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Decay of ^{72}Ga

J.A.G. Medeiros[a], C.B. Zamboni[a], A.L. Lapolli[a], G. Kenchian[b], M.T.F. da Cruz[b,*]

[a]Instituto de Pesquisas Energéticas e Nucleares, IPEN-CNEN/SP, São Paulo, Brazil
[b]Instituto de Física da Universidade de São Paulo, São Paulo, Brazil

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Abstract

The γ-ray spectrum of ^{72}Ge following the β^- decay of ^{72}Ga has been studied using both single and gamma–gamma coincidence spectroscopy techniques. The energies and intensities of 110 γ-rays have been determined, 26 of them were observed for the first time and 20 have been confirmed. Of the total number of γ-rays observed, 95 have been placed in a proposed level scheme containing 31 levels. This includes five new levels at 2303, 2694, 3067, 3097 and 3420 keV.

Keywords: Radioactivity; β decay; γ decay; Energy; Intensity

1. Introduction

Several experiments have been performed to explore the level structure of ^{72}Ge through the β^- decay of ^{72}Ga and β^+/EC decays of ^{72}As. These studies included γ-spectroscopy measurements with NaI(Tl) and Ge(Li) detectors (Vitman et al., 1968; Camp, 1968; Rester et al., 1971a,b) and gamma–gamma and βγ angular correlations of the most intense cascades (Arns and Wiedenbeck, 1958; Alberghini and Steffen, 1963; Newsome and Fischbeck, 1964; Monahan and Arns, 1969; Hsuan et al., 1974; Landulfo et al., 1994). However, the nuclear data published in the literature (King, 1989) point out many discrepancies at low-lying levels. In the present study we have the opportunity to resolve the status of some tentative transitions and in addition to postulating five new levels, by measuring the single and gamma–gamma coincidence using high-resolution Ge detectors.

2. Experimental procedure

The radioactive ^{72}Ga sources were prepared by neutron irradiation of 99.9% pure gallium oxide in the IEA-R1 reactor at São Paulo. Approximately 10 mg of Ga_2O_3 were irradiated in a flux of 10^{13} n/cm^{2}s for a period of 5 min. The samples were stored for 3 h to allow for the decay of ^{70}Ga ($T_{1/2} = 21$ min) formed during the irradiation of natural Ga_2O_3. To assure the purity of the chemical compound to be investigated, neutron activation analysis was employed. This technique permits the determination of elements at concentrations of ng g^{-1} levels. The analysis consists of the irradiation at appropriate time intervals (10 min and 8 h). After a decay time of about 3 h, for the short irradiation, the gamma-ray spectra were recorded through 10 successive half-lives. Using this procedure

* Corresponding author. Tel.: +55-11-818-7055; fax: +55-11-818-6832.
E-mail address: tiago@if.usp.br (M.T.F. da Cruz).

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it was possible to show that there is no evidence for γ-emitting impurities in the source. More details about the experimental set up and procedure have been described in our previous study (Medeiros, 1995).

The single spectra were taken using a HPGe coaxial detector of 50 cm^3 active volume, with energy resolution of 1.8 keV at the 1332 keV transition of ^{60}Co and a 572-ORTEC amplifier in pile-up rejection mode. The background radiation was reduced with the help of an iron shield (Vanin et al., 1985), illustrated in detail in Fig. 1. To determine the gamma-rays energies with a precision similar to that of the primary standards, we used the same procedure described by Vanin et al. (1997).

The measurements of gamma–gamma-coincidences spectra were carried out using an 89 cm^3 and a 60 cm^3 Ge detectors, each having an energy resolution better than 2.0 keV at 1.3 MeV. They were placed at 130° and each of them was shielded with 1 cm of lead to avoid coincidence events due to Compton scattered gamma-rays. A conventional fast-slow coincidence circuit, with time resolution of 11 ns in the range from 130 keV to 3.9 MeV, was used. Two equal-sized hardware gates were set on the timing spectrum, to tag the coincidence events either as "true" or "chance". At every master gate three parameters were recorded (the energies of both detectors and the coincidence tag) with the help of a CAMAC input register, assisted by an MBD-11 microprocessor connected to a PDP-11/84 computer. The method of analysis was that described by Camargo et al. (1998).

3. Experimental results

3.1. Single spectra

In this experiment, we have observed 110 gamma rays belonging to the β^- decay of ^{72}Ga. Table 1 shows the energy (E_γ), relative intensity (I_γ) and the placement of these gamma-rays. The values of relative intensities published previously (Camp, 1968; Rester et al., 1971b) were also included for comparison.

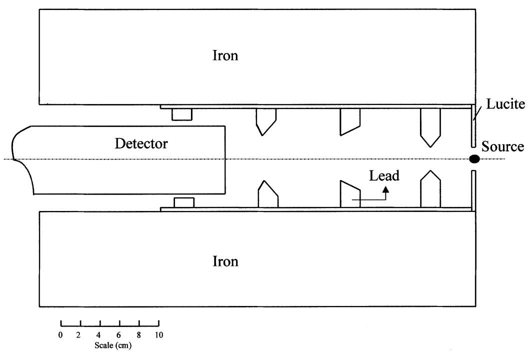

Fig. 1. Iron shield used in the single spectra measurements.

The direct gamma-ray spectrum from about 70 keV to 3.5 MeV, recorded during 200 h of live time, is shown in Figs. 2–5. Twenty five transitions with energies 223.0, 228.2, 374.3, 398.9, 570.9, 633.5, 642.5, 827.1, 839.0, 898.4, 923.0, 932.5, 1361.7, 1368.6, 1374.4, 1476.0, 1479.5, 1633.3, 1822.0, 1898.5, 2116.8, 2585.7, 2694.5, 2831.7, 3678.5 keV and also a doublet at 630.0 keV were observed for the first time. Sixteen γ-transitions with energies 231.1, 306.2, 317.9, 402.0, 738.3, 938.3, 975.5, 1037.3, 1291.4, 1991.2, 2402.6, 2898.4, 2940.2, 2951.1, 3067.3 and 3338.5 keV observed only by Camp (1968) and three γ-transitions at 772.6, 1192.2 and 1629.9 keV observed only by Rester et al. (1971a) were also assigned to ^{72}Ga based on the observed 1051–773, 1192–1861 and 1630–834 coincidence relationships (see Table 2).

Besides, the 3341.8 keV γ-transition, also observed only by Rester et al. (1971a), in the present study it is not seen in coincidence with any gamma-ray, so it is placed as a transition directly to the ground state.

The intensities of the 839.0, 878.5, 898.4, 1192.2, 1479.5, 1519.3, 1613.0, 1821.9, 2109.4 and 2582.4 keV transitions were corrected for single or double escape superposition effects. No evidence was seen of the peaks at 1155.7 and 1541.2 keV, previously reported (Camp, 1968), although the present experiment has achieved better observation limits. Upper limits for the intensities were calculated following Helene's prescription (Helene, 1983) for a 95% confidence level and are presented in Table 1 as well.

The 2942.4 keV transition reported earlier (Rester et al., 1971b) placed as depopulating the 2943.5 keV level, but no evidence for this transition was found in the present work. The region around 2900 keV was examined and the gamma-ray spectrum reveals the resolution of the 2940.2 keV gamma-ray peak, placed as a ground state transition from the level at 2940.0 keV based on the observed 402-2940 and 738-2940 coincidence relationships (see Table 2).

