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New levels and transitions in ^{72}Ge following the decay of ^{72}Ga*

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The decay of ^{72}Ga has been investigated by means of γ-ray spectroscopy. The ^{72}Ga nuclei were produced through the ^{71}Ga(n, γ)^{72}Ga reaction. The Compton-suppressed spectrometer and high-purity Ge detectors have been used singly and in coincidence, separately, to study γ-rays in the β^- decay of ^{72}Ga to ^{72}Ge. Ninety-three events of γ-rays were reported, of which 7 were observed for the first time. A decay scheme of ^{72}Ga including 4 new levels is proposed which accommodates 87 of these transitions. Spins and parities for new levels are proposed from calculated logft values, modes on the observed decay, and some nuclear reaction experimental results.

Keywords: decay, γ-ray, level, coincidence
PACC: 2320L, 2320N, 2340, 2110H

1. Introduction

Previous experimental work on ^{72}Ge has extended over several decades. Many attempts were made to establish a decay scheme for ^{72}Ge populated by the β^- decay of ^{72}Ga ($T_{1/2}$=14.10h) and the β^+/EC decay of ^{72}As ($T_{1/2}$=26.0h). A strongly deformed structure in the ground state was not expected in the A=70 region until nuclear-shape coexistence was first discovered in ^{72}Se by Hamilton *et al.*[1−3] To date, the level structure from ^{72}Ga decay has been studied with Ge(Li) detectors,[4,5] and a literature survey reveals the fact of no recent experimental information concerning the decay scheme of this isotope. To be specific, the last published papers,[6,7] which are widely reported, are over 30 years old. Detailed properties of the level structure of doubly even nuclei in this mass region are currently needed to provide systematic knowledge for the further development of nuclear models. The present work is a study of the decay of ^{72}Ga with a high-purity Ge Compton-suppression spectrometer, and HPGe-HPGe-T coincidence spectrometer.

2. Source preparation

The radioactive ^{72}Ga sources were prepared by neutron irradiation of high-purity gallium oxide in the mini reactor at Shanghai (designed by the Chinese Institute of Atomic Energy, Beijing). Three different targets were used. Every sample containing approximately 20mg of Ga_2O_3 was irradiated in a flux of 2.1×10^{11}n/s for a period of 3.5–4h. The chemical procedure for the extraction of the Ga activity from the target material was started after a waiting period of ∼2h at the end of the irradiation. The samples were stored for about 12h to allow for the decay of ^{70}Ga ($T_{1/2}$=21.15min) formed during the irradiation of natural Ga_2O_3. After cooling for about two hours, and dissolving the target using aqua fortis, one obtains ^{72}Ge solution, then dripping the solution on a special plexiglass. After titration and drying many times, we made the dot radioactive source needed for measurements.

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3. Experimental results

3.1. Measurements of γ-ray singles spectra

The γ-ray singles spectra have been studied using a Compton-suppressed coaxial low background spectrometer of 130cm^3 HPGe with 30% efficiency, and its energy resolution is 1.9keV at FWHM for the 1332.5keV γ-rays of ^{60}Co; non-Compton-suppressed measurements are also carried out at the same time. The total background counts are 0.7cps (Compton-suppressed) and 1.3cps (non-Compton-suppressed) in the energy region at 36–2515keV. The low-energy region of the singles spectrum is shown in Fig.1(a), obtained using a source–detector distance of 25cm. The γ-ray spectrum presented in Fig.1(b) shows the high-energy region recorded with an absorber composed of 2.5cm thick lead and 0.98cm thick cadmium, to attenuate the low-energy radiations, and the source–detector distance in this situation is 11cm. SE or DE in Fig.1 represents single- or double-escape peaks. These spectra were analysed carefully with a computer program which fits each peak with adjustable line shapes (approximately Gaussian), and then the peak area and centroid channel were calculated. The energy of strong peaks acted as calibration standards for weak peaks identified from the spectra. The energy and relative efficiency calibrations were performed with ^{152}Eu and ^{56}Co sources placed at the target position. In this experiment, we have observed 93 gamma rays belonging to the β^- decay of ^{72}Ga. Table 1 shows the energy (E_γ) and relative intensity (I_γ) of these gamma-rays. The relative intensities of the γ-rays were normalized to the intensity of the 834.08keV transition which was set to I_γ=100. The values of relative intensities published previously (see Refs.[6,7]) were also included for comparison. It should be pointed out that the uncertainties of the relative γ-ray intensities include not only the contributions from counting statistics, but also the uncertainties of the efficiency calibrations of the spectrometers and the normalization procedure.

