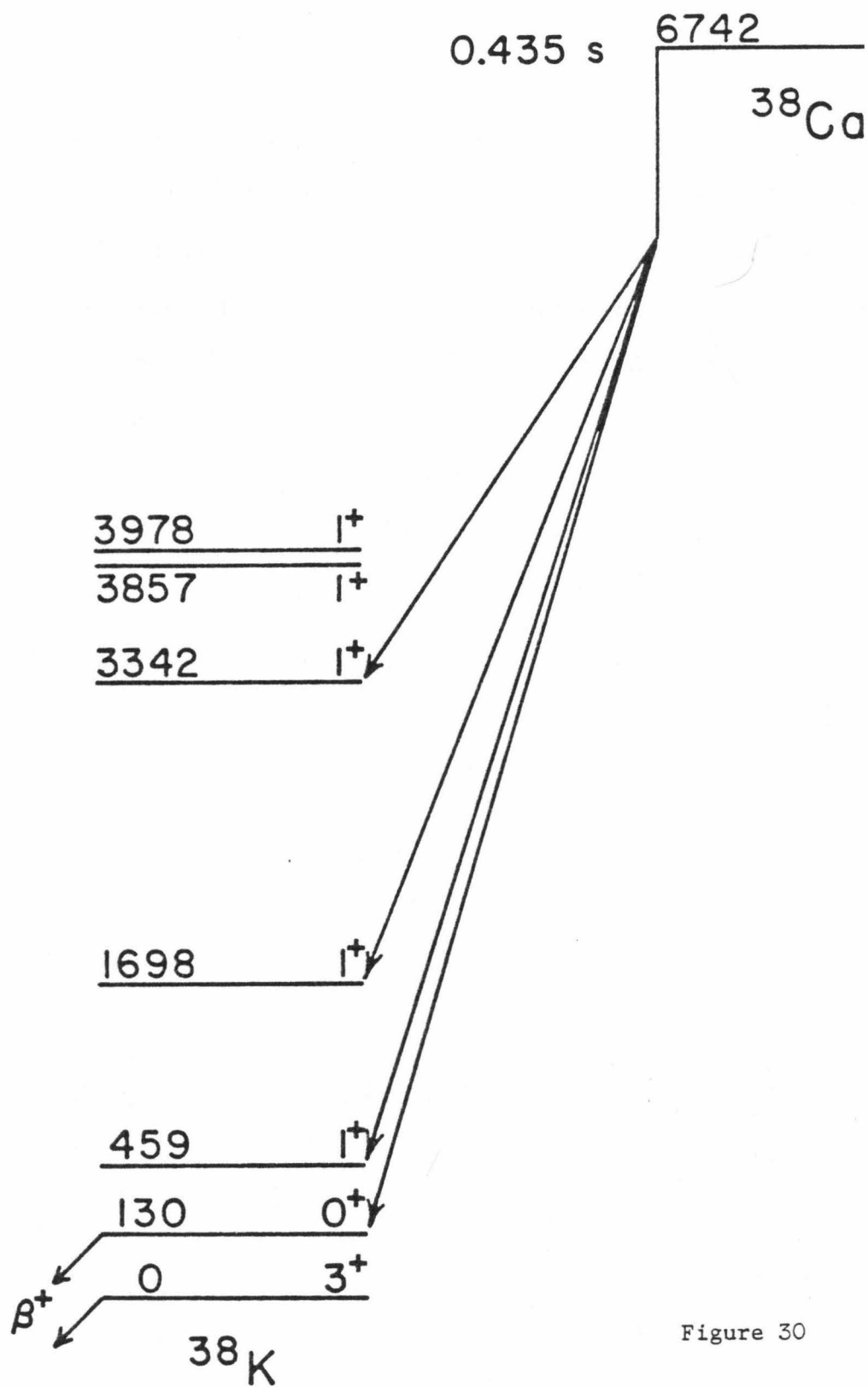
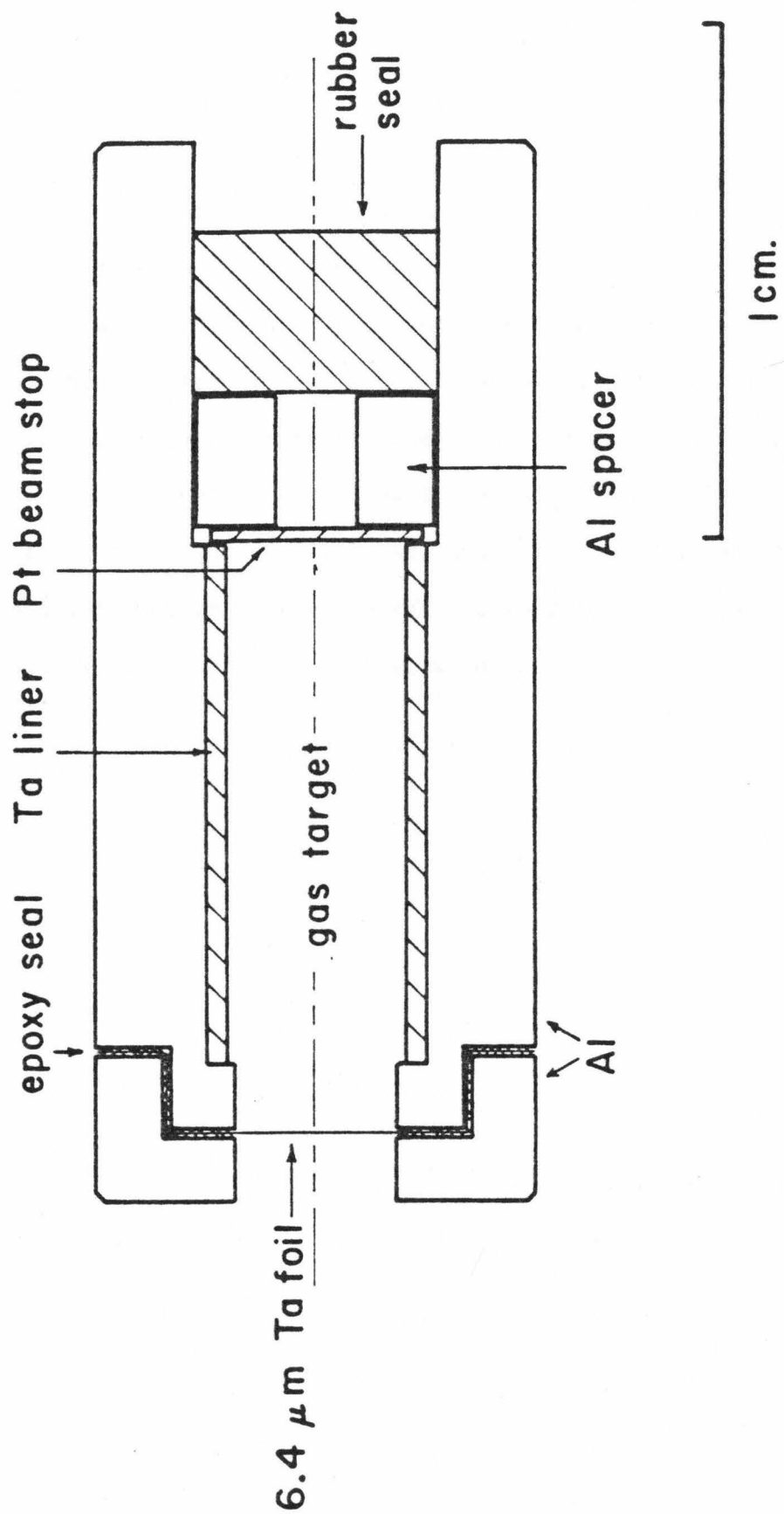


Figure 30

Figure 31.

