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Level Scheme of Ga^{69}[†]

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The gamma-ray spectrum from the decay of Ga^{69} has been studied with the aid of a lithium-drifted germanium detector. Gamma rays of energy 2023, 1922, 1893, 1576, 1525, 1349, 1335, 1206, 1107.2, 1052, 871.8, 788, 763, 587, 573.4, 553, 532, 511, 320, and 237 keV have been observed. A new level scheme consistent with gamma-gamma coincidence measurements is presented for Ga^{69}. The experimental results are compared with a calculation of the energy levels in Ga^{69} based on the intermediate-coupling model.

I. INTRODUCTION

SEVERAL attempts have been made to understand the structure of odd-A nuclei with $28\leq Z$, $N\leq 50$ using an intermediate-coupling approach.[1–4] These efforts are hampered by a lack of experimental information in this "intermediate" region. In the work reported here, the level scheme of Ga^{69} was precisely determined with the aid of a lithium-drifted germanium detector.[5] The experimental results were then compared with calculations based on the intermediate-coupling model, first proposed by Bohr and Mottelson.[6]

The beta decay of Ge^{69} to Ga^{69} has been studied by several groups.[7–9] Huddleston and Smith[7] observed positrons with end-point energies of 220, 616, and 1215 keV, and gamma rays with energies 388, 576, 870, 1120, 1340, and 1610 keV. A more detailed investigation, including measurement of positron spectra, gamma-ray spectra, and gamma-gamma coincidences, was carried out by Nussbaum and Suri.[8] Gamma rays of 2000, 1890, (1730), 1530, 1340, 1120, 880, (800), 576, and 320 keV were observed. They also found positron spectra with end-point energies of 1220 and 620 keV and measured the half-life of Ge^{69} to be 40.4 ± 0.3 h. Schwerdtfeger, Ramayya, and Mitchell[9] have investigated the decay of Ge^{69} using modern equipment to observe both single and coincident events. They detected gamma rays having energies of 2040, 1910, 1560, 1355, 1220, 1120, 1065, 880, 800, 770, 576, 420, 323, and 240 keV, and verified the observations of Huddleston and Smith on positron energies. Their measurement of the half-life of Ge^{69} gave $\tau_{1/2}=38.5\pm0.5$ h. Because of the large number of gamma rays present and the low intensity of coincident events, decay schemes constructed from the above observations were of questionable accuracy. In particular, the existence of several levels was inferred from weak gamma rays which were identified only after large corrections had been made to the singles and coincidence spectra.

Fagg, Geer, and Wolicki[10] observed a ground-state transition of 0.322 MeV from Ga^{69} upon bombardment of natural metallic gallium with alpha particles. Using a pulsed-beam technique, Holland, Lynch, and Shipley[11] measured the mean life of this state to be <0.1 nsec.

The spin of the ground state of Ga^{69} has been found to be $\frac{3}{2}$ from measurements of hyperfine structure of line spectra.[12] Nuclear-magnetic-resonance studies gave $\mu=+2.0161$ nm for the magnetic dipole moment of the ground state.[13] From atomic-beam measurements the electric quadrupole and magnetic octupole moments were found to be $Q=+0.190$ b[14] and $\Omega=+0.137$ nmb,[15] respectively. The parity of the ground state is assumed negative on the basis of shell-model considerations.

In the work reported here, the level scheme of Ga^{69} was clarified by using a lithium-drifted germanium detector to obtain a precise singles gamma-ray spectrum for the decay of Ge^{69} and by using scintillation spectrometers to measure gamma-ray coincidences.

II. SOURCE PREPARATION

Ge^{69} was produced via the Ga$^{69}(d,2n)$Ge^{69} reaction by bombarding 99.9999% pure natural Ga$_2$O$_3$ powder with deuterons from the University of Washington cyclotron. The deuterons, normally 21 MeV, were degraded to 12 MeV by inserting 0.038 cm of steel in front of the target in order to prevent the production of radioactive Ge^{68}. The total integrated beam current used in each bombardment was about 70 μAh. The maximum beam amplitude which could be tolerated was about 23 μA.

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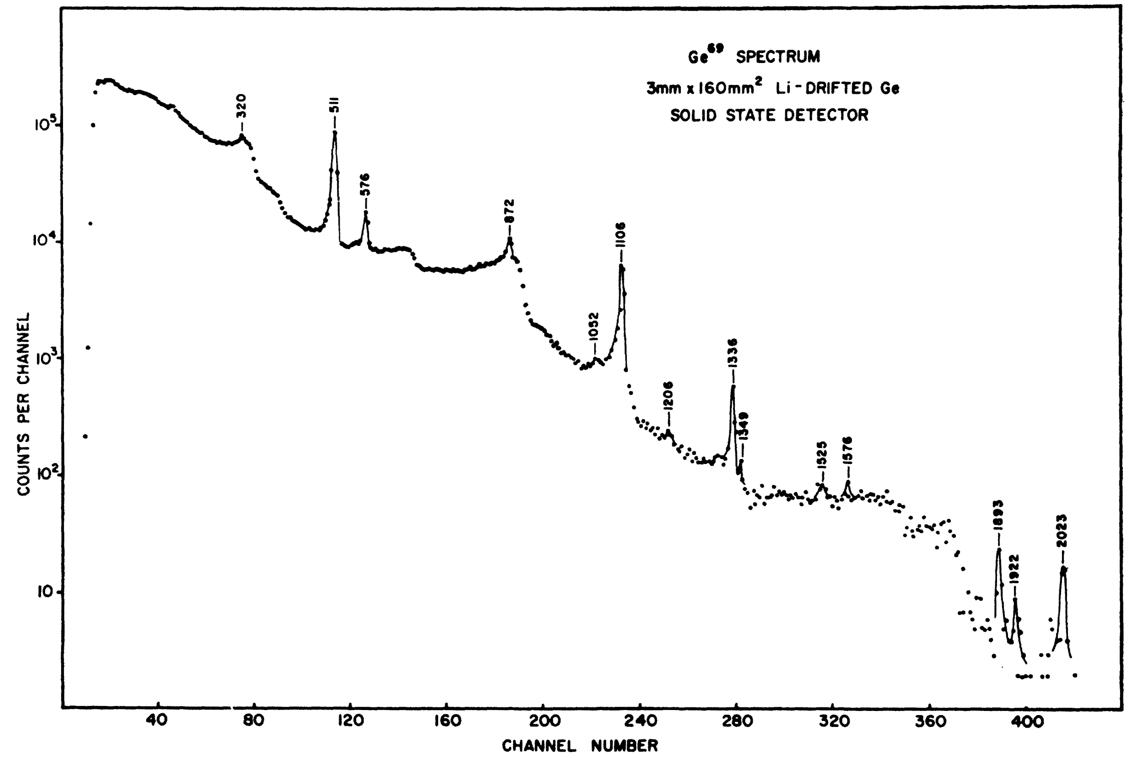