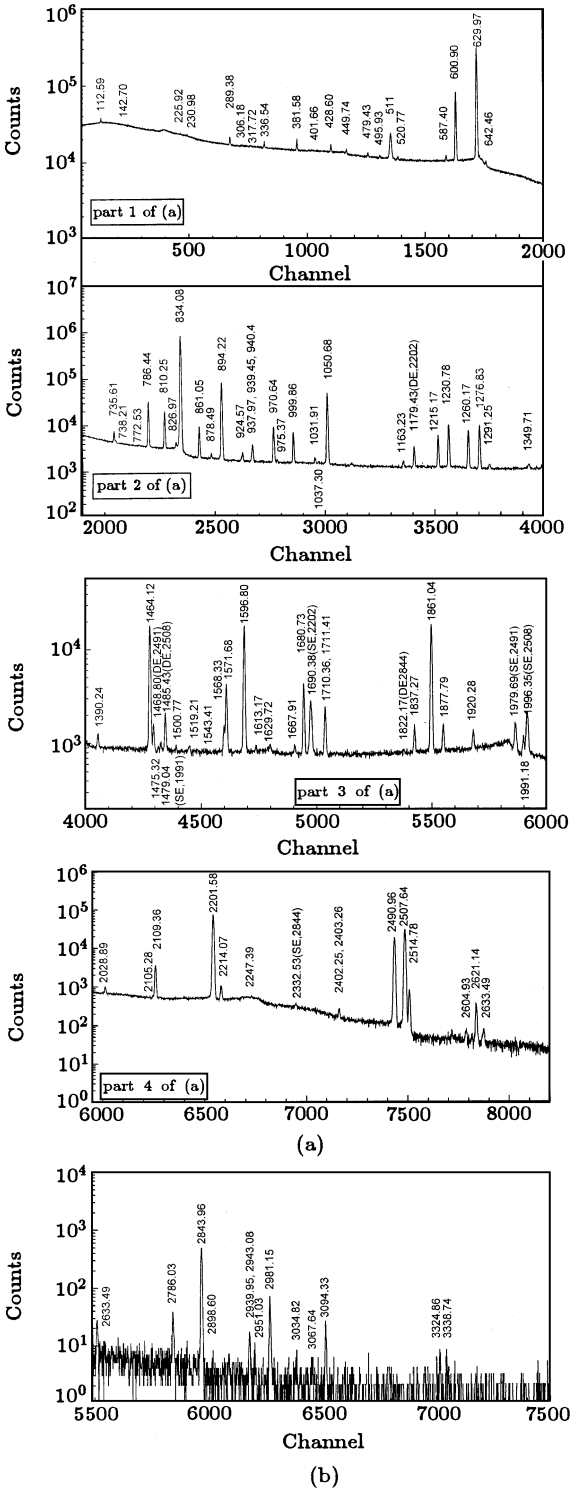


Fig.1. Gamma-single spectra of ^{72}Ge taken with an anti-Compton spectrometer. (a) The low-energy region. (b) The high-energy region. The peaks are marked in keV.

Table 1. The energies and relative intensities of γ-rays following the decay of ^{72}Ga.

