Gamma Rays from the Decay of ^{75}Ge and ^{77}Ge†

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(Received 30 July 1968)

γ spectra from the decay of 82.2-min ^{75}Ge and 11.3-h ^{77}Ge have been studied with several sizes of high-resolution Ge(Li) detectors by singles and coincidence methods. Energies and relative intensities of 7 transitions in the decay of ^{75}Ge and 67 transitions in ^{77}Ge decay have been determined. The transitions in the decay of ^{75}Ge are placed in a level scheme of ^{75}As consisting of levels at 199.2, 264.7, 468.7, and 617.8 keV. All 67 transitions in the ^{77}Ge decay are placed in a level scheme of ^{77}As with levels at 215.6, 264.4, 475.4, 632.0, 634, 795.6, 1077.4, 1094.0, 1190.3, 1214.9, 1319.7, 1339.0, 1378.2, 1384, 1399.5, 1458.3, 1494.7, 1528.4, 1539.2, 1560.8, 1573.3, 1863.9, 2000.3, 2104.9, 2110.9, 2202.2, 2244.8, 2301.7, 2342.0, 2353.4, 2436.6, and 2513.6 keV.

I. INTRODUCTION

THERE is, at present, very little information available concerning the low-lying levels of the odd-mass, medium-weight nuclei. There is also no nuclear model that can explain in detail the experimental data that is available. This paper is a high resolution investigation of the low-lying levels of ^{75}As and ^{77}As by studying the decay of 82.2 minutes ^{75}Ge and 11.3 h ^{77}Ge.

II. 11.3 h ^{77}Ge

With a half-life[1] of 11.3 h and a disintegration energy of 2750±50 keV, ^{77}Ge decays to a number of levels[2–8] in ^{77}As. In turn, 39 h ^{77}As undergoes β decay and forms stable ^{77}Se. Smith[2] studied the β spectrum from ^{77}Ge with a magnetic lens spectrometer and also measured the γ-ray spectrum by analyzing photoelectrons ejected from lead and uranium radiators. With a coincidence

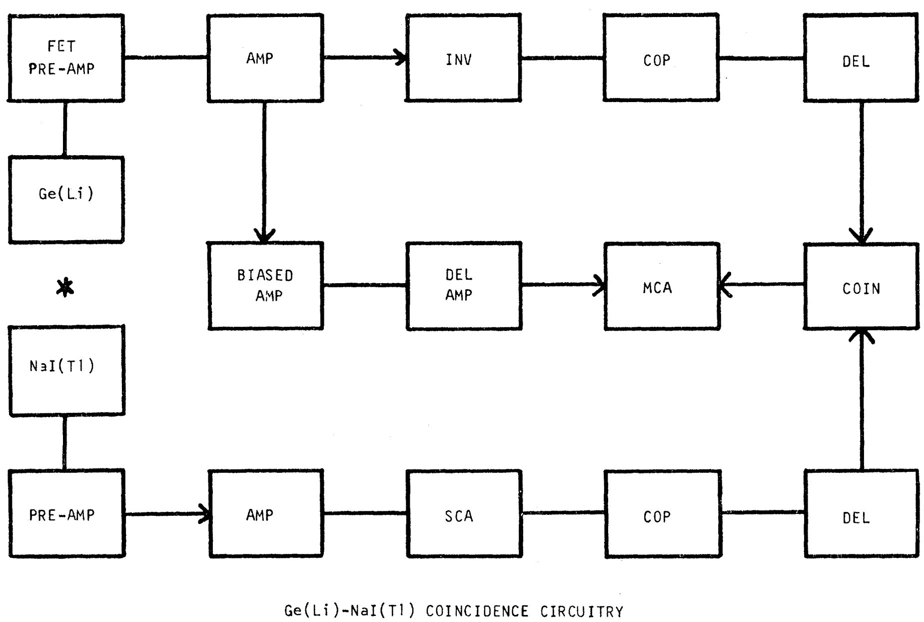

FIG. 1. Block diagram of Ge(Li)-NaI(Tl) coincidence instrumentation.

† Supported in part by the U. S. Atomic Energy Commission through Georgia Tech and the National Institutes of Health through Emory University.
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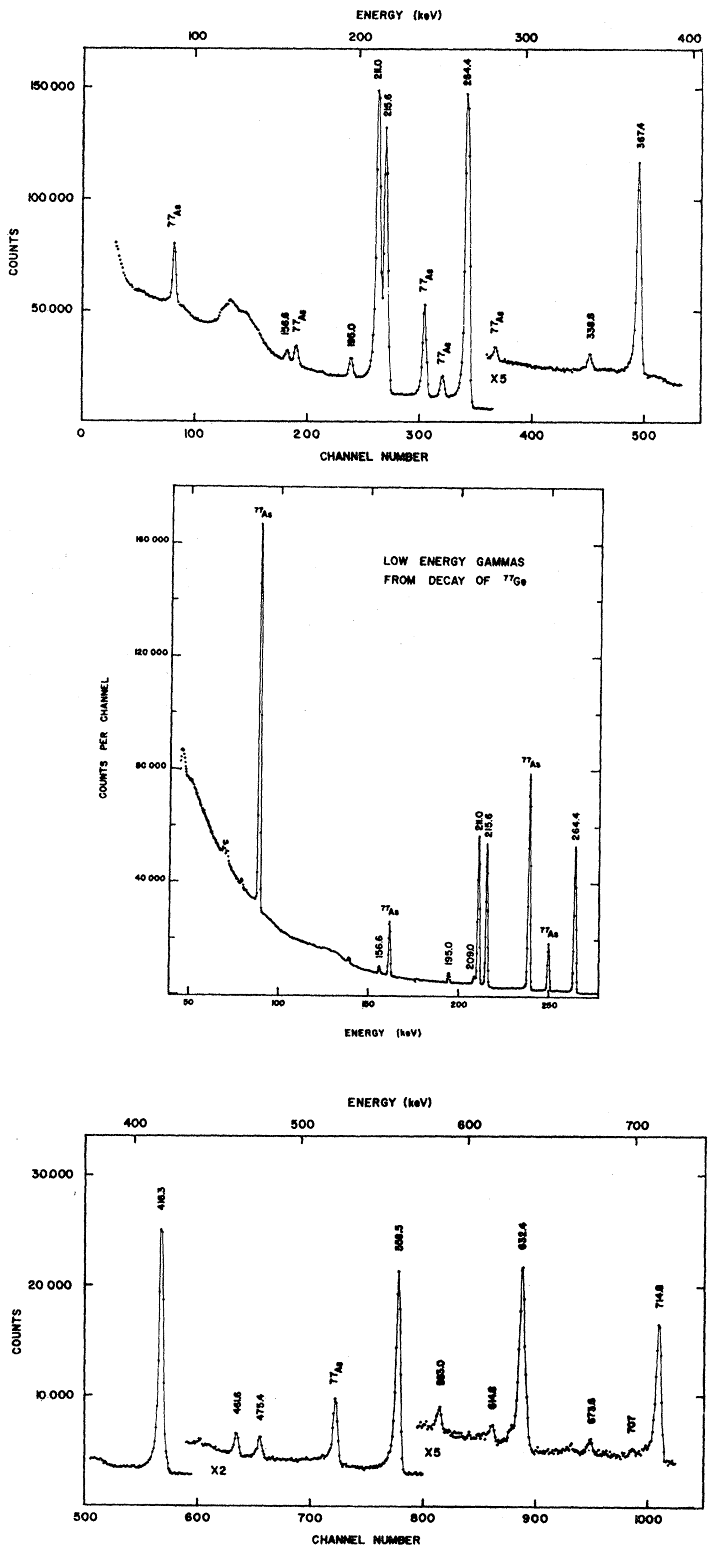

