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DECAY OF ^{73m}gSe , ^{75m}Ge , AND ^{77m}gGe

by

Ralph Dennis Meeker

Ph. D. Thesis, May 1970

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DECAY OF ^{73m}Se , ^{75m}Ge , AND ^{77m}Ge

by

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DECAY OF ^{73m}gSe , ^{75m}Ge , AND ^{77m}gGe *

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ABSTRACT

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The decay of ^{73m}gSe , ^{75m}Ge , and ^{77m}gGe have been investigated using Ge(Li) gamma-ray singles measurements, Ge(Li)-Ge(Li) and NaI(Tl)-Ge(Li) coincidence measurements, and delayed coincidence measurements. A decay scheme for ^{73m}gSe has been constructed using high-resolution gamma-ray singles measurements and Ge(Li)-Ge(Li) and NaI(Tl)-Ge(Li) coincidence measurements. Branching ratios and $\log(ft)$ values for decay to the levels of ^{73}As were calculated. Experiments on the decay of ^{75m}Ge give a value of 139.8 ± 0.1 keV for the isomeric transition and set upper limits on the direct beta decay of this $7/2^+$ isomer to low-lying positive parity levels in ^{75}As . The lifetime of the 632 keV $5/2^+$ level in ^{77}As has been measured to be 75 ± 15 psec using gamma rays emitted following the decay of ^{77g}Ge . Two low-spin negative parity levels have been located in the ^{77}As level scheme using gamma rays following the decay of ^{77m}Ge , including a first excited state at 195 keV with

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$I^\pi = 1/2^-$. The experimental data for the levels of $^{73,75,77}\text{As}$ are compared with the predictions of the Coriolis coupling model.

v

TABLE OF CONTENTS

	Page
I. INTRODUCTION	1
A. Historical Review	1
1. Theory	1
2. Experiment	3
B. Purpose of Investigation	10
II. DECAY OF ^{77}Ge	13
A. Source Preparation	13
B. Instrumentation	16
C. Data Analysis	21
D. Experimental Results	23
1. Lifetime of the 632 keV $5/2^+$ level in ^{77}As	23
2. Transition probabilities	27
III. DECAY OF $^{73\text{m}}_{8}\text{Se}$	30
A. Source Preparation	30
B. Instrumentation	33
1. Gamma-ray singles measurements	33
2. Gamma-ray coincidence measurements	36
C. Data Analysis	50
D. Experimental Results	59
1. Energy and relative intensity measurements	59
2. Coincidence measurements	65
3. Decay schemes	65

	Page
IV. DECAY OF ^{75}mGe AND ^{77}mGe	72
A. Source Preparation	73
B. Instrumentation	73
C. Data Analysis	75
D. Experimental Results	78
1. Decay of ^{75}mGe	78
2. Decay of ^{77}mGe	81
V. CONCLUSIONS	88
VI. LITERATURE CITED	93
VII. ACKNOWLEDGMENTS	97

I. INTRODUCTION

A. Historical Review

1. Theory

The recent application of the collective model to odd-A arsenic isotopes makes these nuclei an interesting subject for investigation.

The large numbers of nucleons outside proton and neutron closed shells makes a rigorous shell model treatment prohibitively complicated. The inadequacy of the elementary single particle shell model (1) is demonstrated by its failure to predict the correct ground state spin for $^{73,75,77}\text{As}$. According to the spherical shell model, the lowest energy state available to the thirty-third proton is a $1f_{5/2}$ orbital, whereas the ground state spins and parities of $^{73,75,77}\text{As}$ have been measured as $I^\pi = 3/2^-$ (2-4). Although nuclei in the $A \sim 75$ mass region do not exhibit the obviously rotational energy level spectra found for $150 < A < 190$ and $A > 220$ (5), calculations based on putting the unpaired particle in an anisotropic potential well have successfully explained much of the data for the odd-A arsenic isotopes.

In 1963, Kisslinger and Sorensen (6) attempted to explain the level spectra and other nuclear properties for isotopes of gallium, arsenic, bromine, and rubidium using a pairing-plus-quadrupole model with the nucleons moving in an iso-

tropic oscillator well. This model did not produce satisfactory results. By introducing an anharmonic phonon quasi-particle coupling, however, Kisslinger and Kumar (7) were able to improve the calculated level spectra of $^{73,75,77}\text{As}$, obtaining the correct ground state spins and parities.

Alternately, Imanishi, Sakisaka, and Fukuzawa (8) described level spectra, moments, and reduced transition probabilities of the odd-A arsenic isotopes by considering collective and intrinsic degrees of freedom. The motion of an unpaired quasi-particle, described by wave functions constructed from only three negative parity intrinsic states (Nilsson levels no. 16, 19, and 20: $|l, j, \Omega\rangle = |1, 3/2, 3/2\rangle$, $|3, 5/2, 1/2\rangle$, and $|3, 5/2, 3/2\rangle$), was coupled to rotations of the core by a Coriolis interaction. By varying the deformation and the rotational constant, they were able to successfully account for many properties of ^{75}As .

A similar core rotation-particle coupling calculation of level spectra, moments, and transition rates of ^{75}As had limited initial success (9). Malik and Scholz refined this Coriolis coupling model by the incorporation of a residual interaction of the pairing type between protons of the even-even core, and considerable improvement in theoretical understanding resulted (10). A complete version of this later model has been applied to the spectra of gallium, arsenic,

bromine, and rubidium (11). Using a basis consisting of the 25 Nilsson levels in the 1f, 2p, 1g, 2d, and 3s subshells, this model successfully predicts many of the characteristic features of the nuclei in this mass region, including ground state spins and parities, the high density of negative parity states at low excitation energy, and the occurrence of a low-lying $9/2^+$ and $5/2^+$ doublet. Malik and Scholz are presently applying their computed wave functions to the calculation of moments and transition rates.

2. Experiment

Critical evaluation of the theoretical work on these nuclei has been limited by the lack of experimental information that is available.

The decay of 11.3 h ^{77g}Ge and 54 sec ^{77m}Ge to levels in ^{77}As has been studied by several investigators (12-22). This work is summarized in Figure 1. The existence of the isomer was established by Arnold and Sugarman in 1947 (12). In 1952, Smith (13) studied the beta spectrum from ^{77g}Ge with a magnetic lens spectrometer and also measured the gamma-ray spectrum by analyzing photoelectrons ejected from lead and uranium radiators. He concluded there was no direct transition from the ground state of ^{77}Ge to the ground state of ^{77}As .

In 1954, Burson, Jordan, and LeBlanc (14) used a NaI(Tl) detector to analyze the gamma-ray spectrum and also

Figure 1. Previous studies of the decay of ^{77}Ge and the energy levels of ^{77}As

measured gamma-gamma and beta-gamma coincidences. They constructed an energy-level diagram for ^{77}As which has remained as the basic structure for subsequent work on this decay.

Schardt (15) measured delayed coincidences with a single, large well-type NaI(Tl) detector to study the metastable 475 keV level in ^{77}As and determined its half-life to be 116 μsec .

Arns, Chen, Sund, and Wiedenbeck (16) and Martin and Wiedenbeck (17) assigned spins and parities to a number of the low-lying levels of ^{77}As on the basis of gamma-ray angular-correlation measurements.

The decay of both ^{77g}Ge and ^{77m}Ge were investigated in great detail by van der Kooi and van den Bold in 1965 (18). They obtained a singles gamma-ray spectrum with a NaI(Tl) detector and also investigated sum peaks, sum-coincidence spectra, delayed coincidence spectra, and a number of gamma-gamma coincidence spectra. The low energy portion of the decay scheme deduced from these data is shown in Figure 1a.

More recently, several investigators (19-22) have studied the singles gamma-ray spectrum from ^{77g}Ge with Ge(Li) spectrometers. Many new gamma rays were observed and placed in the decay scheme on the basis of crossover energy sums and gamma-gamma coincidence measurements.

Figure 1b shows the decay scheme in the region below 1.4 MeV proposed by Donnelly, Reidy, and Wiedenbeck (21), and Figure 1c shows the same region from the decay scheme proposed by Ng, Wood, Palms, Rao, and Fink (22). This later work includes gamma-gamma coincidence measurements using a NaI(Tl) detector to gate a Ge(Li) detector. The use of NaI(Tl) as a gating detector does not completely resolve the gamma rays in a spectrum this complex, but this questionable coincidence data has been used to place several transitions in locations inconsistent with their intensities. An example relevant to the present experiment is the placement of the 195 keV gamma ray as feeding a level at 1190 keV.

The 7.2 h ground state of ^{73}Se was first reported by Cowart, Pool, McCown, and Woodward (23) in 1948. In 1951, Scott (24) proposed a decay scheme based on magnetic spectrometer measurements of the positron spectrum and of the conversion electron spectrum. This decay scheme was revised by Hayward and Hoppes (25) using scintillation spectra measurements in 1956 and by Murray, White, Willmott, and Entwistle (26) and by Marlow and Faas (27) using Ge(Li) spectra measurements in 1969.

Following the discovery of a 42 min isomer by Hooge and Aten (28) in 1953, the decay of $^{73\text{m}}\text{Se}$ was also widely investigated. Rao and Fink (29) studied the decay of $^{73\text{m},\text{g}}\text{Se}$ using both NaI(Tl) and Ge(Li) detectors. Akhmed,

Baskova, Vasil'ev, and Shavtvalov (30) measured the positron spectrum; Murray et al. (26) measured excitation functions for 11 intense gamma rays following ^{73}Se decay produced by the $^{70}\text{Ge}(\alpha, n)$ reaction as well as the subsequent gamma decay; and Marlow and Faas (27) made NaI(Tl)-Ge(Li) coincidence measurements on $^{73\text{m}}\text{Se}$ gamma rays and Ge(Li)-Ge(Li) coincidence measurements on $^{73\text{g}}\text{Se}$ gamma rays. Figure 2a displays the known properties of ^{73}As before publication of these last three reports in 1969, and Figures 2b, 2c, and 2d display the changes in the decay scheme proposed by these three groups. There is disagreement about the presence or absence of many gamma rays and about the placement of some levels.