The gas rabbit used in the study of ^{38}Ca decay. A hypodermic needle, pushed through the rubber seal and into the hole in the aluminum spacer, allowed air to be removed from and ^{36}Ar introduced into the gas rabbit. We were careful to calculate the attenuation of the γ rays in the aluminum body and tantalum liner. The gas rabbit is discussed on page 91 of the text.



Gas rabbit

Figure 31

Figure 32.

The Ge(Li) spectrum taken in group 1 (0.00-0.45 sec) in the second run to measure the intensity of the 328-keV γ ray relative to the 1568-keV γ ray (no 511 anticoincidence system was used in this run). The only heavy absorber used was 0.51 mm of Sn and 0.25 mm of Nb. The energy calibration is 0.598 keV/channel. We have identified all of the peaks in the spectrum except for a small peak at 349 keV. Prominent contaminant activities include ^{34m}Cl , ^{35}Ar , and ^{38}K , all produced in the ^{36}Ar target. Detailed spectra of the 328-keV and 1568-keV γ rays are shown in Figure 33. The decay of ^{38}Ca is discussed on pages 91 to 96 of the text.

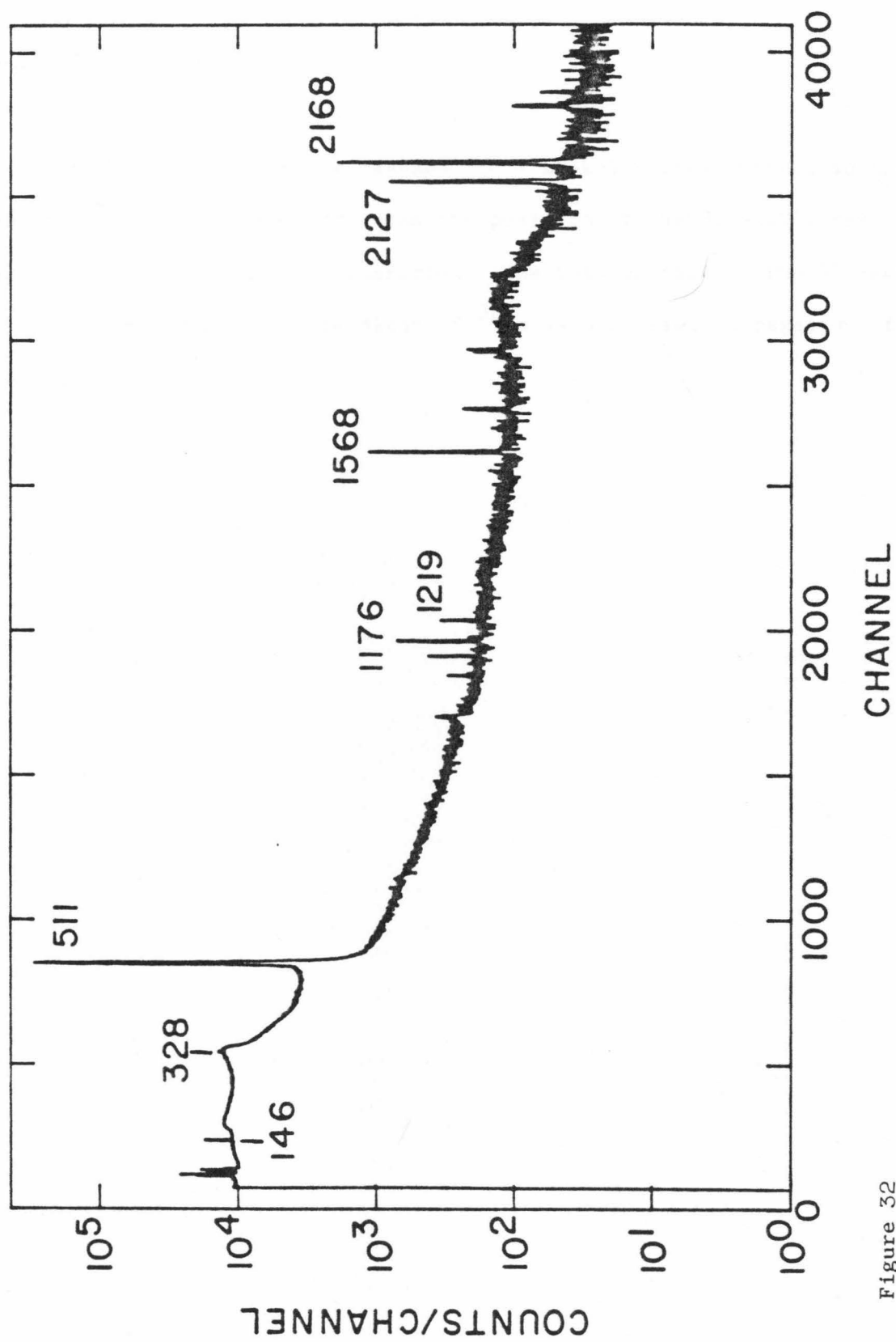


Figure 32

Figure 33.

Detailed spectra of the 328-keV and 1568-keV γ rays emitted in the decay of ^{38}Ca . The arrow indicates the position of the 328-keV γ ray calculated from the energy calibration. The Compton edge of the 511-keV peak is clearly visible. The decay of ^{38}Ca is discussed on pages 91 to 96 of the text.