This work		Rester *et al*[6]		Camp[7]	
E_γ/keV[c]	I_γ/%[c]	E_γ/keV[c]	I_γ/%[c]	E_γ/keV[c]	I_γ/%[c]
		50.89(5)	0.006(3)	50.87(5)	0.011(1)
112.59(4)	0.111(8)	112.52(3)	0.11(5)	112.5(5)	0.142(6)
				113.5(1)	0.006(1)
142.70(9)	0.013(5)[§]	142.54(6)	0.013(2)	142.5(1)	0.011(1)
225.92(14)[n]	0.017(6)[§]				
230.98(6)	0.025(4)			230.6(6)	0.024(7)
289.38(4)	0.220(13)	289.3(3)	0.18(1)	289.5(2)	0.210(7)
306.18(9)	0.046(8)			306.0(3)	0.022(2)
317.72(14)	0.018(6)			317.5(4)	0.023(2)
336.54(4)	0.135(9)	336.3(3)	0.11(1)	336.6(2)	0.112(3)
381.58(4)	0.329(18)	381.2(2)	0.28(1)	381.2(2)	0.289(80)
401.66(14)	0.015(7)			401.3(4)	0.034(2)
428.60(4)	0.238(14)	428.3(3)	0.23(1)	428.4(2)	0.192(8)
449.74(5)	0.201(13)	449.6(3)	0.16(2)	449.5(3)	0.092(6)
479.43(5)	0.105(9)	479.1(3)	0.11(1)	479.6(3)	0.090(6)
495.93(7)	0.049(8)	496.2(4)	0.060(8)	495.7(3)	0.59(5)
520.77(7)	0.061(8)	520.8(4)	0.066(7)	520.7(3)	0.054(4)
587.40(4)	0.152(11)	587.9(4)	0.11(1)	587.4(3)	0.130(4)
600.90(4)	6.11(32)	600.85(3)	5.7(2)	600.9(1)	5.840(135)
629.97(4)	27.2(14)	629.86(4)	26.4(8)	629.9(1)	25.500(670)
642.46(8)[?]	0.068(8)				
735.61(4)	0.388(21)	735.9(2)	0.39(1)	735.6(2)	0.376(11)
738.21(7)	0.055(4)			738.5(4)	0.057(4)
772.53(11)	0.030(6)	772(1)	0.045(9)	772.6(3)	
786.44(4)	3.49(18)	786.4(1)	3.41(9)	786.5(1)	3.314(73)
810.25(4)	2.17(14)	810.24(9)	2.10(9)	810.2(2)	2.100(46)
826.97(5)[n]	0.511(27)				
834.08(4)	100	834.02(3)	100	833.95(5)	100
861.05(4)	0.960(74)	861.11(5)	0.96(3)	861.0(1)	0.953(26)
878.49(6)	0.070(6)	878.0(4)	0.079(8)	878.4(2)	0.074(7)
894.22(4)	10.6(5)	894.22(5)	10.4(3)	894.2(1)	10.300(220)
924.57(4)	0.137(41)	924.1(2)	0.15(1)	924.5(3)	0.149(4)
937.97(9)	0.079(5)			938.4(2)	0.080(3)
939.45(4)	0.282(15)	939.35(8)	0.27(2)	939.4(2)	0.271(7)
940.4[#]	0.008(25)*	940.5(1)	0.11(2)	940.6(3)	0.008(1)
970.64(4)	1.15(6)	970.54(6)	1.14(3)	970.6(2)	1.155(24)
975.37(8)	0.040(3)			975.5(5)	0.035(10)
999.86(4)	0.841(44)	999.86(6)	0.84(2)	999.9(2)	0.832(24)
1031.91(6)	0.074(7)	1032.8(4)	0.079(9)	1032.0(3)	0.065(5)
1037.30(18)	0.018(2)			1037.2(6)	0.022(2)
1050.68(4)	7.29(38)	1050.69(6)	7.2(2)	1050.7(1)	7.243(150)
				1155.7(6)	0.011(2)
1163.23(6)	0.086(8)	1163.3(4)	0.068(9)	1163.1(2)	0.082(6)
		1192.4(4)	0.037(8)	1193.4(3)	
1215.17(4)	0.860(45)	1215.16(8)	0.82(2)	1215.1(2)	0.833(22)
1230.78(4)	1.52(9)	1230.86(7)	1.53(4)	1230.9(2)	1.513(32)
1260.17(3)	1.24(6)	1260.10(8)	1.15(3)	1260.1(2)	1.200(25)
1276.83(3)	1.63(10)	1276.75(8)	1.63(2)	1276.8(2)	1.646(34)
1291.25(9)	0.055(6)			1291.3(4)	0.059(5)
1349.71(10)[n]	0.165(10)				
1390.24(12)	0.089(8)	1390.5(4)	0.09(9)	1390.4(2)	0.089(7)
1464.12(3)	3.71(21)	1464.0(1)	3.7(1)	1464.0(1)	3.717(78)

Table 1. (*Continued*)