From the analysis of the energy determinations, the doublets at 938.3 and 939.7 keV and at 1710.3 and 1711.2 keV, suggested by earlier studies (Camp, 1968; Rester et al., 1971b) were confirmed. No evidence was seen of the doublet at 112.5 and 113.5 keV reported earlier (Camp, 1968).

3.2. Gamma–gamma coincidence spectra

A search was made for gamma–gamma coincidences in the region between 200 and 3900 keV. The counting time for coincidence experiments was 180 h. A summary of the observed coincidences by taking 87 gates is shown in Table 2. According to

Table 1
Energy (E_γ) in keV and relative intensity (I_γ) in % of the gamma-rays following the ^{72}Ga decay

This work		Rester et al. (1971b)	Camp (1968)	This work
E_γ	I_γ	I_γ	I_γ	$E_i \rightarrow E_f$
112.715(32)	0.079(5)	0.11(5)	0.142(6)	2514 → 2402
113.5(1)[a]	–	–	0.006(1)	(3455 → 3341)[a,c]
142.719(35)	0.0087(7)	0.013(2)	0.011(1)	834 → 691
223.03(6)	0.0059(5)	–	–	–
228.227(27)	0.0237(7)	–	–	–
231.061(26)	0.0284(8)	–	0.024(7)	3325 → 3094
289.532(20)	0.2131(14)	0.18(1)	0.210(7)	3325 → 3035
306.190(26)	0.0259(9)	–	0.022(2)	3341 → 3035
317.872(26)	0.0218(5)	–	0.023(2)	3757 → 3439
336.696(19)	0.1308(13)	0.11(1)	0.112(3)	2065 → 1728
374.341(34)	0.0186(8)	–	–	3325 → 2950
381.694(17)	0.3211(17)	0.28(1)	0.289(8)	3325 → 2943
398.92(5)	0.0155(7)	–	–	–
402.03(4)	0.0180(7)	–	0.034(2)	3341 → 2940
428.649(15)	0.2306(19)	0.23(1)	0.192(8)	2943 → 2514
449.840(16)	0.1210(19)	0.16(2)	0.092(6)	2514 → 2065
479.461(17)	0.1071(20)	0.11(1)	0.090(6)	2943 → 2464
496.075(34)	0.0592(9)	0.060(8)	0.059(5)	3439 → 2943
520.851(19)	0.0638(20)	0.066(7)	0.054(4)	3035 → 2514
570.94(6)	0.0169(28)	–	–	–
587.450(21)	0.1493(15)	0.11(1)	0.130(4)	3341 → 2754
600.916(12)	6.13(5)	5.7(2)	5.840(135)	2065 → 1464
629.979(12)	27.38(20)	26.4(8)	25.500(670)	1464 → 834 (3325 → 2694)[c]
633.466(14)	0.1655(25)	–	–	3035 → 2402
642.466(14)	0.1110(11)	–	–	3678 → 3035
735.694(12)	0.3915(27)	0.39(1)	0.376(11)	2464 → 1728
738.271(23)	0.0489(12)	–	0.057(4)	3678 → 2940
772.643(27)	0.0301(15)	0.045(9)	–	1464 → 691
786.529(12)	3.532(16)	3.41(9)	3.314(73)	2514 → 1728
810.355(12)	2.201(10)	2.10(9)	2.100(46)	3325 → 2514
827.145(15)	0.1063(13)	–	–	3341 → 2514
834.170(12)	100.0	100.0	100.0	834 → 0
839.045(13)	0.0262(17)	–	–	2303 → 1464
861.184(12)	0.987(5)	0.96(3)	0.963(26)	3325 → 2464
878.522(20)	0.0705(17)	0.079(8)	0.074(7)	2943 → 2065
894.336(12)	10.63(4)	10.4(3)	10.300(220)	1728 → 834
898.43(5)	0.0097(10)	–	–	–
923.044(38)	0.0435(17)	–	–	3325 → 2402
924.795(17)	0.1223(18)	0.15(1)	0.149(4)	3439 → 2514
932.49(11)	0.0118(13)	–	–	–
938.28(6)	0.0707(33)	–	0.080(3)	3341 → 2402
939.648(16)	0.2937(28)	0.27(2)	0.271(7)	2402 → 1464
940.6(1)[b]	–	0.11(2)	–	(3455 → 2514)[b,c]
970.772(12)	1.163(6)	1.14(3)	1.155(24)	3035 → 2065
975.539(23)	0.0474(11)	–	0.035(10)	3439 → 2464
999.995(12)	0.851(4)	0.84(2)	0.832(24)	2464 → 1464
1032.094(22)	0.0766(17)	0.079(9)	0.065(5)	3097 → 2065
1037.35(6)	0.0183(12)	–	0.022(2)	3439 → 2402
1050.800(12)	7.32(4)	7.2(2)	7.243(150)	2514 → 1464
1155.7(6)[a]	< 0.0005[d]	–	0.011(2)	(3619 → 2464)[a,c]
1163.324(20)	0.1062(16)	0.068(9)	0.082(6)	3678 → 2514
1192.24(7)	0.005(1)	0.037(8)	–	(3708 → 2514)[b]

(continued on next page)

Table 1 (*continued*)

