γ rays from the β^- decay of $^{77}Ge^m$

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The decay of $^{77}Ge^m$ (52.9 s) populating the levels of ^{77}As has been reinvestigated by measuring γ-ray singles spectra as a function of time with an HPGe detector. 13 new γ rays are assigned to the decay of $^{77}Ge^m$ and three new levels are added to the presently accepted level scheme of ^{77}As at the following energies: 503.89, 1604.686, and 1676.49 keV. From γ-ray intensity measurements and log *ft* values determined in this work—combined with previously reported results—tentative J^π assignments have been made for the new levels proposed.

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Experimental method. We have studied the decay of $^{77}Ge^m$ (52.9 s) populating the levels of ^{77}As. Sources were produced by irradiating 180 to 360 mg samples of 1.5 to 1.9 mm-thick detector grade germanium in the RA-6 Bariloche reactor using a pneumatic tube system (about 1 s traveling time). The neutron flux was about 4×10^{12} cm^{-2} s^{-1} thermal, and 8×10^{10} cm^{-2} s^{-1} epithermal. To enhance the capture of neutrons by ^{76}Ge, as compared to the ^{74}Ge isotope, the samples were placed inside 1 mm-thick cadmium covers and irradiated for 60 s. γ-ray singles spectra were obtained with a 12.3% relative efficiency ORTEC HPGe intrinsic-N coaxial detector with a resolution of 2.0 keV FWHM, measuring the samples at a distance of 4.8 cm. A 6.4 mm thick Pb absorber, with Cd and Cu backings, was placed on the detector's front end to avoid prohibitively high dead-time caused mainly by the low-energy (139.5 keV) γ-radiation from the isomeric decay of $^{75}Ge^m$ (47.7 s). Also, these absorbers help to attenuate the bremsstrahlung produced by the strong β rays from the decay of $^{77}Ge^m$. To avoid having to make variable-count-rate dead-time corrections, counting was started as soon as the dead-time was below 5%, typically 40 to 110 s after the end of irradiation. Data were collected in 4096 channels of a Nuclear Data ND76 multichannel analyzer (MCA) which was programmed to count the sample for 50 s real time, store the data on a floppy disk, and then clear the MCA data memory, repeating automatically this counting-storing-clearing cycle ten times. The ND76 is capable of start acquiring a new spectrum within about 0.38 s of having finished the previous one, thus collecting a set of ten 50 s-spectra in less than 505 s for each irradiated sample. Nine different Ge samples were irradiated and counted in this manner. The spectra were analyzed with the Nuclear Data analyzing package [1].

Experimental results. The upper part of Fig. 1 depicts a γ-singles spectrum which is the sum of the first five 50 s individual spectra of all nine sets, that is, the sum of forty-five 50 s spectra. The lower part of Fig. 1 depicts the sum of the second five 50 s individual spectra of these nine sets, clearly showing the vanishing of the $^{77}Ge^m$ γ rays. For the calculation of γ-ray emission probabilities, the upper spectrum shown in Fig. 1 was enriched by the addition of spectra obtained in several other irradiations of 50 and 300 s duration, with counting times of 200 s [13].

γ-ray energies. Energy calibration of the MCA was accomplished by a quadratic fitting routine [1] that was per-