This work		Rester *et al*[6]		Camp[7]	
1475.32(18)[n]	0.029(3)				
1500.77(22)	0.004(4)	1501(1)	0.018(4)	1500.9(6)	0.020(1)
1519.21(28)	0.042(6)	1520(1)	0.021(4)	1519.2(6)	0.036(2)
1543.41(51)[?]	0.020(15)[§]			1541.2(6)	0.017(1)
1568.33(6)	0.197(15)	1567.9(4)	0.21(4)	1568.2(3)	0.208(7)
1571.68(3)	0.871(55)	1571.5(2)	0.84(3)	1571.7(2)	0.873(25)
1596.80(3)	4.61(27)	1596.65(9)	4.5(4)	1596.8(2)	4.428(91)
1613.17(49)	0.042(7)	1615(1)	0.040(8)	1613.5(3)	0.042(8)
1629.72(27)	0.020(3)	1630(1)	0.034(6)		
1667.91(19)[n]	0.054(7)				
1680.73(3)	0.993(52)	1680.77(8)	1.04(4)	1680.8(2)	0.907(24)
1710.36(5)	0.479(26)	1710.9(2)	0.43(2)	1710.9(2)	0.400(10)
1711.41(5)	0.007(3)	1711.3(2)	0.10(1)	1711.0(2)	0.045(2)
1837.27(5)	0.246(15)	1837.8(2)	0.24(1)	1837.1(3)	0.212(6)
1861.04(3)	5.71(33)	1861.09(8)	5.5(1)	1861.1(1)	5.470(116)
1877.79(5)	0.249(27)	1878.0(3)	0.24(2)	1877.8(3)	0.242(6)
1920.28(7)	0.187(14)	1920.2(3)	0.15(2)	1920.2(2)	0.166(5)
1991.18(10)	0.163(9)			1991.3(3)	0.117(3)
2028.89(9)	0.131(20)	2030.4(8)	0.10(2)	2029.1(4)	0.130(4)
2105.28(16)[n]	0.032(3)				
2109.36(3)	1.16(7)	2109.5(1)	1.12(3)	2109.5(2)	1.081(23)
2201.58(3)	28.4(1.6)	2201.67(8)	26.8(8)	2201.6(2)	27.270(570)
2214.07(5)	0.240(21)	2214.5(8)	0.16(2)	2214.3(3)	0.194(11)
2247.39(1)[n]	0.029(8)				
2402.25(24)	0.040(4)			2402.2(4)	0.025(2)
2403.26(55)	0.008(2)	2404.3(8)	0.016(4)	2404.5(3)	0.017(2)
2490.96(3)	8.06(46)	2490.98(8)	8.3(2)	2491.0(2)	7.820(175)
2507.64(3)	13.8(8)	2507.80(8)	13.3(4)	2507.7(2)	13.400(295)
2514.78(4)	0.308(18)	2515.6(5)	0.25(2)	2514.6(4)	0.264(10)
2582.54(16)[?]	0.016(3)	2583.5(4)	0.035(7)	2582.2(1.2)	0.015(1)
2604.93(20)	0.013(2)	2606(1)	0.013(3)	2605.4(4)	0.021(2)
2621.14(5)	0.149(10)	2621.0(4)	0.15(2)	2621.1(3)	0.137(4)
2633.49(15)	0.014(2)	2633.8(4)	0.012(2)	2634.0(7)	0.016(1)
2786.03(11)[?]	0.034(3)	2785.2(6)	0.032(6)	2785.1(5)	0.031(2)
2843.96(4)	0.445(26)	2844.1(2)	0.50(2)	2843.9(2)	0.429(12)
2898.60(4)[?]	0.008(2)			2897.1(8)	0.005(1)
2939.95(15)	0.012(2)			2939.6(4)	0.011(1)
2943.08(96)	0.002(1)	2942.4(9)	0.027(6)		
2951.03(30)[?]	0.005(1)			2950.0(5)	0.004(1)
2981.15(7)	0.056(4)	2981.4(4)	0.072(13)	2981.0(3)	0.055(5)
3034.82(61)	0.007(1)	3034.5(5)	0.004(2)	3035.0(9)	0.005(1)
3067.64(41)[?]	0.008(1)			3067.0(6)	0.003(1)
3094.33(13)	0.024(2)	3093.9(7)	0.026(8)	3093.7(3)	0.017(2)
3324.86(26)	0.008(1)	3324.4(5)	0.004(2)	3325.0(6)	0.003(1)
3338.75(24)[?]	0.006(1)	3340(1)	0.005(2)	3338.0(4)	0.003(1)

[c] The reported uncertainties refer to the last significant digits.