Four groups have investigated the decay of 82 min $^{75\text{g}}\text{Ge}$ to levels in ^{75}As . The first work was done by Schardt and Welker (31) in 1955 using Geiger-Müller tubes to measure the beta spectrum, while Kelly and Wiedenbeck (32) used NaI(Tl) detectors to measure the gamma-ray spectrum in 1956. Van den Bold, van de Geijn, and Endt (33) used a similar method in 1958. While Ng et al. (22) measured the gamma-ray spectrum of $^{75\text{g}}\text{Ge}$ using Ge(Li) spectrometers in 1968, no high-resolution work on the decay of 46 sec $^{75\text{m}}\text{Ge}$ has been done. The decay scheme proposed by Ng et al. (22) is shown in Figure 3a.

Although gamma-ray measurements of the decay of $^{75\text{m},\text{g}}\text{Ge}$

Figure 2. Previous studies of the decay of ^{73}Se and the energy levels of ^{73}As .

Figure 3. Previous studies of the energy levels of 75As .

have been limited, the level structure of ^{75}As has been well established from Coulomb excitation work by Robinson, McGowan, Stelson, and Milner (34) and from the decay of ^{75}Se as reported by Rao, McDaniels, and Craseman (35) and by Nagpal (36). The results of these investigations are summarized in Figures 3b and 3c.

B. Purpose of Investigation

The present work investigates some specific questions about $^{73,75,77}\text{As}$ raised by the recent theoretical calculations for which the existing experimental data are inadequate or inconsistent. This work should provide information about the arsenic isotopes which will help determine the validity of the Coriolis coupling model which recently has been applied to them. Since this model successfully predicts the properties already reported, this investigation will be of value in directing future theoretical work.

The decay of ^{77}Ge to levels in ^{77}As is well understood. Gamma-ray energies and intensities have been measured by several groups (12-22). However, the knowledge of the lifetime of a nuclear level provides the essential information for determining experimental transition probabilities for comparison with theoretical models. The lifetimes of the low-lying positive parity states in the odd-A arsenic isotopes are long enough to be measured by delayed coincidence techniques. Values of 6 μs , 17 msec, and 116 μsec have been

reported for the $9/2^+$ levels in $^{73,75,77}\text{As}$ (2-4). The $5/2^+$ level has not been located in ^{73}As ; its lifetime in ^{75}As is 1.6 nsec (3), approximately 10^4 times the Weisskopf estimate; and no measurement has been reported for ^{77}As . This work provides new information about this level.

In the case of $^{73\text{m},g}\text{Se}$, the experimental evidence available when this research was undertaken was in general disagreement. It was primarily to resolve these differences and to further the understanding of the odd-A arsenic nuclei that this decay was investigated. By employing large, high efficiency Ge(Li) detectors for gamma-ray singles measurements, Ge(Li)-Ge(Li) coincidence measurements, and NaI(Tl)-Ge(Li) coincidence measurements, this work provides evidence for a proposed decay scheme for $^{73\text{m},g}\text{Se}$ to levels in ^{73}As .

As indicated in the last section, the decay of the short lived isomers of ^{75}Ge and ^{77}Ge had last been studied using scintillation techniques. With high-resolution Ge(Li) detectors now available, it was desirable to reinvestigate the decay of these isomers. In particular, the calculations of Imanishi et al. (8) and of Scholz and Malik (11) predict a similar structure for ^{75}As and ^{77}As . As displayed in Figure 3, the ^{75}As ground state has $I^\pi = 3/2^-$ and the first excited states have $I^\pi = 1/2^-, 3/2^-, 5/2^-, 9/2^+$, and $5/2^+$. In the case of ^{77}As , there is a $3/2^-$ ground state and $3/2^-, 5/2^-, 9/2^+$, and $5/2^+$ low energy excited

states (Figure 1) similar to the levels seen in ^{75}As , but the $1/2^-$ state is missing. Since the first excited state of ^{77}Ge is a 54 sec isomeric level with spin and parity believed to be $1/2^-$, allowed beta decay could feed a low-lying $1/2^-$ level in ^{77}As . A search for such a level should provide information which will help determine the validity of the Coriolis coupling model as applied to the arsenic isotopes.

II. DECAY OF ^{77}Ge

The half-life of the $5/2^+$ level at 632 keV in ^{77}As has been measured with the delayed coincidence technique, using gamma rays emitted following the decay of ^{77}Ge . As discussed in the previous section, the decay of ^{77}Ge to levels in ^{77}As has been studied by several investigators (12-22). Recent work includes the decay scheme proposed by Donnelly et al. (21) using data from Ge(Li) and bent-crystal gamma-ray spectrometers. A portion of their decay scheme showing the principal transitions populating and de-exciting the $5/2^+$ level at 632 keV is shown in Figure 4.

A. Source Preparation

Since natural germanium contains only 7.8% ^{76}Ge , a separated isotope sample was purchased from Oak Ridge National Laboratory (principal components: ^{76}Ge --73.89%, ^{74}Ge --10.08%, ^{70}Ge --7.69%, ^{72}Ge --6.65%, and ^{73}Ge --1.69%). The sample was in the form of powdered GeO_2 encapsulated in heat-sealed polyethylene tubing.

Sources of ^{77}Ge were produced by irradiating 10 mg of this material in the Ames Laboratory Research Reactor for a period of 5 minutes. Source strengths of the order of 20 microcuries were normally used for this experiment. The gamma-ray spectrum observed with a 6 cc planar Ge(Li) detector is shown in Figure 5. Immediately after irradiation,

Figure 4. Partial decay scheme of ^{77}Ge . Only transitions populating or de-exciting the $5/2^+$ level at 632 keV are shown

Figure 5. Low energy gamma-ray spectrum of ^{77}Ge observed with a 6 cc Ge(Li) detector. Energies of gamma rays populating or de-exciting the $5/2^+$ level are indicated. Peaks labelled ^{75}Ge are from the decay of ^{75}Ge arising from the 10% ^{74}Ge in the sample irradiated

gamma rays from the decay of 82 min ^{75}Ge were evident. This activity was allowed to die out for 3 hours before timing data were recorded.

B. Instrumentation

For the measurement of long lifetimes ($T_{1/2} > 10^{-3}$ second), standard counting techniques which observe the exponential decay of a sample of excited nuclei can be employed. For the range 10^{-3} second $< T_{1/2} < 10^{-11}$ second, however, the delayed coincidence technique is more commonly used (37).

Delayed coincidence measurements involve the detection of the times of population and decay of the excited nuclear state whose lifetime is being determined. In the present experiment, gamma rays marking the population and de-excitation of the $5/2^+$ level in ^{77}As were detected with Naton 136 plastic scintillators 1.9 cm in diameter and 1.2 cm high coupled to RCA 8575 photomultiplier tubes. The detectors were secured to the laboratory table to reduce errors due to their positioning relative to the sample.

A block diagram of the electronics used to analyze the time distribution of these gamma rays is presented in Figure 6. The electronic logic modules used for these measurements are all commercially available. Interconnections were made using 50 ohm cable and BNC connectors. The photomultipliers were operated at -2300 volts cathode

Figure 6. Block diagram of the delayed coincidence electronics

potential. The duration of the anode pulses was limited to 4 nsec by a shorted 50 ohm clipping line. These clipped pulses were then split; 67% of each signal was routed to a fast trigger which generated a standardized timing pulse when the leading edge exceeded 100 mV. The remaining 33% was sent to a differential discriminator for energy analysis. Windows were set at the Compton edges of the 558 keV gamma ray in the start channel and of the 368 keV gamma ray in the stop channel. With the aid of a gated stretcher amplifier and a multichannel analyzer to display the gamma-ray spectra in the plastic scintillator-photomultiplier detectors, the discriminators were calibrated with 356 and 511 keV gamma rays from ^{133}Ba and ^{22}Na sources. Outputs from the differential discriminators were used to gate the start and stop timing signals into the time-to-amplitude converter (TAC), pulses from which were recorded in a 1024-channel pulse height analyzer.

Gain drifts in any part of the data collecting equipment would appear as shifts in the peak position of data stored in the analyzer memory. Such effects degrade experimental resolution. The pulse height analyzer used in this experiment was provided with a digital stabilizer capable of compensating for drifts occurring in the detection electronics or the analyzer itself. Constant amplitude pulses for gain and zero stabilization were generated by routing two signals

from the start trigger through different lengths of delay cable to the stop input of the TAC. These signals were mixed in an OR circuit which was vetoed whenever a real coincidence occurred and also randomly (by a pulse generator) to keep counting rates in the stabilization peaks close to the coincidence counting rate.

The apparatus was time-calibrated using these same stabilization pulses. A calibrated delay box was used to insert delay lines into the transmission line of the stop pulse. The centroids of the resulting peaks were found, and the positions were plotted versus delay. Figure 7 shows a typical time calibration curve. The slope was found by fitting a straight line to the data using a least-squares technique.

The response of the system to gamma rays in prompt coincidence was checked with a ^{60}Co source. This isotope decays to ^{60}Ni by beta emission and the excited nucleus subsequently de-excites to the ground state by emitting 1.173 and 1.332 MeV gamma rays in cascade. The two photons are emitted about 10^{-12} second apart in time (38). With energy windows set to accept the top 15% of the Compton distribution of the 1.173 and 1.332 MeV gamma rays, the system resolution was 200 psec for the full width at one-half the maximum (FWHM). With 15% windows at the lower energies used for the ^{77}Ge gamma rays, the 360 psec FWHM

Figure 7. The time calibration curve

response curve shown in Figure 8 resulted from a 12 hour data accumulation. A second measure of the resolution is the steepness of the sides of the peak. This parameter is also indicated in the graph. According to Schwarzschild, this is as good resolution as can be expected at these energies (39).