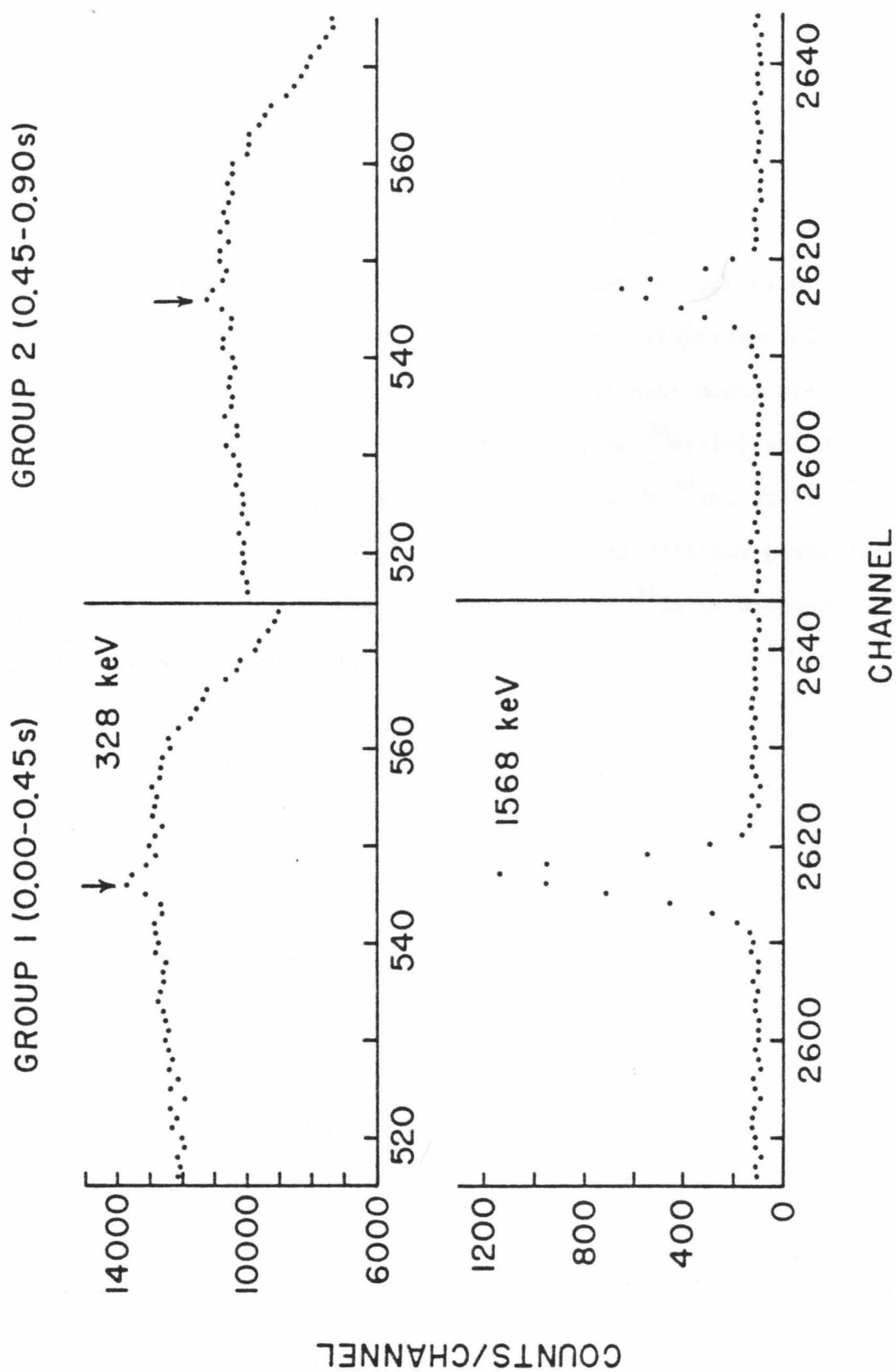


Figure 33

Figure 34.

The Ge(Li) spectrum taken in group 1 (0.00-0.45 sec) of the measurement of the high-energy γ rays emitted in ^{38}Ca decay. A 1.9 cm Pb absorber was used to remove most of the annihilation radiation. The energy calibration is 1.250 keV/channel. We have identified all of the peaks in this spectrum; some of the large contaminant peaks are due to $^{34\text{m}}\text{Cl}$ (2127 and 3303 keV), ^{35}Ar , ^{37}K (2796 keV) and ^{38}K (2168 and 3937 keV) which are produced by various reactions of ^3He with ^{36}Ar , and to ^{14}O (2313 keV). Detailed spectra of the 1568-keV and 3211-keV peaks due to ^{38}Ca decay are shown in Figure 35. The decay of ^{38}Ca is discussed on pages 91 to 96 of the text.

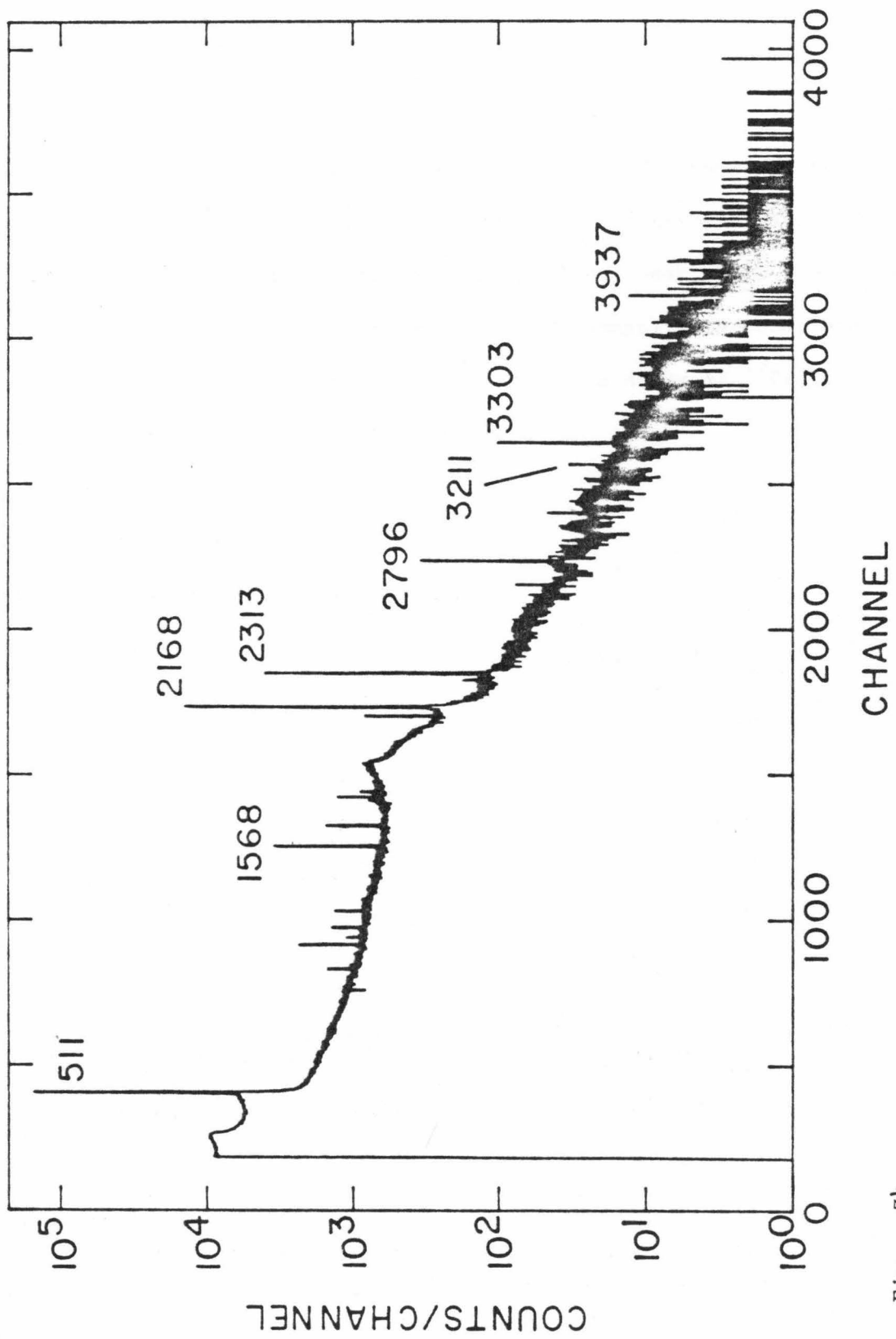


Figure 34

Figure 35.

