Very weak γ transitions in the ϵ/β^+ decay of ^{68}Ga

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(Received 9 February 1994)

The γ rays associated with the decay of ^{68}Ga in equilibrium with ^{68}Ge have been studied using the 20-element High Energy Resolution Array (HERA) facility. Five new transitions were observed along with the known ones from earlier works. The $E2/M1$ mixing ratios for two of these new transitions were obtained by γ-$\gamma(\theta)$ techniques.

PACS number(s): 23.20.Lv, 23.20.En, 23.20.Gq, 27.50.+e

In recent years a number of different groups have searched for resonances produced in the low energy scattering and annihilation of positrons by electrons [1]. The positrons emitted in the decay of ^{68}Ga to ^{68}Zn have been used for a number of these studies. If such resonances are present, they are expected to be very weak and are predicted [1] to decay by multiphoton emission. It is therefore useful for these search experiments to know with greater accuracy the existence of very weak γ rays emitted in these decays, especially in the range of 1.1–2.1 MeV where a number of resonances have been predicted [1]. Having recently carried out such a search [1], we embarked on the careful study of the γ rays present in the ϵ/β^+ decay of ^{68}Ga in order to eliminate possible sources of background. The data used here were obtained simultaneously with the data for the search of Ref. [1].

The decay of ^{68}Ga to ^{68}Zn has been studied extensively using NaI and Ge(Li) detectors [2–5]. Four excited 2^+ states and one excited 0^+ state were already known [2,5]. In the present work, we investigated this decay using the 20-element High Energy Resolution Array (HERA) [6] in order to obtain better values for the transition energies, transition intensities, and the $E2/M1$ mixing ratios of the γ rays. The many-element Ge detector array and Compton-suppressed shieldings have made it possible to investigate the weak γ transitions. We report here five new very weak transitions decaying from the known states of the ^{68}Ga ϵ/β^+ decay.

A source of ^{68}Ga, in secular equilibrium with its 288-day half-life parent ^{68}Ge, was enclosed inside a lead spherical shell. The lead shell was used to absorb the positrons for the resonant e^+e^- scattering study [1]. HERA at Lawrence Berkeley Laboratory was used to detect the γ rays. HERA [6] consisted of 20 Compton-suppressed Ge detectors and a 4π, 40-element bismuth germanate (BGO) inner ball. The solid angle of each Ge detector was 65 msr. The average absolute photopeak efficiency of a Ge detector (for a source at the focal center of HERA) was about 10^{-3} for 0.5-MeV γ rays and 4.5×10^{-4} for 1-MeV γ rays. The angle between any pair of Ge detectors ranged from 37° to 157°. The lead shell had an inner radius of 0.238 cm and an outer radius of 0.476 cm. The source assembly was positioned at the focal center of HERA such that each of the 20 Ge detectors subtended the same solid angle (65 msr). The source strength at the beginning of the experiment was 67 μCi. The counting took place whenever HERA was available for off-line experiments (i.e., not being used for in-beam experiments). The total counting time on HERA using the lead sphere was 94 days (2260 h) over a period of five months. Additional measurements were carried out using a copper sphere identical to the lead sphere in dimensions which contained 44 μCi of activity at the beginning of its measurements. The total counting time using the copper sphere at HERA was 9 days over a one-month period. The results obtained with the Pb and Cu spheres were the same, within experimental uncertainties, so the two data sets were combined for the final results. The experiment was terminated by the permanent shut down of HERA in preparation for the construction of Gammasphere.

During the experiments, the energies of the coincident γ rays from the Ge detectors, the time relationship between the first and second γ rays, plus the total energy and multiplicity from the BGO ball were recorded on magnetic tape. For analysis of coincidence events, the high-fold events (total multiplicity from both the BGO and Ge detectors greater than 5) were rejected because those could not come from the decay of a single nucleus. The average singles rate in each Ge detector was 12 kHz and the average total coincidence rates were 610 Hz and 12 Hz for 2γ and 3γ coincidences, respectively.