C. Data Analysis

In applying the delayed coincidence technique, lifetimes of nuclear states can be determined either from the exponential slope evidenced in the time spectrum or by the shift of the centroid of the delay spectrum relative to the prompt spectrum. As a rule, lifetimes of the order of one-twentieth of the prompt FWHM can be measured using centroid shift analysis, while lifetimes about 30% larger than the prompt slope can be determined using the more reliable slope method (37).

In this experiment, each time spectrum was analyzed with the assumption that it consisted of three parts: a smooth background from chance coincidences, a prompt component with shape identical to that obtained with the ^{60}Co source due to coincident gamma rays, and a delayed component due to gamma rays feeding and de-exciting the 632 keV $5/2^+$ level given by the convolution of the prompt response curve with a simple exponential decay function. The lifetime was obtained by use of maximum-likelihood curve fitting to resolve

Figure 8. Coincidence spectrum for the prompt ^{60}Co gamma rays taken over a 12 hour period. The differential discriminators were set to accept 15% of the Compton distribution at the energies indicated

the data into these three parts. A computer program (developed by R. A. Anderl and C. E. Turner, Jr.) was used to find the parameters (amplitudes of the background, prompt component, and delayed component, and decay constant for the delayed component) which best fit the data. The Newton-Raphson iterative method was employed in solving the extremum equations involved in this analysis (40). A complete description of the computer usage and a program listing are available (41).

The output of the program included the best fit lifetime of the delay data and the final values of the fitting parameters. The statistical standard deviations of these quantities were determined from the error matrix in the usual manner. In addition, the chi square test (42) was incorporated into the program as a gauge of the goodness of the fit.

D. Experimental Results

1. Lifetime of the 632 keV $5/2^+$ level in ^{77}As

Three sets of ^{77}Ge spectra were taken and analyzed as discussed in the previous section. All three sets of data were accumulated for 16 hours. Data obtained during one of these periods are shown in Figure 9. The smooth curve represents the composite fit to the data.

To complete the analysis, the high voltage on the phototubes was reduced so that the pulses produced by the

Figure 9. Delayed coincidence data for the $5/2^+$ level in ^{77}As taken over a 16 hour period. The smooth curve is the computer fit to the data.

558 keV gamma rays would be too small to fire the start differential discriminator. The resulting spectrum reproduced the prompt curve obtained using the ^{60}Co source.

Since the shape of the delay curve indicated the lifetime being measured was near the minimum value that could be unfolded from the experimental data by the computer analysis, the lower limit of the lifetime was calculated from the centroid shift of the delay data relative to the prompt data. This value was 47 ± 5 psec. Next, the data from the three data sets were unfolded. The fit to the data of Figure 9 is shown in Figure 10. Although all three data sets yielded satisfactory fits, the values of the lifetime did not agree, to within the statistical standard deviations. This resulted from errors in the numerical approximations used in evaluating the convolution integral for lifetimes short compared to the width of the prompt response curve. Artificial data for a lifetime this short generated by another computer program were fit to within 5%. The maximum value obtained was used to set an upper limit on the lifetime. This value was 92 ± 6 psec. The data from the three sets were averaged to determine the half-life; the resulting half-life for the 632 keV $5/2^+$ level in ^{77}As is $T_{1/2} = 75 \pm 15$ psec. Because of uncertainty in the accuracy of the computer analysis for lifetimes this short, the quoted uncertainties are larger than those given by conventional averaging techniques.

Figure 10. Unfolded components of the data in Figure 9

2. Transition probabilities

Transition probabilities to the different final states, T_f , are related to the measured half-life and branching fractions, P_f , by

$$T_f = P_f \cdot (\ln 2) / T_{1/2}.$$

The dependence of the lifetime of a nuclear level on the detailed structure of the initial and final states is contained in the reduced transition probabilities. These are obtained by factoring the nuclear and photon dependence of the transition probability so that the nuclear dependence is explicitly exhibited (43):

$$T_f = \frac{8\pi(L+1)}{L[(2L+1)!!]^2} \frac{1}{\hbar} \left(\frac{\omega}{c}\right)^{2L+1} B(\sigma L, i \rightarrow f),$$

where $B(\sigma L, i \rightarrow f)$ is the reduced transition probability for a transition of multipolarity σL .

Table 1 lists the reduced transition probabilities for the four branches of the decay of the 632 keV level in ^{77}As and for the corresponding transitions in ^{75}As (3). The branching fractions were calculated from the gamma-ray relative intensities of references (21) and (36) corrected for internal conversion from the tables of reference (38). Ratios of observed transition probabilities to single proton estimates (43)

Table 1. Reduced transition probabilities for decay of $5/2^+$ level

	Level energy (keV)	I^π	Branching (%)	$T(\text{sec}^{-1})$	Multi- polarity	T/T_{sp}	$B(e^2\text{fm}^{2L})$
^{77}As	476	$9/2^+$	1.1	1.0×10^8	E2	45	1.3×10^3
	265	$5/2^-$	30	2.7×10^9	E1	3.1×10^{-5}	5.1×10^{-5}
	216	$3/2^-$	50	4.6×10^9	E1	3.6×10^{-5}	5.8×10^{-5}
	0	$3/2^-$	19	1.8×10^9	E1	3.8×10^{-6}	6.3×10^{-6}
^{75}As	304	$9/2^+$	6.5	2.8×10^7	E2	150	3.9×10^3
	280	$5/2^-$	18	7.8×10^7	E1	2.4×10^{-5}	4.0×10^{-5}
	265	$3/2^-$	61	2.6×10^8	E1	5.9×10^{-5}	9.5×10^{-5}
	0	$3/2^-$	14	6.1×10^7	E1	5.4×10^{-7}	8.6×10^{-7}

$$T_{sp}(E1) = 1.0 \times 10^{15} A^{2/3} (\hbar \omega)^3 \text{ sec}^{-1}$$

$$T_{sp}(E2) = 7.4 \times 10^7 A^{4/3} (\hbar \omega)^5 \text{ sec}^{-1}$$

are also given. The large $B(E2)$ and small $B(E1)$ values are consistent with the collective nature of the levels proposed by Scholz and Malik (11) and by Imanishi et al. (8).

III. DECAY OF $^{73m,8}\text{Se}$

Data on the properties of the nuclear levels of ^{73}As can be obtained by studying the positron decay of $^{73m,8}\text{Se}$. Previous work has shown the ground state to have $I^\pi = 3/2^-$ (in contrast to the $f_{5/2}$ orbital assigned the thirty-third proton by the elementary shell model) and the first excited state to have $I^\pi = 5/2^-$. There is also a well-known positive parity level at 428 keV with $I^\pi = 9/2^+$ (2). Scholz and Malik (11) and Imanishi et al. (8) have predicted the level structure of this nucleus within the framework of Coriolis coupling models, but the lack of detailed experimental information has hindered extensive comparison between theory and experiment. This chapter discusses the use of Ge(Li) spectrometers and Ge(Li)-Ge(Li) and NaI(Tl)-Ge(Li) coincidence spectrometers to obtain new information about the decay of $^{73m,8}\text{Se}$ to levels in ^{73}As .

A. Source Preparation

Sources of $^{73m,8}\text{Se}$ activity were produced by the $^{74}\text{Se}(\gamma, n)^{73}\text{Se}$ reaction using the Iowa State University 70 MeV Electron Synchrotron. Natural selenium has only 0.87% ^{74}Se , so isotopically enriched samples were used. One sample consisted of 10 mg of metallic selenium powder enriched to 28.7% ^{74}Se (principal contaminants: ^{80}Se --32.9%, ^{78}Se --16.0%, ^{76}Se --9.7%, ^{82}Se --6.8%, ^{77}Se --5.9%). This sample was

bombarded for a period of 30 minutes to prepare a source of ^{73m}Se ($T_{1/2} = 39$ min) and for a period of 6 hours to prepare a source of ^{73g}Se ($T_{1/2} = 7.2$ h). A second sample consisted of 50 mg of selenium enriched to 36.2% ^{74}Se (principal contaminants: ^{80}Se --30.6%, ^{78}Se --14.9%, ^{76}Se --7.4%, ^{82}Se --5.8%, ^{77}Se --5.1%). This sample was bombarded for 15 minutes to prepare ^{73m}Se and for 1-2 hours to prepare ^{73g}Se .

Both metal powder samples were packaged in aluminum capsules five millimeters in diameter by seven millimeters high during irradiation. The method used to irradiate the samples is illustrated in Figure 11. The spread of the beam perpendicular to the plane of the drawing is roughly one millimeter (44).

The irradiation process also produces isotopes other than $^{73m,g}\text{Se}$. Principal background lines had half-lives ranging from a few minutes (^{79}Se , $T_{1/2} = 3.9$ min) to many days (^{75}Se , $T_{1/2} = 120.4$ d). Only activity from ^{70}Se ($T_{1/2} = 44$ min) produced by the $^{74}\text{Se}(\gamma, 4n)^{70}\text{Se}$ reaction and ^{70}As ($T_{1/2} = 52$ min) produced by the $^{74}\text{Se}(\gamma, p3n)^{70}\text{As}$ reaction and the positron decay of ^{70}Se have half-lives near that of ^{73m}Se . No isotopes are expected with half-lives near that of ^{73g}Se . The cross sections for production of ^{70}Se and ^{70}As are expected to be small compared to the $^{74}\text{Se}(\gamma, n)^{73}\text{Se}$ cross section.

The aluminum capsule also emits gamma rays following

Figure 11. The Synchrotron irradiation geometry

Synchrotron irradiation. The large sample, which had been borrowed from Oak Ridge National Laboratory, was left in the container after irradiation to avoid losing any of this expensive material, while the small sample was poured into a clean container after irradiation. Lines in the spectrum produced by container activities were identified by recording the gamma-ray spectrum of an empty can irradiated for 30 minutes (see Figure 12).

