Radiative strength functions of germanium from thermal neutron capture

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Thermal neutron capture gamma rays from germanium have been studied using an internal irradiation facility and a pair spectrometer. Energy and intensity of transitions in four germanium isotopes were determined and their level and separation energies inferred. The separation energies are S_n (^{71}Ge)=7415.95±0.05 keV, S_n (^{73}Ge)=6782.94±0.05 keV, S_n (^{74}Ge)=10 196.31±0.07 keV, and S_n (^{75}Ge)=6505.26±0.08 keV. The $E1$ reduced strength function, $\langle \Gamma_{\gamma i} D^{-1} E_i^{-3} A^{-2/3} \rangle$, of these germanium isotopes was found to be $(1.8\pm0.5)\times10^{-9}$ MeV^{-3}, a value lower than the global average. The $M1$ strength function $\langle \Gamma_{\gamma i} D^{-1} E_i^{-3} \rangle$ of ^{74}Ge was estimated to be $(20\pm9)\times10^{-9}$ MeV^{-3} which agrees with the global average. The average $\overline{B(E2)\downarrow}$ of ^{74}Ge using the present thermal data and the previous resonance data from literature was found to be $18\pm10 e^2$ fm^4 MeV^{-1} which agrees with the value predicted by the Axel-Brink hypothesis.

I. INTRODUCTION

An investigation of the electric quadrupole strength throughout the entire mass region has been ongoing here for some time.[1–7] A search has been underway for primary $E2$ transitions in various nuclei in order to increase the number of known $E2$ transitions[8,9] in thermal neutron capture. A favorable case in which three such transitions can arise is the ^{73}Ge$(n,\gamma)^{74}$Ge reaction. Although there are resonance data[10] on $E2$ transitions in ^{74}Ge, the thermal data[11] are incomplete and lack statistical and calibration precision. Measurements made with the objective of observing $E2$ transitions require the acquisition of data with sensitivity and precision markedly higher than that encountered in typical (n,γ) studies. The possession of such high-quality spectra permits the extraction of additional and important structure information.

The systematics associated with dipole radiative strength functions of nuclei is useful in nuclear modeling. Such information is available[10] for ^{74}Ge but is not available for the isotopes ^{71,73,75}Ge. With high sensitivity, the probability of failing to observe the transitions is reduced. As a consequence, radiative strength estimation will be less biased toward high values. Recent compilations[12–15] on ^{71}Ge, ^{73}Ge, ^{74}Ge, and ^{75}Ge help in the identification of $E1$ transitions. The $E1$ strength function can be determined using these transitions in a combined way. It would be interesting to compare this value with that obtained in the resonance work[10] where fewer unambiguous $E1$ transitions in ^{74}Ge were observed for several neutron resonances. The thermal data can also be utilized to explore the influence of the giant dipole resonance (GDR) and giant quadrupole resonance (GQR) on the $E1$ and $E2$ strength functions, respectively.

For ^{74}Ge, in the compilation of Singh and Viggars[14] there are many cases in which spins of levels are given a wide range. Knowledge of the quadrupole strength might help to reduce the spin range even after considering Porter-Thomas fluctuations.[16]

Precise Q values of (n,γ) reactions are used to calculate the odd-even energy shift and for developing more sensitive models of binding-energy systematics. For the isotopes ^{71,73,75}Ge, the separation energies[17] lack precision and for ^{74}Ge, there is a discrepancy in the literature[11,14,17] by as much as 7 keV. Increasing the precision in the separation energies and resolving the existing discrepancy was another motivation behind the present study. A recently reported calibration standard[18] allowed deduction of separation and level energies with a marked improvement in precision over previous investigations as compiled in Refs. 12–15.

II. EXPERIMENTAL PROCEDURE

The present study was conducted at the tangential irradiation facility[19] of the McMaster University Nuclear Reactor where the flux at the sample position was about 5×10^{12} cm^{-2}s^{-1}. After collimation, the capture radiation was observed 5 m from the target by means of a pair spectrometer. The intrinsic germanium detector, centered within a quadrisected NaI(Tl) annulus displayed a resolution (FWHM) of 2.1–5.0 keV between the energy regions 2500 and 8300 keV. For acceptance, an event was required to be in time coincidence with annihilation photons observed in opposite quadrants of the annulus, and in anticoincidence with the remaining quadrants. The latter condition was included in order to suppress events which emit bremsstrahlung[20] thereby reducing the background continuum. Encodement of acceptable pair events was achieved through use of a NS621 8^k analog-to-digital converter (ADC) with accumulation in a NOVA computer.[21] Dual-point stabilization was used to ensure the acquisition of drift-free data over the entire counting period.

Initially a 4.0-g sample of 99.9999% pure Ge powder (Aldrich Chemical Company, Inc.) was placed within a graphite capsule, inserted into the irradiation position, and counted for a total of 260 h. This measurement was followed by irradiation of a well-mixed sample consisting of 0.761 g of melamine ($C_3H_6N_6$) and 2.050 g of germanium in order to obtain both the energy and the intensity calibration through use of the well-studied $^{14}N(n,\gamma)^{15}N$ reaction.[18] This sample was counted for 140 h. Another calibration experiment with a sample of 0.859 g of melamine and 1.481 g of germanium was conducted for 130 h.

III. DATA ANALYSIS

A portion of the Ge(n,γ) spectrum above 4700 keV is shown in Fig. 1. Initially, the distortion in the data introduced by small-angle scattering of the annihilation photons within the Ge detector was removed through use of an appropriate digital filter.[22] The centroids and areas of the peaks were then determined using a nonlinear least-squares fitting procedure in which a simple Gaussian line was assumed. The energies of photons from capture by nitrogen[18] were used as primary standards to construct the relation between the energy and pulse height. Energies of prominent isolated transitions in germanium were then determined from this relation and used as secondary standards for the calibration of the pure germanium spec-