FIG. 2. γ-singles spectra from 11.3-h ^{77}Ge taken with a Ge(Li) detector in the region up to 720 keV.

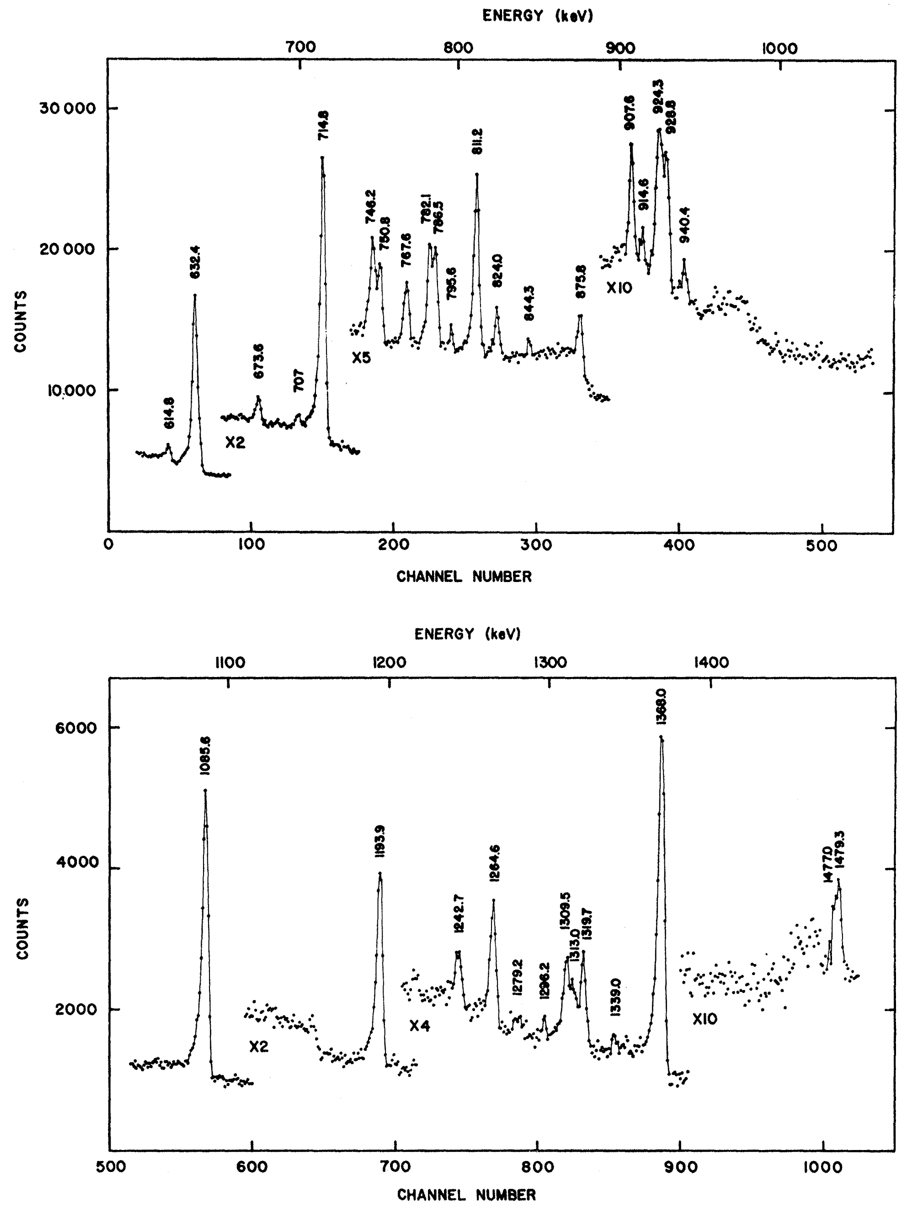

FIG. 3. γ-singles spectra from 11.3-h ^{77}Ge from 610 to 1480 keV.

technique he concluded that there is no direct transition from the ^{77}Ge ground state to the ^{77}As ground state. Subsequent γ studies with NaI(Tl) detectors helped establish a decay scheme.[3]

Burson *et al.*[4] used a NaI(Tl) detector with 8% resolution at 662 keV to analyze the γ spectrum, and also measured γ-γ and β-γ coincidences. They constructed an energy-level diagram for the ^{77}As nucleus which, although now seen to be incomplete, is well substantiated by the more accurate γ-ray energies obtained in the present investigation.