B. Instrumentation

1. Gamma-ray singles measurements

Two Ge(Li) detectors were used for energy and intensity measurements. For most of the work, a detector with 65 cc active volume and 3.5 keV FWHM resolution at 1.332 MeV was employed. The relative efficiency of this detector as a function of gamma-ray energy is shown in Figure 13. This was measured using ^{152}Eu , ^{182}Ta , ^{133}Ba , $^{110\text{m}}\text{Ag}$, and ^{56}Co sources, for which the gamma-ray energies and relative intensities are known (45).

During data accumulations, pulses from the detector's preamplifier were amplified by a Canberra 1417 linear amplifier and recorded in a Nuclear Data 4096-channel pulse height analyzer. Pulse shaping time constants and pole/zero cancellation were adjusted to maximize resolution.

A search for gamma radiations in the energy range 40 keV to 2.8 MeV was made using this spectrometer. Typical spectra

Figure 12. Gamma-ray spectrum of empty aluminum can observed with a 65 cc Ge(Li) detector

Figure 13. Photopeak efficiency versus gamma-ray energy for the 65 cc detector

are shown in Figures 14 and 15. Figure 14 shows a spectrum of the 39 min ^{73m}Se activity recorded in a 30 minute counting period starting 5 minutes after irradiation, and Figure 15 shows a spectrum of the 7.2 h ^{73g}Se activity recorded in a 3 hour counting period starting 5 hours after irradiation. Both spectra were obtained using the 50 mg source. Gamma-ray energies are labelled to the nearest keV and principal background lines are identified as to their origin.

To obtain more precise energy values, a 30 cc Ge(Li) detector with 2.8 keV FWHM resolution at 1.332 MeV was used. The relative efficiency of this detector, determined using ^{133}Ba and ^{152}Eu sources (45), is displayed in Figure 16. Since data obtained with the 65 cc detector had indicated that all the gamma rays from the decay of $^{73m,g}\text{Se}$ were below 1.5 MeV, only the energy range 40 keV to 1.5 MeV was considered using the 30 cc detector. Figure 17 shows a typical spectrum of ^{73m}Se recorded in a 30 minute counting period starting 5 minutes after irradiation. A typical spectrum of the ^{73g}Se activity recorded for 3 hours starting 3 hours after irradiation is shown in Figure 18.

2. Gamma-ray coincidence measurements

To verify that the gamma rays being investigated were due to a positron activity, coincidence spectra were recorded with the 65 cc detector described above gated by annihilation radiation detected in a NaI(Tl) scintillation crystal (7.6 cm

Figure 14. Spectrum of ^{73m}Se gamma rays observed with the 65 cc Ge(Li) detector

Figure 15. Spectrum of ^{73}gSe gamma rays observed with the 65 cc Ge(Li) detector

Figure 16. Photopeak efficiency versus gamma-ray energy for the 30 cc detector

Figure 17. Spectrum of ^{73m}Se gamma rays observed with the 30 cc Ge(Li) detector

Figure 18. Spectrum of ^{73}gSe gamma rays observed with the 30 cc Ge(Li) detector

diameter by 7.6 cm long Harshaw "Integral Line"). A block diagram of the electronics is shown in Figure 19. The detectors were placed at right angles to reduce 511 keV-511 keV coincidences.

Crossover timing with double delay line pulse shaping was used for the timing channel of both detectors. The coincidence resolving time for annihilation radiation in both the NaI(Tl) detector and the Ge(Li) detector was 75 nsec. A single channel analyzer (SCA) was used to select gating pulses due to annihilation radiation in the NaI(Tl) detector. A second SCA selected pulses due to the Compton distribution of higher energy gamma rays just above the 511 keV photopeak. A routing system was used to simultaneously record coincidence and background spectra in separate portions of the analyzer memory, and the background was later subtracted from the coincidence spectrum channel by channel. The gated spectrum obtained by adding two spectra accumulated during 1 hour counting periods starting 5 minutes after 30 minute irradiations is shown in Figure 20. The 50 mg sample was used for this work.

Coincidence spectra were also recorded with the 65 cc Ge(Li) detector gating a 25 cc Ge(Li) detector (resolution 3.4 keV). The timing system was the same one described above for the NaI(Tl)-Ge(Li) coincidence measurements with the NaI(Tl) crystal replaced by a Ge(Li) detector. The

Figure 19. Block diagram of the NaI(Tl)-Ge(Li) coincidence circuit

Figure 20. Coincidence spectrum of ^{73m}Se gamma rays gated by annihilation radiation in the NaI(Tl) detector

coincidence resolving time was 75 nsec. Coincidences with the 67, 85, and 254 keV photons of $^{73\text{m}}\text{Se}$ were recorded using this spectrometer. In each case, four spectra were accumulated during 1 hour counting periods following 30 minute irradiations of the 50 mg sample. The results are displayed in Figures 21, 22, and 23.

As a survey of other possible coincidences, two-parameter Ge(Li)-Ge(Li) coincidence data were recorded using the system shown in Figure 24. This spectrometer employed two 30 cc detectors (each with resolution of 2.8 keV FWHM at 1.332 MeV) and constant fraction time pickoffs (CFPHT) (46, 47). The resolving time was 80 nsec. Data satisfying the coincidence gating requirement were stored on magnetic tape. The information was analyzed at a later time by recalling selected portions of the data. When the tape was played back into the analyzer memory, windows were set on peaks of interest and on background regions to correct for the Compton distribution due to higher energy gamma rays. The two spectra were later subtracted channel by channel. (In Figures 21-23 and 25-29, 10 counts have been added to each channel to exhibit negative fluctuations of the data in semilog plots.) With sources prepared using the 10 mg sample of ^{74}Se , data were obtained on both $^{73\text{g}}\text{Se}$ and $^{73\text{m}}\text{Se}$ decays. For the decay of 7.2 h $^{73\text{g}}\text{Se}$, a 6 hour irradiation was followed by a single 15 hour data accumulation. The

Figure 21. Ge(Li)-Ge(Li) coincidence spectrum of $^{73\text{m}}\text{Se}$ gamma rays gated by the 67 keV gamma ray

Figure 22. Ge(Li)-Ge(Li) coincidence spectrum of $^{73\text{m}}\text{Se}$ gamma rays gated by the 85 keV gamma ray

Figure 23. Ge(Li)-Ge(Li) coincidence spectrum of ^{73m}Se gamma rays gated by the 254 keV gamma ray

Figure 24. Block diagram of the two-parameter Ge(Li)-Ge(Li) coincidence circuit

results of gating on the 67 and 361 keV lines are shown in Figures 25 and 26. In obtaining data for 39 min $^{73\text{m}}\text{Se}$, a series of 30 minute irradiations and 1 hour data accumulations was carried out until data from six irradiations had been collected. Results from gating on gamma rays not selected in previous work are displayed in Figures 27, 28, and 29.

C. Data Analysis

The decay of the irradiated samples of $^{73\text{m},\text{g}}\text{Se}$ was investigated by recording a series of gamma-ray spectra with the Ge(Li) spectrometers discussed in the previous section. Peak positions and areas were analyzed by the computer programs PEAKFIND and SKLN available at this laboratory.¹ The first of these programs automatically finds peaks and performs a least-squares fit of a Gaussian function plus low-energy tail and a quadratic background function to each peak. The program SKLN is a peak fitting routine which contains a high-energy tail in addition to the low-energy tail and Gaussian of PEAKFIND. Both computer programs gave precise channel locations, peak areas, full-widths at half maximum and skewness parameters, and estimates for errors

¹PEAKFIND and SKLN, Instructions for users. Mimeo. Ames, Iowa, Iowa State University of Science and Technology. A complete description of the fitting programs is presented in reference (48).

Figure 25. Ge(Li)-Ge(Li) coincidence spectrum of ^{73g}Se gamma rays gated by the 67 keV gamma ray

Figure 26. Ge(Li)-Ge(Li) coincidence spectrum of ^{73g}Se gamma rays gated by the 361 keV gamma ray

Figure 27. Ge(Li)-Ge(Li) coincidence spectrum of ^{73m}Se gamma rays gated by the 320 keV gamma ray

Figure 28. Ge(Li)-Ge(Li) coincidence spectrum of $^{73\text{m}}\text{Se}$ gamma rays gated by the 393 keV gamma ray.

Figure 29. Ge(Li)-Ge(Li) coincidence spectrum of $^{73\text{m}}\text{Se}$ gamma rays gated by the 402 keV gamma ray

in these quantities for the peaks. Examples of fits are shown in Figure 30. Figure 30a shows an intense peak with good statistics while Figure 30b shows a very weak peak with poor statistics. The theoretical curves are superimposed on the data points.

Energy calibration was performed with sources of ^{241}Am (38), ^{152}Eu , ^{182}Ta , ^{133}Ba , $^{110\text{m}}\text{Ag}$, and ^{56}Co (45). The energy-versus-channel number relation was fit by assuming a linear function and measuring deviations with the calibration sources:

$$E(C) = mC + b + \Delta(C),$$

where $E(C)$ is gamma-ray energy as a function of channel number C , m and b are slope and intercept constants which best fit the calibration spectrum, and $\Delta(C)$ is the deviation from linearity. It was found that the nonlinearity could be minimized by using different linear parameters for different sections of the spectrum. The data for the first 1000 channels of the 4096-channel analyzer are shown in Figure 31. Similar correction functions applied for the remainder of the spectrum.

After the calibration data were accumulated, a second spectrum was accumulated with both $^{73\text{m}}\text{Se}$ and calibration gamma rays. The peaks were analyzed as before, and the energies of the prominent $^{73\text{m}}\text{Se}$ peaks were determined relative

(a) Well defined peak

(b) Poorly defined peak

Figure 30. Typical photopeak fits

Figure 31. Energy calibration correction function for the first 1000 channels of the 4096-channel analyzer

to the calibration source photopeaks to within ± 0.1 keV. The energies of the weak gamma rays in the spectrum were determined from a third spectrum of ^{73m}Se alone. The calibration was performed with the previously measured energies of the intense ^{73m}Se gamma rays. The uncertainties in the energies of these less intense gamma rays is typically ± 0.5 keV, although some lines could only be determined to within ± 0.8 keV.

