Ge(n, $n'\gamma$) Reactions and Low-Lying States of Ge Isotopes*

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The 90° excitation functions of the γ-ray transitions in the Ge($n,n'\gamma$) reactions have been measured at incident neutron energies from 0.5 to 2.55 MeV. Angular distributions at E_n =1.75, 2.13, and 2.55 MeV have also been measured. The γ-ray production cross sections and the neutron inelastic scattering cross sections have been obtained at these neutron energies. Theoretical model calculations have been performed and are in good agreement with the experimental results. The Wolfenstein-Hauser-Feshbach formalism was used for the calculations. The low-lying decay schemes of the four even-A Ge isotopes determined in this work are in good agreement with previous investigations. Branching ratios, as well as mixing ratios, of the γ-ray decay from the second 2^+ state for all the four even-A Ge isotopes have been obtained. The 1698-keV level of ^{74}Ge has been confirmed and its decays to the first and second 2^+ states have been established. The branching ratio and mixing ratios have been determined. A spin of 3 is tentatively assigned to that level for the first time in this work. In addition, a test of the fluctuation corrections to the statistical model at the mass region near $A=70$ has been made. The corrections attempted worsen the agreement between theory and experiment.

INTRODUCTION

The present experiment was conceived with three distinct purposes in mind. First, Ge(Li) detectors are regularly used as γ-ray detectors where substantial neutron backgrounds are present. It is important to know the energies and the relative intensities of the lines produced in the detector itself by the Ge(n,n')Ge* reactions to be able to discriminate between those background lines and the nearby transitions of interest in an experiment. In the early work[1] suggesting the use of Ge detectors for (n,n') experiments, several spectra of Ge γ rays at different incident neutron energies were presented. The present work adds a more detailed study of many of the transitions noted in Ref. 1, and other transitions. Germanium is a constituent of many devices which are operated in a neutron flux; hence the knowledge of the neutron inelastic scattering cross sections of Ge are of value to those who estimate radiation damage to devices.

A second purpose of this experiment is to provide additional information about the low-lying decay schemes of the even-A Ge isotopes. In particular we expected to be able to determine branching ratios for the decay of levels and mixing ratios δ, of mixed $M1$, $E2$ transitions. Further, a spin assignment was sought for the 1689-keV level of ^{74}Ge.

The third purpose of this work was the development of a many-isotope test of the Wolfenstein-Hauser-Feshbach (WHF) formalism[2,3] which has been used extensively and very successfully[4] to represent the neutron inelastic scattering (n,n') cross sections at low energies. Proposed fluctuation corrections[3] of the WHF model suggest noticeable deviations of the calculated (n,n') cross sections, especially for even-A nuclei. The modifications depend on the number of degrees of freedom for decay of the compound system excited by the incident neutrons. The present test of the WHF formalism has been made by the comparison of calculated and measured inelastic scattering cross sections both for the even-A Ge isotopes of this experiment and for the neighboring odd-A Ga isotopes. The large number of excited levels below 1.5-MeV excitation in the Ga isotopes and the very few levels in the Ge isotopes should lead to an odd-even effect in the comparison of the measured and calculated (n,n') cross sections. This odd-even difference should be noticeable if the proposed modifications[3] of the WHF formalism are important. The Ga($n,n'\gamma$)Ga cross sections measured in this laboratory have been recently reported[5], and the comparison of these with the present measurements should provide a reasonably sensitive test of the WHF model.

An additional test of the model is available through the determination of $M1$, $E2$ mixing ratios δ. The simultaneous analysis of $2^+\rightarrow 2^+$ and $2^+(E2)0^+$ transitions from a level which emits both fixes δ for the $2^+\rightarrow 2^+$ transition in a completely reaction-independent manner. On the other hand, the δ may also be fixed by a WHF-model analysis of the $2^+\rightarrow 2^+$ angular distribution. The comparison of the δ values determined in these two ways is a test of the excited-state alignments predicted by the WHF model. Several such tests were completed in this work.

EXPERIMENTAL PROCEDURE

The measurements of differential γ-ray production cross sections with the pulsed-beam time-of-flight detection system have been described in several publications, and the techniques, the sensitivity, and accuracy of the method have been reviewed.[6,7]

The physical and electronic arrangements of this experiment are similar to those of Ref. 5 except a 35-cc Ge(Li) detector was used as principal detector rather than the 15-cc one of the earlier experiment. A tritium gas cell 3 cm in length and 0.74 cm in diameter was loaded to 1 atm and served as the neutron source. A pulsed neutron flux with a burst width of 6–8 nsec and a repetition rate of 2 MHz was produced with the terminal pulsed proton beam of the 6-MeV Van de Graaff accelerator via the $T(p,n)^3He$ reaction. The incident proton beam was collimated to 0.5-cm diam, and time-averaged intensities of 2–4 μA entered the gas cell through a 7.6-μ Mo foil. The neutrons were incident on a cylindrical crystal[8] of Ge containing 1.53 moles of natural Ge and mounted 6 cm from the neutron source. The sample consists of 20.52% ^{70}Ge, 27.43% ^{72}Ge, 36.54% ^{74}Ge, 7.76% ^{76}Ge, and 7.75% ^{73}Ge. The shielded γ-ray detector[5] was operated at a distance of 60 cm from the sample and at angles of 35–150° with respect to the incident beam. The energy spread of the incident neutrons was 50–60 keV and the angular spread was ± 8°. For the purpose of normalization, a long counter served as the neutron monitor. It was set at 90° from the direction of the incident beam and 3.2 m away from the neutron source.