Schardt[5] did delayed coincidences with a single, large, well-type NaI(Tl) detector to study the metastable 475-keV level in ^{77}As and measured its half-life to be 116 μsec. He modified Burson's decay scheme, slightly shifting some energy levels and identifying a few new γ transitions, but essentially left it unchanged.

Martin and Wiedenbeck[6] on the basis of angular-correlation measurements assigned spins and parities to a number of the energy levels.

Van Der Kooi and van den Bold[8] investigated the decay of ^{77}Ge in great detail. They obtained a singles γ spectrum with a NaI crystal with 7.4% resolution at 622 keV. They also obtained a well-type spectrum to investigate sum peaks, a sum-coincidence spectrum of the γ's in coincidence with sums in the interval 2340-2450 keV, a delayed coincidence spectrum similar to Schardt's to investigate the 475-keV metastable state, and a num-

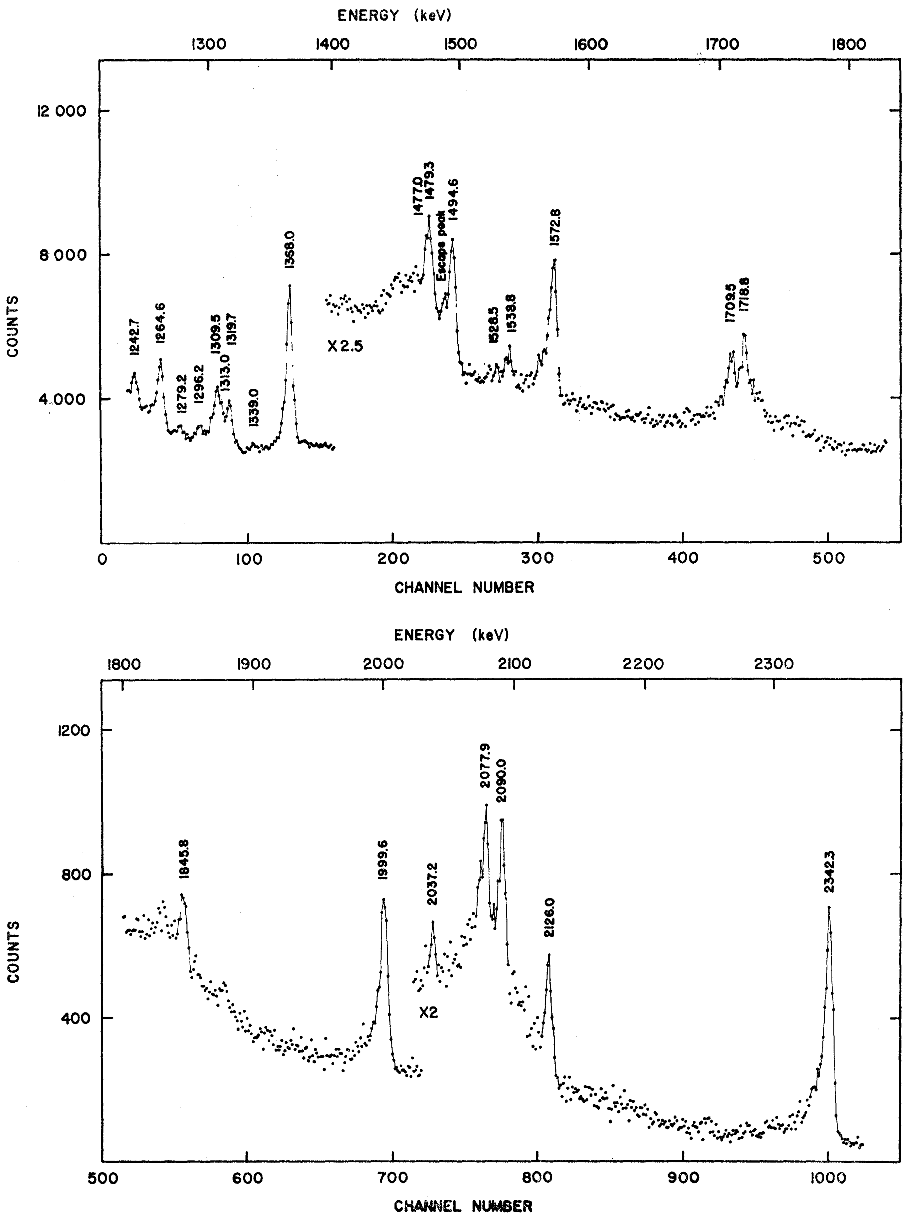

FIG. 4. High-energy γ-singles spectra from 11.3-h ^{77}Ge from 1240 to 2350 keV.

ber of γ-γ coincidence spectra. Finally, they repeated the angular-correlation measurements of Martin and Wiedenbeck.[6] With their data, they constructed a level scheme for ^{77}As which accounted for all the γ's and assigned spins and parities identical to those given by Martin and Wiedenbeck. Aside from being considerably more complex than previous level schemes, to account for their many new weaker γ rays, their level scheme assigned several fairly high-intensity lines to different positions.

Recently several investigators[9–13] investigated the singles γ spectrum from ^{77}Ge with Ge(Li) spectrometers. Many new γ's were observed.

The present investigation also utilizes Ge(Li) detectors and substantiates these as well as other new γ rays observed in Ge(Li)-NaI(Tl) coincidence studies. On the basis of this information a new decay scheme is presented which accounts for all the gammas observed.

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TABLE I. Energies and intensities of γ's in the decay of 11.3-h ^{77}Ge.