Detailed spectra of the 1568-keV and 3211-keV γ rays emitted in the β decays of ^{38}Ca to ^{38}K excited states at 1698 keV and 3342 keV. The straight line in the spectrum of the 3211-keV peak shows the background. The energy calibration is 1.250 keV/channel. The complete spectrum for group 1 is shown in Figure 34. The decay of ^{38}Ca is discussed on pages 91 to 96 of the text.

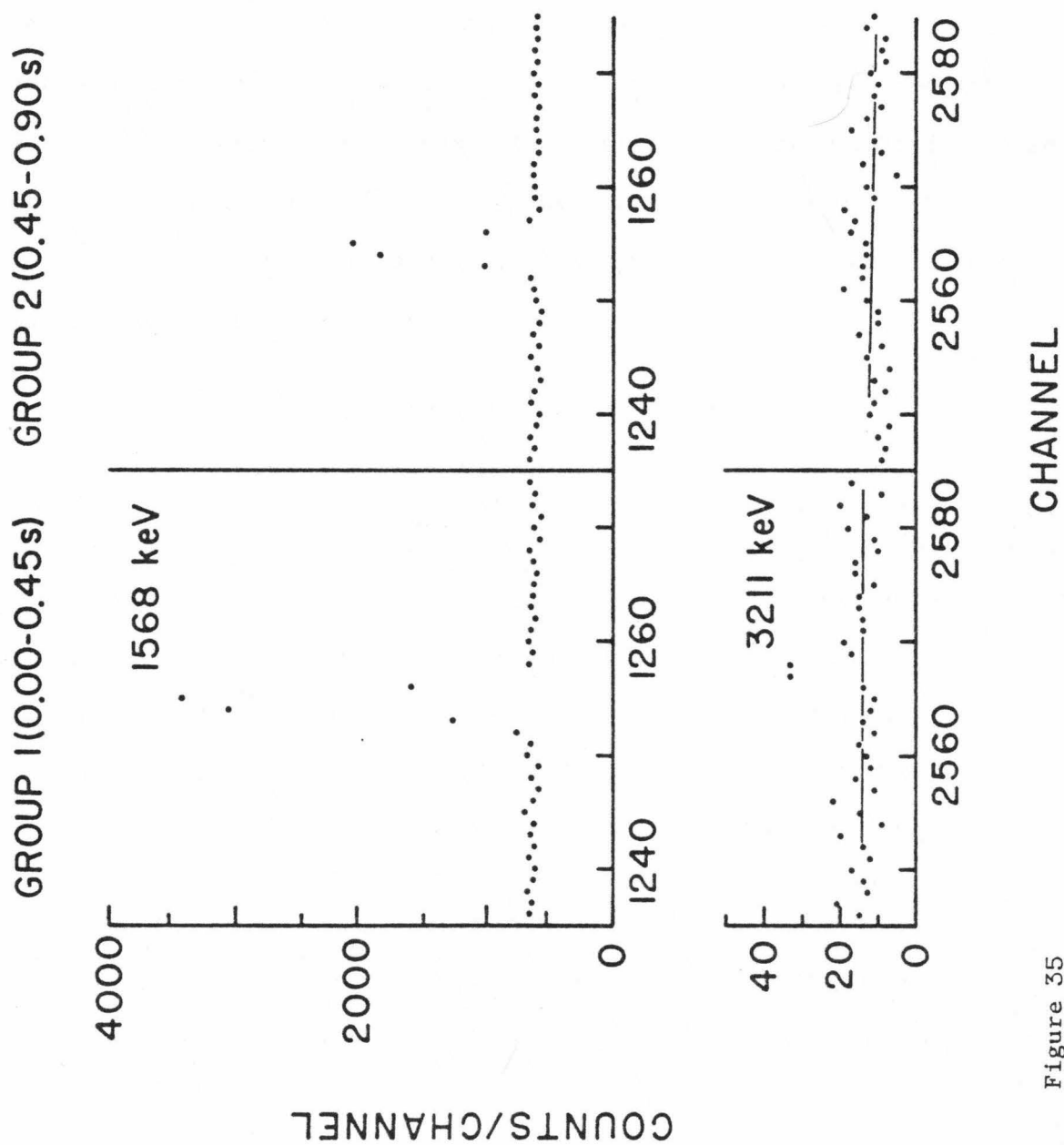


Figure 35

Figure 36.

The data and the exponential fit for one of the four half-life measurements of ^{38}Ca made in this experiment. The 1568-keV peak area has been corrected for the dead time and pileup losses measured with a pulser. The errors shown are purely statistical. The weighted average of the four runs was 0.430 ± 0.012 . sec with a χ^2 value of 4.75 for 3 degrees of freedom. The half-life measurement is discussed on pages 94 and 95 of the text.