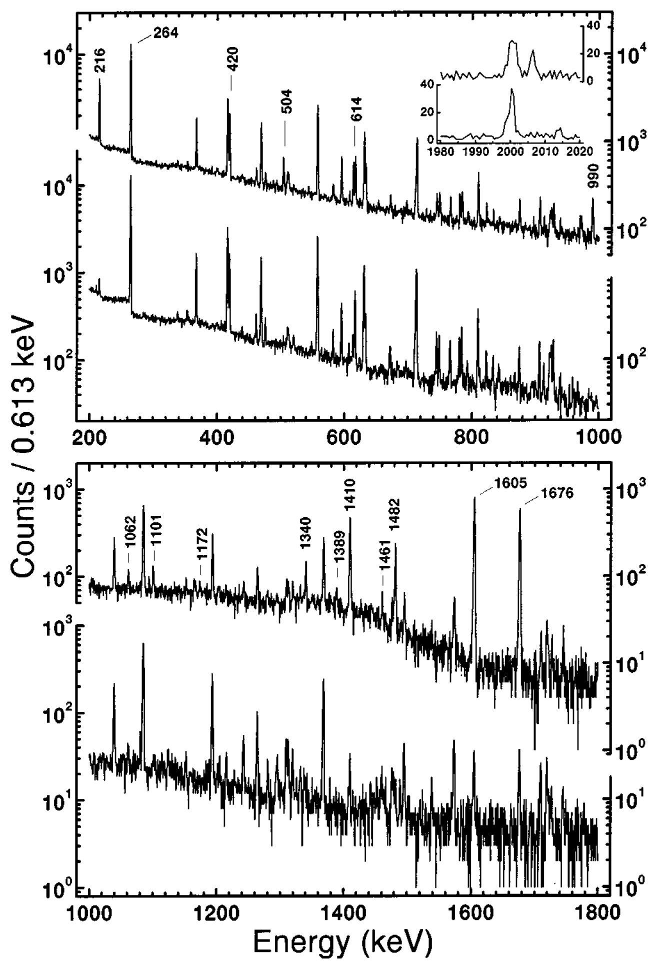

FIG. 1. Upper spectrum: sum of consecutive spectra 1 to 5 for all nine irradiated samples. Lower spectrum: sum of spectra 6 to 10 for the same nine irradiated samples. Labeled energies correspond to $^{77}Ge^m$ decay. Inset shows evidence for a γ ray of about 2006 keV.

TABLE I. Energies and intensities of γ-ray transitions taking place in the decay of ^{77}Ge^m. Uncertainties shown correspond to one standard deviation.

Initial → Final level	Gamma-ray energy (keV) Experimental [a]	Adjusted [b]	Gamma-ray emission probability Relative [c]	Absolute(%) [d]
1→0	(194.76±0.03)	194.756±0.029	——	(0.436±0.049)
2→0	215.532±0.059	215.528±0.059	——	(21.8±2.3)
3→0	(264.44±0.50)	264.44±0.32	——	>0.0155±0.0035[e]
			——	<0.0224±0.0084[e]
5→1	(419.75±0.03)	419.748±0.030	——	(0.097±0.015)
4→0	503.86±0.18	503.89±0.17	1130±97	0.051±0.010
5→0	614.43±0.18	614.504±0.041	1000	(0.0452±0.0081)
6→5	990.29±0.27	990.164±0.085	526±57	0.0238±0.0050
7→5	1061.61±0.50	1061.96±0.12	115±33	0.0052±0.0018
6→4	1100.79±0.50	1100.78±0.18	73±37	0.0033±0.0018
7→4	1172.36±0.50	1172.58±0.19	89±38	0.0040±0.0019
6→3	1339.99±0.49	1340.23±0.32	342±45	0.0155±0.0035
6→2	1389.13±0.50	1389.140±0.098	157±34	0.0071±0.0020
6→1	1409.94±0.16	1409.912±0.081	2380±120	0.108±0.020
7→3	1412.50±0.70	1412.02±0.33	152±41	0.0069±0.0023
7→2	1461.25±0.50	1460.94±0.13	140±33	0.0063±0.0019
7→1	1481.73±0.24	1481.71±0.12	1033±65	0.0467±0.0089
6→0	1604.65±0.10	1604.668±0.079	4820±220	0.218±0.041
7→0	1676.46±0.14	1676.47±0.12	3630±170	0.164±0.031

[a]We do not observe the 195 keV γ ray because of our Pb absorber; the 264 and 420 keV γ rays are both strongly interfered by other Ge decays. Therefore, energies shown in parentheses are those adopted [2] for the corresponding energies in the decay of ^{77}Ge (11.3 h), using the criterion that they are better known than those adopted for the ^{77}Ge^m (53 s) decay. However, since we are here proposing the existence of the 264 keV γ ray, we have arbitrarily increased its energy uncertainty to 0.50 keV (the same as for our weakest lines), with the sole purpose of allowing numerical computations [4], which are not sensitive to the precise value of this uncertainty.

[b]Adjusted least-squares fit [4] using all energy and uncertainty values shown in the second column.

