The level structure of ^{76}Se from ^{76}Br γ-decay*

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Abstract　　The decay of ^{76}Br has been investigated for further study of the ^{76}Se levels. Gamma ray singles were measured with HpGe-NaI Compton-suppressed spectrometer. Coincidence spectra were collected with two HpGe detectors coupled to a three-parameter system. There were 138 γ-rays observed, and 120 of these were fitted into 46 levels in ^{76}Se. 37 γ-rays and 15 new energy levels were found for the first time.

Keywords　　γ-ray, Energy levels, Transition, Coincidence

1 Introduction

Strongly deformed structure in 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] With the beginning of ^{72}Se work, the new region of very strong deformation in Z=38 was discovered. The experimental data show that the near-spherical ground states, the low-lying well-deformed 0^+ state and deformed bands coexist in ^{72,74}Se. Up to now, the level structure from ^{76}Br decay was studied with Ge(Li) detectors.[4~6] 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.

2 Experimental

2.1 Source preparation

Two methods to produce the source of ^{76}Br were used in the present study. First, the ^{76}Br was produced on the Cyclotron in Shanghai Institute of Nuclear Research via the reaction ^{75}As(α, 3n)^{76}Br. The energy of α beam was 32 MeV. The target of monocrystal GaAs was welded on the copper backing. The radioactive target was put into a dry distiller. The radioactive Br distilled at high temperature from target was dissolved in 0.005mol NaOH solution. The solution was dropped on a lucite source holder. After drying, the source was covered with lucite film. Second, ^{76}Br source was produced via the ^{76}Se(p, n)^{76}Br reaction, using 16 MeV proton

beam from the Cyclotron and selenium metal of 99.99% purity as the target. The source was cooled for 23h after bombardment.

2.2 γ-ray singles spectra measurements

The Compton-suppressed spectrometer consisted of 130cm^3 HpGe detector and 6 NaI detectors(made by Canberra Company) were employed to study the singles γ-ray spectra of ^{76}Br decay. The resolution of system was 1.9 keV at 1332 keV. Spectra were taken over a period of several days to ensure that the observed photopeaks were decaying with the half-life of ^{76}Br. The spectra were obtained with and without a lead absorber between the source and HpGe detector. Energies and γ-ray intensities were determined by energy calibration curve and efficiency curve made with the energy standards ^{152}Eu, ^{56}Co sources. Typical spectra are shown in Fig.1 (Fig.1 were taken with no absorber present). The complete inventory of γ-ray energies and intensities observed in these experiments is shown in Table 1.

2.3 Coincidence spectra

A series of coincidence measurements were carried out in order to establish the relation among the γ-rays observed. The experiments were performed with two HpGe detectors coupled to three-parameter γ-γ-T data acquisition system. One of the detectors is a coaxial detector of 115 cm^3 HpGe with 0.5 mm beryllium absorbing layers, and FWHM=1.9 keV at 1332 keV of ^{60}Co. The other is a coaxial detector of 232 cm^3 HpGe. The FWHM is 2.0 keV at