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A total of 4.9×10^9 double and 9.8×10^7 triple coincidence events were recorded from the 94-d total counting time with the lead sphere. For the copper sphere, a total of 6.1×10^8 double and 1.2×10^7 triple coincidence events were recorded. Due to the lack of the timing information for the third γ ray (in triple coincidence), only the double coincidence events were used in the analysis.

Figure 1 shows the decay scheme of ^{68}Ga based on the present work. The ϵ and β^+ intensities and spins of the states were taken from Ref. [7]. Five new transitions are presented. The thicker arrows represent the newly found transitions. Figure 2 shows the gated spectra of the five weak transitions.

To obtain the $E2/M1$ mixing ratios, γ-γ directional correlation measurements were made. There were 14 groups of angles between pairs of HERA's Ge detectors, ranging from 37° to 157°. For each set of detector pairs with the same angle, the gates were set on the 578-, 1077-, 1261-, and 1883-keV peaks. Chance background was corrected by subtracting the chance coincidences. (Chance coincidences were obtained by setting the timing gate about 60 ns from the prompt coincidences.) Compton-continuum background was corrected by subtracting the events in coincidence with the channels on both sides of the gates. Small corrections for the detectors' relative efficiencies were also made by normalizing the coincident data from each set of angles to the 511-1077-keV coincident events in the same set of angles. (The 511-1077-keV coincident events detected are independent of the angle between a pair of the detectors.) To correct the coefficients A_k for the finite solid angles of the Ge detectors,

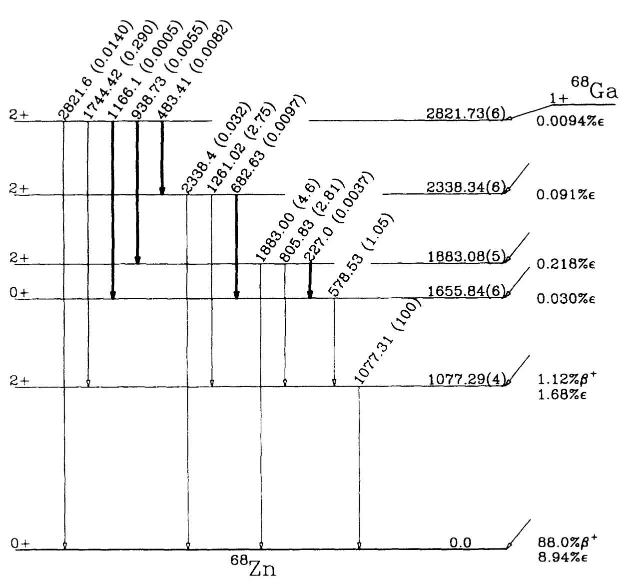

FIG. 1. Decay scheme of ^{68}Ga based on the present work. The ϵ and β^+ intensities were taken from Ref. [7]. The energy (in keV) of each level was deduced from the energies of all transitions populating and depopulating that level. The uncertainties of the least significant digits of the level energies are indicated in parentheses. The values in the parentheses after the transition energies are the relative transition intensities, normalized to the intensity of the 1077.33-keV transition.

we assumed a detector's efficiency was independent of the location on the detector's surface the γ ray hits. This is a good assumption for HERA's detectors which were large and thick detectors with small solid angles. Using the simple formulas given in Ref. [8], the attenuation factors $Q_{22} = 0.9692$ and $Q_{44} = 0.9008$ were obtained.

The known 0^+-2^+-0^+, 578-1077-keV cascade was used to validate the measurements and the above approximate values for the attenuation factors. The results, $A_2 = 0.355(9)$ and $A_4 = 1.161(14)$, obtained with the above attenuation factors, are in reasonable agreement with the theoretical values for the 0^+-2^+-0^+ cascade: $A_2 = 0.357$ and $A_4 = 1.143$. This angular correlation is shown in Fig. 3, in which the data points for angles $\Theta < 90°$ are plotted at their complementary angles, $180° - \Theta$. From the excellent fit of these data, we believe that the attenuation factors for HERA detectors deduced from the fit of the 578-1077-keV cascade (which already include the source size corrections) are better than the approximate values given above. Therefore, the attenuation factors obtained from the fit of the 578-1077-keV cascade, $Q_{22} = 0.965(26)$ and $Q_{44} = 0.915(12)$, were used in correcting the coefficients A_k of other cascades. The directional correlation results are shown in Table I, as are the results from Ref. [5]. The phase convention used for the mixing ratio δ is that of Krane and Steffen [9].