E_γ(keV)	Intensity	Initial	Final	E_γ(keV)	Intensity	Initial	Final
156.6	0.95±0.1	632	475	924.3	1.9 ±0.4	1399	475
195.0	2.9 ±0.1	1384	1190	926	1.2 ±0.4	1190	264
209.0	2.9 ±0.2	1399	1190	928.8	1.9 ±0.4	1561	632
211.0	50.0 ±3.0	475	264	940.4	0.4 ±0.1	1573	632
215.6	47.7 ±3.0	216	0	952	0.08±0.02	2514	1561
264.4	100	264	0	1085.6	11.7 ±0.9	1561	475
338.3	12.0 ±0.5	1528	1190	1152	0.2 ±0.1	2342	1190
367.4	31.0 ±0.3	632	264	1193.9	4.9 ±0.4	1458	264
416.3	49.0 ±4.0	632	216	1215.2	0.3 ±0.1	1215	0
419	<1.8	1215	796	1242.7	0.69±0.14	1458	216
440	0.8 ±0.2	2000	1561	1264.6	1.2 ±0.2	1528	264
461.6	2.8 ±0.3	1094	632	1279.2	0.24±0.12	1495	216
475.4	2.7 ±0.3	475	0	1296.2	0.28±0.07	1561	264
558.5	34.0 ±3.0	1190	632	1309.5	0.76±0.15	1573	264
583.0	1.7 ±0.3	2111	1528	1313.0	0.64±0.25	1528	216
614.8	1.3 ±0.2	2000	1384	1319.7	0.70±0.20	1320	0
632.4	19.0 ±2.0	632	0	1339.0	0.18±0.09	1339	0
634	3.2 ±0.3	634	0	1368.0	5.1 ±0.05	2000	632
673.6	1.4 ±0.3	1864	1190	1477.0	0.23±0.1	2111	634
707	0.6 ±0.1	1339	632	1479.3	0.38±0.09	2111	632
714.8	16.0 ±3.0	1190	475	1494.6	0.65±0.13	1495	0
746.2	3.0 ±0.4	1378	632	1528.5	0.09±0.03	1528	0
750.8	1.8 ±0.4	1384	632	1538.8	0.19±0.04	1539	0
767.6	1.5 ±0.4	2342	1573	1572.8	1.2 ±0.2	1573	0
782.1	2.4 ±0.5	2342	1561	1709.5	0.57±0.17	2342	632
786.5	1.5 ±0.3	2245	1458	1718.8	<0.80	2514	796
795.6	0.4 ±0.1	796	0	1845.8	0.14±0.03	2111	264
811.2	4.6 ±0.5	2000	1190	1999.6	0.91±0.09	2000	0
813	0.1 ±0.07	1077	264	2037.3	0.10±0.04	2302	264
824.0	1.0 ±0.2	2202	1378	2077.9	0.56±0.17	2342	264
844.3	0.19±0.04	1320	475	2090.0	0.48±0.14	2353	264
875.8	1.9 ±0.2	2437	1561	2126.0	0.28±0.08	2342	216
907.6	1.1 ±0.4	1539	632	2342.3	0.79±0.09	2342	0
914.6	0.6 ±0.2	2105	1190				

A. Procedure

Sources were prepared by irradiating natural germanium having less than 1 ppm impurity content, for 6 min with a thermal neutron flux of $(0.9\pm0.1)\times10^{13}$ n/cm^2 sec in the Research Reactor of the Georgia Institute of Technology.

Both ^{75}Ge and ^{77}Ge formed in the irradiation are unstable against β decay, ^{75}Ge having an 82.2-min and ^{77}Ge having an 11.3-h half-life, and both emit γ's after forming excited states of ^{75}As and ^{77}As, respectively. The ^{77}Ge daughter, 39-h ^{77}As, undergoes β decay to stable ^{77}Se, emitting γ's characteristic of the excited states of ^{77}Se (Ref. 14).

High-resolution γ-ray singles measurements were carried out using several Ge(Li) detectors having volumes of 0.2, 4, 10, and 16 cc. The small 0.2-cc detector had an ultra-high resolution (FWHM of 470 eV at 14 keV,

TABLE II. Coincidence relationship observed in the decay of ^{77}Ge.

γ-ray energy selected as the gate in NaI(Tl) (keV)	Coincident γ-ray energy (keV)
195	216, 416, 632, 715
215	416, 558, 768, 782, 811, 908, 929, 1243, 1313, 1368, 2125
264	195, 211, 338, 367, 558, 811, 813, 926, 1194, 1265, 1296, 1309, 1368, 1709, 2078, 2090
367	264, 338, 462, 558, 707, 751, 768, 782, 811, 908, 929, 1368, 1478
416	195, 216, 338, 462, 558, 583, 746, 751, 782, 811, 908, 929, 940, 1368, 1478
558	157, 216, 264, 338, 367, 416, 583, 632, 673, 811, 915, 1152
632	338, 462, 558, 767, 811, 824, 908, 929, 940, 1368, 1478
1086	440, 876, 952, 782
1194	264, 786

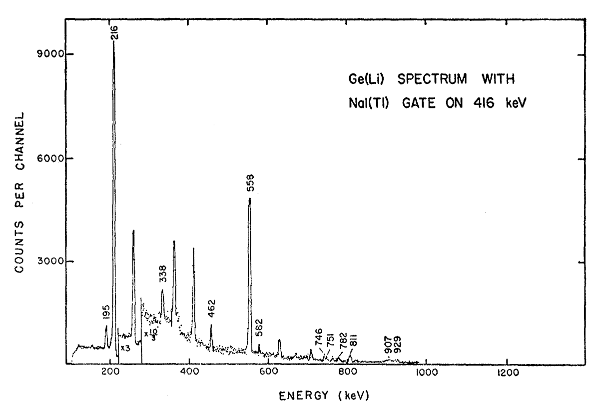

FIG. 5. ^{77}Ge γ-ray spectrum in coincidence with the 416-keV γ ray.