The energies of the ^{73g}Se lines were obtained in a similar manner. Gamma rays from the decay of $^{26}\text{h } ^{72}\text{As}$ (49) which were present in the spectrum were also used as internal calibration lines.

The intensities of the $^{73m,g}\text{Se}$ gammas were calculated by dividing the peak areas by the detector relative efficiency. Since the detector efficiency curves are accurate to $\pm 5\%$ at best and the estimated relative error for the peak areas is typically $\pm 1-2\%$ for strong peaks, intensities of the strong peaks should be accurate to within $\pm 10\%$ or better. The error in intensity for the weak gamma rays is typically larger, depending on the counting statistics.

D. Experimental Results

1. Energy and relative intensity measurements

To identify gamma rays due to the decay of ^{73m}Se , alternate 3 minute and 30 minute spectra were recorded using the 65 cc Ge(Li) spectrometer and the 50 mg sample. Data

collection began 2 minutes after irradiation. The data from the 3 minute counts were used to determine the half-lives of the intense gamma rays in the spectrum. Short counting periods were used to provide a good decay curve despite the varying analyzer live time. Seven intense peaks were shown to decay with a half-life of 39 ± 2 min. Next, the areas of all the peaks in three 30 minute spectra were compared to the area of the 254 keV line. In this way, weak gamma rays due to ^{73}mSe were identified. The NaI(Tl)-Ge(Li) coincidence data were also used to verify that the gamma rays attributed to ^{73}mSe were due to a positron activity.

The decay of 7.2 h ^{73}gSe was studied in the same way with alternate 15 minute and 1 hour counts, using the 361 keV line as a relative intensity standard. Three and six hour counting periods were also used to check for very weak gamma rays.

To obtain energy values, the 30 cc Ge(Li) spectrometer was employed using the calibration technique described in the last section. Table 2 lists the energies and relative intensities of the ^{73}mSe peaks, along with intensities reported by Murray et al. (26) and by Marlow and Faas (27). Energy values from the present work agree within statistical standard deviations with those of these other two reports. The energies and intensities for the ^{73}gSe gamma rays are listed in Table 3. Intensity values reported by Marlow and

Table 2. Gamma rays from the decay of ^{73}mSe

Energy (keV)	Intensity	Intensity ^a	Intensity ^b
84.5 ± 0.1	74.0 ± 7.4	92.0 ± 7.0	79.0 ± 4.0
139.4 ± 0.3	2.0 ± 0.5	- ^c	2.4 ± 1.2
180.7 ± 0.4	19.0 ± 3.0	17.0 ± 4.0	12.0 ± 3.0
253.8 ± 0.1	100	100	100
262.9 ± 0.5	7.7 ± 1.0	- ^c	4.8 ± 1.0
308.9 ± 0.5	6.7 ± 1.0	- ^c	6.2 ± 1.9
320.4 ± 0.1	34.0 ± 4.0	42.0 ± 3.0	36.0 ± 4.0
393.4 ± 0.1	63.0 ± 6.3	84.0 ± 6.0	69.0 ± 3.0
401.6 ± 0.1	48.0 ± 4.8	64.0 ± 4.0	54.0 ± 3.0
442.8 ± 0.6	0.8 ± 0.4	- ^c	1.1 ± 0.2
490.2 ± 0.6	1.5 ± 0.4	- ^c	2.0 ± 0.4
509.7 ± 0.6^d	?	?	?
571.2 ± 0.2	11.9 ± 1.3	- ^c	10.1 ± 0.8
577.5 ± 0.1	42.0 ± 4.2	46.0 ± 4.0	41.0 ± 3.0
588.7 ± 0.5	2.3 ± 0.6	- ^c	3.5 ± 0.3
655.7 ± 0.2	9.3 ± 1.1	7.0 ± 0.9	4.2 ± 0.9

^aReference (26).^bReference (27).^cNot seen.^dEnergy deduced from intensity-weighted energy sums.

Table 2. (Continued)

Energy (keV)	Intensity	Intensity ^a	Intensity ^b
703.1 $\pm$ 0.5	2.6 $\pm$ 0.6	- ^c	3.1 $\pm$ 1.2
725.0 $\pm$ 0.5	1.5 $\pm$ 1.0	3.8 $\pm$ 0.8	2.7 $\pm$ 1.0
769.6 $\pm$ 0.5	6.4 $\pm$ 2.9	8.3 $\pm$ 1.5	5.4 $\pm$ 1.8
823.6 $\pm$ 0.5	4.0 $\pm$ 1.0	5.3 $\pm$ 1.5	4.3 $\pm$ 1.1
850.7 $\pm$ 0.5	7.4 $\pm$ 1.0	12.0 $\pm$ 2.0	9.9 $\pm$ 1.3
935.1 $\pm$ 0.5	0.6 $\pm$ 0.2	- ^c	0.7 $\pm$ 0.1
993.7 $\pm$ 0.3	2.9 $\pm$ 0.4	5.1 $\pm$ 0.5	3.1 $\pm$ 1.0
1002.8 $\pm$ 0.3	2.5 $\pm$ 0.3	3.7 $\pm$ 0.5	2.5 $\pm$ 0.5
1020.8 $\pm$ 0.3	2.5 $\pm$ 1.0	- ^c	0.9 $\pm$ 0.3
1077.8 $\pm$ 0.2	23.4 $\pm$ 2.3	29.0 $\pm$ 2.0	25.0 $\pm$ 2.0
1087.1 $\pm$ 0.6	1.9 $\pm$ 0.4	- ^c	1.4 $\pm$ 0.5
(1188.6 $\pm$ 0.4)	< 0.1 ^c	- ^c	0.3 $\pm$ 0.1
1215.4 $\pm$ 0.8	0.4 $\pm$ 0.2	- ^c	0.3 $\pm$ 0.1
1232.3 $\pm$ 0.8	0.6 $\pm$ 0.2	- ^c	0.5 $\pm$ 0.1
1301.7 $\pm$ 0.3	2.5 $\pm$ 0.3	3.7 $\pm$ 0.6	2.3 $\pm$ 0.7
511.0	1460.0 $\pm$ 146		1680.0 $\pm$ 200

Table 3. Gamma rays from the decay of ^{73}Se

Energy (keV)	Intensity	Intensity ^a
67.0 ± 0.1	73.9 ± 7.4	73.0 ± 7.0
360.9 ± 0.1	100	100
442.5 ± 0.8	0.06 ± 0.01	0.04 ± 0.01
509.5 ± 0.8^b	?	?
(556.9 ± 0.8)	- ^c	0.04 ± 0.01
682.0 ± 0.8	0.09 ± 0.04	0.02 ± 0.01
699.9 ± 1.0	0.04 ± 0.01	0.04 ± 0.01
764.4 ± 0.8	0.14 ± 0.02	0.10 ± 0.03
782.9 ± 0.8	0.06 ± 0.01	0.06 ± 0.02
818.4 ± 0.8	0.04 ± 0.02	0.02 ± 0.01
847.2 ± 0.8	0.08 ± 0.01	0.06 ± 0.02
864.9 ± 0.5	0.55 ± 0.06	0.49 ± 0.03
901.3 ± 0.5	0.15 ± 0.02	0.12 ± 0.03
968.1 ± 0.8	0.02 ± 0.01	0.01 ± 0.005
982.5 ± 0.8	0.03 ± 0.01	0.02 ± 0.01
1110.8 ± 0.5	0.19 ± 0.02	0.18 ± 0.05
1215.4 ± 0.8	0.06 ± 0.01	- ^c

^aReference (27).^bEnergy deduced from energy sum.^cNot seen.

Table 3. (Continued)

Energy (keV)	Intensity	Intensity ^a
1340.7 $\pm$ 0.8	0.09 $\pm$ 0.02	0.07 $\pm$ 0.01
1422.5 $\pm$ 0.5	0.14 $\pm$ 0.02	0.11 $\pm$ 0.03
1482.3 $\pm$ 1.0	0.03 $\pm$ 0.01	0.01 $\pm$ 0.01
1548.0 $\pm$ 0.8	0.04 $\pm$ 0.01	0.03 $\pm$ 0.01
511.0	128.0 $\pm$ 13.0	126.0 $\pm$ 3.0

Faas (27) are included for comparison. The energies and intensities listed for this work are mean values from several determinations.

2. Coincidence measurements

The results of the Ge(Li)-Ge(Li) coincidence measurements are summarized in Table 4.

Table 4. Coincidences observed in the decay of ^{73m}Se

Energy of gating gamma ray (keV)	Coincident gamma-ray energy (keV)
67.0	361, 443, 589, 703, 1111
84.5	309, 490, 571, 994
253.8	139, 320, 402, 824
320.4	254
360.9	67 ^a
393.4	181, 263
401.6	254

^aThe 428 keV level is an isomer with 6 μsec half-life, so no gamma rays which feed it are seen in coincidence.

3. Decay schemes

The level scheme for the decay of ^{73m}Se was constructed with the present energy and intensity measurements and the

results of the Ge(Li)-Ge(Li) coincidence experiments. The resulting level scheme is presented in Figure 32. A dot at the head or tail of a gamma ray indicates a measured coincidence of that gamma ray into or out of the level.

The placement of all the levels up to 1078 keV is verified by the coincidence data with the exception of levels at 851 keV and possibly 510 keV. Marlow and Faas (27) place the 851 keV gamma ray de-exciting a level at 935 keV. This implies a coincidence between the 851 and 85 keV gamma rays, which was not observed in this work. Since the 851 keV gamma is rather intense ($I_{851} = 7.4 \pm 1.0$), it should appear in coincidence with any low-energy line it might feed. Since no such coincidence was observed, it has been placed as a ground state transition.