Time-of-flight spectra of the pulses from the γ-ray detector permitted the setting of a time gate to accept only those pulses corresponding to the prompt γ rays from the scattering sample, and thus a great amount of background caused by neutron scattering in the detector itself or other parts of the laboratory are eliminated. The γ-ray energy resolution of the detection system, with the Ge(Li) detector pulses used for both time and energy measurements,[5] was 5–7 keV full width at half maximum. The transition energies of γ-ray spectra were measured by using both external and internal γ-ray energy standards; spectra including ^{22}Na and ^{88}Y lines were taken to calibrate the amplifier-analyzer combination, and in general each Ge spectrum had four internal standards, the 511-keV photopeak, 2223.3-keV n-p capture line, and the 596- and 834.3-keV well-defined[9,10] transitions of ^{74}Ge and ^{72}Ge, respectively. Transition energies determined in this way have uncertainties of ± 0.5 keV.

In order to reduce the γ-ray yields to differential cross sections, the relative efficiency curves of the detectors were measured by the method described by Freeman and Jenkin.[11] The γ-ray yields of the Ge spectra are normalized to the yields of the 846.8-keV transition of the $^{56}Fe(n,n'\gamma)^{56}Fe$ reaction. Yields of this ^{56}Fe line were measured with a cylindrical Fe sample in the same geometry as that used for the Ge sample. Measurements of the 90° differential production cross sections of the 846.8-keV transition had been evaluated and compiled, and the weighted averages[6,7] had been assigned an uncertainty of ± 8%. New cross-section measurements of the $^{56}Fe(n,n')^{56}Fe$ reaction have been completed and used to provide γ-ray production cross sections.[12] As the new values are transformed to the form of the compilation of Ref. 6, they fall within the ± 8% uncertainties assigned to the weighted averages, supporting the results of the compilation.

The corrections applied to the yields for neutron-flux attenuation in the sample, for sample γ-ray absorption, and for the angular and energy spread of the incident neutrons have been carefully detailed by Nichols[7] and Velkley.[13] The uncertainty determinations are similar to those of the previous work[5] and are estimated to be near ±10%. They are tabulated with the cross sections in the following section.

RESULTS AND DISCUSSION

Pulse-height spectra of γ rays from the $Ge(n,n'\gamma)$ reactions are shown in Figs. 1–3 at the incident neutron energies of 1.75, 2.13 and 2.55 MeV, respectively. Lines from all four even-A Ge isotopes are evident. With the available information about the level schemes of the four isotopes,[10,14,15] many

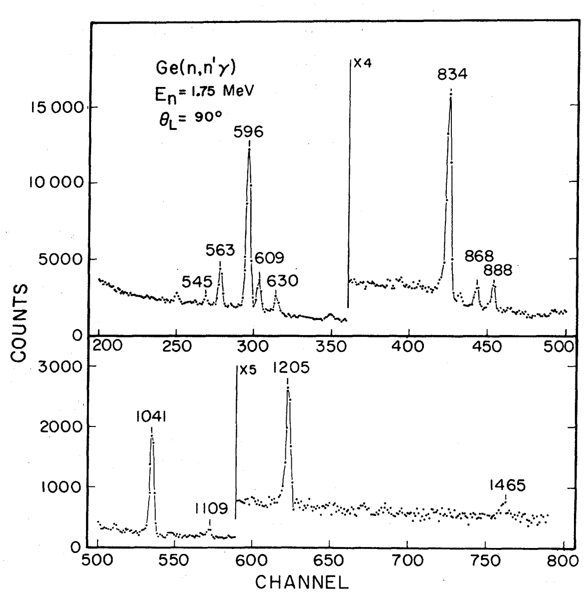

FIG. 1. γ-ray pulse-height spectrum obtained with a 15-cc Ge(Li) detector.

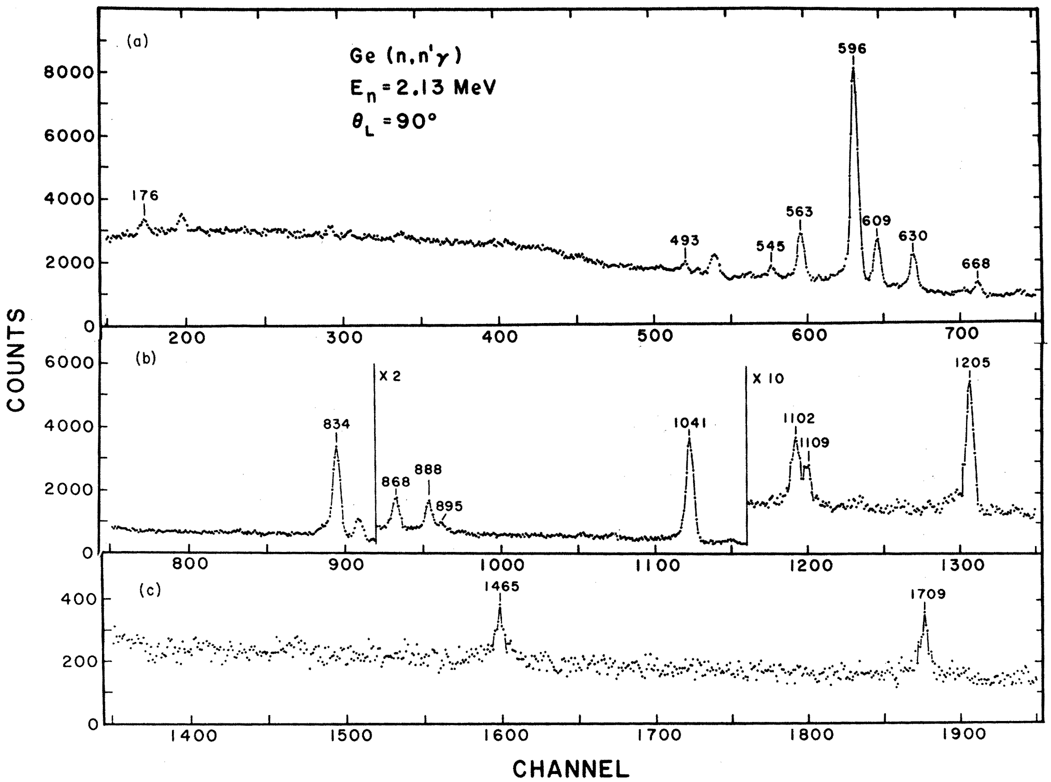

FIG. 2. γ-ray pulse-height spectrum obtained with a 35-cc Ge(Li) detector.