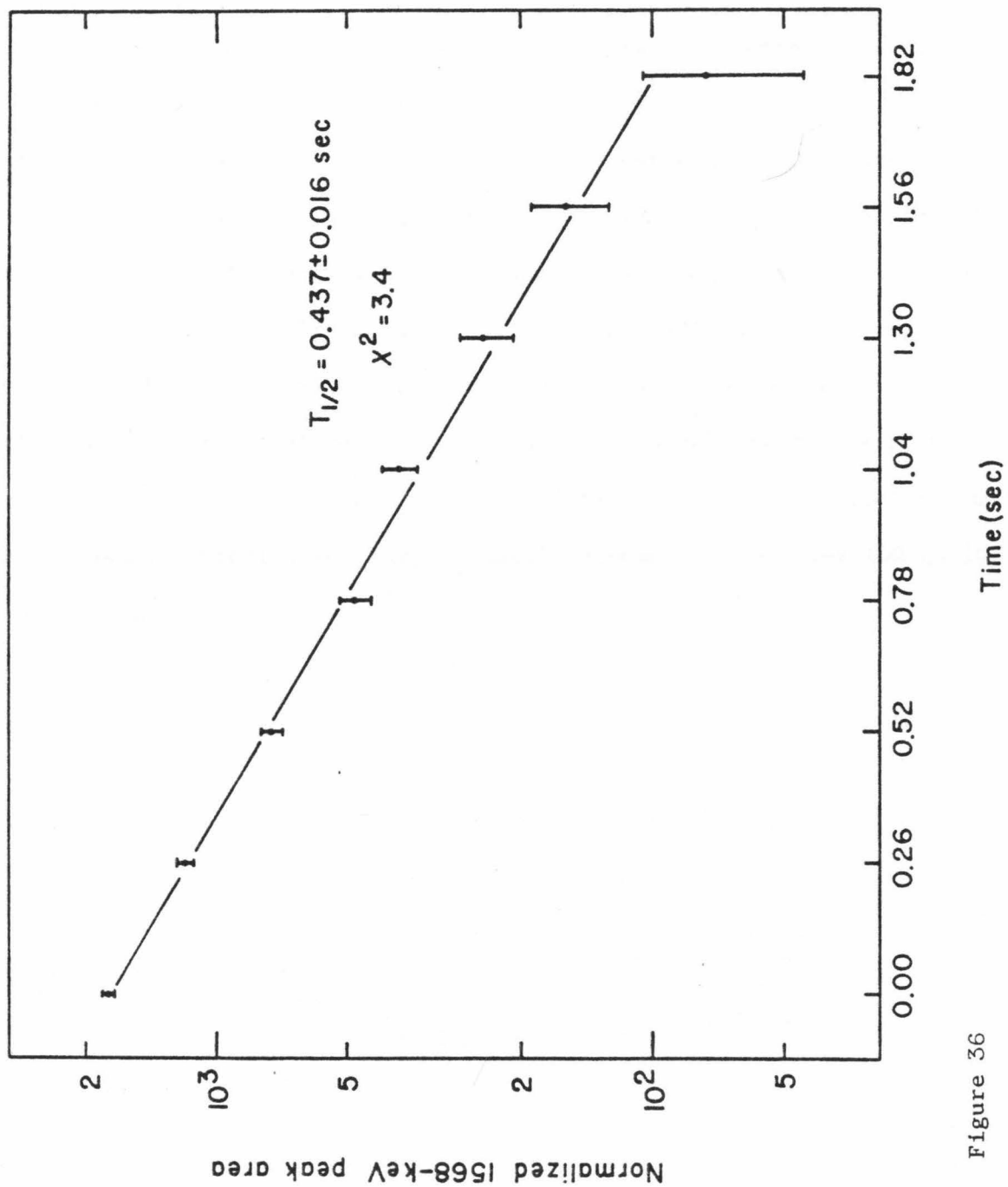


Figure 36

Figure 37.

A comparison of measured Gamow-Teller matrix elements and the calculation of Brown et al. (1978) for $T=1/2$ to $T=1/2$ β decays in $1s-0d$ shell nuclei. Squares indicate transitions between ground states (i.e., between $T=1/2$ isobaric analog states). The experimental values for $T=1/2$ transitions are taken from Table 25 which also lists the results of shell-model calculations. Error bars have been omitted because the experimental uncertainties are usually much less than the differences between theoretical and experimental values. The numbers beside some of the points give the mass of the nuclei involved. Note that the shell-model calculations usually predict too large a matrix element. See pages 100 to 102 of the text.

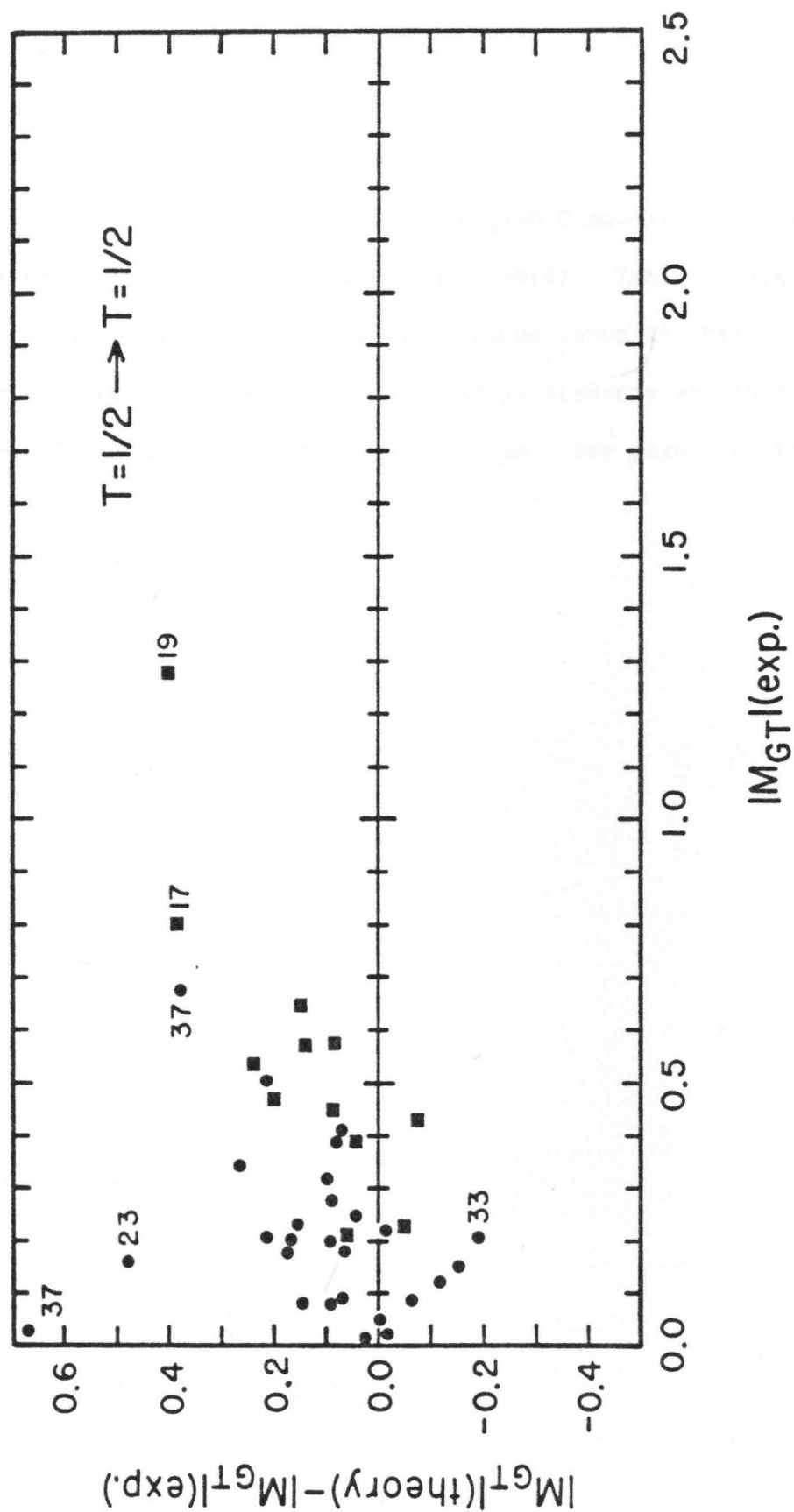


Figure 37

Figure 38.

A comparison of measured $0^{+};T=1$ to $1^{+};T=0$ Gamow-Teller matrix elements and the calculation of Brown et al. (1978). Table 26 lists the theoretical and experimental transition rates shown in this plot. Note the large scatter for even the small matrix elements and that the calculated matrix elements are usually too large. See pages 100 to 102 of the text.