FIG. 1. Typical spectrum taken with the lithium-drifted germanium detector of the gamma transitions in Ga^{69}. Because of the compressed scale many of the weaker gamma lines are not evident.

The germanium was chemically separated from the gallium and the other reaction products by distillation of $GeCl_4$. The only activity other than Ge^{69} present in the separated sources was Ge^{71}, which decays[16] by electron capture with no gamma radiation and hence did not interfere with the measurements.

III. THE GAMMA-RAY SPECTRUM

The gamma-ray spectrum of Ge^{69} was observed using a lithium-drifted germanium detector of 3 mm depletion depth and 160 mm² sensitive area. The pulses from the detector were amplified using a low-noise amplifier system,[17] and were stored in a 512-channel pulse-height analyzer. For runs of short duration ($\lesssim 5$ h) the resolution of the system was 3.9 keV. For longer runs the peak width broadened to about 5 keV due to amplifier drifts. The spectrometer was calibrated with nuclides whose gamma-ray energies are well-known. The sources used for this purpose were Co^{57}(122 keV),[16] Cr^{51}(319.8 keV),[18] Na^{22}(510.976 keV,[19] 1274.6 keV[18]), Bi^{207}(569.7,[20,21] 1063.9 keV[22]), Cs^{137}(661.65 keV),[22,23] Mn^{54}(835.0 keV),[18] Y^{88}(897.5,[24] 1836.2 keV[18]), and Co^{60}(1172.8, 1332.6 keV).[22,23] The axially mounted source, in the form of a disk 1 cm in diameter, was sandwiched between two pieces of 0.6-cm-thick Lucite in order to ensure total annihilation of the positrons. Each of the spectra presented required the accumulation of data for about 36 h.

A typical spectrum covering the entire energy range observed is shown in Fig. 1. All of the peaks represent gamma rays since, for the small angle subtended by the source at the detector in our experiment, the possibility that some of the peaks may be due to accidental summing of coincident gamma rays in the detector is negligible. For purposes of comparison a typical gamma-ray spectrum obtained with a 3-in. by 3-in. NaI(Tl) crystal is shown in Fig. 2. The energies marked at points where no peaks are obvious represent gamma rays which were observed in the coincidence work or which became apparent when the spectrum was unfolded. The energies are those deduced from the germanium-detector data.

In Figs. 3–7 are shown spectra of segments of the

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[16] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C.), NRC 59-2-43.

[17] Ortec Model 101 Pre-Amp, Ortec Model 201 Amplifier.

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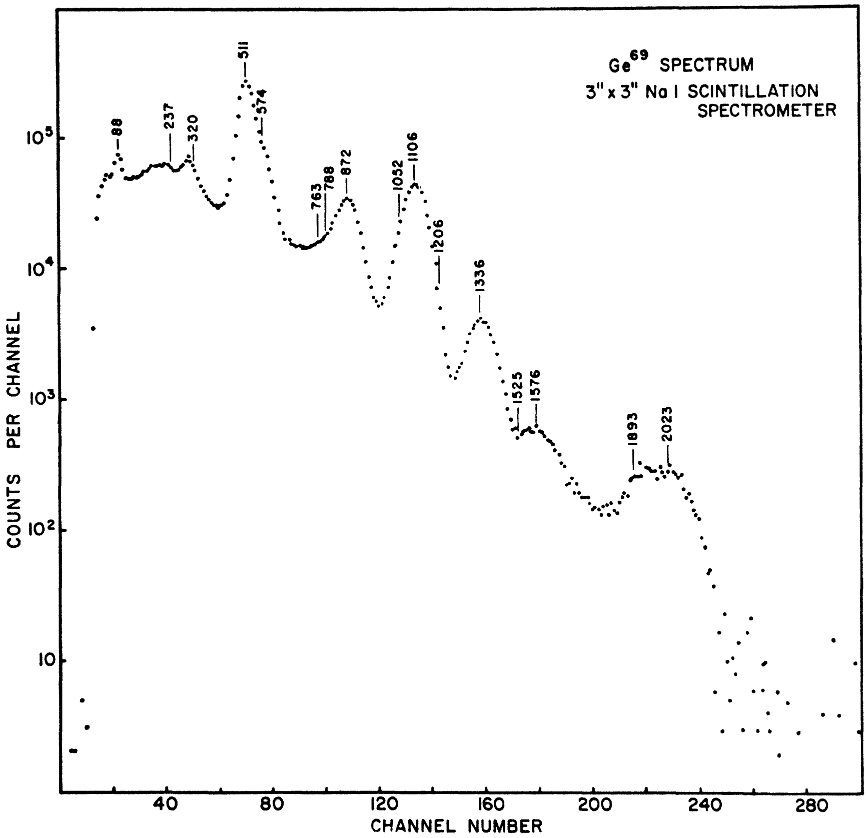

FIG. 2. Ge^{69} single gamma-ray spectrum from a disk source located axially 20 cm from the face of a 3-in. by 3-in. NaI(Tl) scintillation crystal.

energy region from 0 to 2500 keV obtained with the germanium detector and plotted on a linear scale to emphasize small photopeaks. In these spectra each channel represents about 1.3 keV.

A spectrum of the low-energy region is shown in Fig. 3. The broad, prominent peak at about 180 keV is due to backscattered gamma rays. There is a weak gamma ray at 237 keV and a prominent one at 320 keV. The very strong peak at 511 keV is due to annihilation radiation.