[c]The 1σ uncertainties shown include the uncertainties corresponding to the relative efficiency, the peak areas as given by the analyzing package [1], and those associated with the 614 keV reference line. The areas corresponding to the 504, 1062, and 1340 keV lines, were corrected for the contributions from the decay of ^{77}Ge (11.3 h). The area corresponding to the 1100.79 keV peak was corrected for the contribution from the 1101.37 keV γ ray from the decay of ^{74}Ga (8.1 min) formed through the ^{74}Ge(n,p) reaction. For these corrections, pertinent data were taken from Refs. [2,5]. ^{40}K-natural–background contribution to the 1461.25 keV peak is negligible and was not taken into account. Except for the 1412 keV γ ray, all other peaks reported in this column are well resolved singlet peaks. Since the γ rays under study have high enough energy, corrections due to internal conversion were neglected.

[d]As explained in (a) above, values shown in parentheses were taken from Ref. [2] for the 195 and 420 keV γ rays. Given that for the 216 keV peak our efficiency uncertainty is of the order of 50%, and that this is the strongest and a well established peak, we use the absolute emission probability (internal conversion included) given in Ref. [2].

[e]Lower limit: it is obtained under the assumption that the 264 keV level is fed only by the 1340 keV γ ray. Upper limit: from the experimental background around the 264 keV peak we calculate a minimum detectable area [6] in this region and, since the peak is not discernible, take it as the upper limit for that area.

formed for each sample immediately before its irradiation, using a mixed source of ^{60}Co+(^{108}Ag^m+ ^{110}Ag^m)+ ^{182}Ta, with a maximum useful calibration point at 1505 keV. Since the γ rays under study have energies as high as 1676 keV, a fresh source of ^{28}Al was placed along the mixed source each time, thus getting another calibration point at 1779 keV. In each of the nine spectra (each comprising the sum of the first five 50 s individual spectra) we determine—by means of its individual energy calibration—the energies of nine of the most intense peaks from ^{77}Ge (11.3 h), namely [2]: 367.40, 416.33, 558.02, 631.82, 634.39, 810.35, 1085.19, 1193.26, and 1368.4 keV, all having an energy uncertainty $\Delta E = 0.03$ keV, except the last one which has $\Delta E = 0.5$ keV. Depending on the net counts under the corresponding peak in each of the nine spectra, we assigned to each peak an energy uncertainty that varied from 0.15 to 0.50 keV and obtain for