The isotropic γ-γ directional correlation measurements for the 2^+-0^+-2^+, 683-578-keV cascade could also be used to check on the measurements. However, it was found that a fraction of the 683-578-keV measured coincident events came from the scattering of 1261-keV γ rays into two detectors: the 1261-keV γ ray hits a detector, deposits 578 keV (or 683 keV) in that detector, and then scatters into a second detector. This process favors only pairs of detectors at certain angles and makes the fit inaccurate. Therefore the results from the fit of the 683-578-keV cascade were not used. For the 228-keV and 1166-keV transitions, there were not sufficient data to do the γ-γ directional correlation measurements.

Spectra of the singles data were constructed from the chance coincidence data (i.e., using the data at the tail of the timing spectrum where no true coincident events are present) from both the lead and the copper spheres for the purpose of analyzing the noncoincident γ rays. From the singles spectra, the intensities of all the intense and clean peaks were measured. The 2γ sum peaks with sum energies of 1883 keV, 2338 keV, and 2822 keV were significant due to the strong intensities of 806-, 1261-, and 1744-keV γ rays in cascading through the 1077-keV γ ray. The intensity of a sum peak was obtained by calculating the probability of two γ rays hitting the same detector using the measured probabilities of those same two γ rays hitting two detectors at other angles. The result was corrected for the angular correlation and then normalized to the 1588-keV (511 keV + 1077 keV) sum peak using the measured 1588-keV peak intensity. The measured intensity of the 1655-keV (578 keV + 1077 keV) sum peak, 770±230 counts, was used to check the calculations. It agreed nicely with the calculated value of 828 counts. The calculated intensities of the sum peaks account for 0.6%, 40.4%, and 10.0% of the

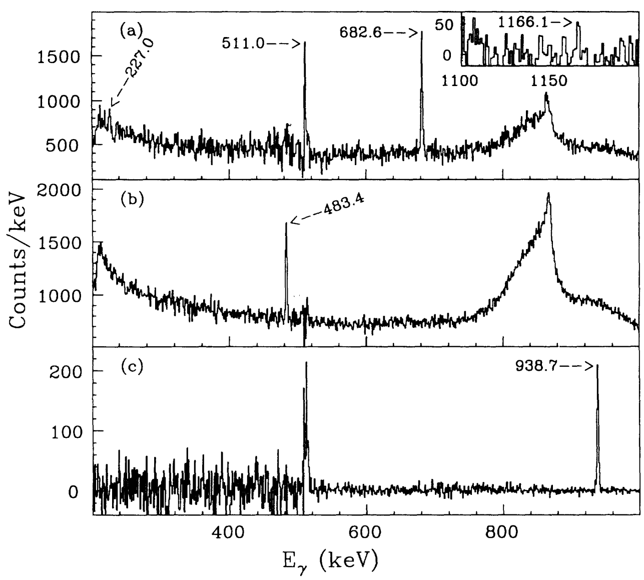

FIG. 2. Weak γ transitions in coincidence with other γ rays, (a) gated on the 578.5-keV transition (the inset shows the region from 1100 to 1200 keV); (b) gated on the 1261.0-keV transition; (c) gated on the 1883.0-keV transition. The bumps at 206.5 keV and 870.8 keV are the backscattered peak and the Compton edge of the 1077.3-keV transition, respectively. The large fluctuations in the difference spectra for energies below about 511 keV are due to small differences between two relatively large numbers, as is especially apparent in (c).