[n] New γ-transition identified in the present work.

[#] The energy of γ-ray is deduced from the peak in the coincidence spectrum.

[?] γ-transition not placed in the decay scheme.

[§] The relative intensity of γ-ray is deduced from the Compton-suppressed spectrum.

[*] The intensity is determined from the total intensity of three γ-rays at 937.97, 939.45 and 940.4keV subtracting the intensity of the two former γ-rays.

3.2. Coincidence spectra

Coincidence measurements were made using two high-purity Ge detectors oriented at 90°, one of which was a planar Ge detector (GMX-20190) with 20% efficiency and 1.85keV resolution at 1332.5keV and placed 10cm from the target; the other was a coaxial Ge detector(GEM-50195) with 50% efficiency and 2.0keV resolution at 1332.5keV and placed 15cm from the target. The data were stored in an event-by-event recording mode on a computer hard disk. For each event one time and two energy parameters of 8192 channels were included. The fast–slow coincidence circuit had a time resolution of about 20ns when gated by the ^{60}Co full energy peaks. For low-energy transitions it can be much larger. About 2.3×10^7 coincidence events were stored. The reconstruction of coincidence spectra was performed off-line. For each gate, a gross spectrum without random coincidence and background correction and a background spectrum were obtained. Coincidence relationships were determined by comparing this pair of spectra. Almost all transitions determined in singles spectra were observed in coincidence spectra too. On the other hand, several weak peaks which could not be separated in singles spectra were also identified in coincidence spectra. Figure 2 shows the coincidence γ-ray spectra gated on 827, 894 and 1350keV photopeaks, respectively. These spectra were corrected for background coincidences.

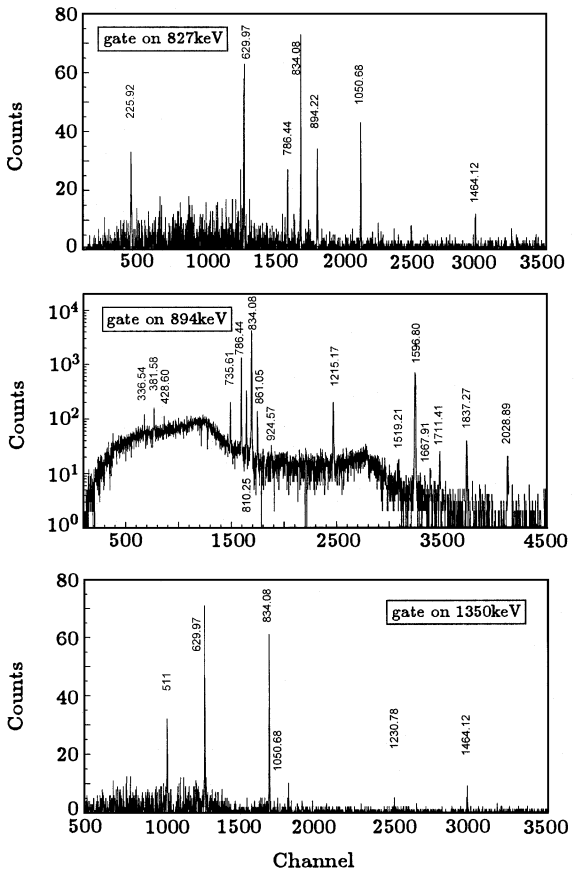


Fig.2. Some examples of coincidence spectra gated on (a) 827keV, (b) 894keV, (c) 1350keV γ-rays following the decay of ^{72}Ga. The peaks are marked in keV.

The present investigation of the ^{72}Ga decay provides an extension of the information concerning this decay. Approximately 93 transitions including 7 new transitions and 4 new levels were assigned to ^{72}Ga, based on the measured half-life and/or the coincidence with well-known transitions. A decay scheme, which is shown in Fig.3, has been constructed consisting of 25 excited states and 87 transitions in ^{72}Ge. Additional new information has been obtained on γ-ray branching ratios, logft values, spins and parities.