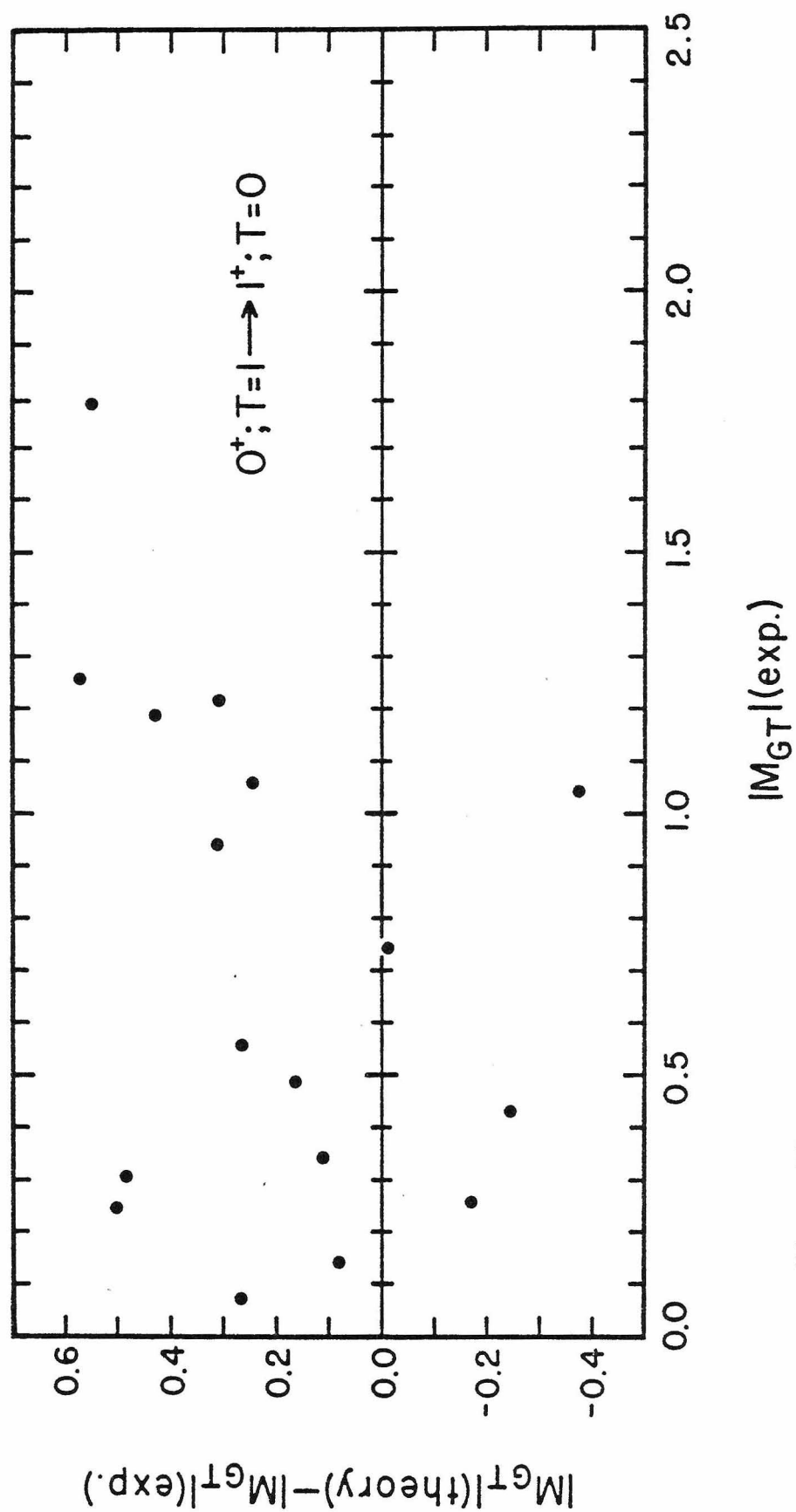


Figure 38

Figure 39.

A comparison of experimental results and the calculations of Brown et al. (1978) for Gamow-Teller transitions connecting $T=0$ and $T=1$ states. The transitions plotted in Figure 38 and their mirrors have been omitted. Note the poor agreement between the measured and calculated matrix elements for these transitions. Experimental and theoretical $\log ft$ values used in this plot are listed in Table 27. See pages 100 to 102 of the text.