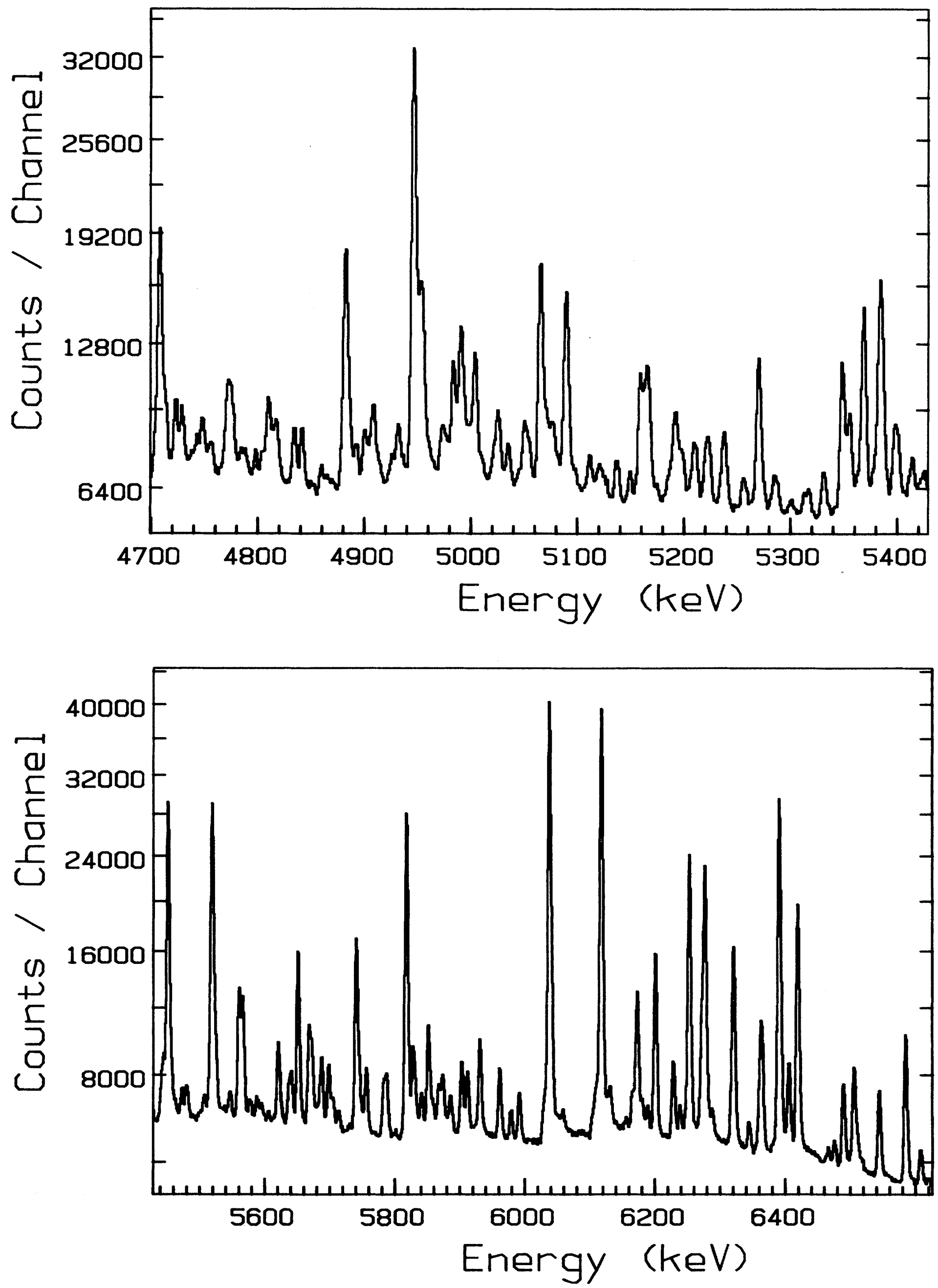
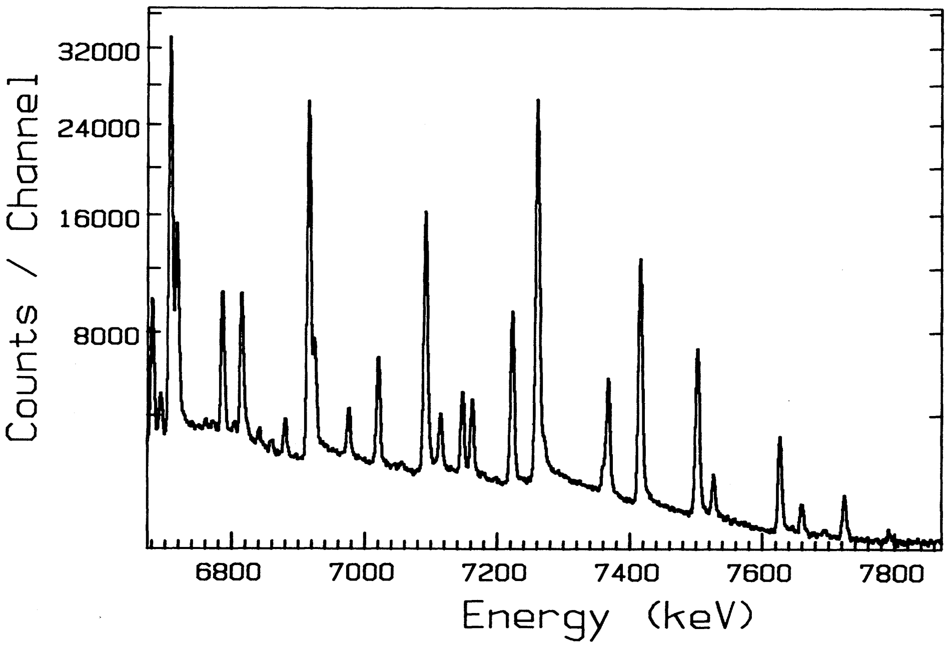


FIG. 1. The upper portion of the Ge(n,γ) spectrum. The $E2$ transitions at 9600, 8992, and 7999 keV are indicated. The ordinate is the square root of the counts per channel thus yielding a constant precision.

trum. The fitting was then repeated for the pure sample in order to obtain estimates for the energies of the remaining transitions. A relative efficiency curve was constructed from the melamine data using the published nitrogen intensities.[18] This was then used to calculate the relative intensities for the germanium transitions. Finally, absolute intensities were determined using the total cross sections of the germanium isotopes[23] and the recently published value for the ^{14}N cross section.[24]

The energies, intensities, and decay modes of the transitions observed for germanium are listed in Tables I–IV. The energy errors were estimated by combining the uncertainty in the centroid with that from the calibration. The same procedure was used for relative intensity error estimates using the area uncertainty with that of the efficiency curve. For absolute intensities, errors must be adjusted to include the additional contributions arising from the uncertainty in the germanium and nitrogen