This work		Rester et al. (1971b)	Camp (1968)	This work
E_γ	I_γ	I_γ	I_γ	$E_i \rightarrow E_f$
1215.139(13)	0.863(6)	0.82(2)	0.833(22)	2943 → 1728
1230.934(13)	1.513(10)	1.53(4)	1.513(32)	2065 → 834
1260.124(13)	1.244(8)	1.15(3)	1.200(25)	3325 → 2065
1276.798(13)	1.669(11)	1.63(2)	1.646(34)	3341 → 2065
1291.4(34)	0.0506(20)	–	0.059(5)	–
1361.66(13)	0.0146(16)	–	–	–
1368.640(38)	0.0553(18)	–	–	3097 → 1718
1374.37(10)	0.189(15)	–	–	–
1390.304(21)	0.0868(20)	0.090(9)	0.089(7)	3455 → 2065
1464.054(14)	3.763(31)	3.7(1)	3.717(78)	1464 → 0
1476.02(14)	0.0072(13)	–	–	2940 → 1464
1479.53(7)	0.0178(13)	–	–	2943 → 1464
1500.47(7)	0.0209(13)	0.018(4)	0.020(1)	3565 → 2065
1519.30(7)	0.039(5)	0.021(4)	0.036(2)	–
1541.2(6)[a]	< 0.0010[d]	–	0.017(1)	–
1568.071(20)	0.1739(24)	0.21(4)	0.208(7)	2402 → 834
1571.600(14)	0.897(9)	0.84(3)	0.873(25)	3035 → 1464
1596.735(14)	4.58(4)	4.5(4)	4.428(91)	3325 → 1728
1613.05(6)	0.0388(29)	0.040(8)	0.042(8)	3678 → 2065
1629.90(22)	0.025(4)	0.034(6)	–	2464 → 834
1633.35(5)	0.114(10)	–	–	3097 → 1464
1680.741(15)	0.960(10)	1.04(4)	0.907(24)	2514 → 834
1710.33(8)	0.19(6)	0.043(2)	0.400(10)	2402 → 691
1711.17(13)	0.27(4)	0.10(1)	0.045(2)	3439 → 1728
1821.961(31)	0.2103(30)	–	–	–
1837.148(19)	0.231(4)	0.24(1)	0.212(6)	3565 → 1728
1860.990(16)	5.67(7)	5.5(1)	5.470(116)	3325 → 1464
1877.680(19)	0.244(4)	0.24(2)	0.242(6)	3341 → 1464
1898.48(20)	0.0121(18)	–	–	–
1920.226(24)	0.176(4)	0.15(2)	0.166(5)	2754 → 834
1991.157(33)	0.0981(25)	–	0.117(3)	3455 → 1464
2028.93(5)	0.1187(20)	0.10(2)	0.130(4)	3757 → 1728
2105.28(32)	0.0469(7)	–	–	2940 → 834
2109.356(17)	1.147(17)	1.12(3)	1.081(23)	2943 → 834
2116.77(8)	0.0286(17)	–	–	2950 → 834
2201.582(17)	28.2(5)	26.8(8)	27.270(570)	3035 → 834
2214.022(20)	0.241(4)	0.16(2)	0.194(11)	3678 → 1464
2402.58(8)	0.0464(18)	–	–	2402 → 0 3094 → 691
2402.2(4)[a]	–	–	0.025(2)	(3094 → 691)[a]
2402.5(3)[a]	–	–	0.017(2)	(2402 → 0)[a]
2404.3(8)[b]	–	0.016(4)	–	(3094 → 691)[b]
2491.029(18)	8.1(2)	8.3(2)	7.820(175)	3325 → 834
2507.714(18)	14.0(3)	13.3(4)	13.400(295)	3341 → 834
2514.857(19)	0.334(7)	0.25(2)	0.264(10)	2514 → 0
2582.37(6)	0.0123(7)	0.035(7)	0.015(1)	2582 → 0
2585.74(19)	0.0053(6)	–	–	3419 → 834
2605.44(5)	0.0152(6)	0.0152(6)	0.021(2)	3439 → 834
2621.281(23)	0.150(4)	0.15(2)	0.137(4)	3455 → 834
2633.57(4)	0.0185(6)	0.012(2)	0.016(1)	3325 → 691
2694.49(15)	0.0026(2)	–	–	2694 → 0
2785.833(37)	0.0315(10)	0.032(6)	0.031(2)	3619 → 834
2831.657(15)	0.0030(3)	–	–	–
2844.171(35)	0.467(13)	0.50(2)	0.429(12)	3678 → 834

Table 1 (*continued*)

This work		Rester et al. (1971b)	Camp (1968)	This work
E_γ	I_γ	I_γ	I_γ	$E_i \rightarrow E_f$
2898.36(12)	0.0037(4)	–	0.005(1)	–
2940.19(6)	0.0154(6)	–	0.011(1)	$2940 \rightarrow 0$
2942.4(9)[b]	–	0.027(6)	–	$(2943 \rightarrow 0)$[b]
2951.09(9)	0.0049(3)	–	0.004(1)	$2950 \rightarrow 0$
2981.50(5)	0.0643(21)	0.0072(13)	0.055(5)	$3815 \rightarrow 834$
3035.52(6)	0.0201(8)	0.004(2)	0.005(1)	$3035 \rightarrow 0$
3067.32(11)	0.0038(3)	–	0.003(1)	$3067 \rightarrow 0$
3094.39(10)	0.0170(6)	0.026(8)	0.017(2)	$3094 \rightarrow 0$
3325.35(11)	0.0081(5)	0.004(2)	0.003(1)	$3315 \rightarrow 0$
3338.55(15)	0.0047(4)	–	0.003(1)	$3338 \rightarrow 0$
3341.77(12)	0.0086(5)	0.005(2)	–	$3341 \rightarrow 0$
3678.5(4)	0.0009(2)	–	–	$3678 \rightarrow 0$

[a] Extracted from (Camp, 1968).
[b] Extracted from (Rester et al., 1971b).
[c] Placement is uncertain.
[d] A transition with an intensity larger than the quoted value has 95% probability of detection in our spectra but was not observed.

these data, the existence of the new transitions observed in the singles spectra were confirmed in the coincidence measurements, where 15 transitions were placed in the present level scheme and 20 transitions previously attributed to this decay (King, 1989) were confirmed. On the same grounds, the transitions of energy 1192, 1291 and 2898 keV could not be placed in the present level scheme.

Several gamma-rays assigned to the decay of ^{72}Ga have multiple placements. The coincidence data indicated that the 630.0, 924.8, 938.3, 1710.3 and 2402.6 keV transitions have ambiguous placements and the

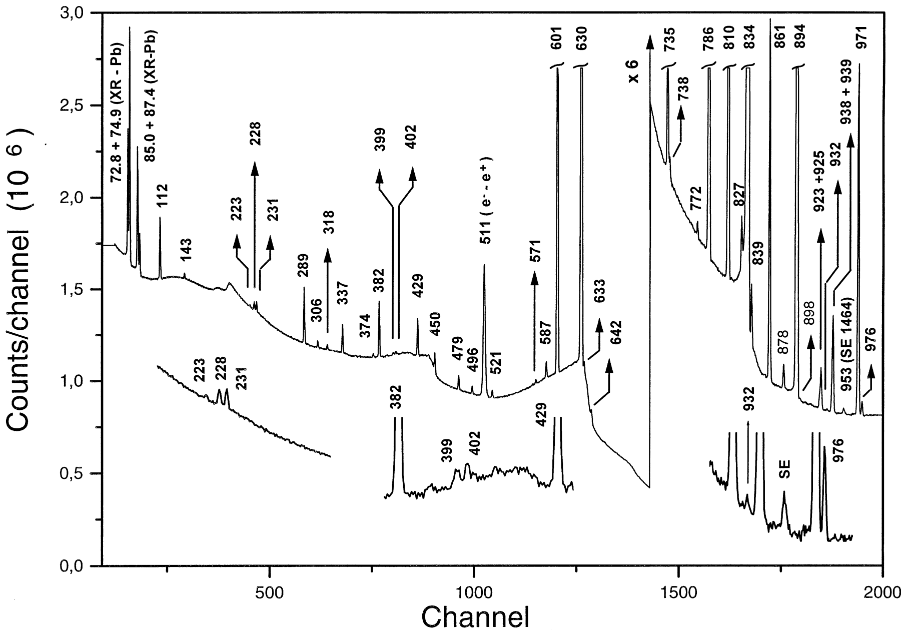

Fig. 2. Gamma-ray singles spectrum of ^{72}Ge (channel 0–2000). Number above the peaks indicate energies in keV.