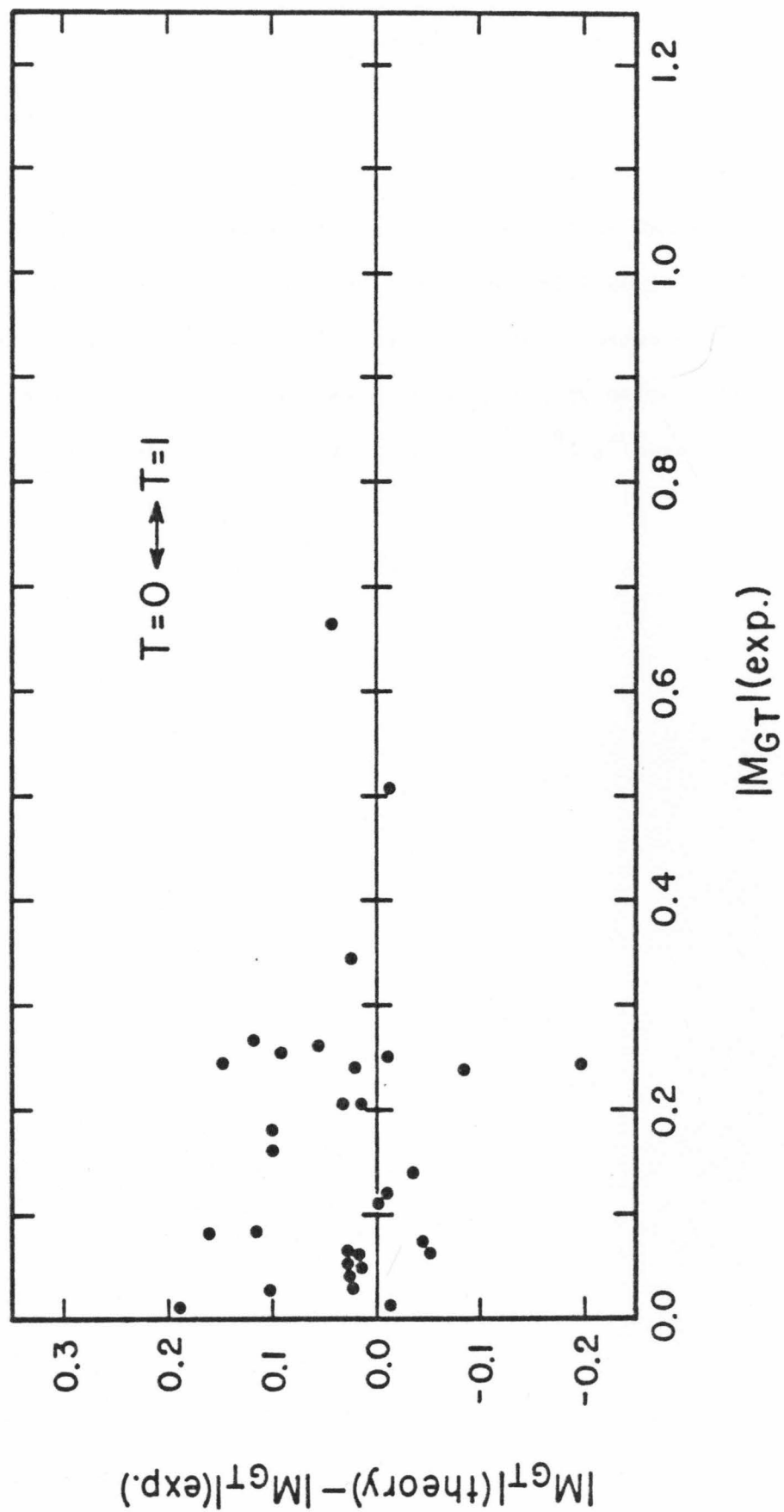


Figure 39

Figure 40.

A comparison of experimental and theoretical Gamow-Teller matrix elements for transitions between $T=3/2$ and $T=1/2$ nuclei. The theoretical values are from the shell-model calculations of Brown et al. (1978). Table 28 lists the theoretical and experimental $\log ft$ values used in this plot. The one very strong transition is in $^{19}\text{O} \beta^-$ decay. See pages 100 to 102 of the text.

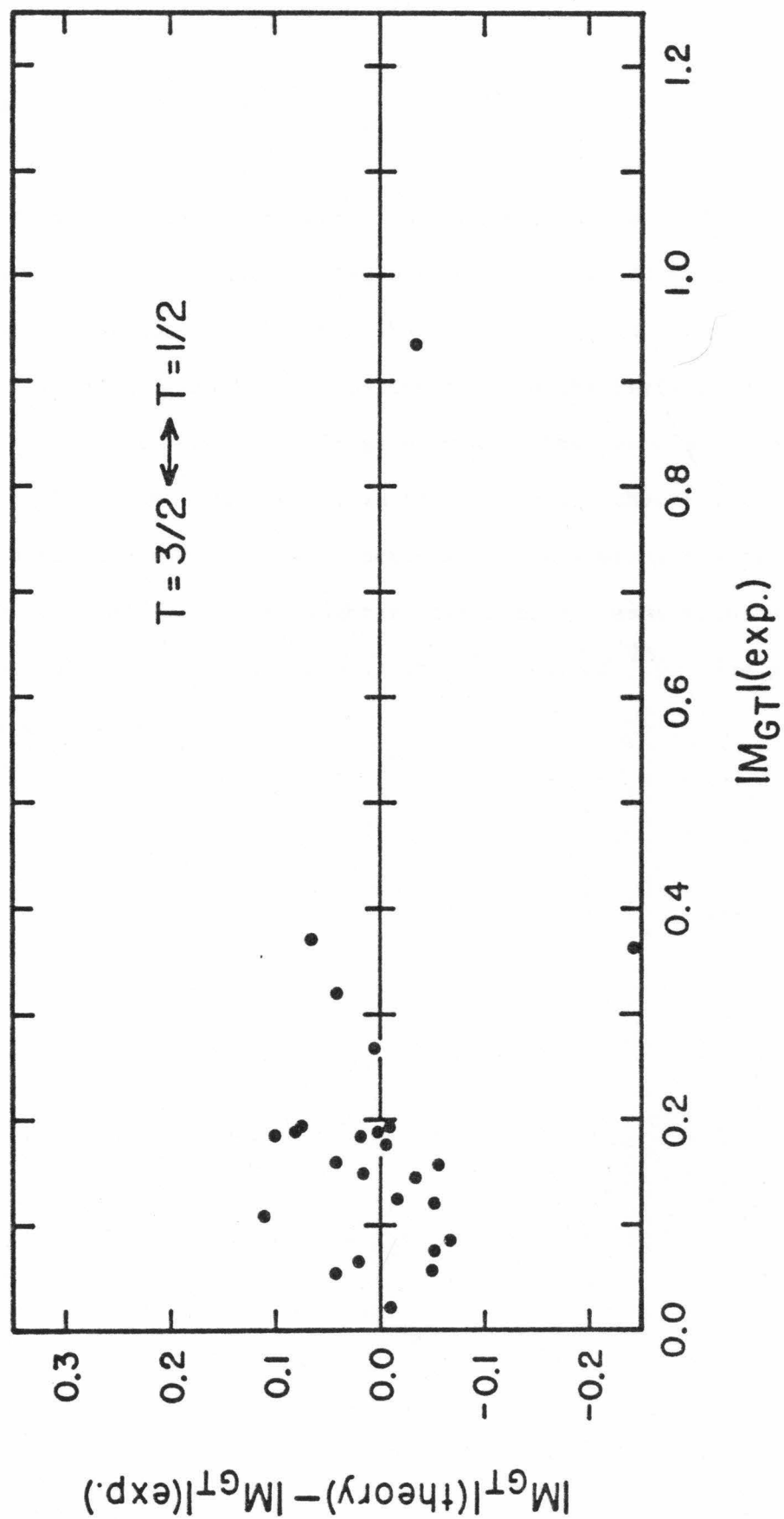


Figure 40

Figure 41.

Comparison of experimental and theoretical Gamow-Teller matrix elements for the β decays of $T=2$ nuclei in the $1s-0d$ shell. The theoretical values are from the shell-model calculation of Brown et al. (1978). Table 29 lists the experimental and theoretical $\log ft$ values used in the plot. Note the large errors in the calculation of transition rates in ^{24}Ne and ^{28}Mg decays; in both cases the theoretical calculation appears to have produced wavefunctions that are wrong linear combinations of two physical parent or daughter states of the same spin and parity. The one very strong transition is the β^- decay of ^{20}O . See pages 100 to 102 of the text.