Figure 4 shows the energy region between 500 and 580 keV. Gamma rays at 511, 532, 553, and 574 keV are apparent. The two weaker peaks are shown on an expanded scale at the right of the figure.

The energy region from 550 to 1150 keV is depicted in Fig. 5. There are weak gamma rays at 588, 763, 788,

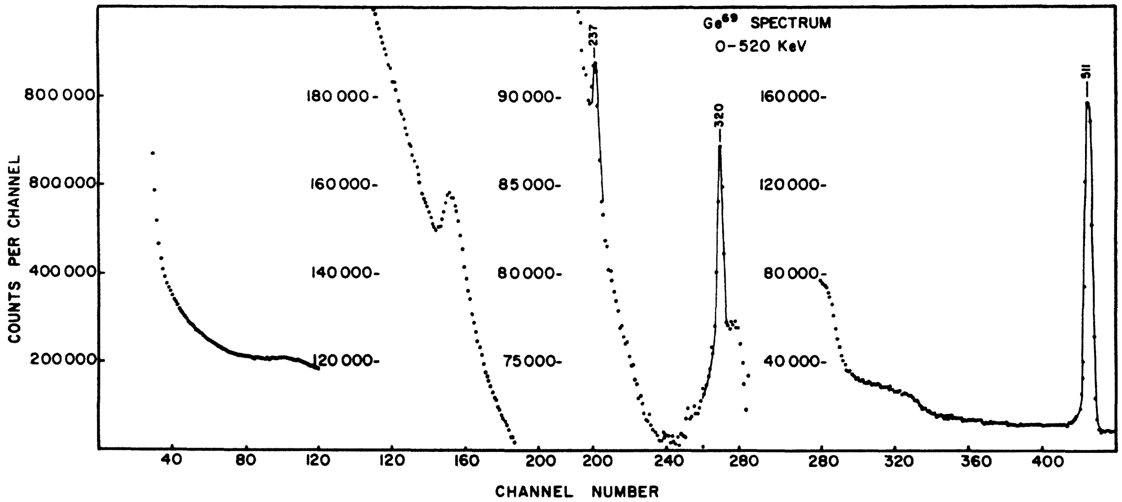

FIG. 3. Ge^{69} single gamma-ray spectrum obtained with a lithium-drifted germanium detector: 0–520 keV.

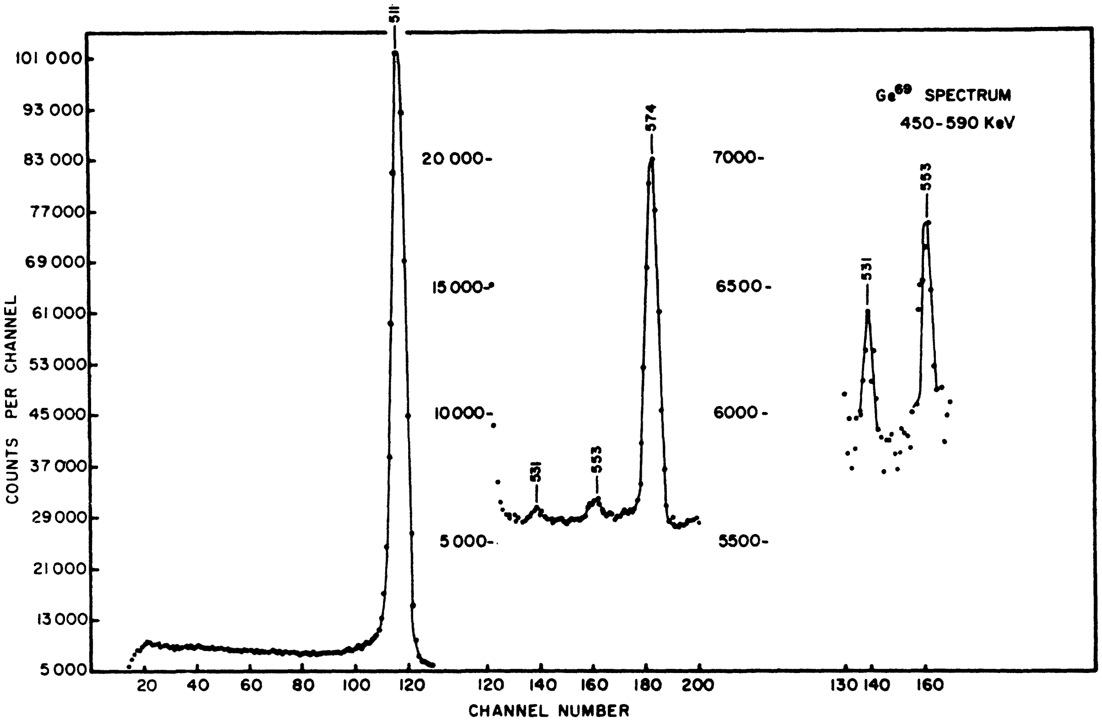

FIG. 4. Ge^{69} single gamma-ray spectrum obtained with a lithium-drifted germanium detector: 450–580 keV. The region between channels 130 and 160 is replotted on an expanded scale on the right side of the drawing.

and 1052 keV, and strong ones at 872 and 1107 keV. The weak peak at 1002 keV is the double-escape peak associated with the 2023-keV gamma ray.

The next region is shown in Fig. 6. The spectrum reveals photopeaks at 1206, 1336, and 1349 keV. The 1349-keV gamma ray is shown on an expanded scale at the right of the figure.

TABLE I. Single gamma rays and coincident events observed in the decay of Ga^{69}.