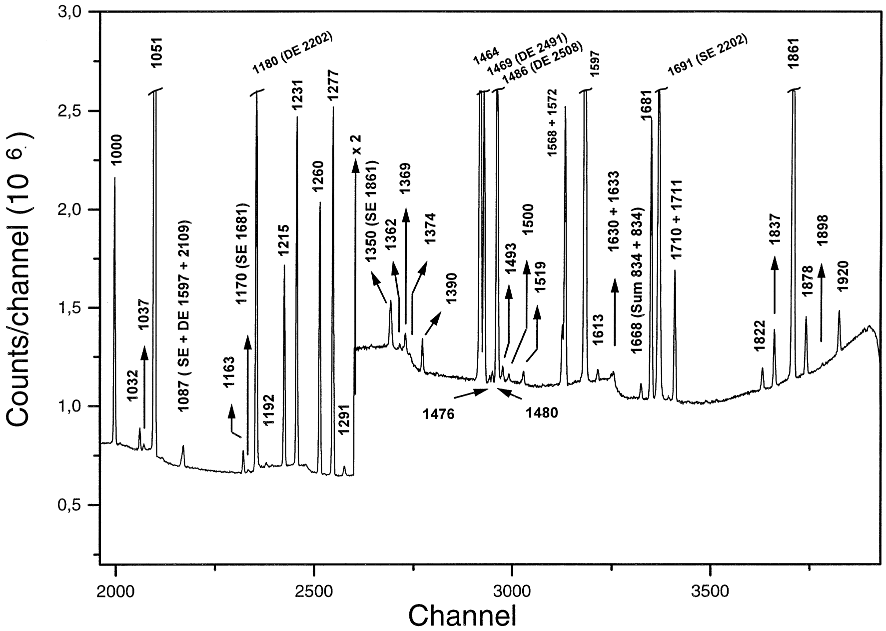

Fig. 3. Gamma-ray singles spectrum of ^{72}Ge (channel 2000–4000). Number above the peaks indicate energies in keV.

photopeaks at 630 and 2402 keV may be unresolved doublets.

The 630.0 keV gamma-ray reported earlier (King, 1989) is assigned to a transition leaving the level at 1464 keV. This is supported by several coincidence relationships in our experiment (see Table 2). Also present in the 630 keV gated spectrum was a peak corresponding to the 2694.5 keV gamma-ray transition as shown in Fig. 6(a). This has led us to try placing another 630.0 keV transition linking the

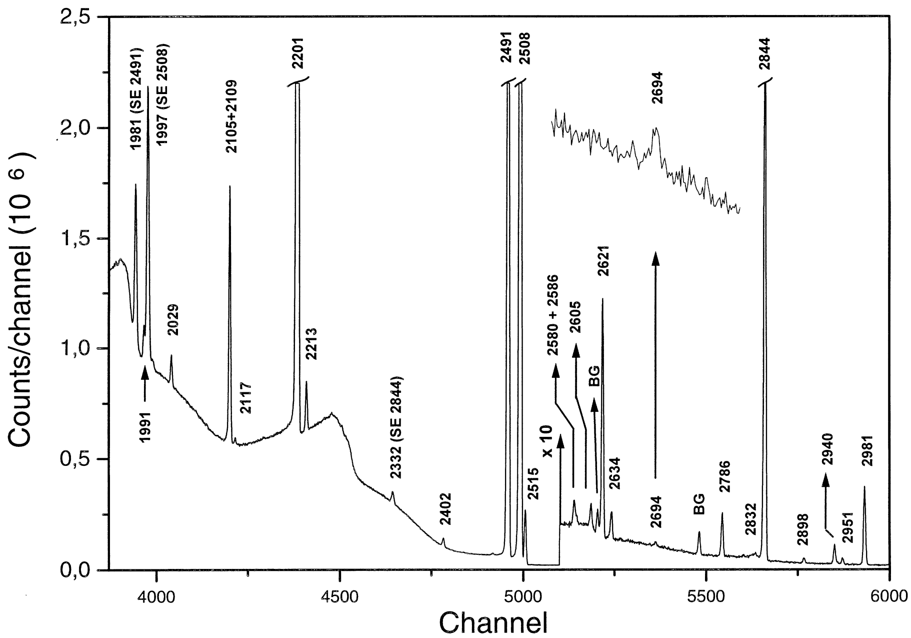

Fig. 4. Gamma-ray singles spectrum of ^{72}Ge (channel 4000–6000). Number above the peaks indicate energies in keV.

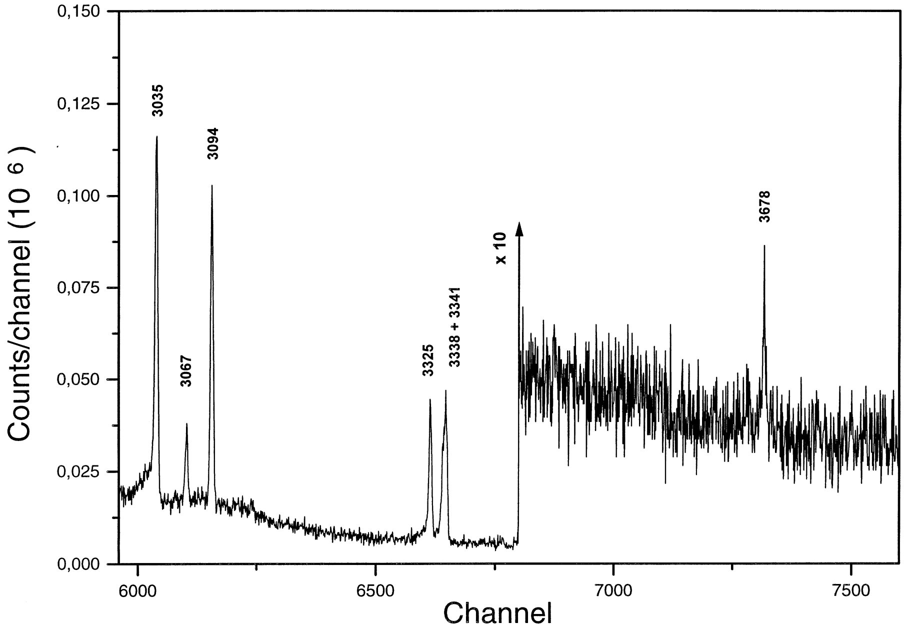

Fig. 5. Gamma-ray singles spectrum of ^{72}Ge (channel 6000–8000). Number above the peaks indicate energies in keV.

3325 keV level to the new level at 2695 keV. The gate at 2695 keV reinforces the suggestion that the 630 keV photopeak is an unresolved doublet.

The photopeak at 924.8 keV presented as a singlet in (Camp, 1968; Rester et al., 1971b) is, in fact, a doublet. It consists of the 923.0 keV transition placed in the proposed level scheme as populating the level at 2402.6 keV based on the 923-1568 and 923-1710 co-

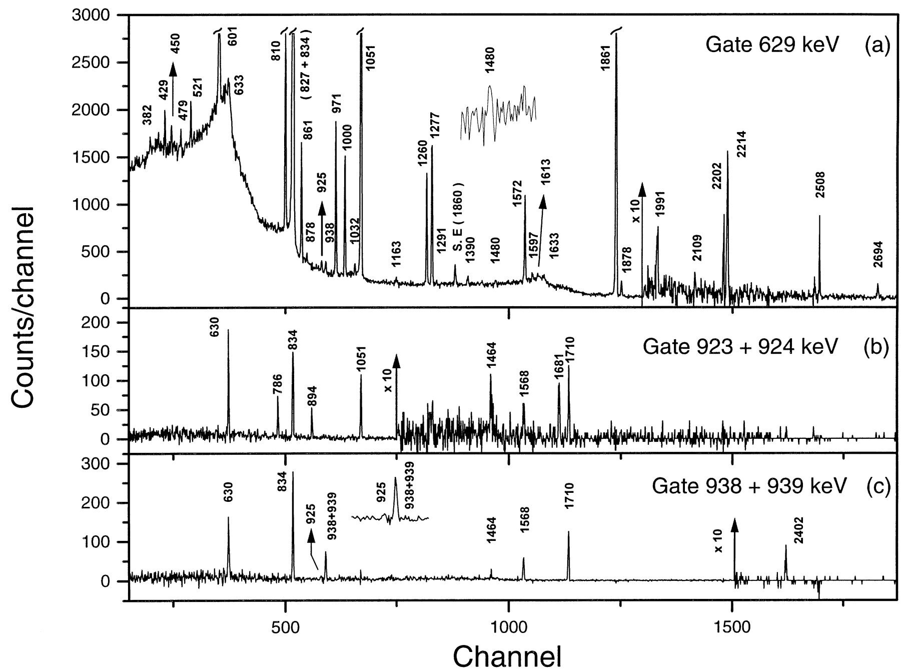

Fig. 6. Gate 629, 923 + 924 and 938 + 939 keV.