1332 keV. The 2.1×10^7 coincidence events were recorded in event by event. Fig.2 shows the coincidence γ-ray spectra were gated on 473, 1769 and 2111 keV photopeaks. These spectra were corrected for background coincidences. Table 2 lists the coincidence relations observed.
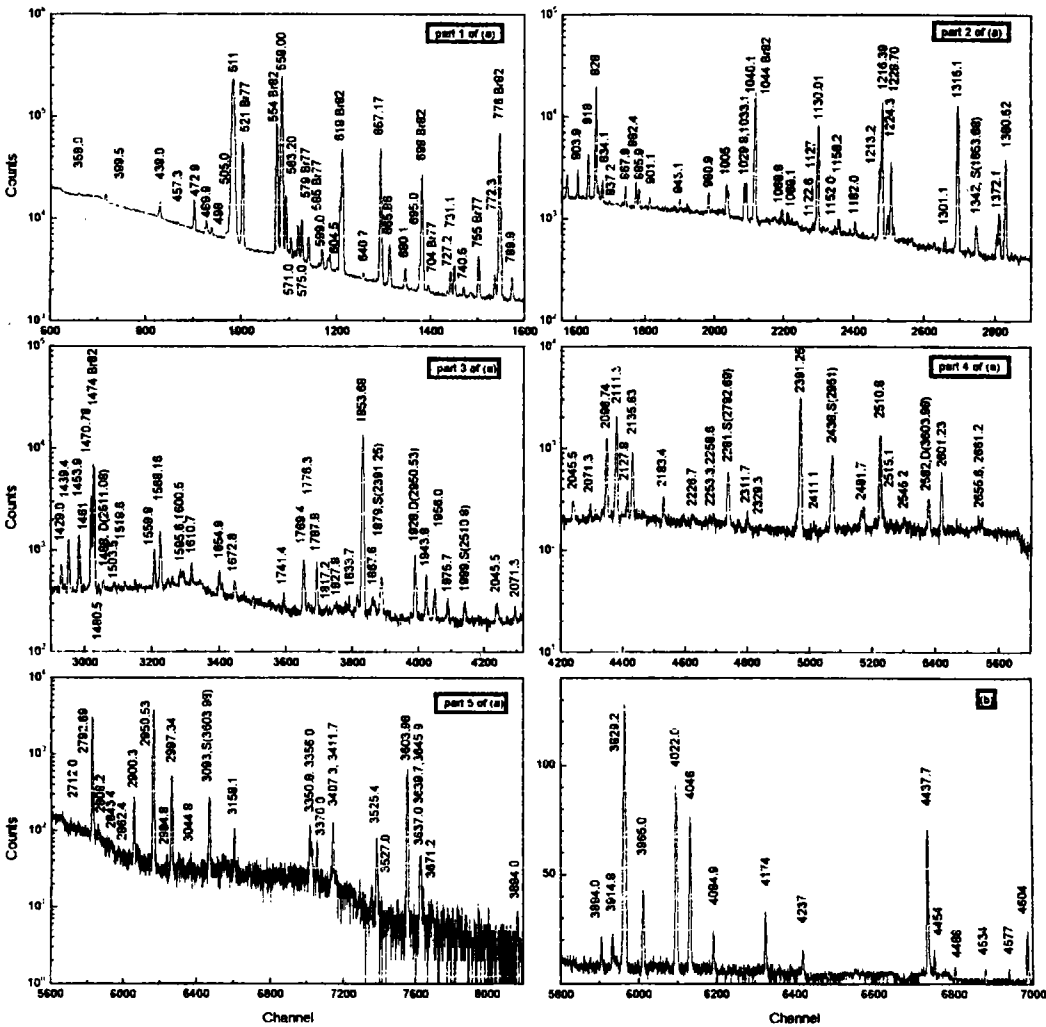

Fig.1 Gamma-ray singles spectra of the decay of ^{76}Br

(a)The lower energy γ-ray spectrum of the ^{76}Br decay; (b)The higher energy γ-ray spectrum of the ^{76}Br decay;

The numbers near peaks are γ-ray energies in keV

Table 1 Energies and relative intensities of γ-rays from the ^{76}Br decay from present work