Based on the ^{73m}Se intensity measurements alone, the order of the 443 and 578 keV gamma rays would be reversed. However, the coincidence data indicates the 443 keV gamma ray feeds the 67 keV gamma ray, placing a level at 510 keV. Because of the intense annihilation radiation in the spectrum, no 510 keV gamma ray could be observed. A relative intensity check using data from the NaI(Tl)-Ge(Li) coincidence measurements supports the present placement of the 578 keV gamma ray. The intensity of the 511 keV gamma ray in the NaI(Tl) gated spectrum is partially due to annihilation radiation since the positrons were not completely stopped by the sample

Figure 32. The decay scheme for ^{73m}Se . Log(ft) values are in parentheses in the column on the right

container. To account for the intensity of the 578 keV line feeding the level at 510 keV, an unseen 510 keV gamma ray has been dotted into the decay scheme.

Finally, no evidence was found for placing the 935 and 1302 keV gamma rays. Marlow and Faas (27) propose a level at 1958 keV which de-excites via 1302 and 1189 keV transitions to the levels at 656 and 770 keV. No 1189 keV photon was found in this work, and the counting statistics place its intensity as $I_{1189} < 0.1$. Marlow and Faas report $I_{1189} = 0.3 \pm 0.1$. More evidence is needed to place these gamma rays in the decay scheme.

The total positron plus electron capture branching to the levels of ^{73}As were calculated from the imbalance of electromagnetic transitions into and out of each level derived from Table 2, corrected for internal conversion (49). It has been shown by Marlow and Faas (27) that there is no direct 39 min feeding to the 67 keV level, and it was assumed there is none to the 510 keV level to simplify the computation. $\log(ft)$ values were found from calculated electron capture to positron ratios and the nomograph in reference (38). The transitions in Figure 32 are labelled with the $\log(ft)$ values and percent of total decays. All $\log(ft)$ values are consistent with allowed transitions with the exception of the value found for the 254 keV level.

The proposed decay scheme for ^{73}Se is shown in Figure

33. The coincidence data for this decay indicates levels at 67, 428, 510, and 1178 keV. Since the 428 keV level is an isomer with 6 μ sec half-life (2), it is not possible to detect cascades involving this level. The remaining gamma rays in the spectrum all have $I_\gamma < 0.2$ with the exception of the 865 keV photon. Marlow and Faas (27) performed Ge(Li)-Ge(Li) coincidence measurements by gating on this gamma ray while absorbing the intense 67 and 361 keV gamma rays with a lead shield. Their coincidence results suggest the levels at 1850 and 1975 keV. Crossover energy sums are used to place levels at 1274, 1293, and either 1329 or 1411 keV. These last two levels will place the 901 keV gamma ray and either the 818 or 983 keV gamma ray. Both possibilities are shown in the decay scheme of Figure 33, and the multiple placement of the 901 keV line is indicated by an asterisk. The placement of all levels above 1178 keV should be considered tentative, so these have been dotted into the decay scheme.

Again a level is placed at 510 keV to account for the 443 keV gamma ray, and it is assumed that the ratio I_{510}/I_{443} is the same as in the decay of ^{73m}Se . This is used to calculate the intensity of the 510 keV transition and the feeding to this level. Gamma-ray intensity imbalance, maximum positron energy, total positron feeding, and calculated electron capture to positron ratios (38) were used to

Figure 33. The decay scheme for ^{73}gSe . $\log(ft)$ values are in parentheses in the column on the right

find total branching to the remaining levels and the $\log(ft)$ values shown in Figure 33.

IV. DECAY OF ^{75m}Ge AND ^{77m}Ge

The decay of ^{75m}Ge and ^{77m}Ge were investigated to obtain more information about the levels of ^{75}As and ^{77}As . Data on ^{75}Ge (Figure 3) shows the ground state has $I^\pi = 1/2^-$ and the first excited state is a 46 sec isomer at about 139 keV with $I^\pi = 7/2^+$ (3). No evidence for direct beta decay of ^{75m}Ge to levels in ^{75}As has been found, despite the presence of low-lying $5/2^+$ (304 keV) and $9/2^+$ (401 keV) levels which could be fed by allowed beta decay. In the case of ^{77}Ge , the ground state has $I^\pi = 7/2^+$ and the first excited state is a 54 sec isomer at about 159 keV with $I^\pi = 1/2^-$ (4). Data obtained by van der Kooi and van den Bold (18) indicated direct beta decay of the isomer to levels at 0, 215, 325, 632, and 755 keV (Figure 1). The levels at 0 and 215 keV have $I^\pi = 3/2^-$, so the beta decays are allowed transitions. The 632 keV level has $I^\pi = 5/2^+$, however, requiring a first forbidden, unique transition. The 325 keV level was proposed as a possible $1/2^-$ level corresponding to the $1/2^-$ level at 199 keV in ^{75}As . Data on the decay of ^{77g}Ge indicates there are no 325 or 755 keV gamma rays in the spectrum of the ground state activity. Since van der Kooi and van den Bold used NaI(Tl) detectors, high resolution Ge(Li) measurements of the decay of ^{77m}Ge should resolve these differences.

A. Source Preparation

Sources of ^{75m}Ge were produced by irradiating approximately 2.5 mg of GeO_2 enriched to 94.48% ^{74}Ge isotopic abundance (principal contaminants: ^{72}Ge --2.21%, ^{70}Ge --1.71%, ^{73}Ge --0.90%, ^{76}Ge --0.70%) in the Ames Laboratory Research Reactor for 2 seconds. The short half-life of ^{75m}Ge imposed the requirement that the time between irradiation and data collection be as short as possible. With this in mind, the data collecting equipment was moved to the basement of the reactor building, about 20 feet from the irradiation port. After irradiation, the sample was removed from the transport "rabbit" and placed in front of a Ge(Li) detector. This procedure took less than one minute. Four separate samples of enriched $^{74}\text{GeO}_2$ were used so that data could be accumulated without building up too much of the long-lived ^{75g}Ge ($T_{1/2} = 82$ min) activity.

The sources of ^{77m}Ge were produced in the same way. Enriched $^{76}\text{GeO}_2$ was used (^{76}Ge --73.89%, ^{74}Ge --10.08%, ^{70}Ge --7.69%, ^{72}Ge --6.65%, ^{73}Ge --1.69%), and four samples were again prepared so that ^{77g}Ge ($T_{1/2} = 11.3$ h) activity would be minimized.

B. Instrumentation

A Ge(Li) detector with 2.8 keV FWHM resolution at 1.332 MeV was used for gamma-ray energy and intensity measurements. The characteristics of this detector were described in the

last chapter, and the relative efficiency curve is shown in Figure 16. A 1.27 cm thick plexiglass absorber was used to stop the strong beta radiation of the germanium sources in this experiment.

Pulses from the detector were fed into a 1024-channel analyzer equipped with a magnetic tape deck for input/output operations. An automatic system for taking a series of counts at regular intervals for a preset clock time was set up using the "recycle" mode of the analyzer. In this mode, data are accumulated for the preset time, and then read out on magnetic tape. During the readout operation the analyzer erases the data so it is ready for the next cycle.

Each data accumulation lasted 20 seconds. The total time for 10 cycles was checked using a stop watch, and the average time for each cycle was found to be 27.6 seconds. This time was checked each time a source was counted, and never varied more than ± 0.02 second.

To correct for "dead time" in the pulse height analyzer, a ^{241}Am source was placed near the detector. The area of the 60 keV gamma ray was used as a record of analyzer live time. This was necessary because the live time changed as the samples decayed. A source of real gamma rays was used instead of a pulser because no pulser was available with satisfactory peak shape at the counting rate used. The dead

time was 5% with the ^{241}Am source alone and 30% at the beginning of data accumulation with a newly prepared source.

C. Data Analysis

With the automatic data accumulation system described above, a series of ten 1024-channel spectra were recorded for each isomer. This procedure was repeated with each of four samples, and the corresponding cycles of each accumulation were added together to improve the statistical quality of the data. Spectra from the residual activity were recorded in 30 minute accumulations starting 30 minutes after the irradiation of the last sample. The first 1024-channel prompt spectrum of $^{75\text{m}}\text{Ge}$ and the residual spectrum of $^{75\text{g}}\text{Ge}$ are shown in Figure 34. The principal gamma rays from $^{75\text{m}}\text{Ge}$ and $^{75\text{g}}\text{Ge}$ are labelled. The corresponding spectra for $^{77\text{m,g}}\text{Ge}$ are in Figure 35.

Photopeak areas and centroids were found using the computer programs PEAKFIND and SKLN as described in the last chapter. Energy calibration was performed using ^{241}Am , ^{133}Ba , and ^{152}Eu . Energies of the isomeric transitions were found using data from a simultaneous accumulation of calibration sources plus the $^{77\text{m}}\text{Ge}$ source (note that the 10% ^{74}Ge in this source causes substantial $^{75\text{m}}\text{Ge}$ activity in the $^{77\text{m}}\text{Ge}$ spectrum of Figure 35).

Gamma rays arising from the beta decay of the short-

Figure 34. Gamma-ray spectra from the decay of ^{75m}Ge and ^{75g}Ge observed with the 30 cc detector

Figure 35. Gamma-ray spectra from the decay of ^{77m}Ge and ^{77g}Ge observed with the 30 cc detector

lived $^{75,77}\text{Ge}$ isomers were identified from their decay curves. The count rate for a given gamma ray was found by dividing its peak area by the area of the ^{241}Am peak. A least-squares technique was used to fit the resulting decay curves to a line of the form

$$\ln N(t) = \ln N_0 - \lambda t$$

from which the half-life was calculated by

$$T_{1/2} = (\ln 2)/\lambda.$$

D. Experimental Results

1. Decay of ^{75m}Ge

The decay curve for the isomeric transition in ^{75}Ge is shown in Figure 36. The half-life found to fit the data is 48 ± 2 sec, in agreement with the accepted value of 46 ± 2 sec (3). The energy of this transition was found to be 139.8 ± 0.1 keV.