Energy (keV)	Intensity[a]	Coincidences
237±2	4.2±0.3	871.8, 553, 320
320±2	14±1	1576, 1206, 788, 553
511	1000	871.8, 573.4, 511, 320
532±1	3.2±1.1	(1349, 1335, 1052, 763, 573.4, 532, 511, 320)
553±1	7.6±0.7	
573.4±0.5	166±1	
587±1	2.7±1.0	
763±2	2.1±1.1	587, 573.4, 320
788±2	4.8±1.1	
871.8±0.5	131±1	1052, 511, 237
1002±2	2.9±0.5	
1052±2	4.0±0.4	871.8, 553, 320
1107.2±0.5	372±3	
1206±2	3.5±0.5	320
1335±1	41±3	573.4, 587
1349±2	3.1±0.3	
1525±2	1.7±0.5	
1576±2	1.7±0.3	320
1893±2	2.6±0.4	
1922±2	0.8±0.1	
2023±2	3.4±0.5	
(1485)	<2	
(1727)	≲1	

[a] Relative to 1000 for annihilation radiation.

The high-energy region of the spectrum appears in Fig. 7. There are gamma rays at (1485), 1525, 1576, (1727), 1893, 1922, and 2023 keV. No gamma rays of energy greater than 2023 keV were observed. The peaks at 1485 and 1727 keV probably do not belong to this decay as is discussed below.

The energies of all gamma rays observed and their intensities relative to 1000 for the annihilation radiation are presented in the first two columns of Table I. The energies of the gamma rays at 573.4, 871.8, 1107.2, and 1335 keV were obtained from an average of many short runs made over a small region of the spectrum with the standard calibration sources superimposed. These lines were then used as secondary standards for obtaining the energies of the remaining gamma rays. The energy calibration for each run was obtained by a least-squares fit of the positions of the standard lines to a quadratic equation in the energy. The dependence of the detector efficiency on gamma-ray energy was obtained by comparing spectra of the calibration sources with spectra of the same sources taken with a 3-in. by 3-in. NaI(Tl) crystal. The relative efficiency of NaI(Tl) was obtained from the tabulation of Heath *et al.*[25]

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[25] S. H. Vegors, L. L. Marsden, and R. L. Heath, U. S. Atomic Energy Commission Report No. IDO-16370, 1958 (unpublished).

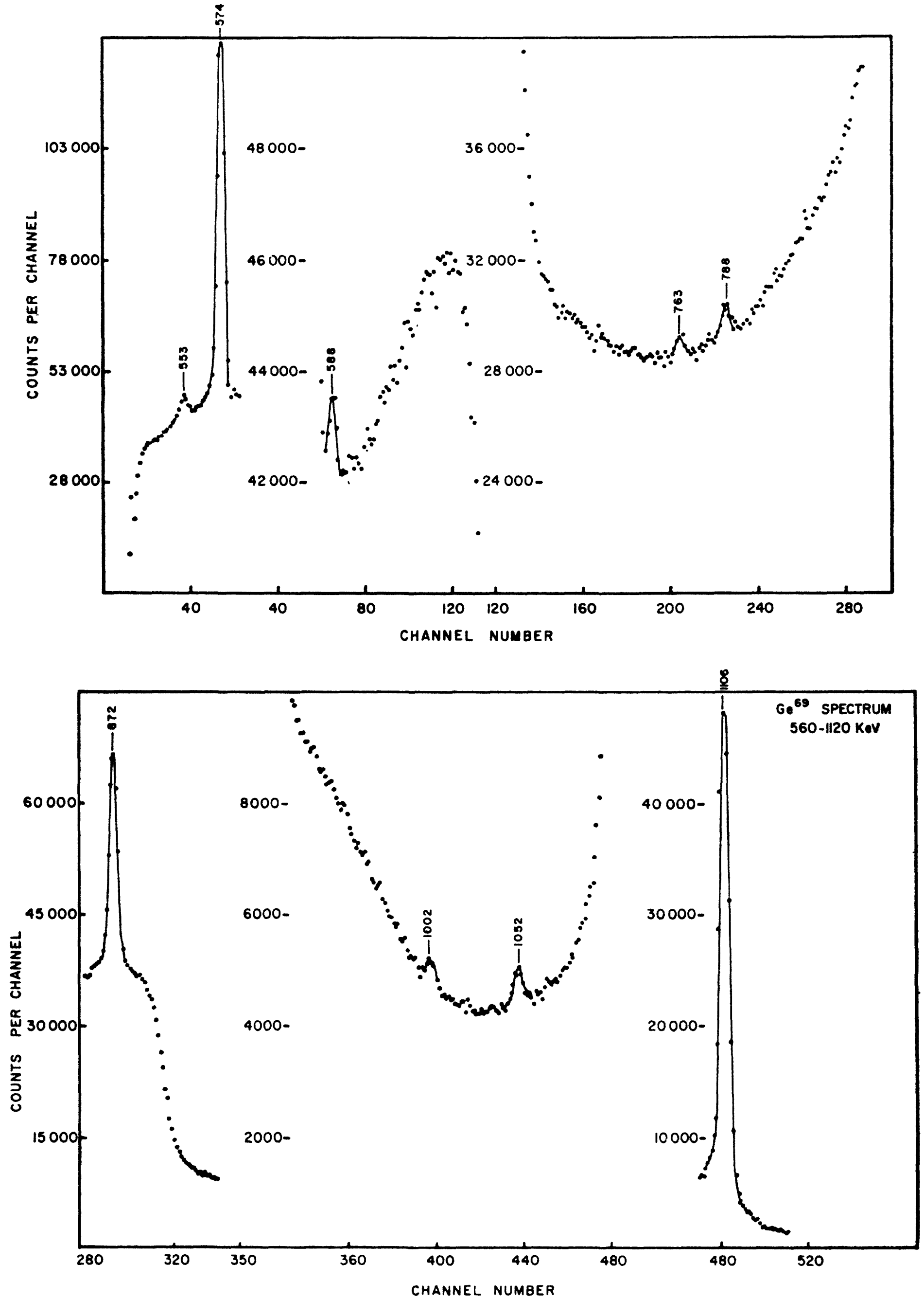

FIG. 5. Ge^{69} single gamma-ray spectrum obtained with a lithium-drifted germanium detector: 540–1150 keV.

IV. GAMMA-GAMMA COINCIDENCE MEASUREMENTS

Gamma-gamma coincidence spectra were measured using a fast-slow coincidence circuit with a resolving time of 12 nsec. A 1.5-in.-by-1.75-in. NaI(Tl) scintillation spectrometer was used for the analyzing side and a 3-in.-by-3-in. NaI(Tl) scintillation spectrometer was used for the discriminating side. The detectors were surrounded by lead shields so constructed that the source subtended the same solid angle at both detectors.