E_γ/keV		I_γ/%		E_γ/keV		I_γ/%		E_γ/keV		I_γ/%	
358.0	3	0.5	2	1228.70	6	2.82	12	2329.3[nb]	8	0.08	2
399.5[a]	2	0.46	5	1301.1	8	0.21	2	2391.25	10	6.4	4
438.0[a]	3	0.37	–	1315.1[a]	10	0.07	2	2411.1[nb]	2	0.08	4
457.3[a]	5	0.09	2	1372.1	2	0.74	6	2481.7	4	0.18	3
472.9	1	2.51	11	1380.52	8	3.4	17	2510.8	2	2.63	15
489.9	2	0.49	6	1429.0	2	0.19*	9	2515.1[n]	6	0.007	2
498[a]	1	0.22	9	–	–	0.17#	3	2545.2[b]	8	0.008	3
505.0[a]	5	0.31	2	1432.7[n]	4	0.05	2	2601.23	15	0.94	5
559.00	5	100	–	1439.4	2	0.78	4	2655.6[nb]	4	0.12	4
563.20	5	4.8	8	1453.9	1	1.08	6	2661.2[n]	4	0.10	3
571.0	5	0.6	3	1461[b]	2	0.18	4	2712.0[a]	9	0.10	2
575.0[n]	1	3.6*	2	1470.78	7	3.12	16	2792.69	8	7.6	4
599.0[n]	2	0.56	2	1480.5[n]	6	0.06	3	2808.2[nb]	9	0.20	3
604.5[n]	5	0.30	10	1503.5[n]	5	0.12	5	2843.4[b]	9	0.20	6
657.17	5	21.5	11	1518.6[n]	5	0.12	2	2862.4[nb]	6	0.10	3
665.2	2	0.95	5	1559.8[a]	5	0.62	3	2900.3	1	0.37	13
680.1	2	0.57	3	1568.16	8	1.3	1	2950.53	6	10.0	5
695.0	2	0.66	4	1595.6[n]	5	0.15	4	2984.8[nb]	10	0.08	2
727.2	1	0.9	2	1600.5[n]	2	0.13*	4	2997.34	9	1.3	1
731.1	2	0.78	10	1610.7	5	0.38	8	3044.8[a]	10	0.03	1
740.5	8	0.21	7	1654.9[a]	5	0.16	3	3158.1	2	0.20	2
772.3	2	0.56	3	1672.6	5	0.32	10	3350.8	10	0.34	3
789.8	2	0.63	4	1741.4[n]	5	0.16	4	3356.0[n]	10	0.10	2
803.9	2	0.71	5	1769.4	1	0.05*	2	3370.0	10	0.12	2
834.1[nb]	10	0.10	2	–	–	0.4*	2	3407.3[n]	11	0.03	1
837.2	2	0.35	2	1776.3	5	0.08	3	3411.7	5	0.39	2
867.8	2	0.41	4	1787.9	3	0.77	8	3525.4	5	0.24	2
882.4	2	0.70	5	1817.2[b]	2	0.20	2	3527.0[n]	10	0.03	–
885.9	2	0.45	3	1827.9[n]	2	0.15	9	3603.98	8	2.10	15
901.1	7	0.21	2	1833.7[n]	8	0.26	13	3637.0[nb]	8	0.10	2
943.1	5	0.22*	5	1853.68	5	19.8	10	3639.7	8	0.10	2
		0.03#	2	1867.6	10	0.20	10	3645.9[n]	10	0.03	1
980.9	5	0.45	4	1943.9	5	0.64	10	3671.2[nb]	15	0.03	1
1029.8	5	0.77	8	1956.0	5	0.40	7	3894.0[n]	15	0.04	1
1033.1	5	0.79	8	1975.7	10	0.14	11	3914.8[b]	10	0.020	5
1040.1	10	0.10	5	1981.5[n]	4	0.05	2	3929.2	7	0.12	2
1068.6[n]	6	0.12	4	2045.5[a]	10	0.24	2	3965.0[nb]	11	0.03	1
1089.1[n]	1	0.08*	3	2071.3	15	0.36	30	4022.0[a]	10	0.08	2
1122.6[nb]	2	0.05	2	2096.74	11	1.84	10	4046	2	0.07	2
1127[n]	1	1.0*	7	2111.3	1	3.36	16	4084.9[b]	15	0.02	1
1130.01	6	6.2	3	2127.8	8	0.27	8	4174[a]	2	0.03	1
1152.0[n]	5	0.12	2	2135.63	10	1.27	10	4237	2	0.007	2
1158.2[n]	5	0.20	2	2183.4	10	0.17	5	4437.7[a]	10	0.07	2
1182.0	8	0.12	5	2226.7	20	0.13	8	4454[b]	2	0.009	2
1213.2	1	2.3	7	2253.3[n]	6	0.08	3	4488[n]	2	0.007	2
1216.39	7	11.9	6	2258.6[b]	6	0.08	3	4534[nb]	3	0.007	2
1224.3	5	0.38	14	2311.7[n]	8	0.14	4	4577[nb]	3	0.007	2
								4604	4	0.03	1

Notes: n: new γ rays; a: placement of transition in the level scheme is uncertain; b: γ rays not placed in the level scheme; *: relative intensity calculated by coincidence spectrum; #: relative intensity calculated from the sum of
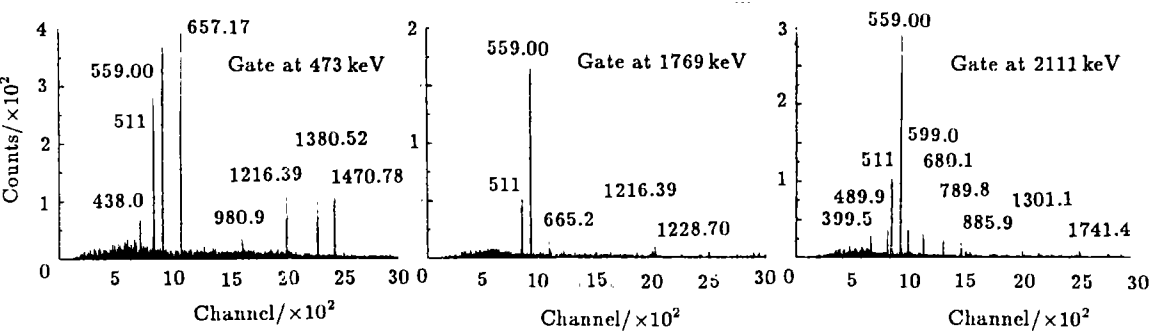
Fig.2 Coincidence spectra obtained by gating on the 473,1769 and 2111 keV peaks
The numbers near peaks are γ-ray energies in keV

Table 2 A part of the γ-γ coincidence relations of ^{76}Br decay obtained from coincidence spectra