No direct beta decay had been reported for this isomer. Since $I^\pi = 7/2^+$ for ^{75m}Ge , the beta decay would be expected to feed the $5/2^+$ and $9/2^+$ states in ^{75}As in preference to any of the low-spin, negative parity levels. To set upper limits on the beta decay to these two levels, a search was made for evidence of the gamma rays known to de-excite them from ^{75}Se decay (35, 36). The results are tabulated in Table 5. Lower limits for the $\log(ft)$ values for feeding

Figure 36. Decay of the isomeric levels of ^{75m}Ge and ^{77m}Ge

Table 5. Gamma rays from the decay of ^{75m}Ge

Energy (keV)	Initial state ^{75}As (keV)	Final state ^{75}As (keV)	Gamma-ray intensity ^a
400.7	401 ($5/2^+$)	0	$< 1.4 \times 10^{-4}$
136.0	401	265	- ^b
121.1	401	280	$< 4.0 \times 10^{-4}$
96.7	401	304	$< 4.5 \times 10^{-4}$
304.0	304 ($9/2^+$)	0	$< 1.3 \times 10^{-5}$

^aRelative to $I_{140} = 100$ before correction for internal conversion.

^bCannot be calculated because of background from 140 keV isomeric transition.

of these two levels were calculated using the upper limits on branching ratios and the nomograph of reference (38). The isomeric transition was corrected for internal conversion (50). For feeding to the $5/2^+$ level, $\log(ft)$ is greater than 7.8; and for feeding to the $9/2^+$ level, $\log(ft)$ is greater than 9.4. Though the values are high for allowed beta transitions, similar results are obtained for the decay of the $7/2^+$ ground state of ^{77}Ge to the corresponding $5/2^+$ and $9/2^+$ levels in ^{77}As . This is consistent with the wave functions for these levels proposed by Scholz and Malik.¹

¹Malik, F. B., Bloomington, Indiana. Private communication. 1970.

2. Decay of ^{77m}Ge

The decay curve for the decay of the isomeric state of ^{77m}Ge is shown in Figure 36. The half-life is 56 ± 2 sec. Earlier measurements gave 59 ± 2 (12), 52 ± 2 (14), 53.6 ± 0.9 (51), and 59 ± 2 (18). Four additional gamma rays were found to decay with this same half-life. Their decay curves are shown in Figures 37, 38, and 39. The energy and relative intensity measurements are summarized in Table 6. Only the 216 keV gamma ray and the isomeric transition had been previously reported as belonging to the decay of ^{77m}Ge (18).

Table 6. Gamma rays from the decay of ^{77m}Ge

Energy (keV)	Gamma-ray intensity
159.7 ± 0.1	54.0 ± 5.4
194.8 ± 0.2	2.3 ± 0.2
215.5 ± 0.1	100
419.4 ± 0.5	0.45 ± 0.05
614.3 ± 0.5	0.21 ± 0.03

No evidence was found for the 325 and 755 keV gamma rays proposed by van der Kooi and van den Bold (18) from NaI(Tl) spectrometer measurements. Counting statistics place upper limits on the intensities of these gamma rays:

Figure 37. Decay of the 195 keV and 216 keV gamma rays of ^{77m}Ge

Figure 38. Decay of the 419 keV gamma ray of ^{77m}Ge

Figure 39. Decay of the 614 keV gamma ray of ^{77m}Ge

$I_{325}/I_{216} < 1 \times 10^{-3}$ and $I_{755}/I_{216} < 7 \times 10^{-4}$. The identification of the gamma rays de-exciting the 632 keV $5/2^+$ level was probably due to detection of the 614 and 419 keV gamma rays, since their energies are near those of the 632 and 416 keV gammas known to de-excite the 632 keV level. A NaI(Tl) detector would not distinguish these gamma energies.

The proposed decay scheme for ^{77m}Ge is shown in Figure 40. The new gamma rays observed from the decay of ^{77m}Ge are all seen in recent reports of the decay of ^{77}Ge (21, 22), but are not placed in the decay schemes in the same places. There are strong objections to the placement of the 195, 419, and 614 keV gamma rays proposed by Ng et al. (22) on the basis of NaI(Tl)-Ge(Li) coincidence data. All three of these gamma rays are shown de-exciting levels with energy above 1.2 MeV. A search for the gamma rays de-exciting the levels fed by these photons in the decay scheme of Ng et al. (22) gave negative results. The most intense gamma that would have to be seen to justify their placement has intensity $I_\gamma/I_{216} < 10^{-3}$, while it must be 23 times as intense to account for the gamma feeding from above.

Agreement with the decay scheme of Donnelly et al. (21) is somewhat better. They propose a level at 614 keV to account for the gamma ray of this energy, but do not propose the level at 195 keV. The 419 keV gamma ray is not seen in

Figure 40. The decay scheme for ^{77m}Ge

their work, and the 195 keV gamma is placed feeding the 265 keV $5/2^-$ level from a level at 460 keV. The intensity of the 265 keV gamma ray in the ^{77}mGe spectrum is a factor of 2 too small to allow this placement, and can be accounted for by the ^{75}Ge contaminant in the irradiated samples.

The proposal of a $1/2^-$ level at 195 keV is consistent with the theoretical predictions of Imanishi et al. (8) and Scholz and Malik (11). These calculations predict such a state at low excitation energy, and the first excited state in ^{75}As is indeed a $1/2^-$ level with nearly the same excitation energy. The level at 614 keV is based on the crossover energy sum. The spin of ($1/2^-$, $3/2^-$) is based on the systematics by comparison with the ^{75}As level scheme. The corresponding level in ^{75}As decays with approximately the same branching ratio to the $3/2^-$ ground state and the $1/2^-$ first excited state (3).

The branching ratios for the ^{77}mGe decay were calculated by correcting the 160 keV gamma ray for internal conversion (50) and using the ratio $I_{216}/I_{\beta} = 0.28 \pm 0.05$ reported by Lyon and Eldridge (51). $\log(ft)$ values were found using the nomograph of reference (38). The results of these calculations are indicated in Figure 40.

The $\log(ft)$ values for beta decay to the 195 and 614 keV levels are high for allowed transitions, but this is not unusual in this mass region. A similar result is seen in

the decay of the $1/2^-$ ground state of ^{75}Ge to the corresponding levels in ^{75}As (22).

V. CONCLUSIONS

Present experimental knowledge about the low-energy structure of $^{73,75,77}\text{As}$ is summarized in Figure 41. The experiments described in preceding sections of this paper have contributed data directly relevant to comparison with the recently published Coriolis coupling model of these nuclei (8-11). Some theoretical predictions from the calculations of Scholz and Malik (11) are also shown in Figure 41.

The present investigation of the decay of $^{77\text{m}}\text{Ge}$ has contributed to the ^{77}As level scheme in two ways. The lifetime of the 632 keV $5/2^+$ level in ^{77}As has been measured with the delayed coincidence technique, using gamma rays emitted following the decay of $^{77\text{g}}\text{Ge}$; and two low-spin negative parity levels have been located in the level scheme using gamma rays following the decay of $^{77\text{m}}\text{Ge}$.

There is good agreement between these new data and the theoretical predictions based on the Coriolis coupling model. Detailed calculations have been carried out only for ^{75}As , and the computed spectra for two choices of deformation parameter are shown in Figure 41. Since ^{75}As and $^{73,77}\text{As}$ differ only by two neutrons, the ^{75}As predictions should be a good representation for $^{73,77}\text{As}$ as well (11). By considering positive deformation, all observed negative parity levels of ^{77}As have a corresponding level in the

theoretical spectrum within 100 keV. In particular, the low-lying $1/2^-$ level predicted by the theory has been located in this experiment. The placement of the lowest positive parity level relative to the ground state cannot be predicted by the model, so this level has been normalized to the corresponding level in ^{75}As . The model correctly predicts both $9/2^+$ and $5/2^+$ levels at low excitation energy.

Reduced transition probabilities for the decay of the $5/2^+$ level at 632 keV were also calculated in this investigation, and the results are in good agreement with the corresponding quantities for ^{75}As . Since Scholz and Malik are presently using their computed wave functions to calculate transition rates,¹ there will also be theoretical values for comparison in the near future.

Future experimental work on the decay of $^{77\text{m,g}}\text{Ge}$ might include measurements of the lifetimes of the low-lying negative parity levels in ^{77}As and two-parameter Ge(Li)-Ge(Li) coincidence measurements to resolve the inconsistencies noted in the NaI(Tl)-Ge(Li) coincidence measurements of Ng et al. (22).

Experiments on $^{75\text{m}}\text{Ge}$ yielded a new value of 139.8 ± 0.1 keV for the isomeric transition, and set upper limits on its decay to the positive parity states of ^{75}As . The

¹Malik, F. B., Bloomington, Indiana. Private communication. 1970.

levels of ^{75}As are well explained by the Coriolis coupling calculations for positive deformation parameter (Figure 41).

An attempt was made to construct a complete decay scheme for $^{73\text{m},g}\text{Se}$ using high-resolution Ge(Li) gamma-ray singles measurements and Ge(Li)-Ge(Li) and NaI(Tl)-Ge(Li) coincidence measurements. Many weak gamma rays were observed and tentatively assigned, and branching ratios and $\log(ft)$ values were calculated. A theoretical explanation of the rather limited experimentally known properties of ^{73}As is possible if negative deformation is considered in the Coriolis coupling model (Figure 41). In this case, the $5/2^-$ first excited state and a single positive parity state with $I^\pi = 9/2^+$ are correctly predicted. If a $5/2^+$ level were present in the ^{73}As spectrum, it should be fed by allowed decay from the $7/2^+$ ground state of ^{73}Se . There are other possible explanations of the differences between ^{73}As and $^{75,77}\text{As}$, however. One possibility is a large change in the moment of inertia parameter in the Coriolis coupling calculation due to the removal of two neutrons from the even-even core in going from ^{75}As to ^{73}As . The effects of this change on the theoretical predictions are being evaluated by F. B. Malik.¹

The beta decay of ^{73}Se does not appear to be the best

¹Malik, F. B., Bloomington, Indiana. Private communication. 1970.

approach to getting information about the levels of ^{73}As . In the future, reaction data from $^{74}\text{Se}(t,\alpha)^{73}\text{As}$ should provide data for direct measurements of the level properties.