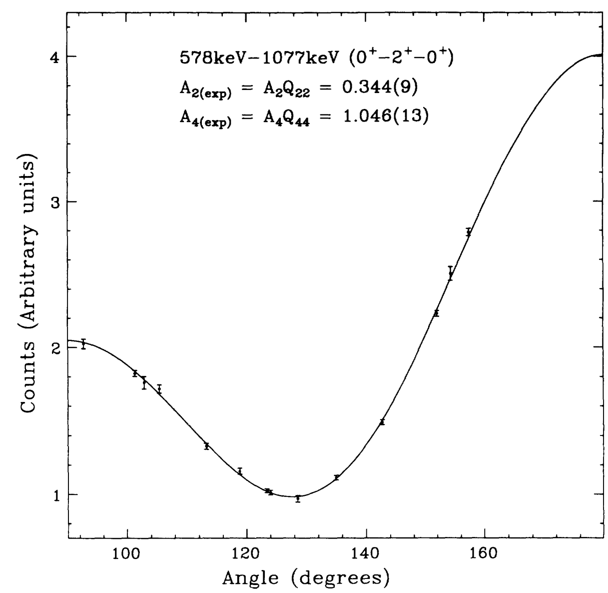

FIG. 3. The angular correlation of the 0^+-2^+-0^+, 578-1077-keV cascade. The solid line represents the least squares fit to the Legendre polynomial (zeroth, second, and fourth orders).

total measured intensities of the 1883-, 2338-, and 2822-keV γ rays, respectively. The intensities of those three γ rays in Fig. 1 have the sum peaks subtracted.

E_γ-E_γ coincidence matrices were constructed to analyze the coincident γ rays using the true coincident data from both lead and copper spheres. The relative intensities of the 578-keV, 806-keV, 1077-keV, 1261-keV, and 1744-keV transitions were deduced from both the coincidence spectra and the singles spectra, normalized to those of the 1077-keV γ ray. All other transitions were too weak to be seen in the singles spectra. Their intensities were determined from the double coincidence spectra. The intensities shown in Fig. 1 have been corrected for the absorption by the lead and copper encapsulating spheres, and the detectors' efficiencies, using the known relative detector efficiency curve for HERA and assuming a 5% uncertainty in this curve.

The results of this analysis are summarized in Table II. With those five new transitions, all possible γ rays except one (the 2338-keV 2^+ level to the 1883-keV 2^+ level) between the energy levels of ^{68}Zn populated in the ϵ/β^+ decays of ^{68}Ga have been observed. An upper limit to the intensity of such a 455-keV γ ray is given in Table II, which also gives the previous results from Refs. [2,3,5]. Inspection of Table II shows that the present intensities are in reasonable agreement with the earlier results for the stronger γ rays, except for the 2338-keV γ ray for which we found a summing correction necessary. The analog-to-digital converters (ADCs) of HERA were found to be nonlinear. A piecewise-linear curve representing the nonlinearities was obtained at the beginning of the experiment using ^{56,57}Co, ^{52,54}Mn, and ^{51}Cr sources. The curve's deviations from linearity were between 0 and 3 keV in the range 0.1 to 3.5 MeV. The 511.00-keV from e^+e^- annihilations and previously observed transitions

TABLE I. Directional correlation results from the decay of ^{68}Ga. The uncertainties of the least significant digits of energies and intensities are indicated in parentheses.

γ ray (keV)	Cascade (keV)	I^π	Lange *et al.* [5] A_2	A_4	δ^a	Present work A_2	A_4	δ^b
483.41	483-1261	2^+-2^+-2^+				0.23(8)	0.05(13)	-0.12(16)[c] -1.7(9)[c]
578.53	578-1077	0^+-2^+-0^+	0.351(54)	1.161(76)		0.357(9)	1.143(14)	
805.83	806-1077	2^+-2^+-0^+	0.369(25)	0.234(34)	-1.46(14)	0.357(13)	0.239(10)	-1.55(5)
938.73	939-1883	2^+-2^+-0^+				0.59(16)	0.21(23)	-0.7(3)
1261.02	1261-1077	2^+-2^+-0^+	0.345(22)	0.005(35)	-0.14(4)	0.344(12)	0.022(11)	-0.15(2)
1744.42	1744-1077	2^+-2^+-0^+	0.028(34)	0.070(50)	0.29(5)	0.043(13)	0.037(22)	0.27(2)

[a] δ obtained from A_2.
[b] δ obtained from both A_2 and A_4
[c] Either value of δ is possible. The multipolarity of the 1261-keV transition was assumed to be 100% $M1$.