The results of the coincidence work are summarized in Column 3 of Table I. The coincidence spectra closely resembled those obtained by Schwerdtfeger, Ramayya, and Mitchell,[9] but in interpreting our coincidence data the precise knowledge of the singles spectrum obtained with the germanium detector has been taken into account. Those cases in which two unresolved gamma rays were included in the window are indicated by brackets. Furthermore, some of the gamma rays listed in Column 3 could not be positively identified in the co-

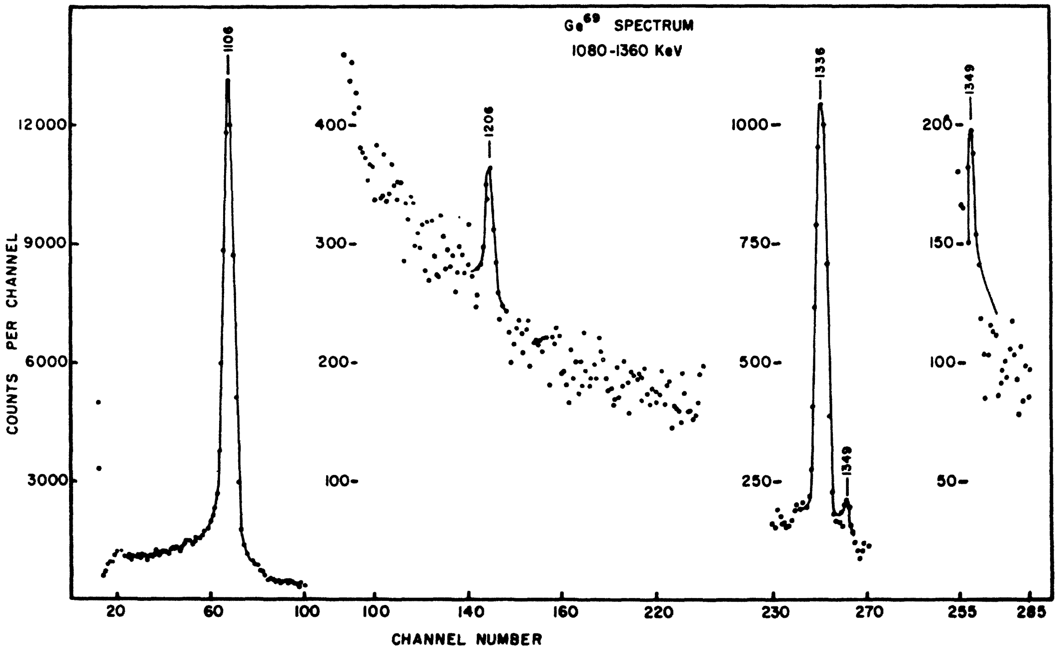

FIG. 6. Ge^{69} single gamma-ray spectrum obtained with a lithium-drifted germanium detector: 1080–1360 keV. The 1349 keV peak is replotted on an expanded scale at the right.

incidence spectra because of the inherently poor resolution of the NaI(Tl) system. Their identification is facilitated by the data obtained with the germanium detector and is in all cases consistent with the results obtained in the coincidence measurements.

V. LEVEL SCHEME

The level scheme which has been constructed from the above data is shown in Fig. 8. The ground state is known to have spin $\frac{3}{2}$,[12] and its parity is assumed negative on the basis of shell-model considerations.

No coincidences were seen with the 2023-, 1922-, 1893-, 1525-, and 1107.2-keV lines, and thus they are ground-state transitions from levels at these energies. The first excited state is at 320 keV in agreement with the coincidence results and with Coulomb excitation studies.[10,11] Since this state is not populated directly by the beta decay of the ground state of Ge^{69}, the decay to this level is expected to be at least second forbidden. The beta decay of the ground state of Ge^{69} to the ground state of Ga^{69} has $\log ft \sim 6$, which in conjunction with shell-model considerations leads to an assignment of $\frac{5}{2}^-$ for the spin of the ground state of Ge^{69}. Hence, it is likely that the 320-keV level has $J^\pi = \frac{1}{2}^-$. A calculation based on the Weisskopf single-particle estimate gives a mean lifetime of 0.5×10^{-10} sec for this state, if it decays by $M1$ radiation. This is in agreement with the measured[11] upper limit of the lifetime of the 320-keV state and supports the $\frac{1}{2}^-$ spin assignment.

The 871.8- and 573.4-keV gamma rays are strongly in coincidence with annihilation radiation and not with each other. Beta-gamma coincidence work[8,9] verifies that they are in coincidence with two different positron branches. Since there is no evidence in the spectrum in coincidence with the 511-keV annihilation radiation of the other gamma rays which are also in coincidence with the 871.8- and 573.4-keV gamma rays, these latter are identified as ground-state transitions from the third and second excited states, respectively.

The 573.4-keV line is in coincidence with a gamma ray of about 770 keV. If this gamma ray is the 788-keV line observed with the germanium detector, there must be a level at 1361 keV; however, there is no other evidence for such a level. If it is the 763-keV gamma ray in coincidence with the 573-keV line, the cascade must depopulate a level at 1336 keV. There is a strong 1335-keV gamma ray which was previously thought to be a transition between a state at 1910 keV and the 573.4-keV level, since a peak of about this energy appears in strong coincidence with the 573.4-keV gamma ray. There is no other evidence of a level at 1910 keV, however, so it has been concluded from our data that the 1335-keV transition is between a level at 1335 keV and the ground state and that the observed coincidence is actually between the weaker 1349-keV line and the 573.4-keV line. The strength of this coincidence is in better agreement with the intensity of these gamma rays and the cascade depopulates the level at 1922 keV. Some of the coincidences seen when gating on the 1335-keV gamma ray are undoubtedly due to coincidences between the 1335-keV line and the weak 587-keV line, which appears from energy considerations to belong between the levels at 1922 and 1335 keV. Adding the energies in the 1052–871.8-keV cascade indicates that it also depopulates the 1922-keV level.