Gate/keV	Coincident γ-rays/keV
559	358,400,438,457,473,490,505,511,563,575,599,605,657,665,680,695,727,731, 790,804,834,868,882,886,901,943,981,1033,1130,1213,1224,1229,1342,1372, 1381, 1429,1439,1454,1471,1560,1568,1596,1601,1611,1769,1854,1879,1944, 1956, 2097,2111,2136,2281,2391,2511,2601,2793,2900,2997,3412,3525,3640
563	511,559,665,695,727,772,868,882,1033,1040,1069,1372,1471,1769,1828, 1854,2482,2511,2515,2808
575	511,559,657,1158,1216,1660
599	559,657,882,981,1454,1471,2111
657	438,473,511,559,571,575,599,680,695,731,790,804,834,1030,1069,1127,1158, 1213,1315,1342,1381,1439,1454,1471,1560,1596,1854,1944,2136,2411
665	511,559,727,837,868,882,1315,1372,1673,1769,2183
772	358,457,511,559,605,1315,1381,1471,1481
1069	511,559,657,1130,2391
1089	511,559,657,727,772
1152	511,559,657,1127,1216,1601,2259
1158	511,559,575,657,1216
1216	473,511,571,575,680,695,731,901,1030,1213,1342,1381,1439,1454,1471, 1560,1854,1944,2136
1433	559,1216
1439	505,511,559,657,695,804,1216,1517
1454	400,511,559,599,657,680,727,790,886,1216
1481	511,559,657,1216
1519	511,559,605,657,1216,2097
1560	511,559,575,1216,1229
1568	511,559,943,1033,1224,1429
1596	657,1216
1601	511,559,657,1216
1741	511,559,1454,1216,2111
1769	511,559,665,1216,1229
1834	511,559,657,1216,1229,1439,2097
1956	511,559,837,1089
1982	511,559
2111	400,490,511,559,599,680,790,886,1301,1741
2259	511,559
2661	559
3356	559
3646	559

3 Decay scheme

The decay scheme constructed from the present experiments is shown as Fig.3. The total γ-ray transitions measured were 138, of them 37 were observed for the first time. 120 γ rays were placed in the level scheme with 46 excited states, including 15 new levels. The energies of the new excited states are 1791.29, 2812.0, 2817.00, 3220.3, 3269.30, 3312.7, 3527.6, 3637.4, 3915.0, 3965.7, 4205.0, 4411.7, 4453.5, 4489.3 and 4778.6 keV. The new γ-rays in the level scheme were seen in coincidence spectra. A new level was confirmed when at least one γ-ray leaving or populating the level was found in coincidence spectra. The initial level energies were determined by sum relations of the most prominent γ-rays. And β^+(EC) intensities were come from the present γ-ray intensities. The logft values of the levels were calculated by using the ENSDF (the Evaluated Nuclear Structure Data File) analysis and checking program by NNDC (the National Nuclear Data Center) at Brookhaven National Laboratory. The β^+(EC) intensities of ^{76}Se ground state was supposed as 6(1). And the ground state spin, parity of ^{76}Br is 1^-.[5] The new energy levels are discussed below in numerical order.

3.1 The 1791.31 keV level

This level is established from coincidence results. The new γ-rays 575.0, 1158.2 and 1559.8 keV of ^{76}Se were observed in singles spectra. And their coincidence relations from 575, 657, 1158 and 1560 keV gates in the present work support the existence of this level (see Table 2). The logft value including the beta transition to the level is allowed or once-forbidden. The possible spin assignments are, therefore, 0-3.

3.2 The 2812.0 keV level

This energy level is placed here for the following reasons. The 2812.5 keV energy level has been reported in ^{75}Se(n, γ)^{76}Se and ^{76}Se(p, p' γ)^{76}Se experiments.[4,5] A new γ-ray 2253.3 keV was found in singles spectra. Based on energy sums, energy level is placed at 2812.0 keV. The other two γ-ray transitions, 1480.5 and 1595.6 keV decay from this level were observed in coincidence spectra gated at 559, 657 keV. The logft value indicates that the spin assign-

ments of the state are 0-3.

3.3 The 2817.02 keV level

This level is proposed in order to place three new γ transitions with energies 1127, 1600.5 and 2258.6 keV observed in the present work. In addition, the energy level was found in ^{75}Se(n, γ) ^{76}Se, ^{76}Se(n, n' γ) ^{76}Se, ^{76}Se(p, p' γ) ^{76}Se and ^{78}Se(n, tγ) ^{76}Se experiments. Its spin and parity was given as 2^+.[4,5] The logft value supports this result.

3.4 The 3220.3 keV level

This level is based on energy sums for the placement of two transitions seen only from the decay of ^{76}Br. The two γ-ray energies are 1432.7, 2661.2 keV. The spin and parity of the level in in-beam work are 1^+, 2^+, 3^+. [4,5] These are compatible with the logft value.

3.5 The 3269.29 keV level

In the work, a coincident peak appears at 599.0 keV in 559, 657, 1454 and 2111 keV gate. These support the existence of this level. The logft value limits the spin to 0-3. NDS[4] has identified the level as 2^-, 3^-, 4^-. Therefore, the spin and parity assignments of the state is 2^-.