of the transitions evident here are readily fitted into the level schemes of the nuclei. In order to confirm and determine the decay schemes with confidence, the 90° excitation functions have been measured at incident neutron energies from 0.5 to 2.55 MeV. The differential cross sections of all observed transitions except the 176- and 1113 + 1117-keV doublet are shown in Fig. 4. The observed thresholds for exciting particular transitions determine the energies of the emitting levels to within 20 keV, and these together with the transition energies fix the decay schemes of the nuclei. The proposed decay schemes of the four even-A Ge isotopes from this work are given in Fig. 5

Ge(Li) *detector backgrounds*. The pulse-height spectra and excitation functions shown provide the information necessary for evaluating backgrounds expected when a Ge detector is used in an experiment which inevitably involves some neutron flux with energies ≤3 MeV. The expected backgrounds will result from low-energy neutron capture in ^{73}Ge and inelastic scattering in the even-A Ge isotopes. Capture effects are illustrated in Fig. 4, which shows the subtantial production cross sections for the 596-, 868-, and 1205-keV lines below the thresholds for scattering to the levels. These yields are those of lines in ^{74}Ge, and result from the thermal capture in ^{73}Ge(n,γ)^{74}Ge reactions. The Li_2C0_3+paraffin shield surrounding the detector enhances the thermal-neutron flux at the detector. At incident energies above 1 MeV, the background includes recoil-broadened spectra as shown in Ref. 1, as well as the capture components, such that as the incident energy is raised, the few sharp background lines are replaced by broad distributions, whose intensities may be estimated by the information of Fig. 4. An example of these recoil-broadened background lines is contained in Fig. 1 of some recent work[16] on ($p,n\gamma$) reactions.

Level and decay schemes. The level and decay schemes determined in this work (Fig. 5) are in good agreement with previous work.[10,14,15,17-23] There are two particularly new features obtained in this work. One is confirmation of the existence of the 1698-keV level of ^{74}Ge and subsequent establishment of its decay as proceeding through cascades to the first and second 2^+ states; the other is the report[24] of the second excited level of ^{76}Ge at 1109 keV.

There is a possible 492-keV transition from the 1709-keV level to the 1216-keV level in ^{70}Ge. Since its intensity had been found in other work[18]

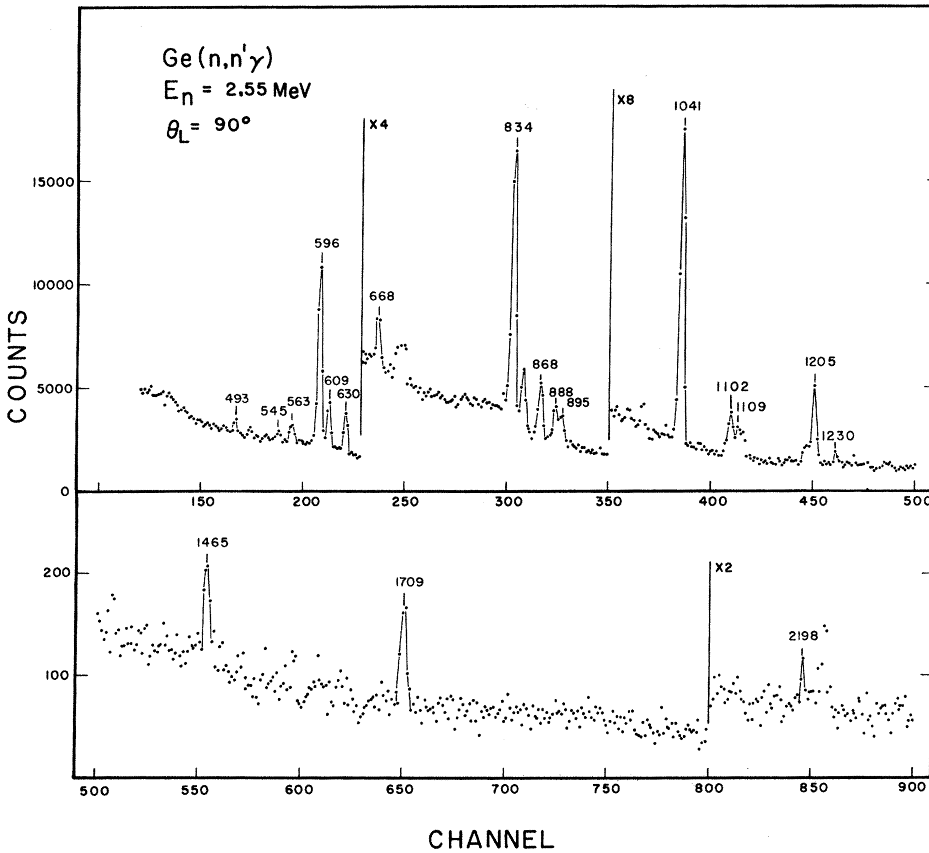

FIG. 3. γ-ray pulse-height spectrum obtained with a 15-cc Ge(Li) detector.

TABLE I. Coefficients of least-squares fits to $Y(\theta)=A_0[1+a_2P_2(\cos\theta_L)+a_4P_4(\cos\theta_L)]$.