[14] A. Antna, Nucl. Data **B1**, 77 (1966).

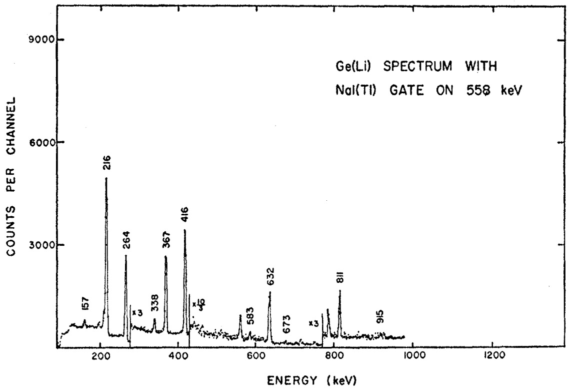

FIG. 6. ^{77}Ge γ-ray spectrum in coincidence with the 558-keV γ ray.

and 1.7 keV at 1332 keV). The characteristics of this detector will be published.[15] A charge sensitive FET preamplifier whose first stage was cooled was used with the small detector. The preamplifier signals were further amplified and treated with a Tennelec TC 200 amplifier and TC 250 biased amplifier and stretcher. The output of the biased amplifier was fed into a TMC 1024-channel pulse-height analyzer.

Representative data were taken with a channel-energy resolution of from 0.10 to 1.53 keV per channel. The resolution was limited primarily by the inherent noise characteristic of the detector used. High-resolution coincidence measurements were also made with a Ge(Li)-NaI(Tl) coincidence system. A block diagram of the electronic system is shown in Fig. 1.

The γ spectra were analyzed to determine the energy and intensity of the individual transitions by fitting the γ energy peak with a skewed Gaussian. The energy calibration and photopeak efficiency of the detectors were obtained with a set of calibrated standard sources obtained from the International Atomic Energy Agency, Vienna. Calibrated γ's from ^{57}Co, ^{203}Hg, ^{22}Na, ^{137}Cs, ^{54}Mn, ^{88}Y, and ^{60}Co were used. For higher γ-ray energies, ^{24}Na was used. The error in the relative photopeak efficiency is 5%.

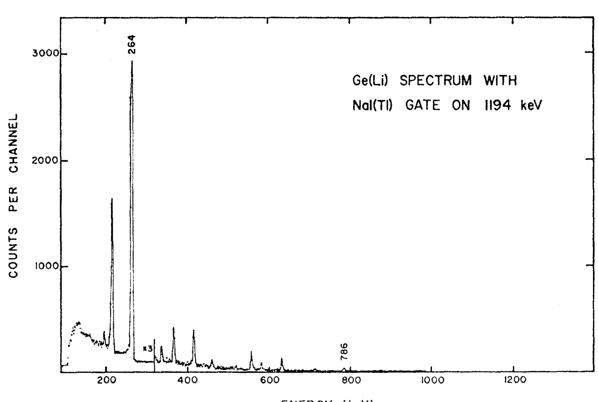

FIG 7. ^{77}Ge γ-ray spectrum in coincidence with the 1194-keV γ ray.

Absorbers consisting of 0.51 cm of lead followed by 0.10 cm of cadmium and 0.03 cm of copper were used to cut down the counting rate at the low-energy end of some of the spectra. Absorption corrections were made for these. In every case, the γ-ray absorption coefficients used were those calculated by Wapstra, Nijgh and van Lieshout.[16] The intensities were obtained by calculating the full energy-peak areas with the same fitting technique used to determine the detector efficiency.

Errors in determining intensities of γ rays arise mainly from uncertainties in estimating the continuum. Errors in γ energies are estimated to be ± 0.5 keV, except for very weak transitions where the uncertainty is somewhat greater. The values quoted for relative intensities and energies are averages obtained from several spectra.

B. Results

1. *γ-Ray Energies and Intensities*

The γ's observed from the decay of ^{77}Ge are shown in Figs. 2–4. All the spectra shown were taken with Ge(Li) detectors. In addition several peaks are shown which arise from 39 h ^{77}As, and all the energies of these γ's agree with the recent published energies.

The energies and intensities and initial and final states of the transitions from ^{77}Ge are listed in Table I. Overall, the energies and intensities compare favorably with those of other recent investigations.[9,11–13]

The results of the Ge(Li)-NaI(Tl) coincidence measurements are listed in Table II. Coincidence γ's were observed in the Ge(Li) detector with the NaI(Tl) detector selecting the following γ-ray gates: 195–215, 264, 367, 416, 558, 632, 1086, and 1194 keV. The following γ's were only observed in coincidence measurements: 440, 707, and 952 keV. Figures 5–7 show typical coincidence spectra with the NaI(Tl) gate at 416, 558, and 1194 keV. The poor resolution of the NaI(Tl) detector and the therefore wide gate which is used, cause many Compton coincidences to show up in the spectra. Careful relative intensity observations were made to determine the real coincidence γ's. Only the true coincidences shown in the figures are labeled with the appropriate energies.

2. *^{77}Ge Decay Scheme*

A proposed decay scheme based on the results given in Tables I and II is shown in Fig. 8 and accounts for all the 67 observed γ rays. The levels at 215.6, 264.4, 475.4, 632.0, 1190.3, 1458.3, 1560.8, 2000.3, and 2342.0 keV have been previously established by γ-ray singles and γ-γ coincidence data[5–7] and are confirmed by the

[15] J. M. Palms, P. Venugopala Rao, and R. E. Wood, Nucl. Instr. Methods (to be published).

[16] A. H. Wapstra, C. J. Nijgh, and R. van Lieshout, *Nuclear Spectroscopy Tables* (Interscience Publishers, Inc., New York, 1959), p. 67.