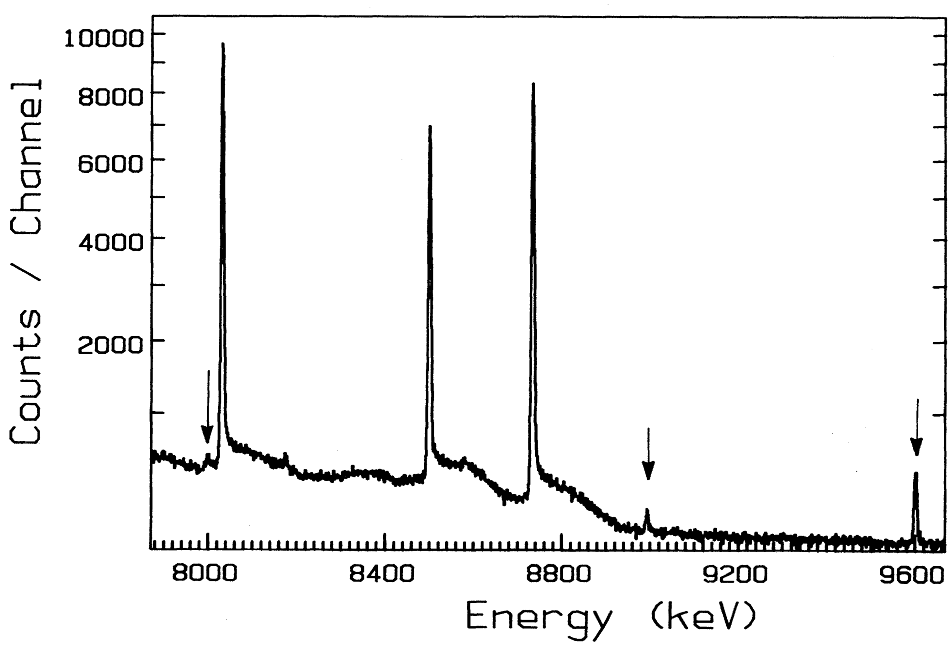


FIG. 1. (*Continued*).

TABLE I. Energy and intensity of gamma rays in $^{70}Ge(n,\gamma)^{71}Ge$.

Energy[a] (keV)		Absolute[b] Intensity (per $10^2 n$ capture)		Level (keV) From	To
7415.58	0.04	1.95[e]	0.09	7416	0
6915.68	0.04	3.83[e]	0.16	7416	500
6707.45	0.04	4.80[e]	0.21	7416	708
6607.45	0.14	0.20	0.01	7416	808
6584.32	0.04	1.10[e]	0.05	7416	831
6319.99	0.04	1.86[e]	0.08	7416	1096
6276.25	0.05	2.62	0.14	7416	1139
6116.86	0.04	5.30	0.23	7416	1299
6037.21	0.06	5.49	0.29	7416	1378
5873.16	0.23	0.36	0.02	7416	1543
5817.15	0.04	3.49[e]	0.15	7416	1599
5672.30	0.27	0.45	0.05	7416	1743
5450.71	0.07	3.50[e]	0.16	7416	1965
5383.88	0.09	1.62	0.07	7416	2032
5269.60	0.04	0.98	0.05	7416	2147
5191.20	0.11	0.71	0.05	7416	2225
5158.80	0.11	0.87	0.07	7416	2258
5064[c]		1.04	0.05	7416	2352
4900.49	0.31	0.32	0.03	7416	2515
4989[d]		0.23	0.03	7416	2427
4951[c]		0.41	0.08	7416	2465
4881.81	0.06	2.09	0.13	7416	2534

[a]Error in energy is due to statistics and the calibration.
[b]Error in absolute intensity is due to statistics and efficiency calibration. To this, a 6% error (Ref. 23) due to the uncertainty in σ_γ of ^{70}Ge has to be added.
[c]Correction of intensity for interference with ^{74}Ge is made with the help of relative intensities from the compilations of Refs. 12 and 14.
[d]Correction of intensity for interference with ^{75}Ge is made with the help of relative intensities from the compilations of Refs. 15 and 12.
[e]Intensities used to determine the $E1$ strength function.

TABLE II. Energy and intensity of gamma rays in $^{72}Ge(n,\gamma)^{73}Ge$.

Energy[a] (keV)		Absolute[b] Intensity (per $10^2 n$ capture)		Level (keV) From	To
6717[c]		1.43	0.05	6783	67
6418.60	0.04	4.80[d]	0.09	6783	364
6390.17	0.04	10.52[d]	0.11	6783	392
6227.89	0.16	1.54	0.14	6783	555
5867.12	0.23	0.75	0.23	6783	916
5850.97	0.08	2.21	0.11	6783	932
5740.21	0.04	4.82[d]	0.06	6783	1042
5650.86	0.08	4.14[d]	0.11	6783	1132
5518.30	0.04	9.35[d]	0.17	6783	1264
4890.71	0.37	0.62	0.17	6783	1892

[a]Error in energy is due to statistics and the calibration.
[b]Error in absolute intensity is due to statistics and efficiency calibration. To this, a 9% error (Ref. 23) due to the uncertainty in σ_γ of ^{72}Ge has to be added.
[c]Correction of intensity for interference with ^{74}Ge is made with the help of relative intensive from the compilations of Refs. 13 and 14.
[d]Intensities used to determine the $E1$ strength function.

TABLE III. Energy and intensity of gamma rays in $^{73}Ge(n,\gamma)^{74}Ge$.