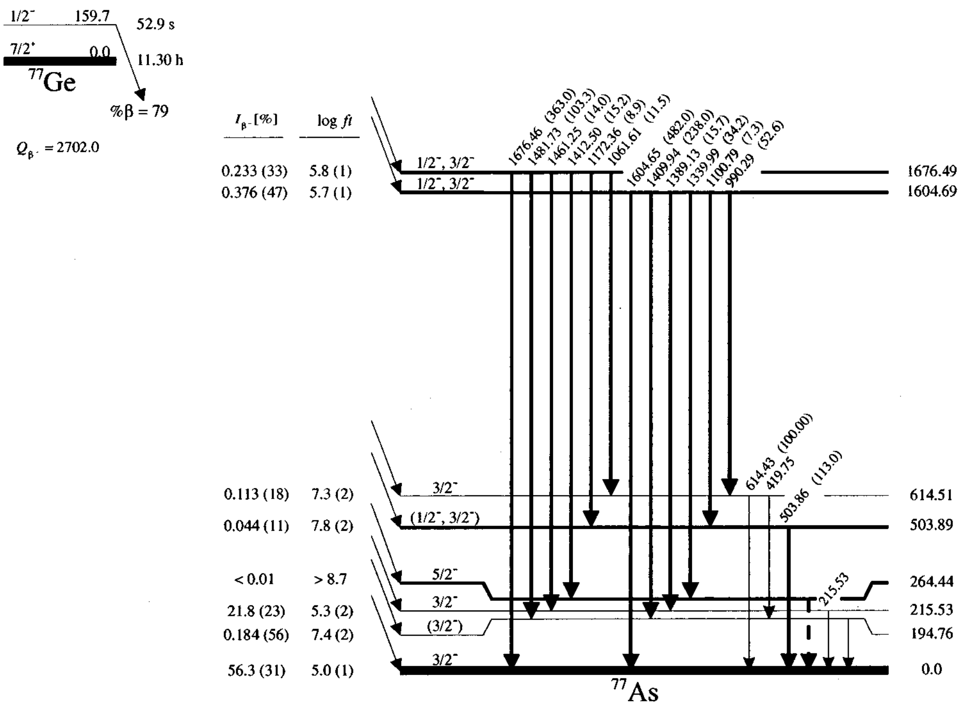

FIG. 2. Decay scheme for ^{77}Ge^m as deduced from the present results. Thin line: known transitions and levels. Thick line: proposed new transitions and levels. We only show those energy values and γ-ray intensities that were experimentally determined in the present work. The 264-keV transition is shown as a dashed line because its presence is suggested, but not actually observed in our experiment (see text). Beta intensities and $\log ft$ values are given with their uncertainties in parentheses, e.g., 56.3 (31) means 56.3 ± 3.1

the total sum spectrum a weighted average for that energy. These averaged energies coincide, within uncertainties, with the accepted energy values quoted above. The uncertainties obtained for these averages are 0.05 keV for the five stronger peaks, and between 0.07 and 0.11 keV for the four weaker peaks. Having thus checked that our energy calibration, and procedure, are reliable, we apply the same procedure to the ^{77}Ge^m γ rays except that, since the areas involved are generally smaller, this time we conservatively assign energy uncertainties varying from 0.20 to 1.0 keV, again depending on the net area under each peak. The energies and uncertainties thus obtained are those indicated in the second column of Table I. The peaks shown with energy uncertainties equal to 0.50 keV are those lines which are not discernible in any of the nine spectra mentioned above but only show up in the total sum of these nine spectra. This 0.50 keV uncertainty was assigned somewhat arbitrarily, taking into account that when comparing the energies determined by the previous procedure with those obtained from the total sum spectrum [Fig. 1(a) in Ref. [13]]—internally calibrated with the ^{77}Ge (11.3 h) main lines—they are within 0.30 keV in the worst case (989.99 keV for the 990.29 keV line), and within 0.20 keV or less in all other cases. It is worth noting that we are now reporting new energy values, with corresponding lower uncertainties, for the known 215 and 614 keV lines.

Half-life check. Decay studies [13] on the four most intense peaks agree with the value (52.9 ± 0.6) s for the ^{77}Ge^m half-life [3].

γ-ray intensities. Because of our experimental procedure (Pb+Cd+Cu absorbers), we can only use as a reference line the 614.3 keV γ ray. The contribution of the 614.39 keV γ ray from the decay of ^{77}Ge (11.3 h) was taken into account. All areas were corrected for self-attenuation produced in the germanium samples. Details on the measurement of the relative efficiency curve can be found in Ref. [13]. Its estimated resulting uncertainties (one standard deviation), lie between 1.2% and 2.5% in the energy interval of interest, i.e., 500 to 1700 keV.

Table I summarizes the energies and intensities of the γ-ray transitions taking place in the decay of ^{77}Ge^m. Based on these results, and energy-sum relations, the decay scheme for ^{77}Ge^m was established as that given in Fig. 2. Regarding the proposed 264 keV line, since we detect a γ ray with an energy of 1339.99 keV, we assign its origin to a partial depopulation of the proposed level at 1604.65 keV leaving the ^{77}As nucleus in its well established level [2] at (264.401 ± 0.014) keV: $(1604.65 \pm 0.10) - (1339.99 \pm 0.49) = (264.66 \pm 0.50)$ keV. We are unable to detect this peak with the present experimental setup because of strong interferences from other Ge decays. The absolute γ-ray emission probabilities shown in the last column of Table I are based [2] on $I_\gamma = (0.0452 \pm 0.0081)\%$ for the 614 keV reference line. With these absolute emission probabilities, and through a detailed intensity balance [7] for each level, we get the β branching ratios, and thereby the corresponding $\log ft$ values shown in Fig. 2. For the detailed intensity balance calculation, the total β branching for the 160 keV metastable state in ^{77}Ge was assumed [2] to be $(79 \pm 2)\%$. The β branching ratios obtained are shown in Table II where the energies for the different levels involved have been corrected for nuclear recoil, although this correction never amounts to more than 0.02 keV.

Spin assignments. All $\log ft$ values found in this work agree within uncertainties with those given in Ref. [2] for the previously known β decays to the levels at 0, 195, 215, and 614 keV. Therefore, in what follows we shall refer only to the newly proposed levels in ^{77}As.