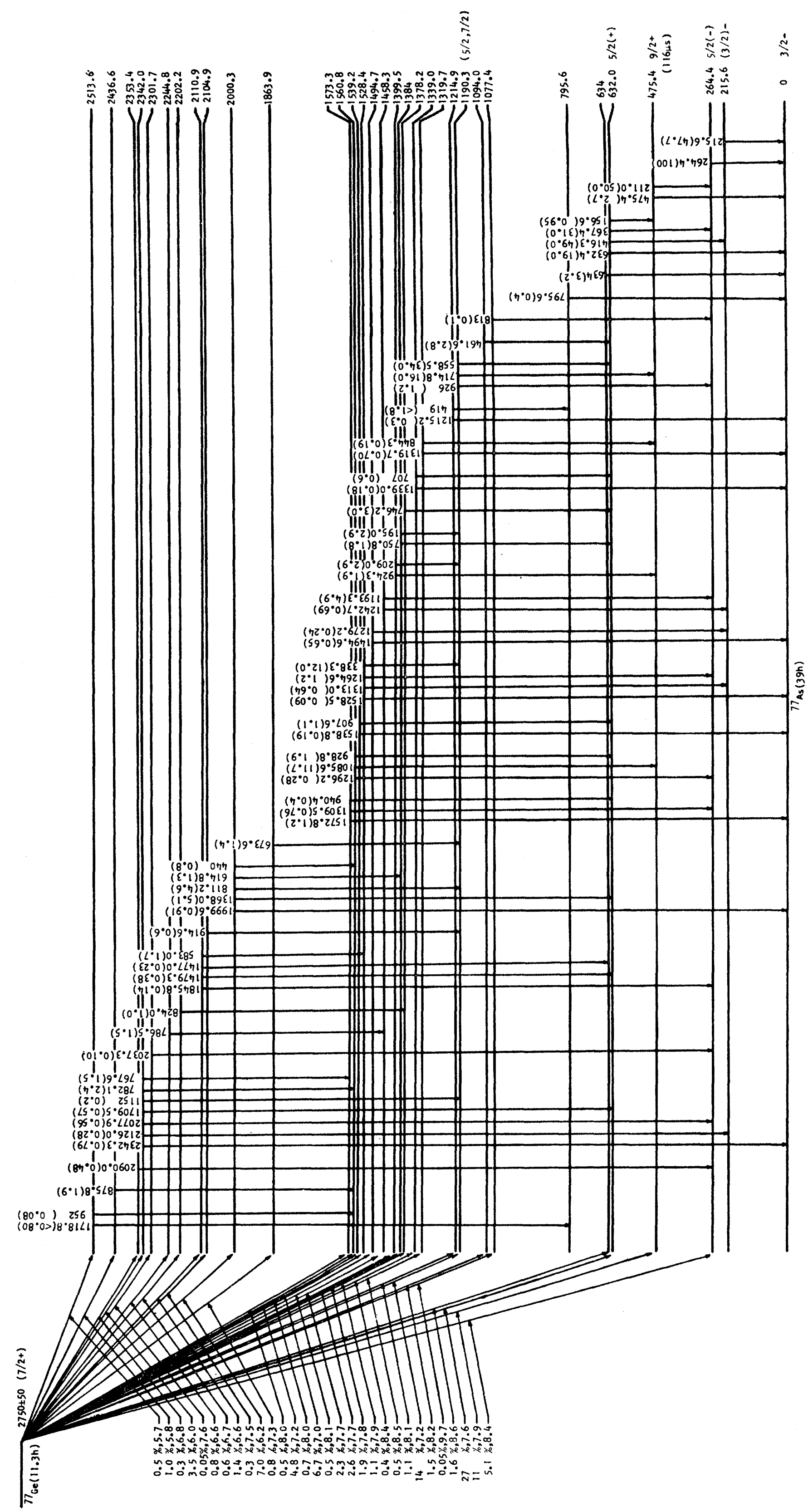

FIG. 8. Proposed decay scheme for 11.3-h ^{77}Ge. Observed γ relative intensities are shown in parentheses after the energies in keV.

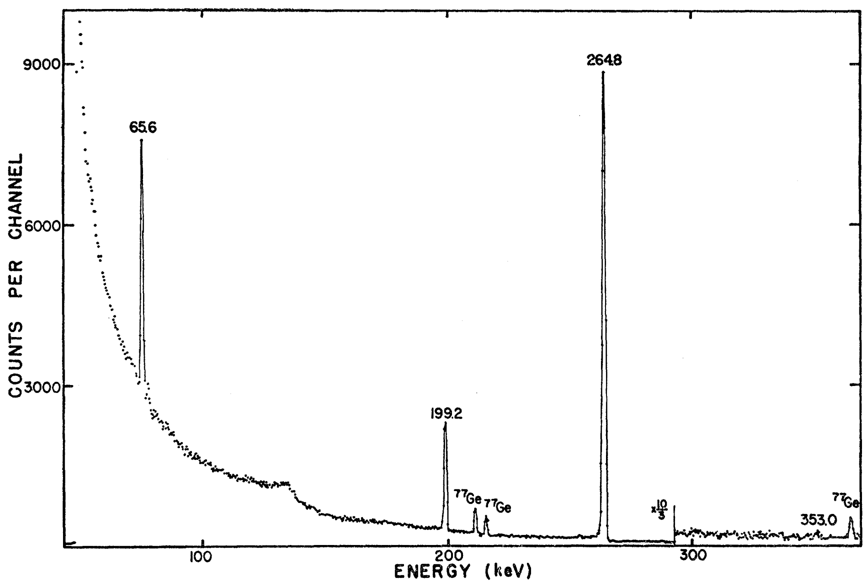

FIG. 9. γ-singles spectra from 82.2-min ^{75}Ge from 60 to 360 keV.

same data here. The spin and parity assignments of the lower-lying levels are taken from Ref. 8. The levels at 1319.7, 1384, 1399.5, 1539.2, 2110.9, 2301.7, and 2513.6 keV have been previously proposed by Donnelly *et al.*[13] on the basis of singles energy and intensity measurements and are here confirmed by γ-γ coincidences. Other levels proposed as the result of this study are at 634, 795.6, 1077.4, 1094.0, 1214.9, 1339.0, 1378.2, 1494.7 1528.4, 1573.3, 1863.9, 2104.9, 2202.2, 2244.8, 2353.4, and 2436.6 keV. The proposed decay scheme explains all of the prominent features of the coincidence spectra presented in Ref. 8, albeit not necessarily explained the same way. The following discussion is concerned only with those levels not previously confirmed by coincidence data in Ref. 5–7.