Table 2
Summary of the gamma–gamma coincidences in the ^{72}Ga decay

Gate (keV)	Gamma-rays in coincidence (keV)
223	1898
228	1898
289	450 630 834 2202
306	786 834 1231 2202
318	496 834 894 1519 1681 2109
337	429 834 894 971
374	834 1369 2117
382	429 479 630 834 894 1215 2109
399	601 630 633 894
402	630
429	382 630 786 834 894 1051 1464 1681
450	337 601 630 810 834 1163 1231
479	382 630 736 834 1000
496	786 834 894 1215 2109
521	786 1051
571	834
587	834 1291 1920
601	450 630 834 878 971 1032 1260 1277 1390 1464 1500 1613
630	382 429 450 479 521 601 633 810 827 834 861 878 925 939 971 1000 1032 1051 1163 1260 1277 1291 1390 1480 1572 1597 1613 1633 1861 1878 1991 2109 2202 2214 2508 2694
633	1568 1710
642	834 2202
736	479 834 861 894 976
738	1476 2105
786	429 810 834 894 925 1163 1291
810	630 786 834 894 1051 1464 1681 2515
827	630 786 834 894 1051
834	289 337 382 429 450 479 496 521 587 601 630 642 736 786 810 827 839 861 878 894 925 938 + 939 971 1000 1032 1051 1163 1215 1231 1260 1277 1291 1362 1369 1374 1390 1500 1519 1568 1572 1597 1630 1681 1710 1837 1861 1878 1920 2105 2109 2202 2214 2491 2508 2621
839	630 834 1464
861	630 736 834 894 1000 1464 1630
878	382 601 630 834 1231
894	337 382 429 736 786 810 827 834 861 925 1215 1277 1519 1597 1710 1837 1898 2029
923 + 925	630 786 834 894 1051 1464 1568 1681 1710
938 + 939	630 834 925 938 + 939 1464 1568 1710 2402
971	337 601 630 834 894 1231 1464
976	630 736 894 1000
1000	479 630 834 861 976 1464
1032	601 630 834 1231
1037	834 898 1710 2402
1051	429 521 630 773 810 827 834 925 1163 1291 1464
1163	630 786 834 894 1051 1681
1192	1861
1215	382 496 834 894
1231	450 834 878 971 1032 1260 1277 1390 1613
1260	337 601 630 834 894 898 1231 1464
1277	337 601 630 834 1231 1464
1291	587 630 786 834 1051 1464
1362	1051
1369	834 894
1390	601 630 834 894 1231 1464
1464	450 601 810 861 878 938 + 939 971 1000 1032 1051 1260 1277 1291 1572 1861 1878 1991 2214
1476	738
1480	382 630 834

Table 2 (*continued*)

Gate (keV)	Gamma-rays in coincidence (keV)
1500	601 1231
1519	318 894
1568	633 827 834 923 938 1037
1572	630 834 1464
1597	834 894
1613	601 630 834 1231
1681	429 810 834 925 1291
1710 + 1711	633 642 810 834 894 923 938 1037
1822	834
1837	834 894
1861	630 834 1464
1878	630 834 1464
1920	587 834
1991	630 834 1464
2029	834 894
2105 + 2109	382 496 834
2117	143 374 834
2202	289 642 834
2214	630 834 1464
2402	231 633 938 + 939
2491	834
2508	834
2515	810 827
2605	834
2621	223 834
2694	630
2786	834
2844	834
2940	402 738
2951	374
2981	834
3035	–
3067	–
3094	231
3338	–
3342	–

incidence relationships, and the 924.8 keV transition which feeds the level at 2514.9 keV based on the observation of the 630, 786, 834, 894, 1051, 1464 and 1680 keV gamma-rays in the spectrum gated by the 923 + 925 keV gamma-rays. These coincidences are clearly observed in Fig. 6(b).

Camp (1968) reported that the 939 keV transition is part of a triplet, composed by the 938.4–(2402–1464), 939.4–(3341–2402) and at 940.6–(3455–2514) keV transitions, but according to (Rester et al., 1971b) this transition is part of a doublet at 939.3 and 940.5 keV. The results of the present experiments showed that the 939.6 keV photopeak exhibits clear evidence of having a lower energy component at 938.3 keV. The gates at 630, 834, 1464, 1568, 1710 + 1711 and 2402 keV support the proposed placements. Besides, we have found that the 938.3 and 939.6 keV transitions were in coincidence (see Fig. 6(c)).

Our data for the photopeak at 2402 keV is consistent with a doublet as suggested earlier (Camp, 1968). Here, this transition is placed as depopulating the 3094.2 keV level, supported by the appearance of 231 keV gamma-ray in the spectrum gated at 2402 keV. The additional placement, between the level at 2402.3 keV and the ground state, is supported by the 633–2402 coincidence relationship.

3.3. Decay scheme

The proposed level scheme for β^- decay of ^{72}Ga consistent with the present measurements is shown in Figs. 8 and 9. The spin assignments were based on the $\log ft$ values calculated according to Nuclear Data

Table (Gove and Martin, 1971) and the observed decay modes. The intensity of the β feeding to the ground state is negligible since the ground-state spins and parities are 3^- for ^{72}Ga and 0^+ for ^{72}Ge suggesting a third-forbidden β transition. The intensities of the other β branches were obtained from the intensity balance of the transitions feeding and de-exciting the levels. The energies of the levels were obtained through a least squares fit using the 95 transitions that could be placed in the scheme. The levels indicated by dashed lines in Figs. 8 and 9 are new. The levels at 834, 1464, 1728, 2065, 2402, 2464, 2514 and 3094 keV were known from the radioactive decay and nuclear reaction studies (King, 1989) as well as the isomeric state at 691 keV. Discussions about them can be found in several works (Camp, 1968; Rester et al., 1971a, 1971b; Landulfo et al., 1994). They are shown in Figs. 8 and 9 being supported by the coincidence data and will not be discussed here (see Table 2).

The new levels suggested in this investigation are discussed, together with the results which allow us to confirm several other levels.

The introduction of the new 2303.2 keV level is supported by the appearance of the 630, 834 and 1464 keV gamma-rays in the coincidence data gated by the 839 keV gamma-ray. This is shown in Fig. 7(a). The $\log ft$ value of the β decay to this state limits the spin between 2 and 4 and suggests positive parity.