Gamma rays of 1206 and 1576 keV are in coincidence

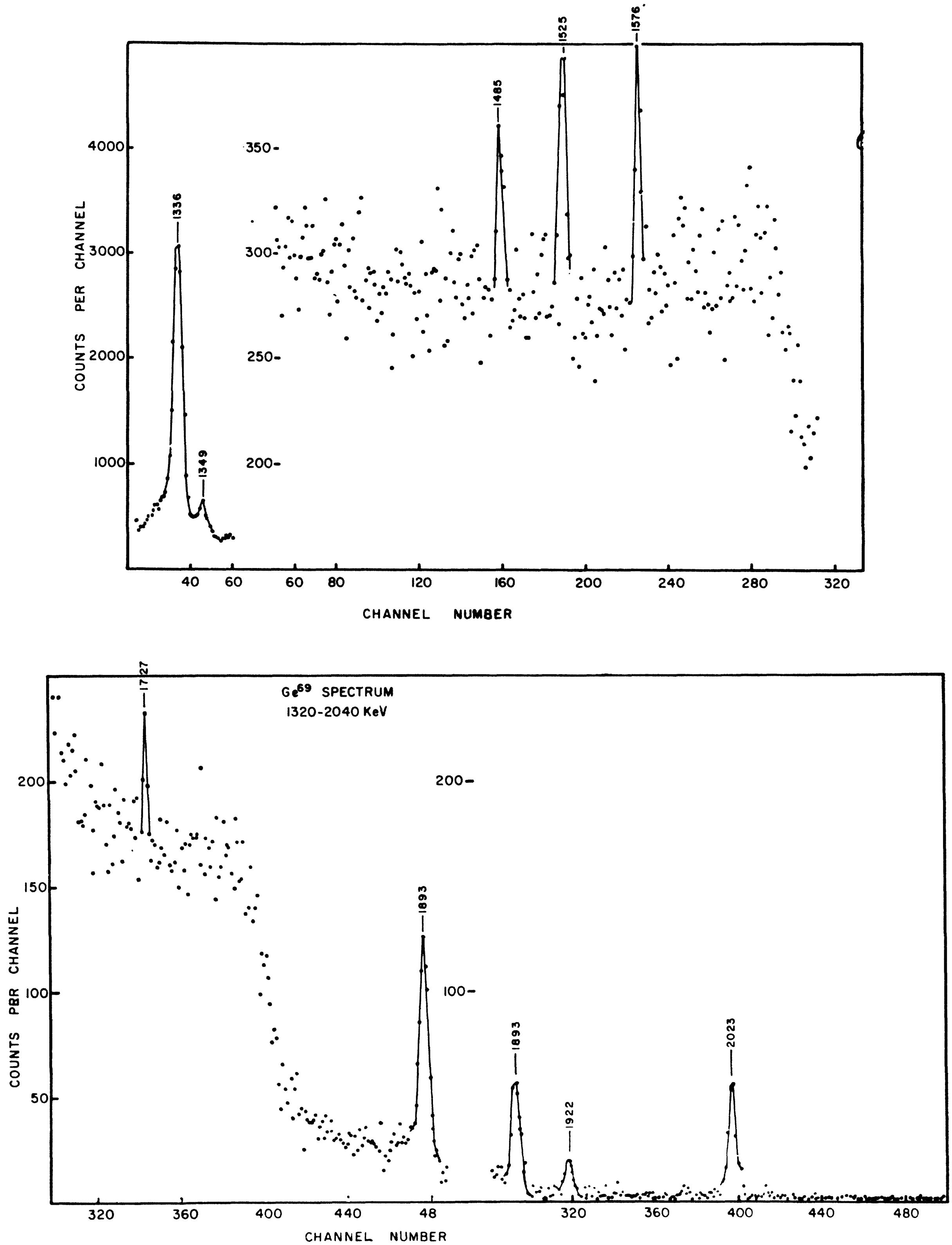

FIG. 7. Ge^{69} single gamma-ray spectrum obtained with a lithium-drifted germanium detector: 1320–2040 keV.

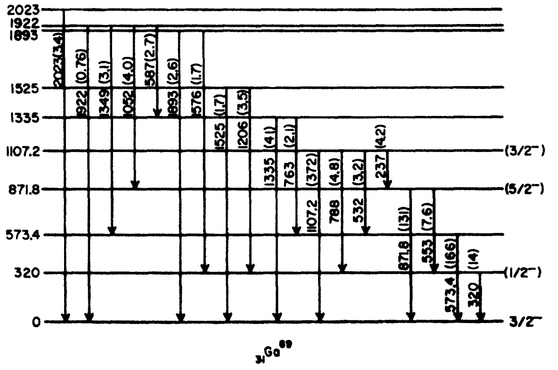

FIG. 8. Energy levels and gamma transitions in Ga^{69} observed in the decay of Ge^{69}. Numbers in parentheses are the relative intensities.

with the 320-keV line, which then depopulate the levels at 1525 and 1893 keV, respectively. The 320-keV line is also in coincidence with a gamma ray of about 770 keV. Since the 763-keV line has been identified as a transition between the levels at 1335 and 573.4 keV, the 320-keV gamma ray must be in coincidence with the 788-keV line and the cascade must depopulate the 1107.2-keV level. The 532-keV gamma ray observed with the germanium detector is probably a transition between the 1107.2- and 573.4-keV levels, again from energy considerations. This gamma ray would be completely masked by the 511-keV annihilation gamma ray in the coincidence work.

Energy considerations alone indicate that the 553-keV line seen with the germanium detector could be a transition between either the 1893- and 1335-keV levels or the 871.8- and 320-keV levels. However, a gamma ray between 520 and 600 keV was consistently observed in coincidence with the 320-keV gamma ray. Furthermore, the 553-keV line was included in the discriminator window when set on the 573.4-keV line, and the 320-keV line is in evidence in these coincidence spectra. Hence, the 553-keV gamma ray is probably a transition between the 871.8- and the 320-keV levels. Since a gamma ray of 298 keV proceeding from the 871.8-keV level to the 573.4-keV level could also explain these coincidences, a search was made for such a line and none was seen.