The new levels for which there is strong support on the basis of coincidence data are those at 1378.2, 1384, 1528.4, 1539.2, 1573.3, and 2110.9 keV. For each of these levels there are at least two strong coincidences supporting the level's existence.

The following levels have only one γ ray in coincidence to explain their position: 1077.4, 1094.0, 1339.0, 1863.9, 2104.9, 2202.2, 2244.8, 2436.6, and 2513.6 keV.

The next levels do not have any coincidence evidence

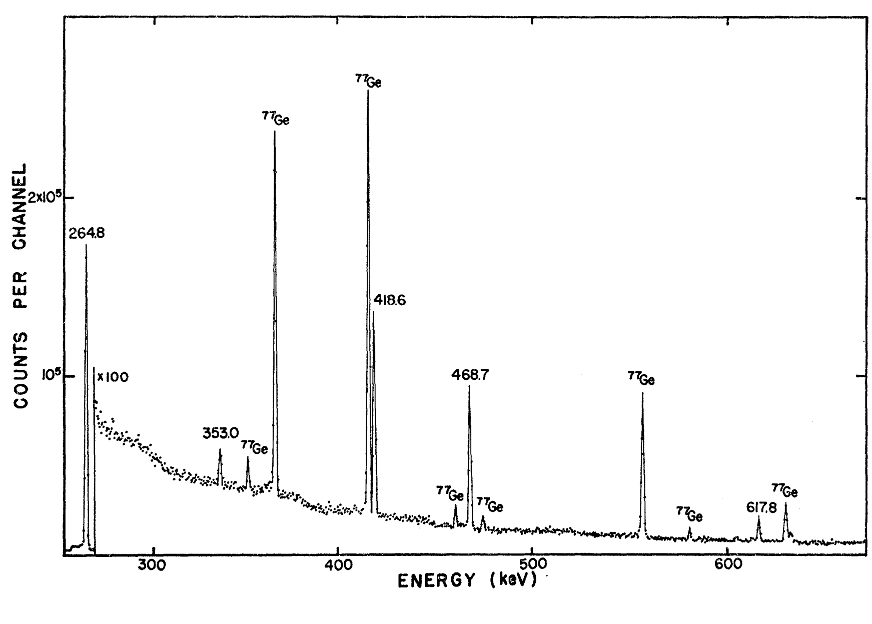

FIG. 10. γ-singles spectra from 82.2-min ^{75}Ge from 265 to 650 keV.

to substantiate their existence but are placed strictly on the basis of single γ-ray energies and intensities. The evidence for these levels is therefore quite weak. The levels are at 634, 795.6, 1214.9, 1319.7, 1399.5, 1494.7, and 2301.7 keV.

Log ft and β branching based on the γ-ray-transition intensity values are presented in Fig. 8. The intensity balance for the various transitions in the present decay scheme is very satisfactory except for two discrepancies. The total intensity of γ's populating the 795.6-keV level is 1.8, whereas the intensity of the 795.6-keV γ depopulating the level is only 0.4. Also, the total intensity of γ's populating the 215.6-keV level is 50.8, whereas the intensity of the 215.6-keV γ depopulating the 215.6-keV level is 47.7. In light of the spin assignments and transition energy, it is not possible to explain this imbalance by internal conversion.

This decay scheme differs greatly from the one proposed by van der Kooi and van den Bold. On the basis of the higher resolution of the γ-ray energies, many of van der Kooi and van der Bold's new levels must be rejected, because the γ transitions involved are now seen to be nonexistent, or to have energies which simply do not fit.

The agreement with the level scheme proposed by Donnelly[13] is somewhat better. There is agreement with 16 of the 28 levels proposed by Donnelly. There is no conclusive evidence, however, for the levels Donnelly proposes at 459.6, 461.4, 613.6, 784.9, 875.3, 914.2, 1202.7, 1280.6, 1479.9, 1717.4, 1719.7, and 2143.7 keV.

C. Discussion

The spins of the low-lying levels of ^{77}As have been tentatively assigned,[5–7] however, there is at present very little detailed information available concerning the low-lying levels of the odd-mass, medium-weight nuclei, so that any view of a systematic behavior of the nuclear properties is not possible. In a recent paper Robinson *et al.*[17] discussed their Coulomb excitation studies of a limited group of odd-proton nuclei with ground-state spin $\frac{3}{2}$, ^{63}Cu, ^{65}Cu, ^{75}As, and ^{79}Br and indicated the level structure similarities. In each one of these nuclei there is a spin-$\frac{7}{2}$ state at approximately 1.1 to 1.4 times the 2^+ state in the neighboring even-mass nucleus which

TABLE III. γ rays from the decay of ^{75}Ge.

E_γ(keV)	Intensity	Initial	Final
65.6±0.8	0.89±0.12	264.7	199.2
199.2±0.5	7.48±0.3	199.2	0
264.8±0.2	100	264.8	0
353.0±0.8	0.196±0.02	617.8	264.8
418.6±0.5	2.47±0.12	617.8	199.2
468.7±0.5	1.81±0.09	468.7	0
617.8±0.8	0.503±0.04	617.8	0

[17] R. L. Robinson, F. K. McGowan, P. H. Stelson, and W. T. Milner, Nucl. Phys. **A104**, 401 (1967).