TABLE II. Beta branching ratios in the decay of $^{77}Ge^{m}$.

Level	Energy (keV)	Intensity balance (β^{-}%) This work	Ref. [2]
0	0.0	56.3 ± 3.1	57 ± 3
1	194.756 ± 0.029	0.184 ± 0.056	0.41 ± 0.07
2	215.528 ± 0.059	21.8 ± 2.3	21.2 ± 2.3
3	264.44 ± 0.32	0.0000 ± 0.0094	
4	503.89 ± 0.17	0.044 ± 0.011	
5	614.507 ± 0.041	0.113 ± 0.018	0.138 ± 0.019
6	1604.686 ± 0.079	0.376 ± 0.047	
7	1676.49 ± 0.12	0.233 ± 0.033	

264 keV level. The intensity measured for the 1412 keV γ ray shows that the β branching to the 264 keV level lies below 0.01% and is probably zero. This result is compatible with the well established value $J^{\pi}=5/2^{-}$ for this level because this assignment would suggest a second forbidden β transition for the decay of $^{77}Ge^{m}$ to this level.

504 keV level. Our log *ft* value of 7.8 for this level would seem to indicate that it is probably fed through a first forbidden transition. However, it is not uncommon to find high log *ft* values for allowed transitions in this region of the nuclide chart and, in effect, there is enough evidence for a $J^{\pi}=1/2^{-}$ or $3/2^{-}$ assignment from nuclear reactions experiments performed by Betts *et al.* [8], Schrader *et al.* [9], and Rotbard *et al.* [10].

1605 and 1676 keV levels. Our respective log *ft* values of 5.7 and 5.8 for the decay to these levels suggest an allowed transition in both cases. Therefore, since the $J^{\pi}=1/2^{-}$ value for the 160 keV parent level in ^{77}Ge is well established, we propose $J^{\pi}=1/2^{-}$ or $3/2^{-}$ for both these levels. This assignment agrees with the J^{π} found by Betts *et al.* [8] for their 1674 keV level, and with the work by Rotbard *et al.* [10] for their 1606 and 1660 keV levels.

Discussion. Reference [2] reports a level diagram for the decay of $^{77}Ge^{m}$ that is almost exclusively based on the works of Imanishi and Nishi and of Meeker and Tucker [11], both dating back to 1970. Since Imanishi and Nishi were trying to establish the existence of a low-lying triplet of levels in ^{77}As, they only measured γ rays up to an energy of about 580 keV. Meeker and Tucker measured γ rays with an energy cutoff at 1000 keV. Therefore, in both cases, they were unable to see most of the new γ rays we are reporting here.

Except for the energies of the 195, 264, and 420 keV γ rays, the intensities for the 195, 216, and 420 keV γ rays, and the spin assignment to the 504 keV level, the level scheme and data shown in Fig. 2 were obtained from the energy and intensity measurements performed in the present work. As can be seen in the inset of Fig. 1, we also observe in the decay of $^{77}Ge^{m}$ a peak at an energy of 2006.2 keV, with an absolute intensity of about 0.005%. Insufficient data prevent us from placing this γ ray in the decay scheme given in Fig. 2.

A few words about expected—but not observed—γ rays: The levels of ^{77}As that are fed by the decay of both the ground and metastable states of ^{77}Ge, are the 195, 215, and 614 keV levels. All γ rays depopulating these levels and observed for the ground-state decay but not for the metastable decay originate in the 614 keV level, having the following energies: 350, 399, and 420 keV. These γ rays should also be present in the decay of $^{77}Ge^{m}$, but a study of the spectrum obtained shows that the expected count rates for the peaks at 350 and 399 keV are both well below the background count rate in these energy regions. The 420 keV γ ray—although observed—is strongly interfered by peaks from both ^{75}Ge (1.38 h) and ^{77}Ge (11.3 h) decays.

Except for slight differences, the main results of this work have been reported by Farhan and Singh in [12] as a private communication.

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[13] See AIP Document No. E-PAPS:E-PRVCAN-61-015006 for full-size graphs, decay curves, relative efficiency, and details on adopted levels. E-PAPS document files may be retrieved free of charge from our FTP server (http://www.aip.org/epaps/epaps.html) or from ftp.aip.org in the directory /epaps/. For further information, email: paps@aip.org; or fax: 516-576-2223.