Energy[a] (keV)		Absolute[b] Intensity (per $10^2 n$ capture)		Level (keV) From	To
9599.96	0.10	0.06	0.003	10 196	596
8992.22	0.18	0.008	0.0001	10 196	1204
8732.01	0.04	1.02[g]	0.04	10 196	1464
8498.64	0.04	0.80[g]	0.04	10 196	1697
8030.47	0.04	1.07[g]	0.05	10 196	2165
7998.76	0.77	0.011	0.003	10 196	2197
7659.43	0.12	0.063[e]	0.004	10 196	2536
7626.39	0.05	0.27[g]	0.01	10 196	2569
7526.24	0.21	0.09[g]	0.02	10 196	2670
7501.90	0.04	0.67	0.03	10 196	2694
7367.16	0.04	0.43[g]	0.02	10 196	2829
7359.97	0.17	0.073	0.004	10 196	2836
7269.01	0.28	0.12	0.01	10 196	2927
7260.13	0.04	2.54[e]	0.11	10 196	2936
7222.17	0.04	0.78	0.03	10 196	2974
7161.73	0.05	0.27[g]	0.01	10 196	3034
7147.15	0.04	0.32[g]	0.01	10 196	3049
7114.19	0.20	0.18[g]	0.01	10 196	3082
7091.21	0.04	1.46[e]	0.07	10 196	3105
7020.36	0.04	0.46[e]	0.02	10 196	3175
6924.33	0.06	0.49	0.02	10 196	3271
6879.81	0.07	0.13[g]	0.01	10 196	3316
6859.60	0.28	0.039	0.004		
6840.81	0.25	0.05	0.01		
6821.87	0.36	0.054	0.004	10 196	3374
6814.38	0.04	0.72[e]	0.03	10 196	3381
6803.39	0.29	0.04	0.01	10 196	3392
6785.64	0.04	0.71[g]	0.03	10 196	3410
6771.31	0.44	0.04	0.01	10 196	3424
6760.45	0.40	0.04	0.01	10 196	3435
6717[c]		0.89	0.95	10 196	3479
6692.64	0.19	0.21	0.01		
6680.18	0.07	0.72[g]	0.03	10 196	3516
6543.76	0.04	0.36[g]	0.02	10 196	3652
6510.50	0.23	0.11	0.01	10 196	3685
6489.03	0.08	0.36	0.02	10 196	3707
6475.13	0.09	0.089	0.005	10 196	3721
6465.61	0.25	0.048	0.004		
6419[c]		0.34	0.05		
6405.04	0.09	0.38[g]	0.02	10 196	3791
6383.24	2.28	0.022	0.003		
6363.98	0.08	0.45[g]	0.02	10 196	3832
6360.75	0.10	0.36[g]	0.02	10 196	3835
6344.00	0.22	0.10	0.01		
6286.13	1.38	0.10	0.01		
6271.19	0.11	0.57	0.03		
6238.36	0.32	0.14	0.02	10 196	3957
6200.19	0.04	1.04	0.05	10 196	3996
6179.87	0.22	0.14	0.01		
6172.24	0.04	0.76	0.03	10 196	4024
6165.54	0.17	0.18	0.01	10 196	4030
6153.13	0.37	0.003	0.001		
6129.50	0.59	0.16	0.02	10 196	4066
6057.61	3.01	0.03	0.01	10 196	4138
6029.95	0.61	0.18	0.02		
5991.05	0.07	0.21	0.01	10 196	4205
5978.33	0.11	0.12	0.01	10 196	4218

TABLE III. (*Continued*).

Energy[a] (keV)		Absolute[b] Intensity (per $10^2 n$ capture)		Level (keV) From	To
5960.93	0.05	0.33[g]	0.02	10 196	4235
5902.41	0.07	0.33	0.02		
5884.94	0.57	0.12	0.01		
5857.49	1.21	0.09	0.01	10 196	4338
5840.38	0.57	0.13	0.01		
5827.99	0.14	0.42	0.05	10 196	4368
5787.08	0.05	0.25	0.01	10 196	4409
5782.43	0.06	0.22	0.01	10 196	4413
5755.64	0.10	0.30	0.02	10 196	4440
5745.5[d]	0.2	0.15	0.01		
5704.29	0.41	0.082	0.005		
5697.90	0.24	0.25	0.02		
5686.66	0.16	0.31	0.04		
5667.98	0.11	0.43	0.04	10 196	4528
5639.27	0.34	0.16	0.02		
5634.75	1.00	0.08	0.01		
5624.45	0.41	0.07	0.01		
5605.31	0.41	0.03	0.01		
5594.12	0.28	0.07	0.02		
5587.47	0.22	0.10	0.03		
5577.25	0.28	0.09	0.02		
5565.45	0.04	0.60	0.03	10 196	4630
5559.84	0.04	0.68	0.03		
5546.00	0.19	0.10	0.01		
5523.29	0.19	0.41	0.04		
5507.55	0.91	0.05	0.04		
5479.79	0.10	0.15	0.01		
5472.61	0.12	0.12	0.01		
5442.95	0.33	0.30	0.05		
5398.25	0.20	0.29	0.03		
5379.02	1.06	0.13	0.01		
5368[d]		2.45	0.18		
5354.85	0.19	0.33	0.03	10 196	4841
5348.12	0.10	0.56	0.03		
5330.65	0.07	0.17	0.02		
5316.79	0.07	0.07	0.005		
5312.47	0.10	0.06	0.004		
5300.10	0.20	0.03	0.01		
5285.34	0.13	0.12	0.01		
5255.63	0.16	0.11	0.01		
5237.10	0.04	1.42	0.09		
5221.53	0.07	0.35	0.03	10 196	4974
5209.33	0.07	0.31	0.03		
5197.75	0.19	0.22	0.02		
5184.69	0.44	0.20	0.02		
5165.18	0.08	0.61	0.04		
5148.47	0.48	0.09	0.02		
5125.28	0.41	0.03	0.01		
5120.30	0.22	0.07	0.02		
5111.03	0.13	0.10	0.02		
5075.96	0.16	0.16	0.01		
5070.23	0.16	0.20	0.01		
5065[f]		0.35	0.02	10 196	5131
5053.82	0.18	0.11	0.01		
5049.64	0.11	0.39	0.02		
5034.38	0.14	0.18	0.05		
5025.23	0.10	0.30	0.06		

TABLE III. (*Continued*).

Energy[a] (keV)		Absolute[b] Intensity (per $10^2 n$ capture)		Level (keV) From	To
4972.67	0.18	0.10	0.01		
4952[f]		0.69	0.04		
4931.31	0.29	0.19	0.03		
4914.30	0.78	0.10	0.06		
4907.82	0.19	0.37	0.05		
4858.71	0.16	0.09	0.06		
4840.78	0.06	0.20	0.02		
4833.62	0.05	0.21	0.03		
4808.84	0.08	0.76	0.25		
4803.43	0.06	0.53	0.23		
4797.80	0.06	0.39	0.16		
4788.00	0.43	0.07	0.02		
4783.69	0.50	0.07	0.02		
4775.19	0.14	0.29	0.02		
4771.03	0.10	0.37	0.03		
4755.59	0.20	0.06	0.01		
4742.36	0.22	0.05	0.01		
4728.41	0.16	0.26	0.03		
4722.22	0.13	0.32	0.03		
4693.91	0.35	0.10	0.02		
4686.25	0.04	0.77	0.05		
4676.54	0.16	0.15	0.03		
4667.62	0.24	0.13	0.02		
2331.85	0.31	0.21	0.04		
2327.82	0.16	0.39	0.05		
2313.59	0.13	0.72	0.08		
2257.74	0.14	0.45	0.04	3721	1464
2215.02	0.74	0.25	0.14		
2097.77	0.07	0.56	0.09	2694	596
2073.71	0.04	1.17	0.10	2670	596
2014.28	0.05	0.63	0.06	3479	1464
2010.87	0.30	0.11	0.03		
1971.24	0.14	0.13	0.02	3175	1204
1940.48	0.04	2.96	0.18	2536	596
1640.66	0.14	0.83	0.19	3105	1464
1635.49	0.14	1.11	0.21		
1631.56	0.12	1.18	0.19	2228	596
1617.48	0.12	1.33	0.27	3081	1464
1513.85	0.23	0.54	0.10		
1509.73	0.05	2.47	0.17	2973	1464
1471.61	0.05	3.60	0.29	2936	1464