		E_n (in MeV)			
	E_γ	1.75		2.13	2.55
Isotope	(keV)	a_2	a_4	a_2	a_2
^{70}Ge	668			−0.19 ± 0.03	−0.24 ± 0.02
	1041	0.21 ± 0.01	−0.10 ± 0.01	0.20 ± 0.01	0.16 ± 0.01
	1709			0.53 ± 0.02	0.34 ± 0.04
^{72}Ge	630	0		0	0
	834	0.23 ± 0.01		0.18 ± 0.01	0.12 ± 0.01
	895			0.49 ± 0.04	
	1465			0.39 ± 0.03	0.49 ± 0.06
^{74}Ge	493			0.66 ± 0.03	0.50 ± 0.03
	596	0.18 ± 0.01		0.16 ± 0.01	0.09 ± 0.01
	609	0.13 ± 0.01	−0.09 ± 0.01	0.24 ± 0.01	0.10 ± 0.01
	868	0.21 ± 0.02		0.27 ± 0.01	0.23 ± 0.03
	888	0		0	0
	1102			0.20 ± 0.01	
	1205	0.35 ± 0.01		0.28 ± 0.01	0.22 ± 0.03
^{76}Ge	545	0.20 ± 0.03		0.30 ± 0.02	0.14 ± 0.04
	563	0.16 ± 0.01		0.14 ± 0.01	0.14 ± 0.02
	1109	0.48 ± 0.02		0.37 ± 0.01	

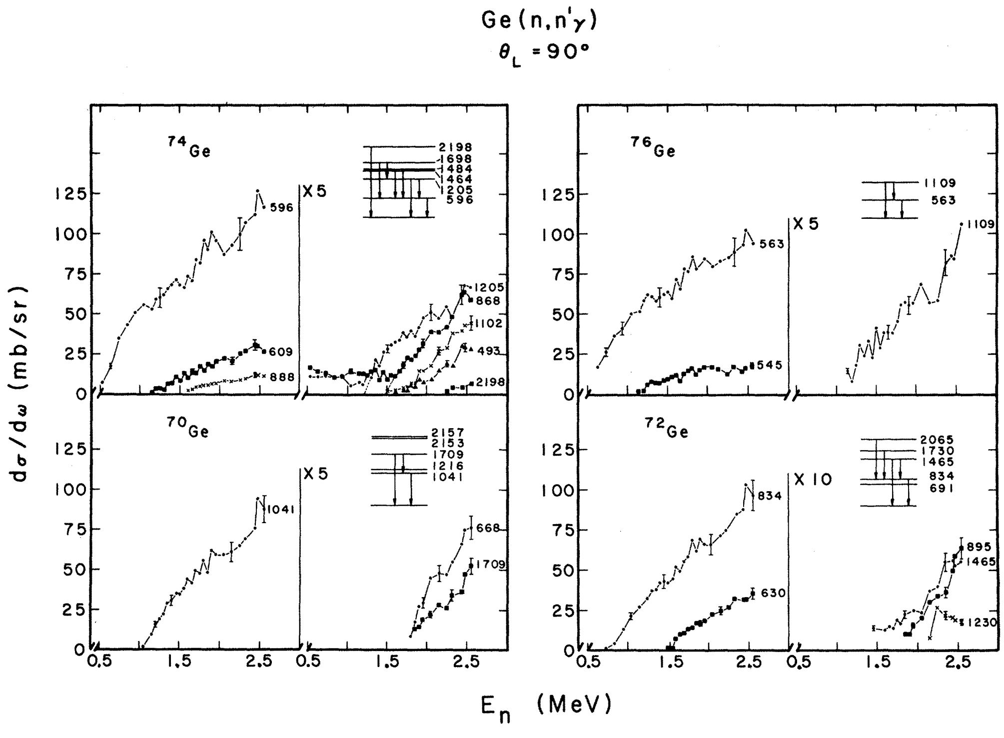

FIG. 4. Excitation functions of γ-ray production cross sections at 90°. The error bars represent absolute uncertainties of the measurements. Numbers by curves indicate γ-ray energies in keV and transitions are shown in the level diagrams.