The 2582.4 keV level was proposed (Ottmar, 1968; Rester et al., 1971b) based on the observation of the 2582.4 keV transition, presumably to the ground state. Camp (1968) had also reported this transition, although not placing it in the decay scheme. The photopeak at 2582.4 keV was present in our singles spectra but was not observed in coincidence with any gamma-ray. The $\log ft$ value of 11.11 suggests a first- or second-forbidden β-transition and a spin assignment of 1 or 2, but a $J^\pi = 2^-$ assignment is less probable, since it requires that the transition to the ground state be of M2 character.

The 2694.5 keV level is new and established by the ground state transition, based on the observed 630-2694 keV coincidence (Fig. 6(a)). The fact that this level decays to the 0^+ state restricts the spin and parity to 1^+ or 2^+.

The 2754.5 keV level was proposed in the decay scheme of ^{72}Ga (Camp, 1968; Rester et al., 1971b) and the (^{3}He, d) nuclear reaction (Ardowin et al., 1975), where an assignment of 1, 2 or 3 is favoured. This level was also observed in (t, p) (Lebrun et al., 1979; Mordechai et al., 1984) and (^{6}Li, d) (Ardouin et al., 1980) reactions experiments, in which an assignment of 0^+ was indicated. This level was confirmed in the present work based on 587–834 and 1920–834 keV coincidence relationships and our results are consistent with spin and parity 1^+, 2^+, 3^+. The 0^+ assignment was excluded because it implies a high $\log ft$ value (17–19)

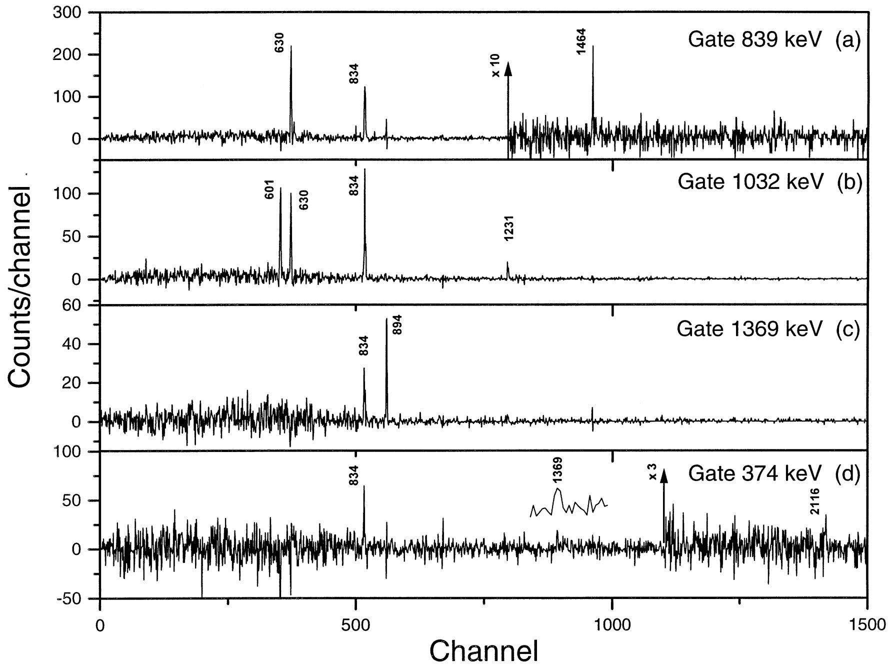

Fig. 7. Gate 839, 1032, 1369 and 374 keV.

and requires the β-transition to this level to be third-forbidden.

The coincidence data on the 1476.0, 1479.5 and 2105 keV photopeaks resulted in their placement in the decay scheme. The 1476.0 and 2105 keV transitions were placed as depopulating the level at 2940.0 keV, based on the 738–1476 and 738–2105 coincidence relationships. These transitions were also observed in the β^+ decay (Camp, 1968; Rester et al., 1971a). The 1479.5 keV gamma-ray can be assigned to a level at 2943.6 keV, based on the observed 382–1480, 630–1480 and 834–1480 coincidence relationships. A spin and parity of 1^- for the 2940.0 keV level was assigned in the decay of ^{72}Ga (Camp, 1968) and our results support it. A spin and parity of 3^- has been assigned to the level at 2943.6 keV based on the results of the (t, p) reaction (Lebrun et al., 1979; Mordechai et al., 1984). Earlier angular correlation results (Monahan and Arns, 1969) for the 1215–894–834 cascade are consistent with a spin assignment of 3 or 4. Our results are in agreement with these attributions, but a $J^\pi = 4^-$ assignment is less probable, since it would require the 2109.4 keV transition to be of M2 character.

The 2950.9 keV level was previously suggested (Camp, 1968), based upon a transition to the ground state, observed in the decays of ^{72}Ge and ^{72}As. This level was established in the present decay scheme by the placement of the 2116.8 and 2951.1 keV gamma-rays, the former observed for the first time, through coincidence relationships listed in Table 2. The 2116.8 keV transition was also observed in the decay of ^{72}As (Camp, 1968; Rester et al., 1971a) but it was not placed in the decay scheme. The $\log ft$ value of 10.4 and the fact that the level decays to 2^+ and 0^+ states restrict the spin and parity assignment to 2^+.

The spin of the 3035.8 keV level is known to be 2 from earlier angular correlation results for the 2202–834 keV γ-cascade (Belyalv et al., 1966; Tirsel and Bloom, 1967; Landulfo et al., 1994). This level is depopulated through the 520.8, 970.8, 1571.6, 2201.6 and 3035.5 keV transitions (King, 1989). The 633.5 keV transition, observed for the first time, was also found to depopulate this level based on the 633–630, 633–1568, 633–1710 and 633–2402 coincidence relationships. A $\log ft$ value of 6.85 agrees with the 2^- assignment and suggests the 633.5 keV transition to be predominantly of electric dipole.

The peak at 3067.3 keV, reported previously (Camp, 1968), is present in our singles spectra but it does not appear in coincidence with any gamma-ray. It is placed as a ground state transition from the 3067.4 keV level. This is a new level and it is consistent with a spin and parity of 1^+ or 2^+.

As seen in Fig. 7(b) and (c), the gates at 1032 and 1369 keV and the observation of the 1633 keV transition in coincidence with the 630 keV gamma-ray (see Fig. 6(a)) suggest a new level at 3097.2 keV. The $\log ft$ value of 8.8 and the fact that this new level decays to 3^+, 4^+ and 2^+ states restrict the spin and parity assignment to 2^+.

The 3325.2 keV level is depopulated through the 231.1, 289.5, 381.7, 810.3, 861.2, 1260.1, 1596.7, 1861.0, 2491.0, 2633.6, and 3325.3 keV transitions (King, 1989). It has spin 3, established by angular correlation on ^{72}Ga (Landulfo et al., 1994) with negative parity (Belyalv et al., 1966; Monahan and Arns, 1969). The 374.3 and 923.0 keV gamma rays, observed for the first time, were also found to depopulate this level. The 374.3 keV transition is seen in coincidence with the 449.8 and 834.2 keV transitions (see Fig. 7(d)) and the 923.0 keV transition is coincident with the transitions at 1568.1 and 1710.3 keV (see Fig. 6(b)). Several other coincidence relationships listed in Table 2 also support the placements attributed.

Since the 3338.5 keV photopeak is not seen in coincidence with any other gamma-ray, it is placed as a transition directly to the ground state, without any gamma feeding. The present investigation determines a relative intensity for this γ-transition which is in agreement with that from Camp (1968). The 3338.4 keV level was also proposed in the decay of ^{72}Ga and ^{72}As (Camp, 1968) with spin-parity assignment of 1^+ or 2^+. The $\log ft$ value of 9.47 also agrees with the assignments 1^+ or 2^+.