[a]Error in energy is due to statistics and the calibration.
[b]Error in absolute intensity is due to statistics and efficiency calibration. To this, a 14% error (Ref. 23) due to the uncertainty in σ_γ of ^{73}Ge has to be added.
[c]Correction of intensity for interference with ^{73}Ge is made with the help of relative intensities from the compilations of Refs. 13 and 14.
[d]Correction of intensity for interference with ^{75}Ge is made with the help of relative intensities from the compilations of Refs. 15 and 14.
[e]Intensities used to determine the $E1$ strength function.
[f]Correction of intensity for interference with ^{71}Ge is made with the help of relative intensities from the compilations of Refs. 12 and 14.
[g]Intensities used to determine the $M1$ strength function.

cross sections. Isotopic and decay-mode assignments were made through use of previous studies.[12–15]

IV. RESULTS AND DISCUSSIONS

A. Intensity of transitions

The intensity of the transitions in ^{74}Ge found here are, on an average, 70% higher than those reported by Magruder *et al.*[11] Later studies[25] of ^{74}Ge, as well as for the isotopes ^{71}Ge, ^{73}Ge, and ^{75}Ge, were[12,13,15] normalized to the work of Magruder *et al.*, and hence are not useful in resolving this discrepancy. The need to arrive at a conclusion regarding this very significant difference is clear since several isotopes are involved.

Initially it was decided to repeat the absolute calibration experiment by making and irradiating a second sample. The results of this were in excellent agreement with our original calibration. As a result it was necessary to look at other possibilities for the intensity difference.

The earlier authors[11] used the ^{12}C and ^{73}Ge cross sections to normalize to absolute intensity while we used ^{14}N and ^{73}Ge. A check on the cross sections used indicates that complete consistency exists between the two investigations thereby eliminating this as a possibility for the discrepancy. Examination of the spectrum shown in Fig. 1 reveals that there is a strong ^{74}Ge transition about 6-keV higher in energy than the 4946-keV transition of carbon. If Magruder *et al.* failed to identify this interference and included it with the carbon intensity, their absolute intensity would be too low. An examination of their data suggests the system resolution and response were inadequate to reveal this interference and it seems quite possible that this is the source of the discrepancy.

B. Neutron separation energy

To determine the neutron separation energy of ^{71}Ge, recoil-corrected energies of 12 primary transitions have been added to the corresponding precisely known energy levels.[12] In the cases of ^{73}Ge and ^{75}Ge, six and four primary transitions have been used, respectively, and the energies of the corresponding populated levels were taken from Refs. 13 and 15. For all these nuclei, only strong transitions with no known or potential interference were utilized. To determine the neutron separation energy of ^{74}Ge, the average of the recoil-corrected energies of one transition to the first excited state and three pairs of transitions connecting the capture state with this state were used. The average was added to the precisely known first excited state[14] to find a value of the separation energy. This value was again averaged with the separation energies obtained from two primary transitions at 8732 and 8499 keV and the populated levels at 1464 and 1697 keV. Thus, six transitions and three precisely known levels were used in the calculation. As the energies of excited levels populated by the observed primary transitions in ^{74}Ge abruptly become high and the precision assigned to highly excited states is not always dependable, the aforementioned route has been adopted.

The values of the separation energies of the four isotopes of germanium obtained in this work are presented in Table V along with those reported previously.[17] The present values for ^{71}Ge, ^{73}Ge, and ^{75}Ge agree well with the published values, but show a marked increase in precision. The S_n (^{74}Ge)$=$10 196.3$\pm$0.07 keV of this work is much lower than the 10 200.0$\pm$0.6 keV from the compilation of Wapstra[17] and 10 203.1$\pm$0.9 keV reported by Magruder *et al.*,[11] but is near the value 10 196.00$\pm$0.15

TABLE IV. Energy and intensity of gamma rays in ^{74}Ge(n,γ)^{75}Ge.

Energy[a] (keV)		Absolute[b] Intensity (per $10^2 n$ capture)		Level (keV) From	To
6505.09	0.06	2.83[e]	0.15	6505	0
6252.16	0.04	11.75[e]	0.51	6505	253
5930.34	0.05	2.91[e]	0.13	6505	575
5620.09	0.08	2.35	0.11	6505	885
5745[c]	2	0.61	0.08	6505	760
5368[c]	2	2.45[e]	0.14	6505	1137
5088[c]	1	4.35	0.19	6505	1417
5003.22	0.06	2.27[e]	0.12	6505	1502
4990[d]	2	1.97	0.23	6505	1515
4816.86	0.11	3.06	0.85	6505	1688
4747.63	0.08	0.78	0.12	6505	1757
4707[c]	1	7.14[e]	0.32	6505	1798

[a]Error in energy is due to statistics and the calibration.

[b]Error in absolute intensity is due to statistics and efficiency calibration. To this, a 16% error (Ref. 23) due to the uncertainty in σ_γ of ^{74}Ge has to be added.

[c]Correction of intensity for interference with ^{74}Ge is made with the help of relative intensities from the compilations of Refs. 15 and 14.

[d]Correction of intensity for interference with ^{71}Ge is made with the help of relative intensities from the compilations of Refs. 15 and 12.

[e]Intensities used to determine the $E1$ strength function.

TABLE V. Neutron separation energies of germanium isotopes.