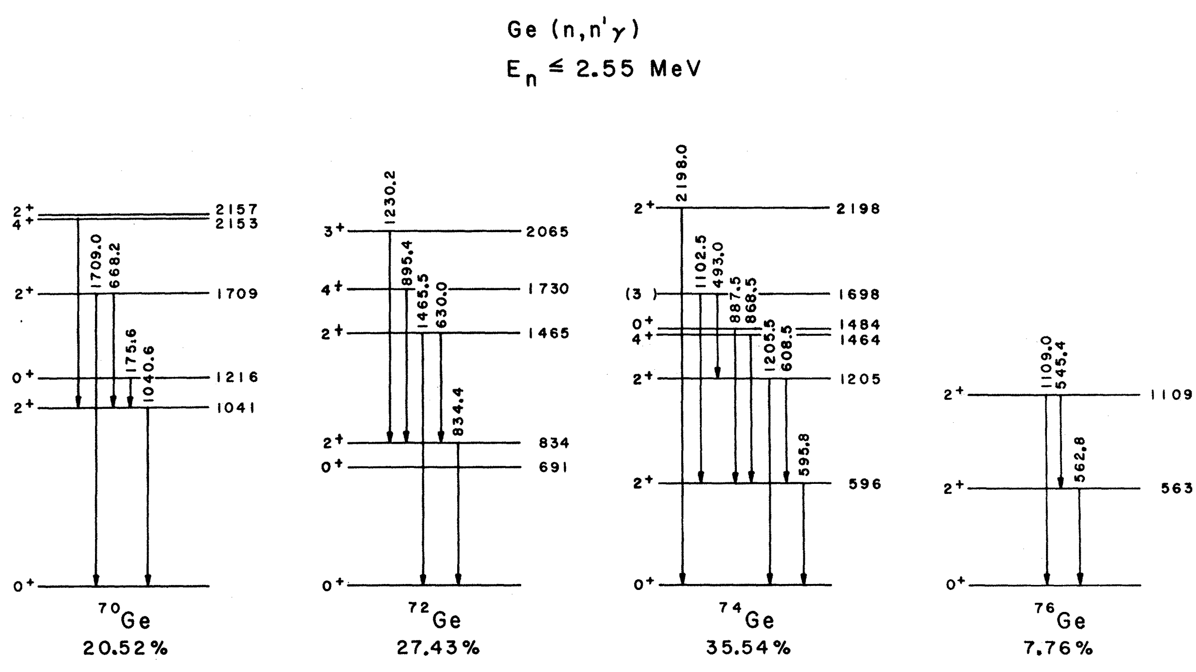

FIG. 5. Decay schemes of the four even-A Ge isotopes proposed in this work. The transition energies in keV are determined with uncertainties of ±0.5 keV. The γ-ray decays from the 2153 + 2157-keV doublet of ^{70}Ge had been observed; their energies were not accurately defined, therefore they are not indicated.

to be negligible, only about 1.3% of the 1709-keV line, the observed 493-keV γ ray together with the 1102-keV transition are to be attributed to the 1698-keV level of ^{74}Ge.

A level near 1465 keV has been established in ^{74}Ge and the same is true of the ^{72}Ge nucleus. As this level of ^{74}Ge has no ground-state transition reported, and has been assigned[15,21] as 4^+, while that of ^{72}Ge is a well-defined 2^+ level, we conclude that the observed 1465-keV γ ray comes totally from ^{72}Ge.

A search was made for γ rays deexciting the proposed[21,22] 2168-keV level of ^{74}Ge, but none were found. We have therefore omitted this level from the scheme of Fig. 5.

Angular distributions, mixing ratios of the $2_2^+ \to 2_1^+$ transitions, and branching ratios. Angular distributions have been obtained for observed transitions in Fig. 5 except the 176-, 1113+1117-keV lines of ^{70}Ge, the 1230-keV line of ^{72}Ge, and the 2198-keV line of ^{74}Ge. Figures 6–8 show the results at three incident neutron energies of 1.75, 2.13, and 2.55 MeV, respectively. The solid curves are the least-squares fits of the data represented by the normalized formula:

$$Y(\theta) = A_0\,[1 + a_2 P_2(\cos\theta_L) + a_4 P_4(\cos\theta_L)]\ ,$$

where A_0 is a normalization factor. The error bars indicated in Figs. 6–8 are relative errors of the data points. The calculated coefficients of the fits are listed in Table I. Where $|a_4| \leq 0.08$ they are not listed, as their uncertainties are about ±0.05. The anisotropies of all the angular distributions are consistent with the spin assignments indicated in the decay schemes of Fig. 5. The 1486-keV level of ^{74}Ge had been assigned[15,20] as 0^+ and the isotropy of the 888-keV cascade from the level is consistent with that assignment. The fit to the 868-keV transition from the 1464-keV level is consistent with the 4^+ assignment to that level.[15,21] It should be noted also that the fit to the 895-keV transition is consistent with 4^+ assigned to the 1730-keV level of ^{72}Ge.[10]

The angular distributions may be used to obtain mixing ratios δ for the mixed multipole transitions.[6] In all four isotopes, the second 2^+ state decays both by cascade to the first 2^+ state and by crossover to the ground state. The presence of the two decays makes it possible to determine δ for the $2^+ \to 2^+$ transition in a manner which is independent of the mechanism of the exciting reactions. The population parameter method (PPM)[25] in effect uses the angular distribution of the $2^+(E2)0^+$ transition to fix the excited-state alignment. Then this and the $2^+ \to 2^+$ angular distribution determine δ of the latter transition. The PPM calculations have been completed through a simultaneous analysis of the two γ rays emitted by the second 2^+ level using the

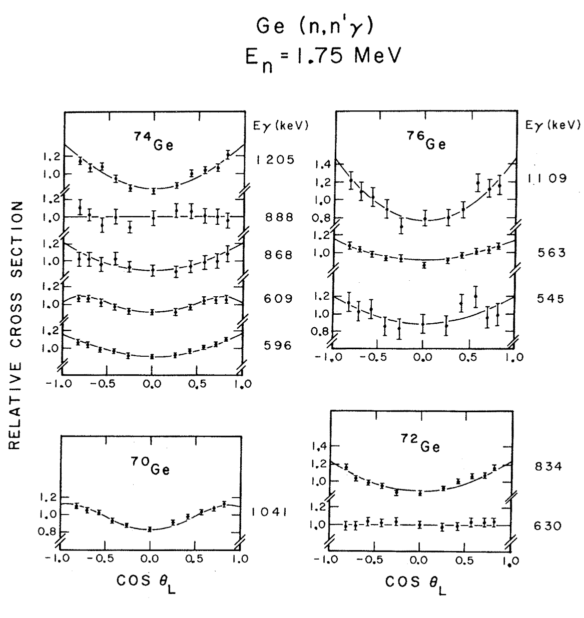

FIG. 6. γ-ray angular distributions. Solid curves are least-squares fits to the measurements. The error bars indicate relative uncertainties of the data points. WHF-model calculations are indistinguishable from the least-squares fits.