4. Discussion

The relative γ-ray intensities were normalized to give 100 for the total feeding of the ground state, excluding a direct feeding of the ground state because of spin arguments. The decay scheme constructed from the present experiment is shown in Fig.3. The total γ-ray transitions measured were 93, of which 7 were observed for the first time. 87 γ-rays were placed in the level scheme with 25 excited states, including 4 new levels. The energies of the new excited states are 3248.01, 3396.27, 3806.10 and 3864.56keV. New γ-rays of 225.92, 826.97, 1349.71, 1475.32, 1667.91, 2105.28 and 2247.39keV are identified in the present work, among them some new γ-rays in the level scheme were seen in coincidence spectra. A new level was confirmed when at least one γ-ray depopulating or populating the level was found in coincidence spectra. The level energies were obtained by the energy sum relations of the gamma-ray transitions. The multipolarity of the γ transition is taken from Ref.[4]. From the γ-ray and internal-conversion electron intensities (only the K-conversion electron is considered),[4] the β^- branching to excited levels was calculated from the $I_{\gamma+\mathrm{ce}}$ intensity balance. Finally, based on the 3992.4±23keV of Q-value for β^--decay,[8] the log ft values and the intensities of the β^- branches to the ^{72}Ge levels were calculated by using the ENSDF (the Evaluated Nuclear Structure Data File) analysis and checking program offered by NNDC (the National Nuclear Data Centre) at Brookhaven National Laboratory. The ground state spin, parity of ^{72}Ga is 3^-.[4] The result is pre-

sented in the decay scheme (Fig.3). The construction of the level scheme (Fig.3) was based on spectra obtained in coincidence with a selection of gating transitions and on previous work. Energy sum relations were used in only a few instances to place transitions within the scheme. The β^- branching ratio and $I_{\gamma+ce}$ are absolute in Fig.3. The discussion below is limited to levels which have not been observed before, to those observed in previous work but were not confirmed by present work, and to those for which the population and depopulation mode or spin, parity assignment has been revised significantly with respect to previous works. Spins and parities are assigned based on selection rules for β decay ($\log ft$ values), de-excitation modes of the observed states.