The 3341.9 keV level is depopulated through the 306.3, 402.0, 587.4, 939.6, 1276.8, 1877.7, 2507.7, and 3349 keV transitions (King, 1989). It has spin 2, established in the angular correlation works (Monahan and Arns, 1969; Landulfo et al., 1994), with negative parity (Belyalv et al., 1966; Rester et al., 1971b). The 827.1 keV transition, observed for the first time, was also found to depopulate the 3341.9 keV level. It is seen in coincidence with the 629.9, 786.5, 834.2, 894.3, 1050.8, 1568.1 and 2514.9 keV transitions. Several other coincidence relationships listed in Table 2 also support the placement chosen. The $\log ft$ value calculated in this work is consistent with the spin assignment and suggests mixed character M1 and E2, for the 827.1 keV ($2^- \rightarrow 3^-$) transition.

The 3419.9 keV level was proposed in this decay study. It was indirectly inferred in the decay scheme of ^{72}As (Camp, 1968; Rester et al., 1971a) on the basis of the energy sums of the 2586 and 834 keV transitions. This level was also observed in the ^{74}Ge(p, t) nuclear reaction study (King, 1989), with energy 3421 ± 3 keV, in which an assignment 2^+ was also indicated. According to our coincidences data in the 834 keV gated spectrum, there was a peak corresponding to the 2585.7 keV gamma-ray transition. The $\log ft$ value is 9.22 and limits the spins to 1, 2 or 3.

The 3439.7 keV level has been shown to decay through the 496.1, 924.8, 975.5, 1037.3, 1711.2 and

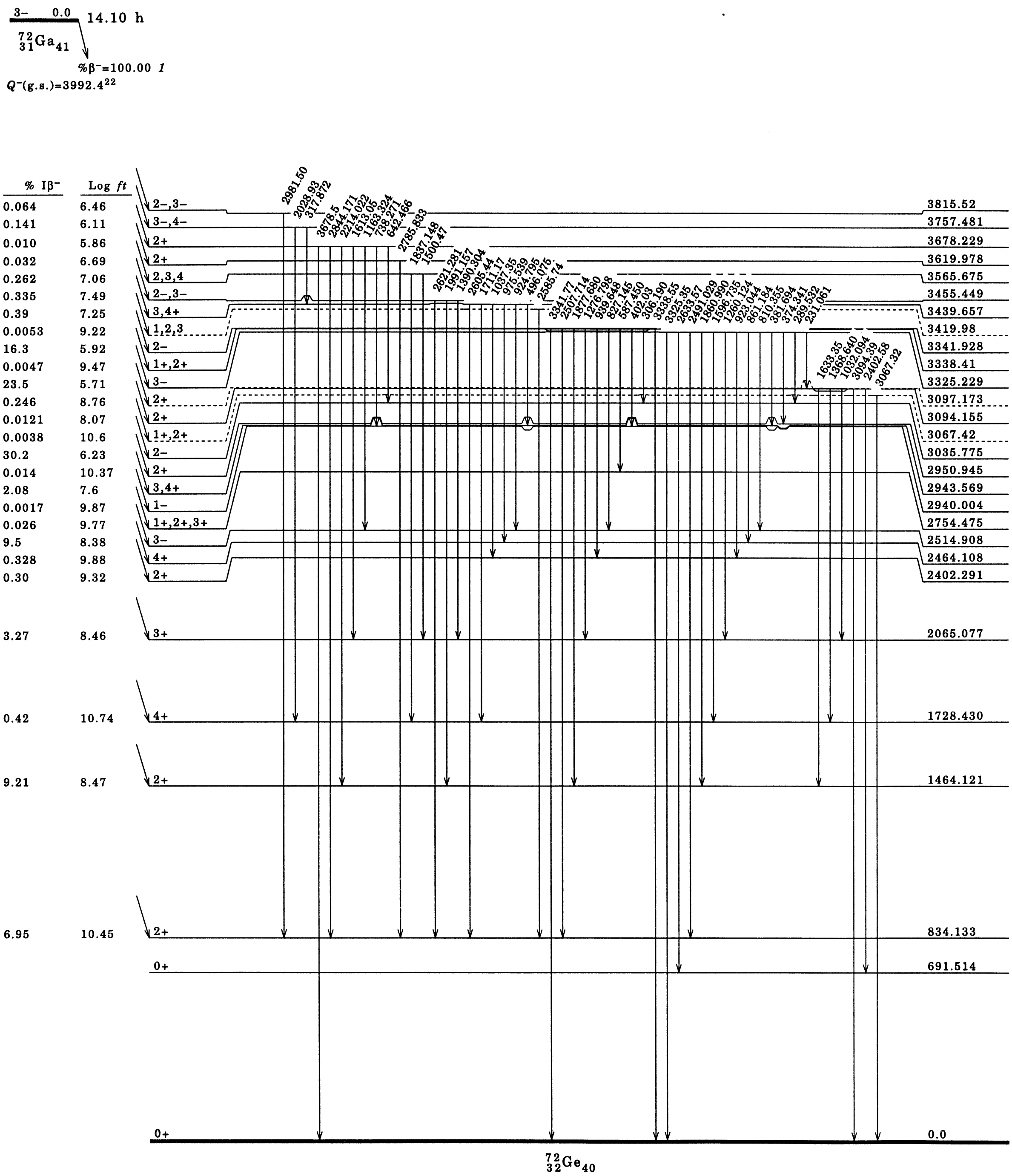

Fig. 8. Proposed level scheme for ^{72}Ge — Part 1 of 2.