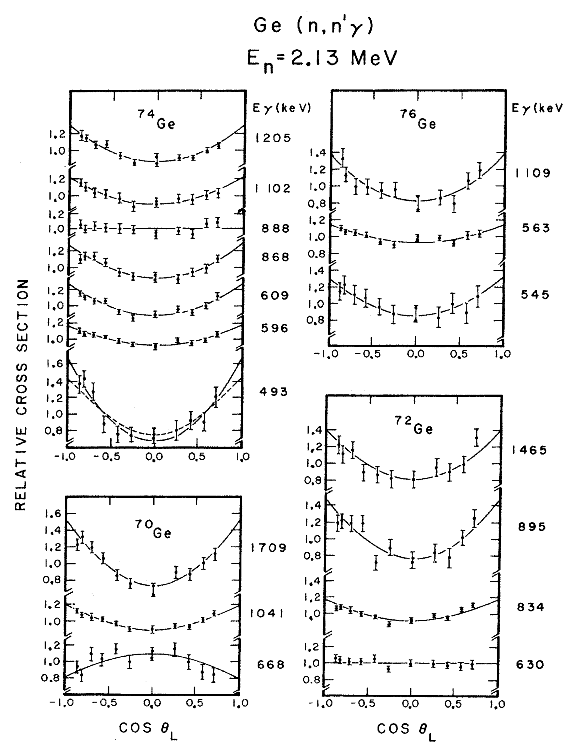

FIG. 7. γ-ray angular distributions. See caption of Fig. 6 for descriptions. The WHF calculations are represented by the dashed curve when they deviate from the least-squares fits. See text for explanation.

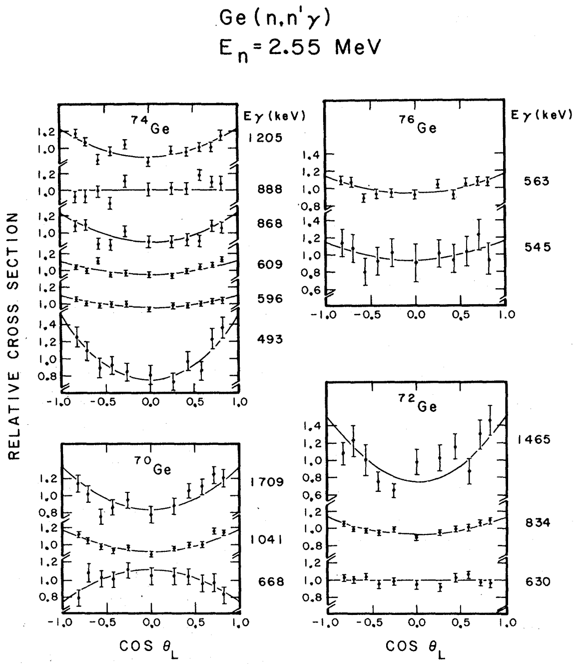

FIG. 8. γ-ray angular distributions. See caption Fig. 6 for descriptions.

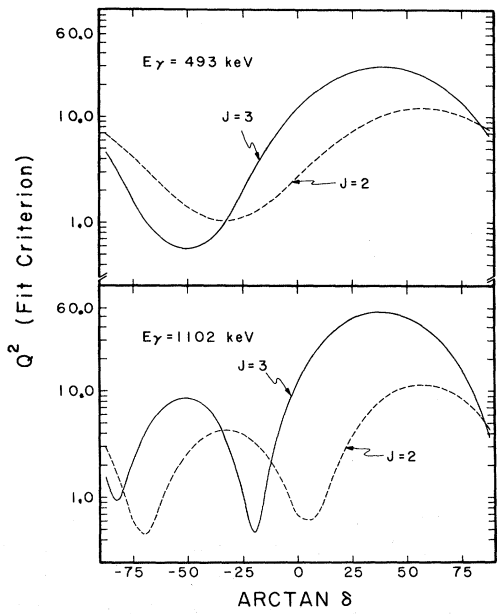

FIG. 9. Criterion of statistical consistency, Q^2 versus δ. The calculations have been computed to fit the angular-distribution measurements at $E_n = 2.13$ MeV.

computer code[26] *AC*5. The excited-state alignment may also be calculated with the WHF model, and δ is determined from the calculation and the $2^+ \rightarrow 2^+$ angular distribution. The δ values have been determined by both methods at at least two of the three neutron energies of Figs. 6–8. The results are summarized in Table II, where the comparisons in all four isotopes confirm the validity of the WHF formalism as a tool for analyzing angular distributions. The $2_2^+ \rightarrow 2_1^+$ mixed multipole transition of ^{72}Ge was determined as $\delta^2 \geqslant 19$ by Coleman[27] and as $\%(E2) \gtrsim 90$ by Arns and Wiedenbeck.[28] For the corresponding ^{74}Ge transition, δ was reported by Yamazaki, Ikegami, and Sakai[29] and Eichler *et al*[19] to be $-(1^{+9}_{-0.5})$ and $-3.4^{+1.1}_{-1.6}$, respectively. These are consistent with present results in Table II.

The branching ratios for the decay of the second 2^+ state are obtained and given in Table III along with some earlier results[17] where available.

The 1698-*keV level of* ^{74}Ge. The 1698-keV level of ^{74}Ge has been observed by some investigators[15,19,21] and rejected by others.[20,22] As stated in the previous section, this work definitely confirms the level at that energy and establishes the principal decay modes. These have not been reported before. The branching ratio of these two transitions is given in Table III. Analysis of both the 1102- and 493-keV transitions can be fitted with $J = 2, 3$ assigned to the 1698-keV level. The quality of the angular-distribution fits and the dependence on mixing ratio δ is shown in Fig. 9. The sum of the squares of deviations of calculated from measured points is normalized to the number of points and the experimental relative uncertainties[30] and then plotted as Q^2. The calculations use the excited-state alignments of the WHF formalism, so that the mixing ratio δ is the only free parameter. Since values of $Q^2 \lesssim 1$ indicate statistical consistency between calcula-

TABLE II. Mixing ratios δ for the $2_2^+ \rightarrow 2_1^+$ transitions in even-*A* Ge. PPM refers to population parameter method and WHF refers to the Wolfenstein-Hauser-Feshbach statistical-model calculations. See text for a description of the two methods.