Final nucleus	Neutron separation energy (keV) Present work[a]	Ref. 17
^{71}Ge	7 415.95±0.05	7 415.7±1.1
^{73}Ge	6 782.94±0.05	6 782.4±0.9
^{74}Ge	10 196.31±0.07	10 200.0±0.9
^{75}Ge	6 505.26±0.08	6 505.5±1.6

[a]Based on a ^{15}N Q value of 10 833.30±0.02 keV (Ref. 17).

quoted by Singh and Viggars.[14]

The compiled ^{74}Ge separation energy of Wapstra was derived mainly from the resonance work of Chrien *et al.*[10] The latter authors used a single transition, that to the 596-keV state, to deduce a Q value. This transition in the present work is found to be some 3 keV less than that used by Chrien *et al.* An examination of their transition energies reveals that, above 7.9 MeV, values are systematically higher than ours. In contrast, the values below this energy are in general agreement with the present work. This situation may arise from the fact that they calibrated with ^{64}Cu which has a maximum energy of only 7.9 MeV, a value well below the energy in question. In contrast, the present study utilized calibration energies up to 10.8 MeV, thereby encompassing the ^{74}Ge separation energy.

Singh and Viggars deduced[14] the ^{74}Ge separation energy by appropriate combination of both high- and low-energy transition values that were obtained, via private communication, from Hofmeyr *et al.*[25] The transition energies and separation energy, which are tabulated by Singh and Viggars, are in close agreement with the present findings.

C. Level energies

The recoil-corrected transition energies were subtracted from the separation energy of each isotope to obtain the level energies. The values are presented in Tables VI–IX. For ^{71}Ge, the agreement with the adopted values

TABLE VI. Level energies of ^{71}Ge.

This work energy (keV)		Ref. 12 energy (keV)	
499.91	0.04	499.904	0.006
708.16	0.04	708.198	0.005
808.17	0.14	808.251	0.013
831.30	0.04	831.296	0.008
1095.66	0.04	1095.510	0.006
1139.40	0.05	1139.443	0.007
1298.80	0.04	1298.737	0.015
1378.46	0.06	1378.71	0.05
1542.53	0.23	1542.5	0.2
1598.55	0.04	1598.534	0.017
1743.41	0.27	1743.425	0.016
1965.01	0.07	1965.06	0.07
2031.85	0.09	2031.9	1.1

TABLE VII. Level energies of ^{73}Ge.

This work energy (keV)		Ref. 13 energy (keV)	
364.03	0.06	364.02	0.05
392.47	0.05	392.45	0.06
554.76	0.16	554.91	0.08
915.57	0.23	915.5	0.3
931.72	0.09	931.7	0.3
1042.48	0.05	1043.17	0.19
1131.85	0.09	1131.86	0.06
1264.42	0.06	1264.4	1.0
1892.05	0.37	1892.1	1.6

is generally very good. The level energies 1095.66 and 1378.46 keV are, however, slightly higher. The precision at 2032 keV has been much improved. The agreement with previously reported values and improvement in precision for some levels of ^{73}Ge is evident in Table VI. The value at 1042 keV seems to be slightly lower than the published values. Improvement of precision in some ^{75}Ge levels is achieved. Two new levels at 1688.23 and 1757.47 keV are suggested. These levels are implicitly supported in the work of Groshev *et al.*[26] The level energies for ^{74}Ge for lower excitation agree with the adopted values.[14] For energies above 2550 keV it is found that the previously adopted values are systematically lower than the present values.

D. Electric and magnetic dipole strength function

The average gamma-ray reduced strength functions, $\bar{k}_{E1}$ and $\bar{k}_{M1}$, as defined by Bartholomew *et al.*[27] are

$$\bar{k}_{E1}=\left\langle\frac{\Gamma_{\gamma i}(E1)}{E_i^3 D_\lambda A^{2/3}}\right\rangle \tag{1}$$

and

$$\bar{k}_{M1}=\left\langle\frac{\Gamma_{\gamma i}(M1)}{E_i^3 D_\lambda}\right\rangle , \tag{2}$$

where $\Gamma_{\gamma i}$ denotes the partial radiative width of the capture state for transition i and D_λ the average spacing of accessible neutron resonances at the neutron binding energies. The partial width may be obtained from the intensity I_i by the relation

$$\Gamma_{\gamma i}=\frac{I_i(\bar{\Gamma}_\gamma)_J}{F_J} , \tag{3}$$

where $(\bar{\Gamma}_\gamma)_J$ is the average total radiative width of resonances with spin J and F_J the fractional contribution from resonances of spin J to the total cross section. The values for $(\bar{\Gamma}_\gamma)_J$, D_λ, and F_J for different isotopes of germanium were taken or calculated from data of Ref. 23 and are presented in Table X.

The reduced strength function $\bar{k}_{E1}$ was determined using 24 transitions identified as electric dipole. Of these, 8 transitions are in ^{71}Ge, 5 in ^{73}Ge, 5 in ^{74}Ge, and 6 in

TABLE VIII. Level energies of ^{74}Ge.

This work energy (keV)		Ref. 14 energy (keV)		This work energy (keV)		Ref. 14 energy (keV)	
595.69	0.10	595.852	0.006	3424.67	0.44	3423.8	0.6
1203.50	0.18	1204.209	0.007	3435.53	0.40	3436.3	0.9
1463.75	0.04	1463.76	0.01	3515.81	0.08	3515.45	0.02
1697.15	0.04	1697.15	0.01	3652.24	0.04	3651.90	0.03
2165.37	0.04	2165.26	0.01	3685.50	0.23	3685.42	0.12
2197.08	0.77	2197.97	0.03	3706.98	0.09	3706.8	0.1
2536.46	0.12	2536.31	0.02	3720.88	0.09	3720.79	0.04
2569.50	0.06	2569.33	0.02	3790.97	0.09	3790.70	0.08
2669.66	0.21	2669.63	0.04	3832.04	0.09	3831.99	0.06
2694.00	0.05	2693.77	0.05	3835.27	0.10	3835.28	0.05
2828.76	0.04	2828.51	0.01	3957.67	0.32	3957.89	0.09
2835.94	0.17	2835.94	0.03	3995.85	0.04	3995.77	0.05
2926.91	0.28	2925.46	0.09	4023.79	0.05	4023.37	0.04
2935.79	0.04	2935.48	0.02	4030.49	0.17	4030.49	0.10
2973.77	0.04	2973.48	0.02	4066.54	0.59	4064.68	0.03
3034.20	0.06	3033.91	0.10	4205.00	0.08	4204.75	0.04
3048.79	0.05	3048.56	0.03	4217.73	0.11	4217.34	0.05
3081.75	0.20	3081.32	0.02	4235.12	0.06	4235.3	0.2
3104.74	0.05	3104.50	0.02	4338.57	1.21	4339.71	0.04
3175.60	0.05	3175.37	0.03	4368.08	0.14	4367.2	0.5
3271.63	0.07	3271.25	0.06	4413.64	0.07	4413.46	0.13
3316.16	0.08	3315.71	0.03	4440.43	0.10	4439.97	0.05
3374.10	0.36	3372.4	0.5	4528.10	0.11	4527.85	0.05
3381.59	0.04	3381.46	0.05	4630.63	0.05	4630.37	0.04
3392.59	0.29	3392.62	0.02	4841.25	0.19	4841.04	0.05
3410.34	0.04	3409.96	0.03				