The gamma rays of 1727 and 1485 keV have been observed with only one source. They do not fit into the level scheme and are believed to arise from a contaminant.

VI. HALF-LIFE OF Ge^{69}

The half-life of Ge^{69} was measured by following the decay of the prominent peaks at 511, 573.4, 871.8, and 1107.2 keV with the germanium detector for a period of five days in a fixed geometry. Seven different spectra were recorded. The areas under these peaks were fit to an exponential function by the method of least squares, and the half-life was determined after averaging to be 35.5±0.8 h.

VII. DISCUSSION

The spins and positions of the energy levels of Ga^{69} were calculated on the basis of the intermediate-

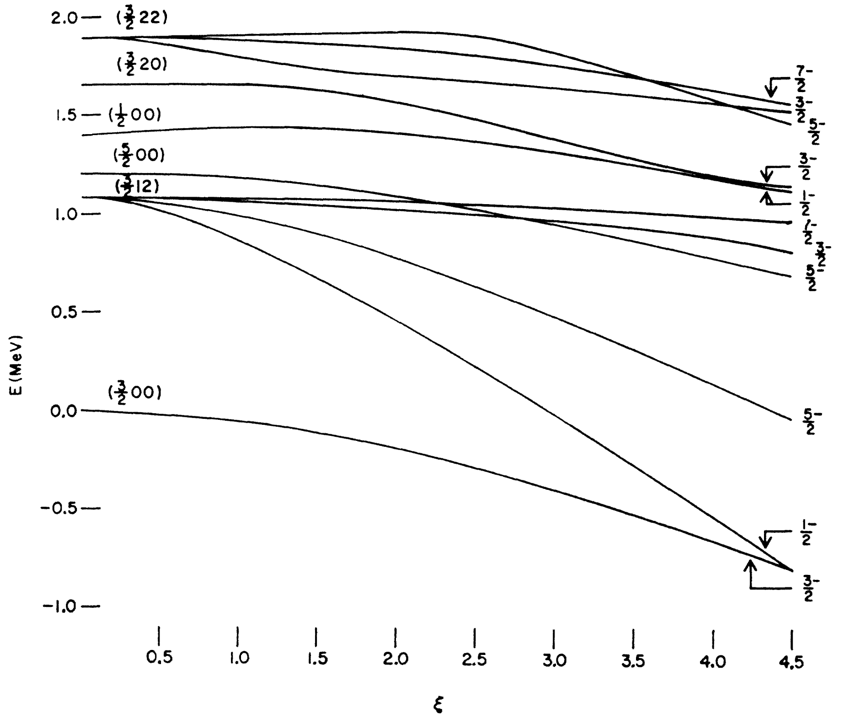

FIG. 9. Energy levels versus the dimensionless coupling constant ξ for single-particle level spacings $E(f_{5/2}-p_{3/2})=1.2$ MeV, $E(p_{1/2}-p_{3/2})=1.4$ MeV. A Gaussian radial dependence is assumed for the radial part of H_{int}.

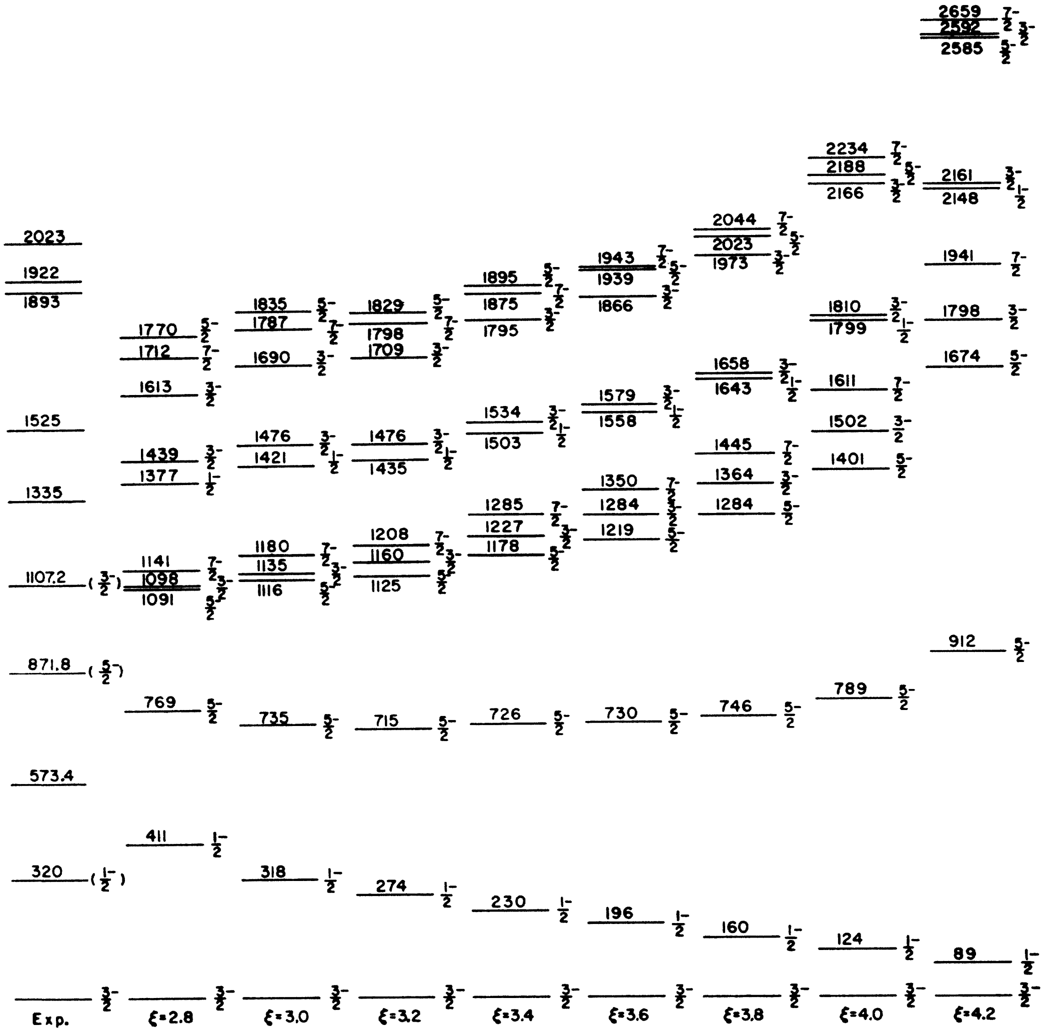

FIG. 10. Calculated level schemes for a Gaussian radial dependence using selected values of the coupling constant ξ. Best agreement with experiment is obtained for $\xi=3.6$.

coupling model. The method followed closely that of Glendenning,[26] with the exception that a Gaussian form was assumed for the radial dependence of the single-particle potential.