TABLE II. Energies and relative intensities from the decay of ^{68}Ga. The uncertainties of the least significant digits of energies and intensities are indicated in parentheses.

Present work	Relative intensity			
γ-ray energy (keV)	Vaughan *et al.* [3]	Carter *et al.* [2]	Lange *et al.* [5]	Present work
227.0(3)[a]				0.0037(15)
455				<0.003
483.41(5)[a]				0.0082(9)
578.53(5)[a]	0.7(1)	1.1(2)	1.00(12)	1.05(5)
682.63(7)				0.0097(6)
805.83(5)[a]	2.2(2)	2.8(2)	2.95(12)	2.81(14)
938.73(6)				0.0055(5)
1077.33(5)[a]	100	100	100	100
1166.1(2)				0.0005(3)
1261.02(5)[a]	3.1(2)	2.9(2)	3.00(7)	2.75(14)
1744.42(8)[a]	0.5(1)	0.28(4)	0.30(4)	0.295(15)
1883.00(8)[a]	4.8(3)	4.1(4)	4.33(12)	4.6(2)
2338.4(2)[a]	<0.1	0.04(2)	0.050(6)	0.031(3)
2821.6(2)[a]			0.015(2)	0.0139(11)

[a] γ rays used in the internal energy calibration [7].

[7] between excited states in ^{68}Ga were used for the energy calibration. These internal calibration points were fitted to a curve similar in shape to the piecewise-linear curve representing the nonlinearities of the ADCs. All energies determined in these measurements agreed with those from earlier works to within the experimental uncertainties.

Figure 1 shows the excited states of ^{68}Zn we observed to be populated in the decay of ^{68}Ga. However, there are four other levels in ^{68}Zn that were observed in the β^- decay of ^{68}Cu. Such states that lie below the 2921.1-keV excitation limit for ^{68}Ga decay could be populated in ^{68}Ga decay but so weakly that they were not observed in previous studies of this decay. We looked for the known γ rays from these levels, but none were observed. Thus, if such states were populated in ^{68}Ga decay, they are populated too weakly to be seen in the present study as well. The Q value for the decay of ^{68}Ge to ^{68}Ga is only 107(6) keV, which is less than the energy of the first-excited state in ^{68}Ga at 175.06(4) keV [7]; thus no γ rays are emitted in the decay of ^{68}Ge.

In conclusion, the present results confirm the earlier works on the decay of ^{68}Ga. The 2338-keV transition intensity does not completely agree with the result of Ref. [5] because we corrected the total intensity for the sum peak, which was large, whereas this was not done in Ref [5]. We also added five new transitions to the level scheme.

In experiments that have searched for predicted resonances in e^+e^- scattering using sources of ^{68}Ge/^{68}Ga, typically searches are for events with sum energies between 1.1 MeV and 2.1 MeV. It can be helpful in similar experiments with this source to know that, with the five newly found γ rays, a number of weak coincident pairs and triplets do have sum energies in this region.

This work was supported in part by the Research Corporation Grant No. R-152 and an IPA Independent Research Agreement with the Division of Undergraduate Education of the National Science Foundation (Kelly), the U.S. Department of Energy Division of High Energy and Nuclear Physics under Grants No. DE-FG02-92ER40692 and No. DE-FG02-87ER40371 (ISU), and under Contracts No. DE-AC03-76SF00098 (LBL) and No. W-7405-ENG-48 (LLNL).

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