^{75}Ge. All these transitions are marked in Tables I–IV. The isotope ^{74}Ge has two possible capture states with spins 4^+ and 5^+ which necessitates correction for fractional contribution. The experimental value of the $E1$ reduced strength function was found to be $(1.8\pm0.5)\times10^{-9}$ MeV^{-3}. This is lower than the global average[28] $(2.9\pm0.3)\times10^{-9}$ MeV^{-3}. If one averages four $E1$ transitions in ^{74}Ge for each of five neutron resonances[10] and then normalizes using the recent value of level density, a value of 2.5×10^{-9} MeV^{-3} is obtained. From the Porter-Thomas distribution alone, the error in this number is 30%. Thus, the present value of $(1.8\pm0.5)\times10^{-9}$ MeV^{-3} agrees well with that obtained from the resonance capture experiment. This agreement shows that, for determining strength function, the thermal data can be used in lieu of resonance data when the latter is unavailable.

The quantity $\bar{k}_{M1}$ was estimated from the 17 cases that could be classified as $M1$ transitions in ^{74}Ge. The transitions used are marked in Table III. The $M1$ transitions used for this nucleus populate two levels with spin 3^+, seven levels with spin 4^+, and eight levels with spin 3^+ or 4^+ (exact spin is not known). In the present study, calculations were done assuming these eight levels have either spin 3^+ or spin 4^+. Thus two values of the $M1$ strength function for germanium isotopes were obtained, i.e., $(17\pm4)\times10^{-9}$ or $(23\pm6)\times10^{-9}$ MeV^{-3}. (The errors quoted here are due to Porter-Thomas fluctuations[16]

TABLE IX. Level energies of ^{75}Ge.

This work energy (keV)		Ref. 15 energy (keV)	
252.82	0.09	252.86	0.10
574.67	0.09	574.38	0.11
884.94	0.11	885.19	0.10
1137	2	1133	10
1416	1	1417	5
1501.86	0.10	1501.28	0.13
1688.23	0.14		
1757.47	0.11		
1516	2	1507	10

TABLE X. Values of F, Γ_γ, and D for ^{71,73,74,75}Ge taken or calculated from Ref. 23.

Final Nucleus	Resonance spins	F	$\langle\Gamma_\gamma\rangle$ (meV)	D (eV)
^{71}Ge	$\frac{1}{2}^+$	1	165	930
^{73}Ge	$\frac{1}{2}^+$	1	162	960
^{74}Ge	4^+	0.64	200	147
	5^+	0.36	200	185
^{75}Ge	$\frac{1}{2}^+$	1	195	3000

only. In ^{74}Ge, the width of the transitions populating 4^+ levels were assumed to have χ^2 distributions with 2 degrees of freedom since they can arise from 4^+ or 5^+ capture states. For all other transitions χ^2 distributions with 1 degree of freedom were used.) The average value is taken as $(20\pm9)\times10^{-9}$ MeV^{-3}. This value may be compared with the global average of the $M1$ strength function which was reported[29,28] to be 18×10^{-9} and $(30\pm4)\times10^{-9}$ MeV^{-3}. Averaging three $M1$ transitions, each corresponding to five resonances in the resonance experiment,[10] and normalizing with the current value of level density one can obtain a value of 12×10^{-9} MeV^{-3}. The error in this number is 37% from the Porter-Thomas distribution alone. Thus, the present value of $\bar{k}_{M1}$ overlaps with the resonance result.

The experimental value of the $E1$ strength function, $\langle \Gamma_{\gamma i} D_\lambda^{-1} \rangle$, was compared with the prediction of the $E1$ giant dipole resonance model. Assuming the validity of the Brink-Axel hypothesis[30] and a Lorentz shape for the GDR, one obtains

$$\Gamma_{\rm GDR}(E1)=\frac{1}{3\pi\hbar^2c^2}D_\lambda\sigma_0\Gamma_0^2\frac{E_\gamma^2}{(E_0^2-E_\gamma^2)^2+\Gamma_0^2E_\gamma^2} . \quad (4)$$

The quantities E_0, Γ_0, and σ_0 denote the GDR energy, width, and peak cross section. A global fit of the three parameters as a function of the mass number A was arrived at by Schumacher *et al.*[31] who reported

$$E_0=31.2A^{-1/3}+20.6A^{-1/6}\ \text{MeV} ,$$
$$\Gamma_0=4.5\ \text{MeV} , \quad (5)$$
$$\sigma_0=45.84NZ/(\Gamma_0 A)\ \text{mb} .$$

Using (4) and (5), the values for the strength $\langle \Gamma_{\gamma i} D_\lambda^{-1} \rangle_{\rm GDR}$ of ^{71,73,74,75}Ge were computed for relevant photon energies. The average of the ratios of the experimental and predicted values was found to be 1.2±0.3. In this instance, the GDR model appears to agree well with observation.

E. E2 strength in neutron capture

A primary transition in ^{74}Ge populating a 2^+ or 7^+ level will be a pure $E2$ transition, provided that the p-wave capture contribution is negligible. Using the data of Ref. 23, the ratio of $E1$ transitions arising from p-wave capture to $E2$ transitions is found to be less than 0.01 for ^{74}Ge. A list of three 2^+ levels in ^{74}Ge and the energies and intensities of the corresponding $E2$ primary transitions are given in Table XI. The primary $E2$ transitions are indicated in Fig. 1.

To compare the experimental $E2$ strength with that expected from giant quadrupole resonances,[1,32] we estimated the reduced transition probability[33]

$$\overline{B(E2)\downarrow}\ (\text{per MeV})=1.25\times10^{12}f_{E2}(E)\quad (e^2\,\text{fm}^4\,\text{MeV}^{-1}) , \quad (6)$$

where $f_{E2}=\langle \Gamma_{\gamma i} D^{-1} E_{\gamma i}^{-5} \rangle$. Here $\Gamma_{\gamma i}$ is the partial $E2$ radiative width of the capture state for transition i, D the average level spacing of the resonances of a given spin and parity, and $E_{\gamma i}$ denotes the transition energy.