3.6 The 3312.8 keV level

This level (3^-, 4^-, 5^-) was reported in NDS.[5] By this reason, the 3312.7 keV level is placed in the decay scheme. The logft value restricts the spin of the level to 0-3. The new 1981.5 keV γ-ray transition to 4^+ state eliminates the 0, 1 possibility. Thus the possible spin-parity assignment is 3^-.

3.7 The 3527.6 keV level

This level is based on an energy fit of 2311.7 keV and 3527.0 keV transitions. The logft value indicates that the spin of the level is 0-2.

3.8 The 3637.4 keV level

This level is based on the 2515.1~563 keV coincidence relation. There is no supporting evidence such as other γ-rays leaving the level. The logft for the β^+(EC) transition to this state indicates a spin of 0-3.

3.9 The 3915.0 keV level

This level was observed in ^{75}Se(n, γ)^{76}Se, ^{76}Se(p, p' γ) ^{76}Se experiments and the 3^+, 4^+, 5^+ of the level were given.[5] In the present work 3356.0~559 keV is cascade γ-ray. The logft value limits the spin to 0-2. Therefore the tentative assignment is 3^+.
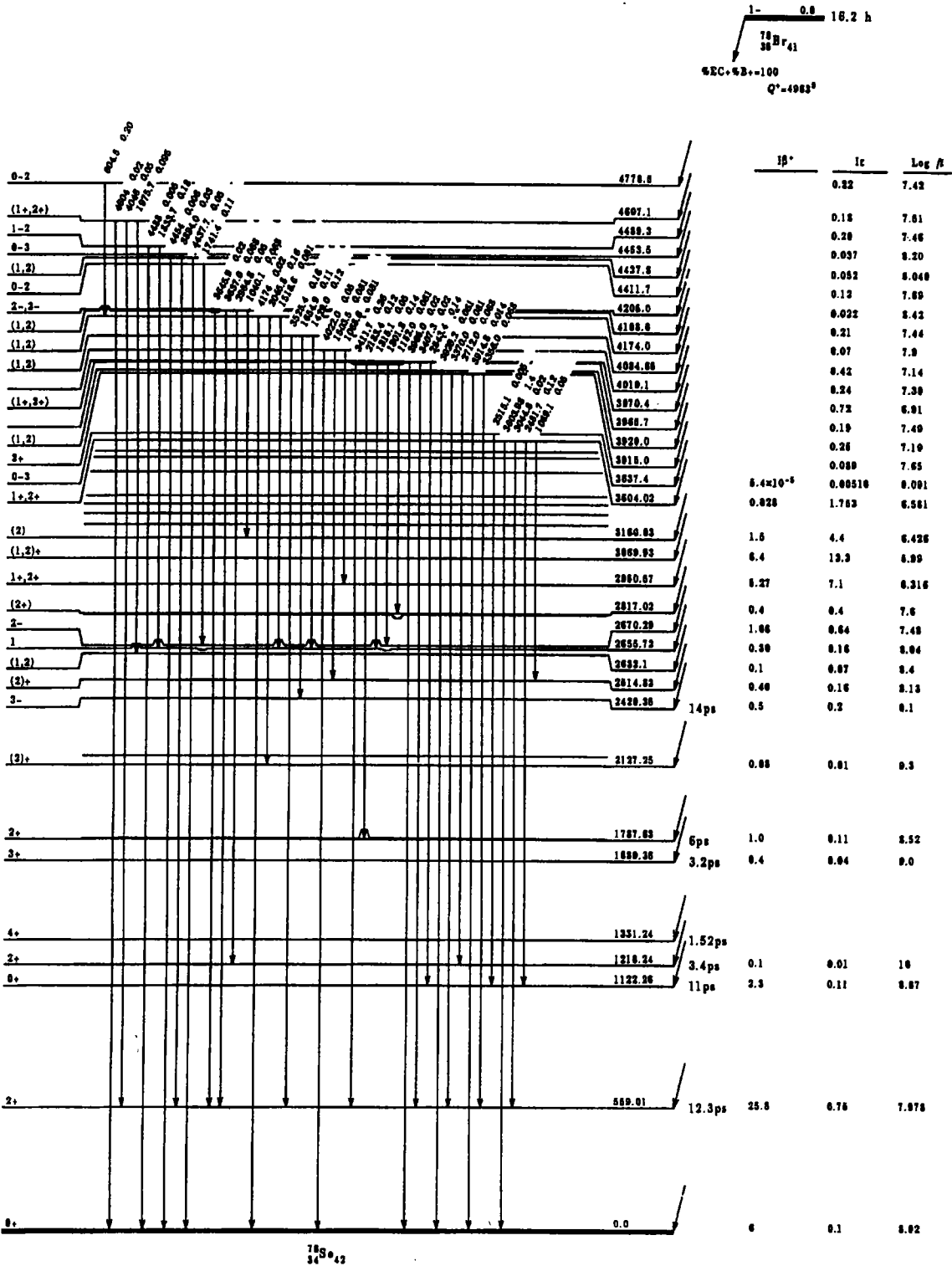
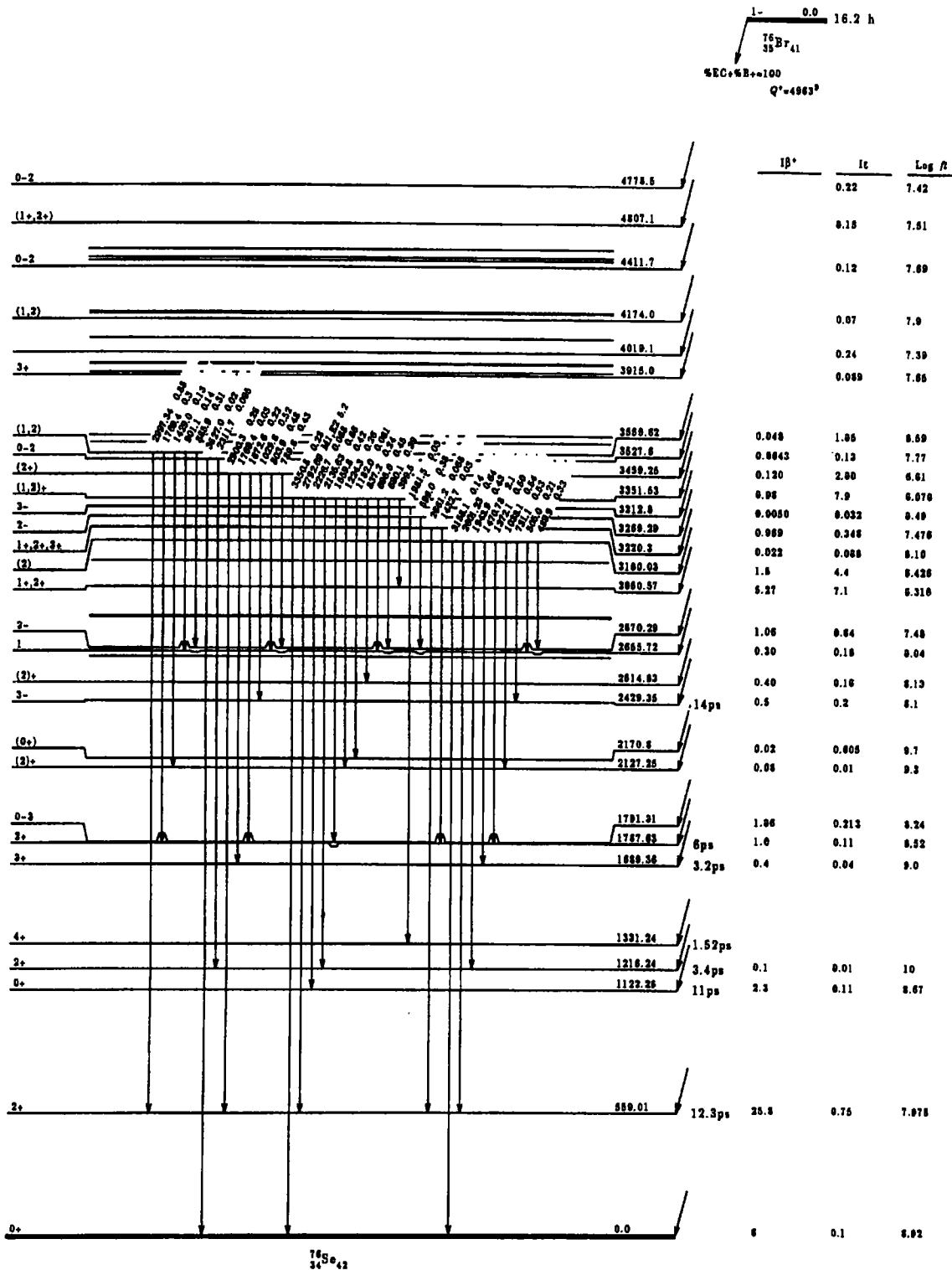**Fig.3** The level structure of ^{76}Se from ^{76}Br γ-decay