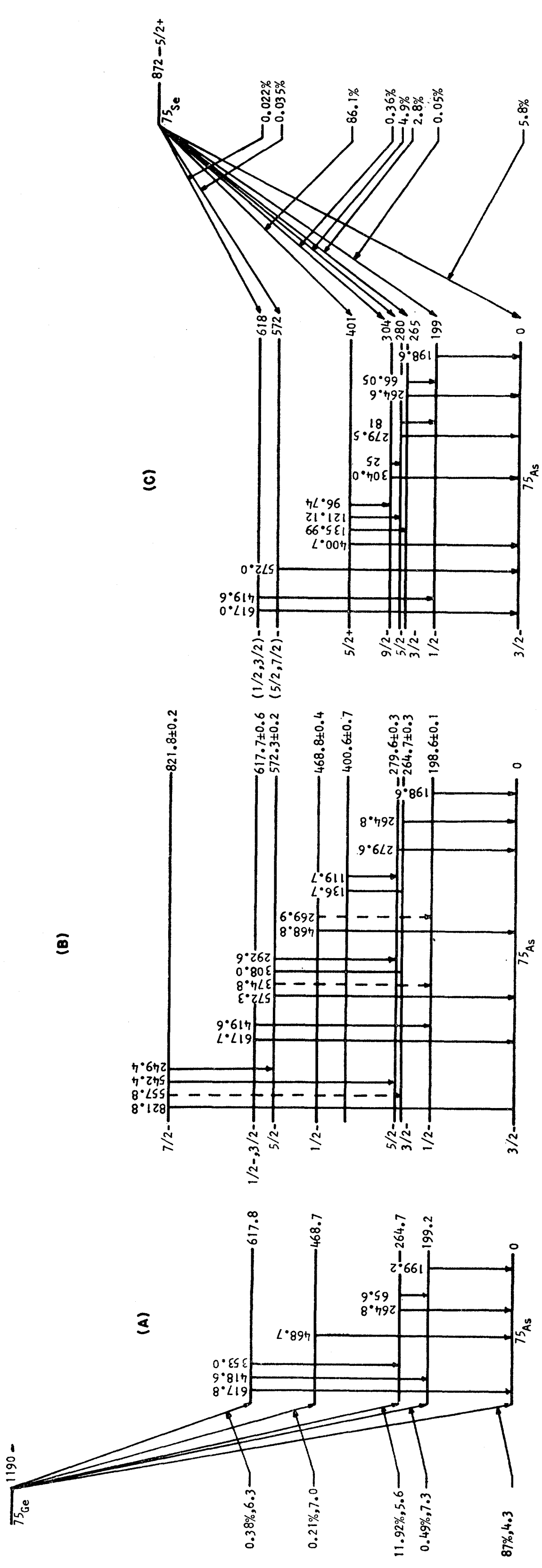

FIG. 11. Level structure for ^{75}As. The three schemes are conclusions drawn from the following studies: (A) decay of ^{75}Ge; (B) Coulomb excitation; (C) electron capture in ^{75}Se (Ref. 23).

has one less proton. The energy of the 2^+ state in ^{76}Ge is 563 keV,[18] so if a spin-$\frac{7}{2}$ level were present in ^{77}As then it should lie between 620 and 790 keV. There are two possible levels (634 and 795.6 keV) in our decay scheme.

Robinson *et al.*[17] and Donnelly[13] also discuss a possible triplet of low-lying levels in ^{75}As and ^{79}Br with probable spins $\frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$. Donnelly suggested the possibility of a 338.5-keV unplaced γ being a ground-state transition. A level at this energy along with the levels at 215.6 and 264.4 keV would constitute the triplet. A γ-ray at 338.3 keV is seen by us but is substantiated by many coincidences to be a transition between the 1528.4 and 1190.3-keV levels. There is no further evidence for a level to complete this triplet.

As has been pointed out[13,17] no nuclear model has as yet been able to predict in detail even the limited number of measured properties. A model which has had a limited amount of success has been the single-particle coupling model. In its simplest form the ground state of ^{77}As is a result of the coupling of a $p_{3/2}$ proton to the ground state of ^{76}Ge. Four excited states with spins $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ would result from a coupling of this single proton to the 2^+ core state. The model also predicts that the energy of the four members of this multiplet, weighted according to their spins, equals that of the 2^+ state in ^{76}Ge. Three members of this multiplet could be 215.6, 264.4, and either 634 or 795.6 keV. A fourth member is not evident here. Without more experimental data comparisons with model predictions are limited.

III. 82.2-MIN ^{75}Ge

The decay of 82.2-min ^{75}Ge has been studied by several authors,[19–22] and a decay scheme has been well established. The purpose of the present study was to make further investigations with the aid of high-resolution Ge(Li) detectors. Pure germanium was irradiated with neutrons in the Georgia Tech reactor. The γ spectrum was studied with Ge(Li) detectors as described above. Typical low-energy spectra are shown in Figs. 9 and 10, and the energies and intensities of the observed γ's are summarized in Table III. The results agree well with previous studies except for a new γ ray at 353.0 keV, which is the transition from the 617.8- to 264.7-keV level and has not previously been observed.

The level structure of ^{75}As as determined by this study is shown in Fig. 11 along with the conclusions drawn from Coulomb excitation studies[17] of ^{75}As, and an investigation of the decay of ^{75}Se as reported by Rao *et al.*[23] For the decay of ^{75}Ge the calculated percentages of the β transitions and the resulting log ft values are indicated in the figure. The level structure of ^{75}As as determined here agrees very well with the previous studies.

ACKNOWLEDGMENTS

We are indebted to Milton McClain for irradiations in the Georgia Tech reactor. One of us (PVR) wishes to acknowledge financial support under National Aeronautics and Space Administration Grant No. NsG-657 through the Georgia Institute of Technology. We would also like to thank B. K. Tanner and L. A. Rauber for assisting in the analysis of the data.

[18] *Nuclear Data Sheets*, edited by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D.C.).
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