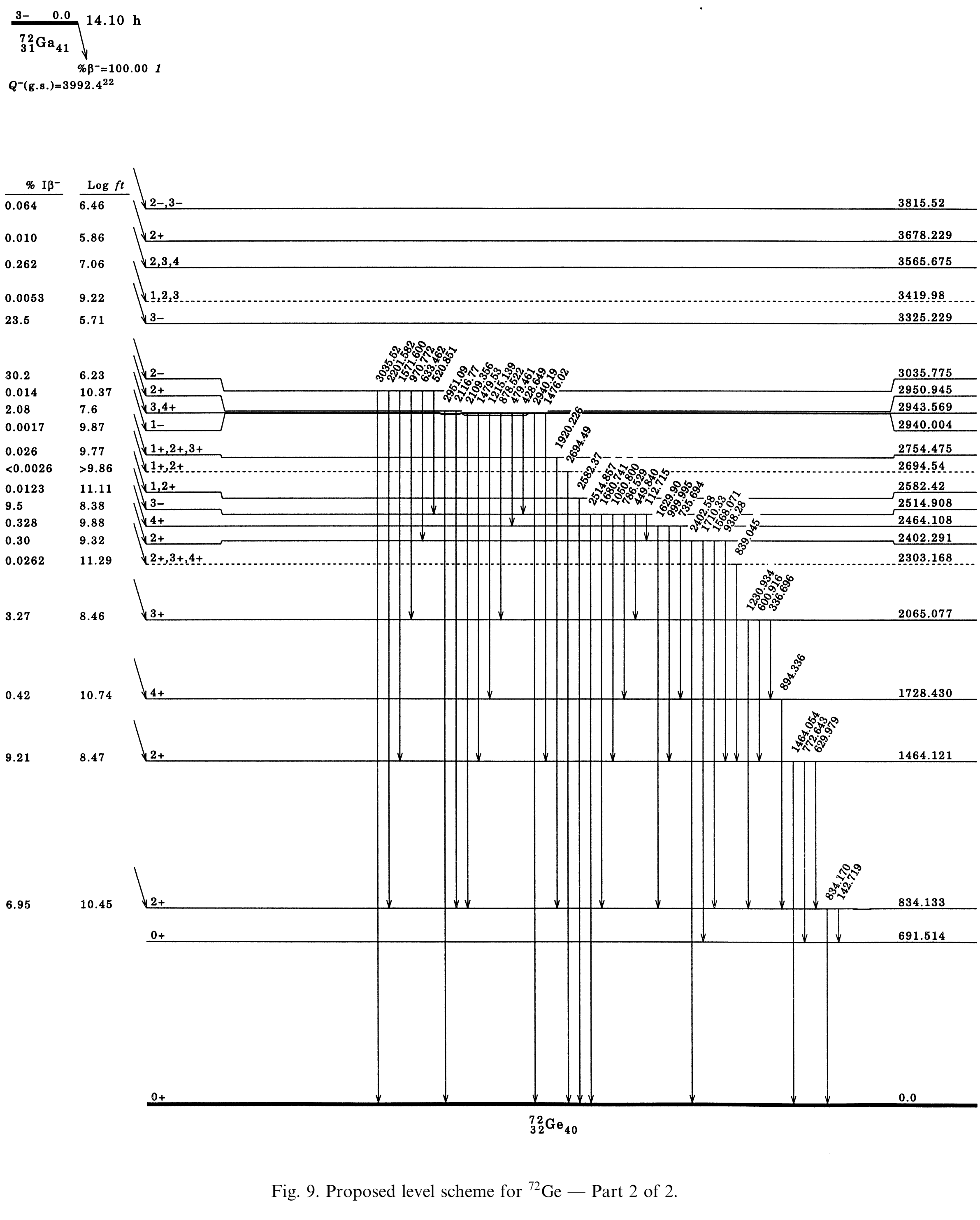

Fig. 9. Proposed level scheme for ^{72}Ge — Part 2 of 2.

2605.4 keV γ-transitions. Several coincidence relationships shown in Table 2 confirm it. The $\log ft$ value of 7.25 limits the spin to 2–4, whereas a 2 assignment would require the 317.9 and 496.1 keV transitions to be of M2 character, which is unlikely. Nevertheless, the 4^- assignment, suggested by one previous author (Rester et al., 1971b), would require the 2605.4 keV transition to be predominantly M2 in character. Thus, the 3, 4^+ assignments are the most probable ones.

The 3455.5 keV level, proposed in previous decay studies (King, 1989), is depopulated through the 113.5, 940.5, 1390.3, 1991.2 and 2621.3 keV transitions. The spin and parity are known to be 2^- or 3^- from the $\log ft$ inferred in ^{72}Ge β^- decay (King, 1989). In this study, the 1390, 1991 and 2621 keV gates (see Table 2) confirm the placement chosen, but the transitions with energies 113.5 and 940.5 keV, reported previously (King, 1989), were not placed as depopulating this level. Camp (1968) pointed out that a transition of 113.5 keV could be a doublet with at 112.5 and 113.5 keV, but these energies are too close to be resolved and our coincidence data were taken above 200 keV, so it was not possible to confirm it. According to Rester et al. (1971b) the transition at 940.5 keV is also part of a doublet at 939.3 and 940.5 keV but our singles and coincidence data are not consistent with that.

The 3565.7 keV level was tentatively proposed (Rester et al., 1971b) on the basis of the appearance of the 1837 keV transition in the 894 keV coincidence gate. It is now confirmed by coincidence relations from the 600, 834, 894, 1500 and 1837 keV gates (Table 2). The low $\log ft$ limits the spin to 2, 3 or 4.

The 3619.9 keV state is de-excited through the emission of two gamma-rays, of energies 1155.7 and 2785.8 keV and it has $J^\pi = 4^+$ (Camp, 1968). The 1155.7 keV photopeak is not present in our singles spectra and is not observed in coincidence with other gamma-ray as well. We thus set an upper limit for its presence in our data (see Table 2) and do not place it in the proposed level scheme (Figs. 8 and 9). Differently, the observed 2786-834 coincidence allowed to confirm a level at 3619.9 keV. A calculated $\log ft$ value of 6.69 suggests a first-forbidden transition, and a possible spin and parity assignment of 2, 3 or 4^+. The 2^+ assignment is the only choice that agrees with the results of (t, p) reactions (Lebrun et al., 1979; Mordechai et al., 1984).

The 3678.2 keV level has been shown to emit the following gamma-rays: 738.3, 1163.3, 1613.0, 2214.0 and 2844.2 keV. It is confirmed by coincidence relationships from several gates (see Table 2). The 642.5 and 3678.5 keV gamma-rays, observed for the first time, were also found to depopulate this level. The 642.5 keV transition is seen in coincidence with 633.5, 834.2 and 2201.6 keV gamma-rays and the 3678.5 keV transition is placed as a transition directly to the ground state. The $\log ft$ value ($\sim$6) is too low for a spin 1 assignment. A spin 3 assignment would require the 3678.5 keV transition to be predominantly octupole in character. Thus, one is left with the assignment of 2, where positive parity is the most probable one.

The 3707 keV level (Rester et al., 1971b) has been shown to emit the 1192 keV gamma-ray, without any feeding. The same authors have reported that the transitions at 1192.2 and 1050.8 keV are in coincidence. We observed that the 1192.2 keV transition is in coincidence with that of 1861.0 keV. So, it does not fit between the 3707 and 2514 keV levels. Place in the present decay scheme for these transitions could be not found. Based on these facts, the level at 3707 keV is not placed in the decay scheme of ^{72}Ga. No evidence for it was seen in the ^{72}Ga (Camp, 1968), neither from studies of ^{72}As decay nor from nuclear reactions (King, 1989).

The 3757.5 keV level was proposed from the decay studies (Camp, 1968; Rester et al., 1971b) depopulated through the 317.9 and 2028.9 keV transitions. Our results are in agreement with these attributions and are consistent with a 3 or 4 assignment. This level was also observed in (p, d) nuclear reaction study (Fournier et al., 1973) and was attributed negative parity.

The 3815.5 keV level was suggested from the decay of ^{72}Ga (Camp, 1968) based on the 2981–834 keV coincidence relationship where an assignment of 2^- or 3^- is favorable. In the present work it is confirmed by the gate at 2981 keV (see Table 2) and the $\log ft$ value of 6.46 is also consistent with the 2^- or 3^- assignments.

The present experiment on the structure of ^{72}Ge was undertaken to provide more information on its low lying excited states from β^- decay of ^{72}Ga. A detailed level scheme has been built from the present data. Twenty new gamma-ray have been placed into a decay scheme which includes five new levels. Five γ-transitions previously attributed to this decay were not confirmed and no evidence was found requiring the inclusion of the 3707 keV level previously proposed. In addition, spin assignments for several levels were made based on observed decay modes. These results should stimulate theoretical studies to elucidate the structure of this nucleus.

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