Fig.3 The level structure of ^{76}Se from ^{76}Br γ-decay (continued)
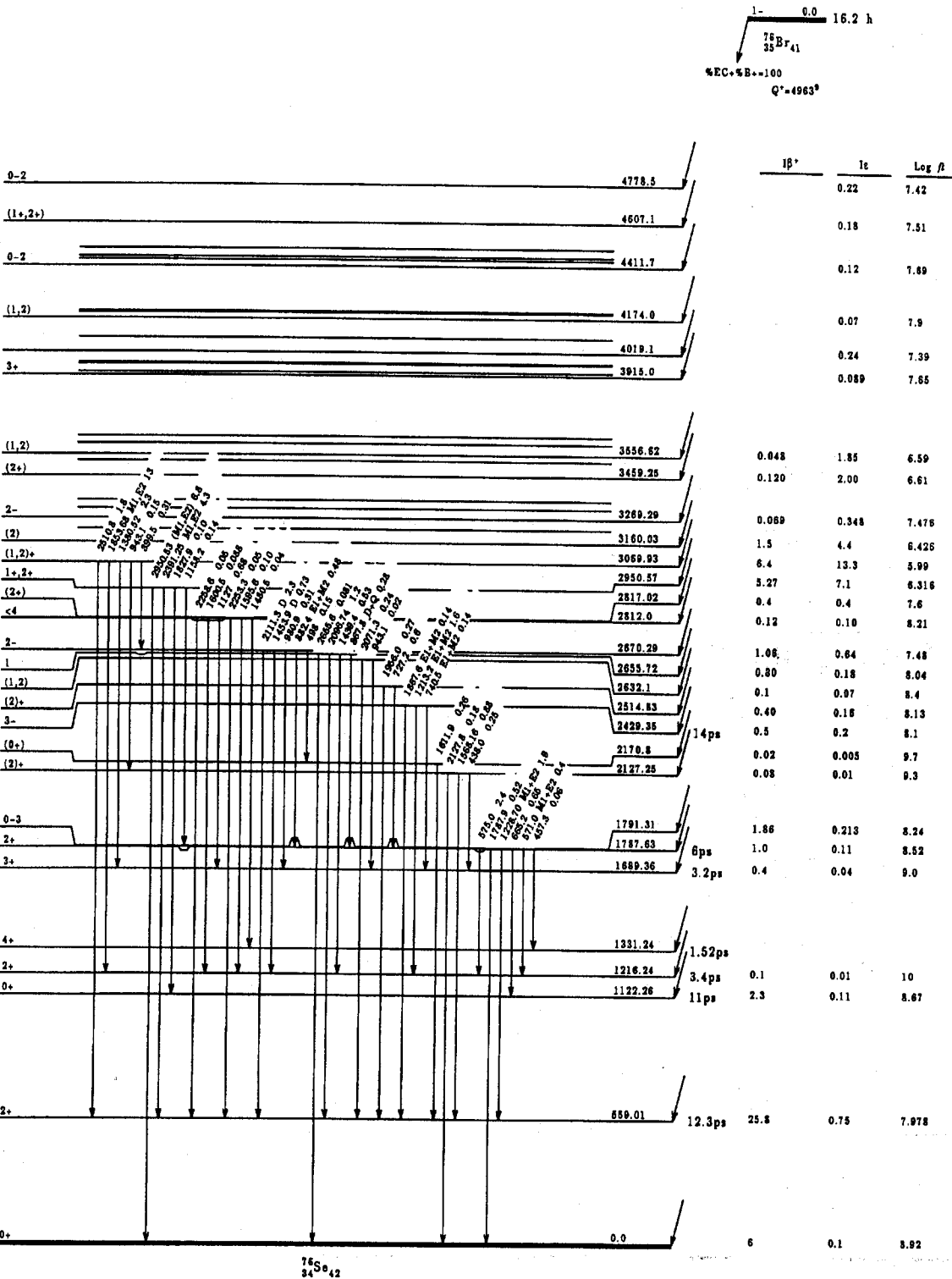
Fig.3 The level structure of ^{76}Se from ^{76}Br γ-decay (continued)
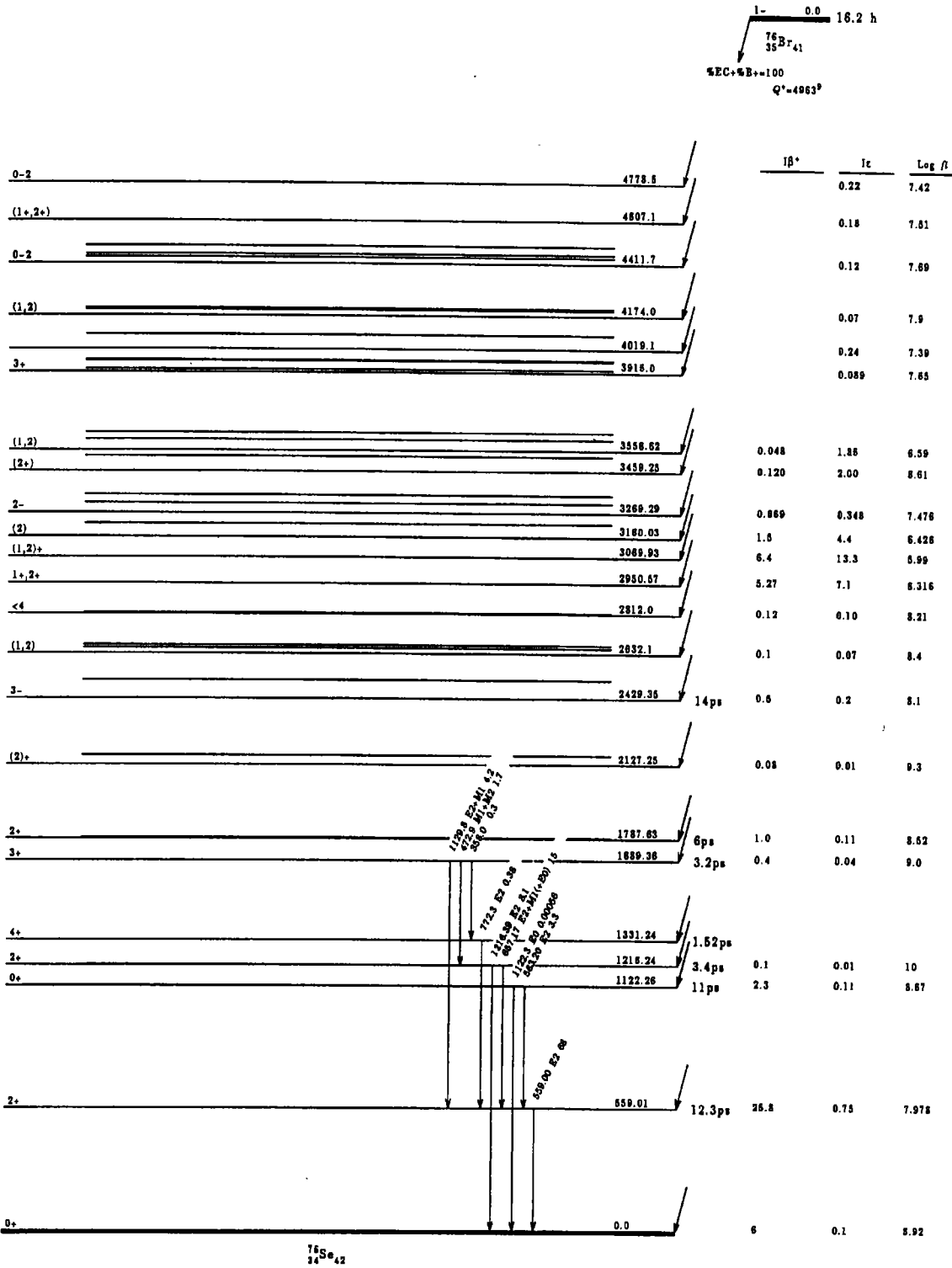
Fig.3 The level structure of ^{76}Se from ^{76}Br γ-decay (continued)