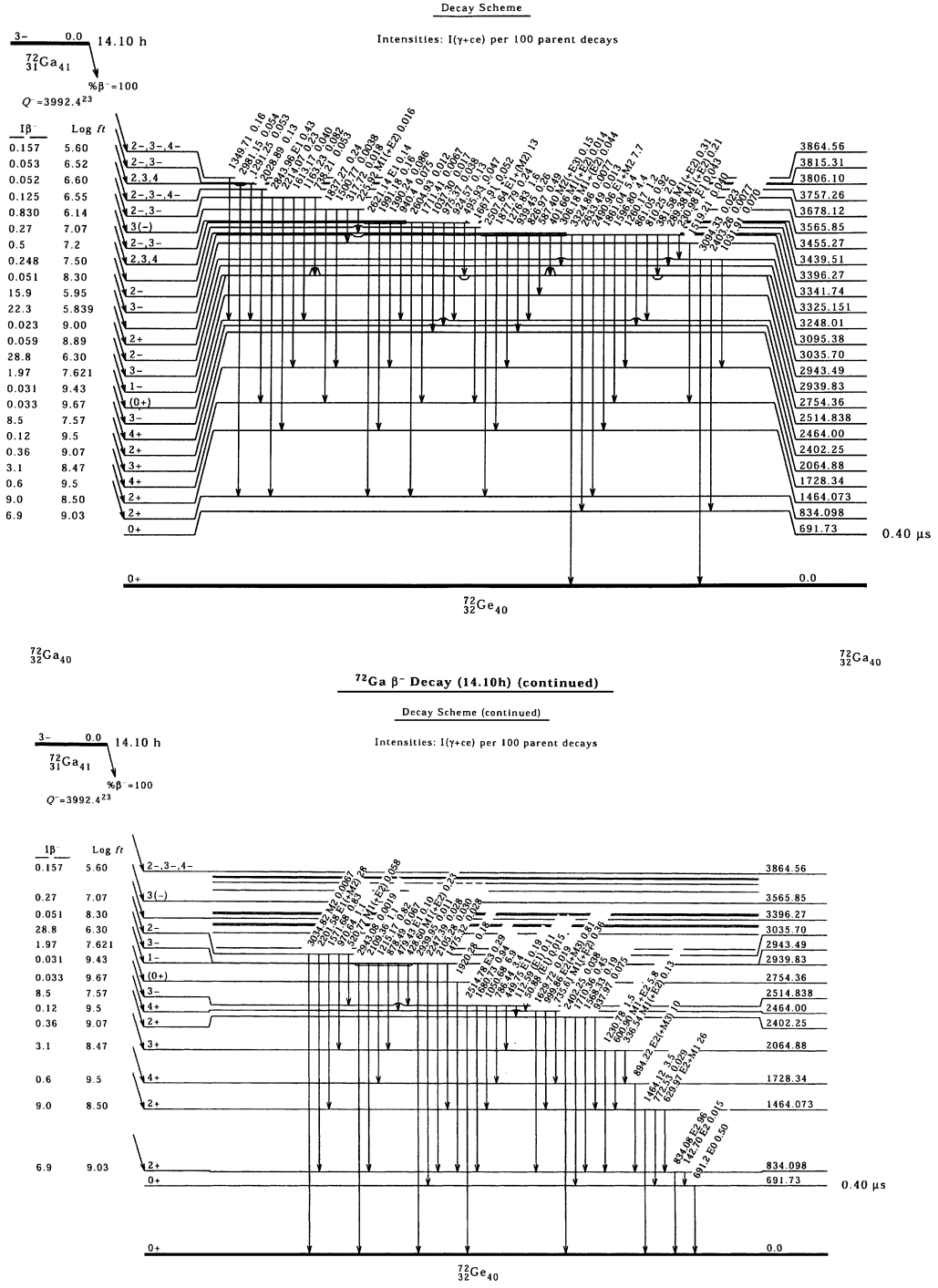


Fig.3. Decay scheme of ^{72}Ga proposed in this experiment.

4.1. The 3248.01 and 3396.27keV levels

Two relatively weak lines at 1519.21 and 1667.91keV are identified from singles spectrum. These two transitions appear in the spectrum gated by 894.22keV line, and the 894.22keV γ-rays can be found in the spectra gated by 1519.21 and 1667.91keV γ-rays, respectively. Therefore two new levels at 3248.01 and 3396.27keV are proposed.

4.2. The 3439.51keV level

The $\log ft$ value indicates that the β^- transition to the level is allowed or once-forbidden. The possible spin assignments are, therefore, 2, 3, or 4.

4.3. The 3757.26keV level

The $\log ft$ value indicates that the β^- transition to the level is allowed or once-forbidden. The negative parity assignment was proposed previously.[4] Therefore, the Jπ value of this level can be restricted to 2^-, 3^- or 4^-.

4.4. The 3806.10keV level

The 1291.25keV γ-ray is observed in coincidence spectrum gated by 1050.68keV transition. Therefore a new level at 3806.10keV is proposed. The $\log ft$ value of 6.60 for the β^- decay of the 3806.10keV level indicates the allowed or first forbidden transition, which limits the spin to 2–4.

4.5. The 3864.56keV level

A new γ-ray at 1349.71keV is identified from singles spectrum although it is weak. The 1050.68keV transition was observed in coincidence spectrum gated by 1349.71keV γ-ray. Therefore a new level at 3864.56keV is proposed. The $\log ft$ value indicates that the β^- transition to the level is allowed. The possible spin assignments are, therefore, 2^-, 3^-, or 4^-.

4.6. The 2939.83keV level

The 1475.32, 2105.28 and 2247.39keV γ-rays can be identified in the singles spectra measurements, and the coincidence counts are too few to assign their placements in the decay scheme. Considering in the low-spin states of ^{72}Ge excited in the ^{72}As(β^++EC)^{72}Ge decay,[9] to above three γ-rays are all depopulated from the level 2939.95keV, and populated to 1464.073, 834.098 and 691.73keV levels, respectively; thus from the existence of the 2939.95keV γ-ray, the 2939.83keV level is proposed again.

4.7. The 3707.1keV level

The level at 3707.1keV adopted in the previous decay scheme is not placed in the present decay scheme because the 1192.4keV γ-ray cannot be assigned in the singles spectra measurements.[4]

In addition, the tentative placements of transitions of 112.59, 937.97, 2402.25 and 2939.95keV in the previous works are confirmed in the present work.[6,7] The new position of the 317.72keV transition has been found between the 3565.85 and 3248.01keV levels.

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