It was assumed that the thirty-first proton is weakly coupled to the even-even Zn^{68} core. Recent work on the even isotopes of nickel and zinc by Broek[27] indicates that the low-lying states of Zn^{68} can be interpreted as collective vibrational excitations. Broek interprets the 2^+ level at 1.08 MeV as a one-phonon vibrational excitation, and the levels at 1.66 and 1.89 MeV as the 0^+ and 2^+ members of the two-phonon triplet, respectively. The 4^+ member has not been observed. The next known core state lies at 2.31 MeV, and this and higher states were neglected in the calculation. The odd proton was restricted to the $2p_{3/2}$, $1f_{5/2}$, or $2p_{1/2}$ shell-model states.

The representation for the wave functions used in the calculation was defined by the uncoupled Hamiltonian

$$H_0=H_c+H_p{}^0, \tag{1}$$

where H_c represents the vibrational core and $H_p{}^0$ the spherical single-particle potential. The total Hamiltonian used was

$$H=H_c+H_p{}^0+H_{\text{int}}, \tag{2}$$

where

$$H_{\text{int}}=-(V_0/2a)\exp(-[(r-c)/2a]^2)\textstyle\sum_\mu \alpha_\mu Y_2{}^\mu(\theta,\varphi)\,, \tag{3}$$

with $a=0.55$ F and $c=4.3$ F. Best results were obtained for the single particle level spacings $E(f_{5/2}-p_{3/2})=1.2$ MeV and $E(p_{1/2}-p_{3/2})=1.4$ MeV in agreement with the work of other investigators.[4,26] The eigenvalues of H_c were taken from the experimentally determined[27] level scheme of Zn^{68}. Harmonic-oscillator radial wave

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[26] N. K. Glendenning, Phys. Rev. **119**, 213 (1960).

[27] H. W. Broek, Phys. Rev. **130**, 1914 (1963).

functions were used in evaluating the matrix elements of H_{int}.

A total of 28 possible energy levels were obtained in this treatment. In Fig. 9 the behavior of the first 11 of these is shown as a function of the dimensionless coupling parameter ξ. The level schemes obtained for various values of ξ are presented in Fig. 10. The values of ξ chosen are within the range for which the calculation gives the correct ordering of spins for the low-lying states—viz., $\frac{3}{2}^-$ for the ground state, $\frac{1}{2}^-$ for the first excited state, $\frac{5}{2}^-$ for the third excited state, and $\frac{3}{2}^-$ for the fourth excited state, where the spins of the third and fourth excited states are taken from preliminary results of angular correlation measurements on the 237–871.8-keV gamma-gamma cascade.[28]

The best agreement with experiment is obtained for $\xi=3.6$. The spins of the low-lying levels are reproduced, so far as they are known, and the high-energy triplet observed experimentally at about 2 MeV is also apparent in the calculation. The values of log*ft* for the beta transitions to the various states of Ga^{69} range from 5.0 to 7.0. These indicate that the transitions are all allowed, which supports the assignment of $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{7}{2}^-$ as the spins of most of the levels. The extra level predicted in this energy region is probably the second $\frac{1}{2}^-$ level, since one would not expect such a state to be populated directly by the ground-state decay of Ga^{69}, and thus it might easily remain unobserved experimentally.

The assumption of a collective core for Ga^{69} is supported by the strong ground-state transitions observed from the low-lying excited states. Comparison with single-particle estimates indicates that these are enhanced $E2$ in nature, as would be predicted by this model. However, from a shell-model point of view, the 2^+ core states can be described as a superposition of states with the protons or neutrons coupled to spin 2^+. The $(2p_{3/2})^2$, $J_{\text{proton}}=2^+$ contribution to the first excited Zn^{68} level is expected to be important. Coupling an additional $2p_{3/2}$ proton to this part of the first-excited-state wave function can give only one state, namely, the seniority one ground state $[(2p_{3/2})^3, J_{\text{proton}}=\frac{3}{2}^-]$. This effect has been neglected in these calculations, leading perhaps to the persistent energy gap evident between the second and third excited states in the results of the calculation.

VIII. CONCLUSIONS

Five new gamma rays in the spectrum of Ge^{69} have been identified. The ground-state transition from the Ga^{69} level at 1922 keV was previously unobserved, as were the gamma rays with energies 1349, 587, 553, and 532 keV. Moreover, the greatly improved resolution obtainable with the germanium detector has made possible the assignment of precise energy values to the gamma rays and the construction of an unambiguous level scheme for Ga^{69}. The level which Schwerdtfeger *et al.*[9] place at 1910 keV was found to have an energy of 1893 keV. Their 1560–323-keV cascade has been identified as being 1576–320 keV, which then depopulates this level. Hence, the present data do not support the existence of a level at 1880 keV as reported by them. The identification of the 1335-keV gamma ray as a ground-state transition has been discussed above. No evidence was found for the 420-, 300-, and 260-keV transitions reported by Schwerdtfeger *et al.*[9]

The intermediate-coupling model appears to give a reasonable explanation of the level scheme of Ga^{69}. The assumption in the calculation that the contribution to the 2^+ core states by the recoupling of the two $2p_{3/2}$ protons is negligible may possibly be responsible for the energy gap which occurs between the second and third excited states, which is the main discrepancy with experiment. Further conclusions must wait until spin assignments have been made experimentally to more of the levels.

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[28] G. Moss, D. O. Wells, and D. K. McDaniels (private communication).