Isotope	PPM	WHF
^{70}Ge	$+6^{+10}_{-3}$ or $+0.6 \pm 0.5$	$+7 \pm 4$ or $+0.75 \pm 0.25$
^{72}Ge	-5^{+3}_{-1} or $+0.10 \pm 0.1$	-7 ± 2 or $+0.3 \pm 0.05$
^{74}Ge	-3 ± 1 or -0.1 ± 0.2	-2.3 ± 0.3 or 0.0 ± 0.1
^{76}Ge	-3.5 ± 1.5 or -0.1 ± 0.3	-1.8 ± 0.3 or 0.1 ± 0.1

TABLE III. Branching ratios of γ-ray pairs.

Isotope	E_γ (keV)	Branching ratio This work	Previous report (Ref. 14)
^{70}Ge	668	51	53
	1709	49	47
^{72}Ge	630	86	89
	1465	14	11
^{74}Ge	609	65	68
	1205	35	32
^{74}Ge	493	39	
	1102	61	
^{76}Ge	545	58	
	1109	42	

tions and measurements, the assignment $J=2$ provides a barely acceptable fit to the 493-keV transition while $J=3$ provides an excellent fit to both transitions. The level therefore can be definitely assigned as 3 or 2 with the tentative choice being $J=3$. The mixing ratios of the 493- and 1102-keV transitions are then determined to be $\delta = 1.3 \pm 0.4$ and -0.34 ± 0.05, respectively.

In a very recent report Magruder and Smither[31] propose a close doublet, separated by 2 keV, near 1700 keV. The doublet is proposed because two sets of cascade decays from a level or levels near 1700 keV are observed, one having 596.3- and 1103.4-keV transitions and the other having 1204.9- and 493.0-keV transitions. The 1.8-keV difference in the sums of the cascades is the evidence[31] for the doublet. In this work we find transitions of 493.0, 595.8, 608.5, 1102.5, and 1205.5 keV, in excellent agreement with all energies of Ref. 31 except that of the 1102.5-keV transition. The cascade sums of the present experiment are consistent with a single level at 1698 keV to within 0.3 keV. The reported[31] energy of 1103.4 keV is for a line which is not apparently resolved from an 1109-keV transition in Fig. 3 of Ref. 31. The line is resolved in Fig. 2 of the present work. We note that the angular distributions of the 493.0- and 1102.5-keV transitions are consistent with the suggestion that they come from a single level and the neutron inelastic scattering cross section inferred from the production cross sections of the two transitions is consistent with that expected for a single level. The cross sections and expectations are discussed in the next section. For the reasons given, we conclude that a single level is present near 1700 keV, at 1698 keV. The fact that this level is found to be fed strongly in the ^{73}Ge(n,γ) reaction[31] supports our

TABLE IV. Production cross sections of the γ rays in mb/atom of isotope.

Isotope	E_γ (keV)	E_n (in MeV) 1.75	2.13	2.55
^{70}Ge	668		105 ± 11	154 ± 16
	1041	682 ± 68	814 ± 81	1087 ± 118
	1709		92	163 ± 16
^{72}Ge	630	165 ± 17	248 ± 25	406 ± 41
	834	827 ± 83	937	1170 ± 117
	895		45 ± 5	83 ± 9[a]
	1230			22 ± 3[a]
	1465	18 ± 2[a]	47 ± 5	85 ± 9
^{74}Ge	493		51 ± 5	136 ± 14
	596	1129 ± 113	1186 ± 119	1390 ± 140
	609	235 ± 24	220 ± 22	343 ± 34
	868	65 ± 6	109 ± 11	151 ± 15
	888	54 ± 5	92 ± 9	123 ± 12
	1102	10 ± 1[a]	78 ± 8	102 ± 10[a]
	1205	106 ± 11	146 ± 15	171 ± 17
	2198			16 ± 2[a]
^{76}Ge	545	202 ± 20	206 ± 21	220 ± 22
	563	1044 ± 114	1109 ± 111	1200 ± 120
	1109	152 ± 15	142 ± 14	244 ± 25

[a]The cross section obtained by the form $4\pi(d\sigma/d\omega)$ (90°), without anisotropy correction.

TABLE V. Measurements of neutron inelastic scattering cross sections of Ge, $\sigma(M)$, and results of the WHF calculations, $\sigma(T)$, in mb/atom of isotope. Energy levels are in keV. J^π are the spin and parity assigned to the level. E_n are in MeV.

Isotope	Level	J^π	$E_n=1.75$ $\sigma(M)$	$\sigma(T)$	$E_n=2.13$ $\sigma(M)$	$\sigma(T)$	$E_n=2.55$ $\sigma(M)$	$\sigma(T)$
^{70}Ge	1040	2^+	682	675	709	704	933[a]	850[a]
	1216	0^+		162		184		167
	1709	2^+			197	223	317	341
	2153	4^+						74
	2157	2^+						135
	2307	0^+						20
	2452	3^+						18
^{72}Ge	691	0^+		268		248		226
	834	2^+	662	645	645	663	660	637
	1465	2^+	182	158	294	302	491	374
	1730	4^+			45	74	83	150
	2065	3^+				13	22	34
	2402	2^+						4
^{74}Ge	596	2^+	765	741	688	698	672	672
	1205	2^+	341	307	315	398	377	432
	1464	4^+	65	43	109	119	151	197
	1484	0^+	54	59	92	100	123	113
	1698	3^+	10	12	129	124	238	223
	2198						16	84
^{76}Ge	563	2^+	842	795	903	796	980	794
	1109	2^+	354	399	348	500	464	540
	1412	4^+		61		162		251
	1908	2^+				74		217

[a]Including contributions of cascades from the 2153- and 2157-keV levels.

tentative assignment of spin 3 for the level.