Future theoretical work should include an extension of the Coriolis coupling model to the odd-neutron nuclei in the $1f-2p$ and $1g-2d-3s$ shells. This would allow detailed calculations of comparative half-lives for the beta decay to the odd-proton nuclei, and should hopefully explain the causes of the many high $\log(ft)$ values for allowed transitions observed in this investigation.

VI. LITERATURE CITED

1. Mayer, M. G. and Jensen, J. H. D., Elementary theory of nuclear shell structure (John Wiley and Sons, Inc., New York, N.Y., 1955).
2. Pancholi, S. C., Way, K., and Ikegami, H., Nuclear data sheets for $A = 73$, Nuclear Data, B1-6-48 (1966).
3. Pancholi, S. C. and Ikegami, H., Nuclear data sheets for $A = 75$, Nuclear Data, B1-6-81 (1966).
4. Artna, A., Nuclear data sheets for $A = 77$, Nuclear Data, B1-4-2 (1966).
5. Mottelson, B. R. and Nilsson, S. G., The intrinsic states of odd- A nuclei having ellipsoidal equilibrium shape, Mat. Fys. Skr. Dan. Vid. Selsk. Vol. 1, No. 8 (1959).
6. Kisslinger, L. S. and Sorensen, R. A., Spherical nuclei with simple residual forces, Rev. Mod. Phys. 35, 853 (1963).
7. Kisslinger, L. S. and Kumar, K., Static quadrupole moment of vibrational, even nuclei and the coupling scheme for odd nuclei, Phys. Rev. Letters 19, 1239 (1967).
8. Imanishi, N., Sakisaka, M., and Fukuzawa, F., Coriolis-coupling calculation of low-lying states in As isotopes, Nucl. Phys. A125, 626 (1969).
9. Scholz, W. and Malik, F. B., Properties of As^{75} in the Coriolis coupling model, (Abstract) Bull. Am. Phys. Soc. Series 2, 12, 66 (1967).
10. Malik, F. B. and Scholz, W., Application of a rotation quasi-particle coupling model to ^{75}As , (Abstract) J. Phys. Soc. Japan Suppl. 24, 639 (1968).
11. Scholz, W. and Malik, F. B., Level spectra of odd isotopes of Ga, As, Br, and Rb in the Coriolis coupling model with a residual interaction of the pairing type, Phys. Rev. 176, 1355 (1968).
12. Arnold, J. R. and Sugarman, N., Short-lived isomeric states of Se^{83} and Ge^{77} , J. Chem. Phys. 15, 703 (1947).

13. Smith, A. B., The nuclear spectrum of Ge^{77} , Phys. Rev. 86, 98 (1952).
14. Burson, S. B., Jordan, W. C., and LeBlanc, J. M., Decay of $\text{Ge}^{75\text{m}}$ (49 sec), $\text{Ge}^{77\text{m}}$ (52 sec), and Ge^{77} (12 hr), Phys. Rev. 96, 1555 (1954).
15. Schardt, A. W., Short-lived isomers of As^{75} and As^{77} , Phys. Rev. 108, 398 (1957).
16. Arns, R. G., Chen, C. H., Sund, R. E., and Wiedenbeck, M. L., Energy levels of As^{77} , Nucl. Phys. 40, 132 (1963).
17. Martin, M. B. and Wiedenbeck, M. L., The decay of Ge^{77} , Nucl. Phys. 48, 65 (1963).
18. van der Kooi, J. B. and van den Bold, H. J., The decay of ^{77}Ge and $^{77}\text{Ge}^{\text{m}}$, Nucl. Phys. 70, 449 (1965).
19. Palms, J. M., Ng, A., Wood, R. G., Rao, P. V., and Fink, R. W., The energy levels in ^{77}As from the decay of 11.3-h ^{77}Ge , (Abstract) Bull. Am. Phys. Soc., Series 2, 13, 248 (1968).
20. McClure, D. A. and Bolotin, H. H., Excited states of As^{77} populated in the 11-h decay of Ge^{77} , (Abstract) Bull. Am. Phys. Soc., Series 2, 13, 118 (1968).
21. Donnelly, D. P., Reidy, J. J., and Wiedenbeck, M. L., A high-resolution gamma-ray spectroscopic study of the decay $^{77}\text{Ge} \rightarrow ^{77}\text{As}$, Nucl. Phys. A112, 145 (1968).
22. Ng, A., Wood, R. E., Palms, J. M., Rao, P. V., and Fink, R. W., Gamma rays from the decay of ^{75}Ge and ^{77}Ge , Phys. Rev. 176, 1329 (1968).
23. Cowart, W. S., Pool, M. L., McCown, D. A., and Woodward, L. L., Artificially radioactive Se^{73} and Se^{75} , Phys. Rev. 73, 1454 (1948).
24. Scott, F. R., The radioactivity of Se^{73} , Phys. Rev. 84, 659 (1951).
25. Hayward, R. W. and Hoppes, D. D., Disintegration of selenium-73, Phys. Rev. 101, 93 (1956).
26. Murray, G., White, W. J. K., Willmott, J. C., and Entwistle, R. F., The decay of ^{73}Se , Nucl. Phys. A130, 563 (1969).

27. Marlow, K. W. and Faas, A., The radioactive decay of ^{73}gSe and ^{73}mSe , Nucl. Phys. A132, 339 (1969).
28. Hooge, F. N. and Aten, A. H. W., Jr., The short-lived neutron-deficient isotope of selenium, Physica 19, 1047 (1953).
29. Rao, P. V. and Fink, R. W., Gamma decay of $\text{Se}^{73\text{m,g}}$ and $\text{Se}^{81\text{m,g}}$ isomeric pairs, Phys. Rev. 154, 1028 (1967).
30. Akhmed, M. P., Baskova, K. A., Vasil'ev, S. S., and Shavtvalov, L. Ya., Study of the radiation of Se^{73} , (Translated title) Yadernaya Fizika 8, 240 (1968). Original not available; translated in Soviet Journal of Nuclear Physics 8, 138 (1969).
31. Schardt, A. W. and Welker, J. P., Energy levels of As^{75} , Phys. Rev. 99, 810 (1955).
32. Kelly, W. H. and Wiedenbeck, M. L., Directional correlation of the gamma rays of La^{140} , Ce^{140} , Pt^{192} , and As^{75} , Phys. Rev. 102, 1130 (1956).
33. van den Bold, H. J., van de Geijn, J., and Endt, P. M., The decay of the nuclides of ^{75}Se and ^{75}Ge , Physica 24, 23 (1958).
34. Robinson, R. L., McGowan, F. K., Stelson, P. H., and Milner, W. T., Coulomb excitation of ^{75}As , Nucl. Phys. A104, 401 (1967).
35. Rao, P. V., McDaniels, D. K., and Craseman, B., Decay of ^{75}Se , Nucl. Phys. 81, 296 (1966).
36. Nagpal, T. S., Gamma rays following the decay of ^{75}Se , Nucl. Phys. A121, 176 (1968).
37. Schwarzschild, A. Z., and Warburton, E. K., The measurement of short nuclear lifetimes, Ann. Rev. Nucl. Sci. 18, 265 (1968).
38. Lederer, C. M., Hollander, J. M., and Perlman, I., Table of isotopes, 6th ed. (John Wiley and Sons, Inc., New York, N.Y., c1967).
39. Schwarzschild, A. Z., A survey of the latest developments in delayed coincidence measurements, Nucl. Instr. Methods 21, 1 (1963).

40. Scarborough, J. B., Numerical mathematical analysis, 2nd ed. (John Hopkins Press, Baltimore, Md., 1950).
41. Turner, C. E., Jr. and Anderl, R. A., Complex delayed-coincidence distributions; maximum-likelihood analysis with numerical convolution integration, development. Unpublished manuscript. Department of Physics, Iowa State University of Science and Technology, Ames, Iowa, 1970.
42. Bevington, P. R., Data reduction and error analysis for the physical sciences (McGraw-Hill Book Co., New York, N.Y., c1969).
43. Moszkowski, S. A., Theory of multipole radiation, in Siegbahn, K., ed., Alpha-, beta- and gamma-ray spectroscopy, Vol. 2, pp. 863-886 (North-Holland Publishing Co., Amsterdam, 1965).
44. Bureau, A. J. and Hammer, C. L., Procedure for making intense sources in an electron synchrotron, Rev. Sci. Instr. 32, 93 (1961).
45. Gunnick, R., Niday, J. B., Anderson, R. P., and Meyer, R. A., Gamma-ray energies and intensities, Lawrence Radiation Laboratory Report UCID-15439 (Lawrence Radiation Laboratory, Livermore, California, 1969).
46. Gedcke, D. A. and McDonald, W. J., A constant fraction of pulse height trigger for optimum time resolution, Nucl. Instr. Methods 55, 377 (1967).
47. Gedcke, D. A. and McDonald, W. J., Design of the constant fraction of pulse height trigger for optimum time resolution, Nucl. Instr. Methods 58, 253 (1968).
48. Larsen, J. T., Gamma ray decay schemes for ^{142}Xe , ^{142}Cs , ^{142}Ba , ^{142}La . Unpublished Ph.D. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. 1970.
49. Camp, D. C., Energy levels in ^{72}Ge from the decays of ^{72}Ga and ^{72}As , Nucl. Phys. A121, 561 (1968).
50. Hager, R. S. and Seltzer, E. C., Internal conversion tables, part 1: K-, L-, M-shell conversion coefficients for $Z = 30$ to $Z = 103$, Nuclear Data A4, 1 (1968).
51. Lyon, W. S. and Eldridge, J. S., Radioactive Ge^{77} and $\text{Ge}^{77\text{m}}$, Phys. Rev. 107, 1056 (1957).

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