3.10 The 3965.7 keV level

The energy level around 3965 keV was reported in inelastic scattering experiments and two γ-rays 2843.4, 3965.0 keV were not placed in the level scheme.[5] The 3407.3~559 keV coincidence relation were seen in the present work. For the above reasons, this level is placed here. The logft value makes it possible that the β^+(EC) transition to the level be allowed or once-forbidden. The spin of 2 is reasonable.[5]

3.11 The 4205.0 keV level

This level was reported in ^{75}Se(n, γ)^{76}Se, ^{76}Se(p, p' γ)^{76}Se experiments. The spin and parity assignments are 2^-, 3^-, 4^-.[5] Here new γ-ray 3645.9 keV was found in coincidence with 559.00 keV γ-ray. So the 4205.0 keV level was placed in the level scheme. The logft value restricts the spin to 0-3. This leaves 2^-, 3^- as possible assignments.

3.12 The 4411.7 keV level

This level is simply established by the appearance of the 1740.75 keV transition in the 2111 keV coincidence gate. The logft value requires the β^+(EC) decay to the level to be allowed or first-forbidden. Therefore, the possible spin is 0-2.

3.13 The 4453.5 keV level

The γ-rays 3892(2), 4455(3) keV were not placed in the level scheme reported in former work.[5] In the present work, new γ-rays 3894.0 keV was supposed to be a decay from a level with the ^{76}Br half-life. So the level is established. The logft value limits the spin to 0-3.

3.14 The 4489.3 keV level

This level is proposed on the basis of the appearance of new γ-rays 1833.7, 4488 keV and 1834-2096.74 keV cascade. On the other hand, the 4488.9(4) keV level was observed in ^{75}Se(n, γ)^{76}Se experiment and the range of spin was given as 1-4.[5] The logft value indicates an allowed or first-forbidden β^+(EC) transition to the level. This rules out the spin of 3, 4.

3.15 The 4778.5 keV level

The reason why this level is established is the new γ-rays 604.5 keV existence in the coincidence spectra gated at 559, 772 and 1519 keV γ-ray. The logft value limits the spin to 0-2.

In addition, the 4215.6 keV level in the level scheme[4,5] was cancelled because no γ-ray is related to the level. The new position of 1769.4 keV transition has been found between the levels 3556.62 keV and 1787.63 keV.

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