Cross sections and the WHF *model.* The differential γ-ray production cross sections of Fig. 4 have been integrated over angles with the aid of angular distributions to obtain the production cross sections of Table IV, and from these and the γ-ray branching ratios the neutron inelastic scattering cross sections of Table V are determined.

Recently Lister and Smith[32] have completed an analysis of their neutron total, elastic, and inelastic scattering cross sections of the even-A Ge isotopes, and provided a complex-potential representation of the data. We have taken this potential, designed especially for the Ge $+n$ system, and used it to calculate neutron inelastic scattering cross sections. Two modifications to the potential were made. Test calculations gave inelastic scattering cross sections altered by 1% or less when the spin-orbit term was ignored. To simplify the many calculations needed, all results reported here are calculated ignoring the spin-orbit term. The second, and more significant modification to the potential was to make its imaginary or absorptive part dependent on the neutron energy. The form $W = 2 + 1.5E_n$ was used. The energy-dependent imaginary part of the potential had been introduced years ago by Lind and Day[33] and used by Towle and Gilboy[34] to fit neutron inelastic scattering cross section and has invariably been required to fit measurements from this laboratory[5,7,35] over the last several years. Since the inelastic scattering measurements of Ref. 32 spanned a small neutron energy interval, that analysis would not have been sensitive to the variations of W.

The WHF-model calculations using this potential are shown in Table V in comparison with the measurements, and give an excellent fit to the inelastic scattering cross sections at all three incident neutron energies and in all four Ge isotopes. Generally the deviations between calculations and measurements are about 10% or less with a few deviations of 20–25%.

Since this potential was so successful for the cross sections of the even-A Ge isotopes, we elected to test its validity for the neighboring odd-A Ga isotopes.

The level-width fluctuation corrections proposed[3] for the WHF model have the property that they reduce the calculated inelastic scattering cross sections for even-A isotopes, when only a few decay channels are open. If the present potential has been tailored to "reduced" even-A Ge cross sections, it should then underestimate the cross sections in the neighboring odd-A Ga isotopes. These

TABLE VI. Measurements of neutron inelastic scattering cross sections of Ga, $\sigma(M)$, and results of the WHF calculations using the Ge potential, $\sigma(T)$, in mb/atom of isotope. See caption, Table V, for definitions of the other symbols.

Isotope	Level	J^π	$E_n = 0.80$ $\sigma(M)$	$E_n = 0.80$ $\sigma(T)$	$E_n = 1.50$ $\sigma(M)$	$E_n = 1.50$ $\sigma(T)$	$E_n = 1.78$ $\sigma(M)$	$E_n = 1.78$ $\sigma(T)$	$E_n = 2.50$ $\sigma(M)$	$E_n = 2.50$ $\sigma(T)$
^{69}Ga	319	$1/2^-$	85	191	99	184	138	172	60	148
	573	$5/2^-$	127	223	209	326	255	311	338	282
	873	$3/2^-$			175	166	202	185	199	184
	1027	$(9/2^+)$			57	89	73	116	76	153
	1108	$(3/2^-)$			115	95	185	129	222	152
	1334	$7/2^-$			28	48	89	90	129	151
	1527	$(9/2^-)$					28	28	50	92
	1724	$(3/2^-)$						9	66	75
	1893	$(1/2^-)$							41	29
	1924	$(5/2^-)$								64
	2025	$(7/2^-)$							17	49
^{71}Ga	390	$1/2^-$	110	133	125	145	182[a]	164[a]	169[a]	192[a]
	487	$5/2^-$	169	252	194	284	218	256	295	233
	512	$3/2^-$	151	189	235	236	278	218	278	197
	911	$(3/2^-)$			103	126	159	140	220	144
	965	$(7/2^-)$			85	130	129	139	131	162
	1108	$7/2^-$			75	89	86	108	166	144
	(1395	$5/2^-)$				22		58		107
	1474	$(7/2^-)$						42	53	99
	1487	$(5/2^-)$						42	35	97
	1495	$9/2^+$					60	29	25	73
	1700	$(7/2^-)$						10	83	72
	1750	$(5/2^-)$								66
	(2010	$3/2^-)$							40	34

[a]Including a contribution from the 387-keV cascade.

have many decay channels open, and the fluctuation corrections are thus insignificant. The relevant comparison is shown in Table VI, where the Ga measurements of Ref. 5 are compared to the WHF calculations using the Ge potential. The comparisons or fit of Table VI is very similar to the fit obtained in Ref. 5 with a different potential determined in that work. The comparison made near the lowest neutron energy used in this experiment, 1.78 MeV, shows that the unmodified WHF model has the same degree of success in the neighboring odd- and even-A nuclei. The Ga cross sections certainly are not underestimated by the calculations using the Ge potential.

SUMMARY

The γ-ray production cross sections and neutron inelastic scattering cross sections have been obtained for incident neutron energies at 1.75, 2.13, and 2.55 MeV. The γ-ray intensities and angular distributions have been employed to determine branching ratios and multipole mixing ratios in the four even-A Ge isotopes. A tentative spin assignment has been made for the previously unassigned 1698-keV level of ^{74}Ge. The γ-ray energy measurements provide level excitation energies which agree with those of previous investigators to within 1 keV. The analysis of $M1$, $E2$ mixing ratios of four $2^+ \rightarrow 2^+$ transitions provided an unusual and stringent test of predictions of the WHF model. The success of the unmodified WHF model in determining mixing ratios and neutron inelastic scattering cross sections is as complete as the accuracy of the measurements permits.

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