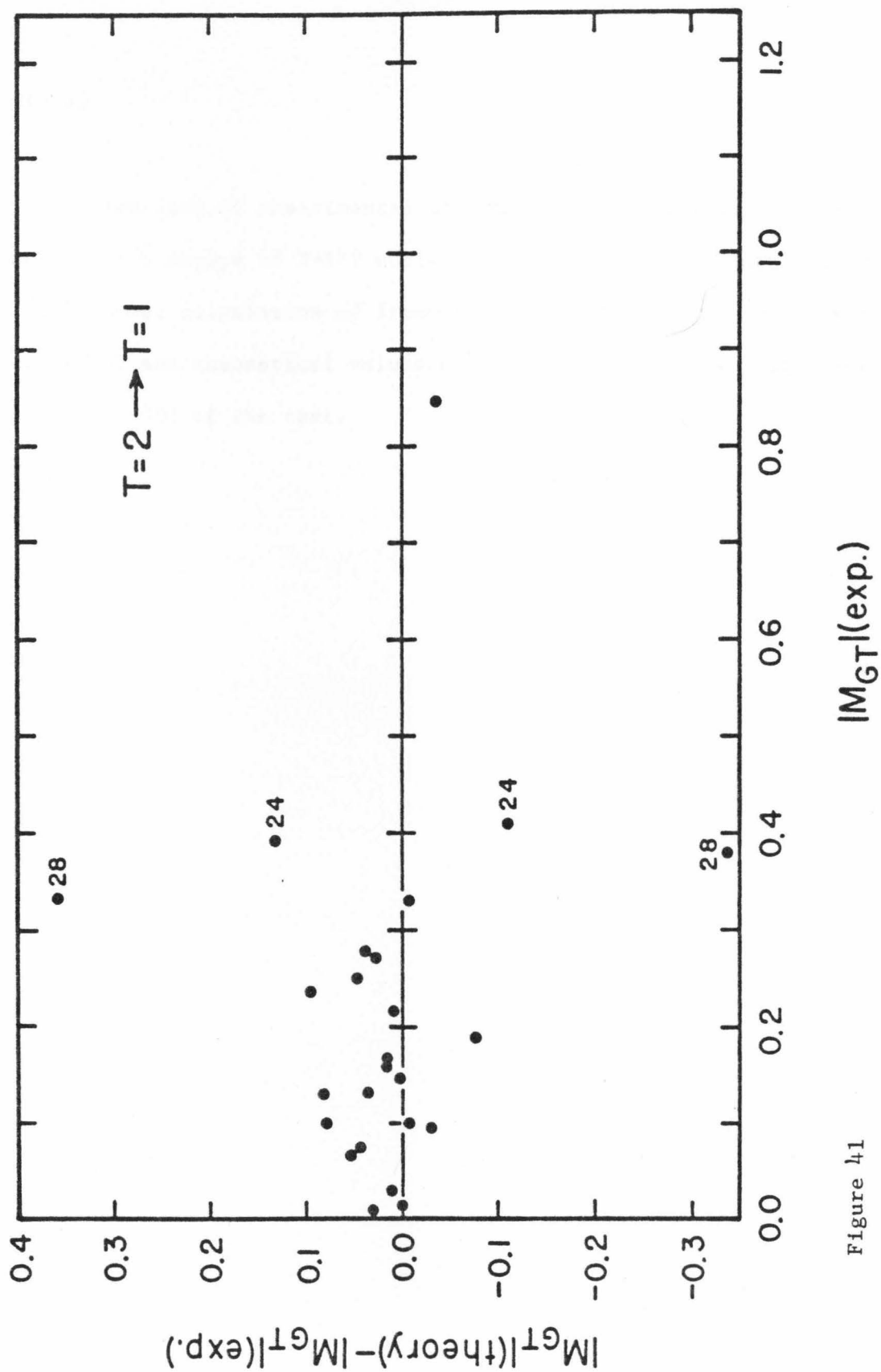


Figure 41

Figure 42.

A comparison of experimental and theoretical Gamow-Teller matrix elements for β decays of $T=5/2$ nuclei. The theoretical values are from the shell-model calculation of Brown et al. (1978). Table 30 lists the experimental and theoretical values of $\log ft$ used in this plot. See pages 100 to 102 of the text.

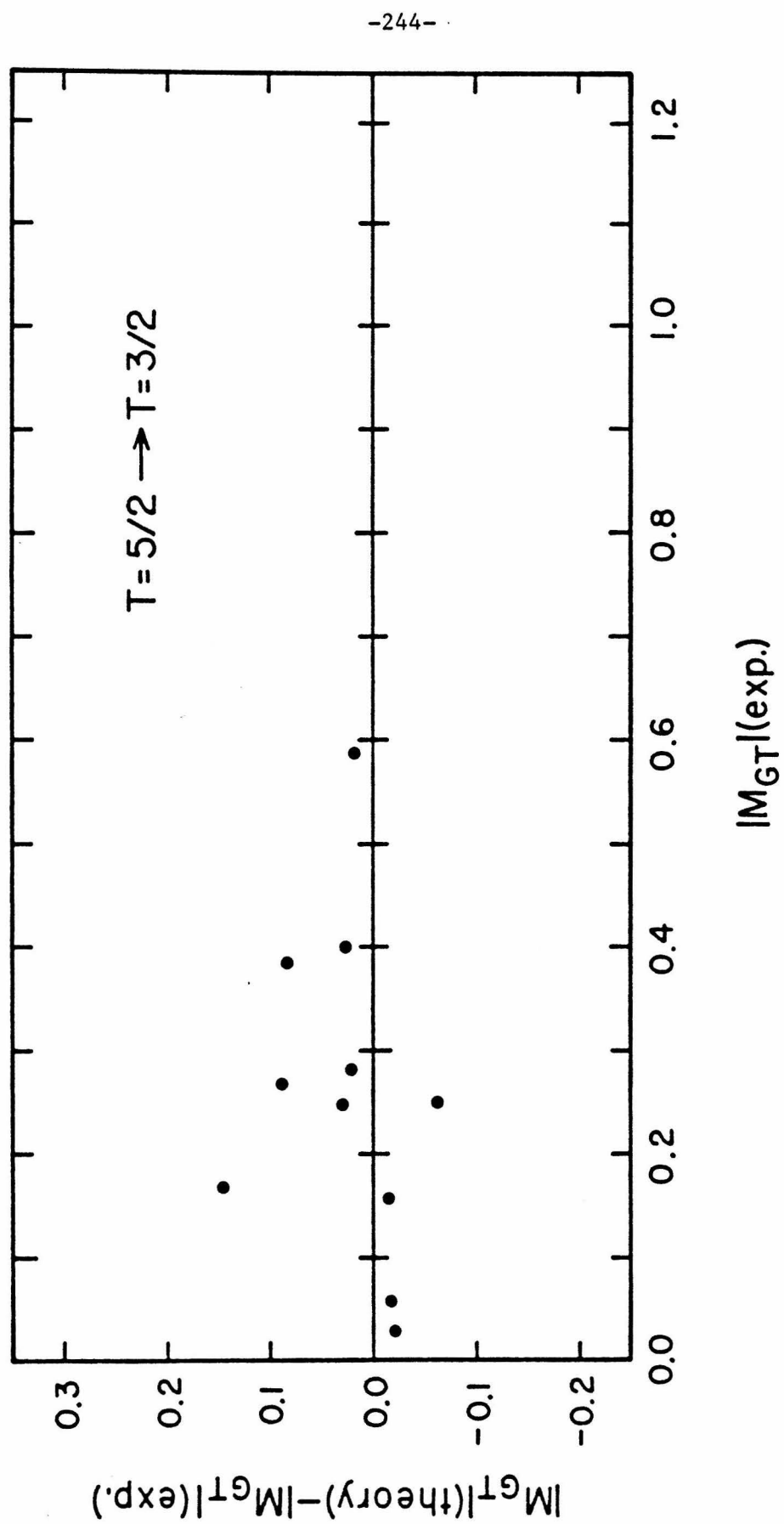


Figure 42