The absolute intensities of the primary $E2$ transitions were converted to radiative widths. The values for Γ_γ, fractional contribution F_J, and D used were calculated from the data of Ref. 23 and are given in Table X. The $\overline{B(E2)\downarrow}$ values for the transitions are presented in Table XI. The average $\overline{B(E2)\downarrow}$ is found to be 11 ± 8 $e^2\,\text{fm}^4\,\text{MeV}^{-1}$. The same quantity on the basis of the data of the resonance experiment[10] is calculated to be 27 ± 16 $e^2\,\text{fm}^4\,\text{MeV}^{-1}$. In both cases the error is derived from a combination of counting statistics, calibration, and P-T distribution. The weighted average of the $\overline{B(E2)\downarrow}$ values is 18 ± 10 $e^2\,\text{fm}^4\,\text{MeV}^{-1}$.

The quadrupole strength function, on the basis of the giant resonant model, is the sum of the contribution from the isoscalar and isovector giant quadrupole resonances:[1]

$$\left\langle \frac{\Gamma_{\gamma i}}{D} \right\rangle = \left\langle \frac{\Gamma_{\gamma i}}{D} \right\rangle_{T=0} + 1.8\left\langle \frac{\Gamma_{\gamma i}}{D} \right\rangle_{T=1} . \quad (7)$$

The enhancement of the isovector resonance is due to the effect of the exchange corrections.[34] Each of the contributions is given by[32]

$$\left\langle \frac{\Gamma_{\gamma i}}{D} \right\rangle_{T=0,1} =7.77\times10^{-12}E_\gamma^4E_{0T}^2C_T\frac{\Gamma_T}{(E_\gamma^2-E_{0T}^2)^2+\Gamma_T^2E_\gamma^2} , \quad (8)$$

where E_{0T} and Γ_T are the giant resonance energy and width, respectively, for isospin T. For $T=0$ and 1, $C=Z^2A^{-1/3}$ and $NZA^{-1/3}$, respectively. The E_0 and Γ_T were calculated from the mass-number systematics compiled by Bertrand.[35] The $\overline{B(E2)\downarrow}$ values were determined using the theoretical $\langle \Gamma_{\gamma i}/D \rangle_{\rm GQR}$ for each of the transitions. The average $\overline{B(E2)\downarrow}$ is 21.6

TABLE XI. Electric quadrupole strengths in ^{74}Ge.

Level energy (keV)	Photon energy (keV)	Intensity (per 10^3n)	$\Gamma_{\gamma i}$ (meV)	$\overline{B(E2)\downarrow}$ ($e^2\,\text{fm}^4\,\text{MeV}^{-1}$) expt.	calc.
596	9600	0.6	0.188	19.6	21.1
1204	8992	0.08	0.025	3.6	21.5
2198	7999	0.11	0.11	8.7	21.2
			Average:	11±8	

$e^2\,\mathrm{fm}^4\,\mathrm{MeV}^{-1}$, which is in good agreement with the experimental value of $18\pm10\ e^2\,\mathrm{fm}^4\,\mathrm{MeV}^{-1}$.

F. Spins of ^{74}Ge levels

In the compilation of Singh and Viggars,[14] many levels have been assigned with tentative spins of 2^+ or 2^+ and above. If a level has spin 2^+, the corresponding primary transition would be a pure $E2$ transition. From knowledge of the $E2$ strength and consideration of the Porter-Thomas variation,[16] it is possible to exclude this spin assignment in some cases. There are some borderline cases where, although it is improbable that the transition is $E2$ (the transition strength is four to ten times the average $E2$ strength), we selected only those cases where it is virtually impossible for the transition to be $E2$ (the strength is 15–60 times the average $E2$ strength). In the compilation, the spin of the levels at 2973, 3271, and 3996 keV is given as (2^+). The spin of these levels should be higher than 2 and less than 7. The spin at 3081 keV listed as $(2^+,3^+)$ appears to be (3^+). The spins of the levels at 2694, 3034, 3316, 3410, 3515, 3721, 3790, 3832, and 4235 keV assigned as $(2^+,3,4^+)$ in the compilation should be $(3,4^+)$. The spin of the levels at 2925 and 3707 keV should be (3–5) instead of (2–5). The level at 3958 keV should have spin (3–6) not (2–6).

The level at 1379 keV in ^{71}Ge has been assigned[12] with spins $(\frac{7}{2}^-)$, $(\frac{5}{2}^+)$. This level is populated by the strongest primary tarnsition which is highly unlikely to be an $E2$ transition. Thus, the level seems not to have spin $(\frac{5}{2}^+)$. The $(\frac{7}{2}^-)$ spin assignment is out of the question. Assuming a dipole transition, the possible spin is $\frac{1}{2}$ or $\frac{3}{2}$.

V. CONCLUSIONS

Neutron separation energies have been determined with improved precision for four isotopes of germanium. There is a general agreement in values for ^{71}Ge, ^{73}Ge, and ^{75}Ge with those of the literature. The separation energy of ^{74}Ge is 4 keV less than the value compiled by Wapstra[17] and slightly higher than that quoted by Singh and Viggars.[14] Level energies determined for all but ^{74}Ge agree well, in general, with the published values. For ^{74}Ge, the adopted values[14] for energies above 2550 keV appear to be systematically higher than the present value. The absolute intensities of transitions in the four germanium isotopes differ significantly from the reported values.[12–15]

Adopted spins[14] of (2^+) for some of the levels seem to be erroneous on the basis of the intensity of corresponding primary transitions. In some cases, dispersion of possible spins can be reduced.

The reduced $E1$ strength function $\langle \Gamma_{\gamma i} D^{-1} E_i^{-3} A^{-2/3} \rangle$ of germanium isotopes is found to be less than the global average. The $E1$ strength function $\langle \Gamma_{\gamma i} D^{-1} \rangle$ is, however, found to agree with the prediction of the $E1$ GDR model. The $M1$ strength function $\langle \Gamma_{\gamma i} D^{-1} E_i^{-3} \rangle$ of ^{74}Ge is in agreement with the global average. Both these strength functions agree with that obtained from the resonance capture experiments.[10]

Three primary $E2$ transitions are observed in ^{74}Ge. The quadrupole strength function of ^{74}Ge is found to agree with that expected on the basis of the GQR model.

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