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## Low-spin States of $^{70}\text{Ge}$ Excited in the $^{70}\text{As}(\beta^+ + \text{EC}) ^{70}\text{Ge}$ Decay

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**Abstract:** The excited states of the  $^{70}\text{Ge}$  nucleus are investigated in radioactive decay of the  $^{70}\text{As}$ . Four new transitions with 1 036.99, 1 196.66, 1 539.29 and 2 531.7 keV are found for the first time. The position of 2 219.34 keV transition are reassigned, the transition positions of 496.74, 1 295.24 and 1 417.24 keV  $\gamma$ -rays are assigned for the first time, and the placements of 1 881.67, 2 325.42 and 2 424.41 keV  $\gamma$ -rays are confirmed in the present work. Two new levels, at 4 243.10 and 5 265.81 keV excitation energy, respectively, are proposed. The decay scheme is established and for a number of levels spin-parity assignments are suggested on the basis of  $\log ft$  values and  $\gamma$ -branching ratios.

**Key words:** decay; gamma ray; level; coincidence

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### 1 Introduction

The decay of  $^{70}\text{As}$  was previously studied by Ruiter *et al.*<sup>[1]</sup>. In their work, it should be pointed out that many  $\gamma$ -rays which belong to the decay of  $^{70}\text{As}$  were not placed in level scheme. A literature survey reveals no recent experimental information concerning the decay scheme of this isotope. To be more specific, the last published paper<sup>[1]</sup>, which is widely reported, is nearly 50 years old. This serious inadequacy has motivated the need for new and more accurate measurements in this nucleus. The results of our investigation of the  $^{70}\text{Ge}$  isotope in radioactive decay are presented. In Sect. 2 the preparation of the  $^{70}\text{As}$  source is presented. Sect. 3 and 4 report on the results of singles and coincidence measurements and the model independent level scheme construction.

### 2 Source

The source of  $^{70}\text{As}$  is produced through the  $^{70}\text{Ge}(p, n)^{70}\text{As}$  reaction by irradiating natural germa-

nium foil with beams of 16 MeV protons ( $I \approx 1 \mu\text{A}$ ), obtained from the variable energy cyclotron ( $K = 40$ ) at Shanghai Institute of Applied Physics (SINAP). There is a trace of element gallium in the target material. Small amounts of disturbing  $^{71-74,76}\text{As}$  and  $^{69}\text{Ge}$  activities, which are formed via (p, n) reactions, can be recognized by their half-lives. Due to the difference in half-life, a short-term irradiation of  $^{70}\text{Ge}$  can be used to produce sufficient interference-free activity for the determination of the decay of  $^{70}\text{As}$ .

### 3 Experimental results

The  $\gamma$ -ray singles spectra are studied by using a Compton-suppressed coaxial low background spectrometer of  $130 \text{ cm}^3$  HPGe with 30% efficiency and an energy resolution of 1.9 keV at FWHM for 1 332 keV  $\gamma$ -ray of  $^{60}\text{Co}$ , none Compton-suppressed measurements are also carried out at the same time. The total background counts are 0.7 cps (Compton-suppressed) and 1.3 cps (none Compton-suppressed) in the energy region 36~2 515 keV. The low-energy region part of the

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singles spectrum is shown in Fig. 1(a), using a source-detector distance of 25 cm. The  $\gamma$ -ray spectrum presented in Fig. 1(b) shows the high-energy region above 1.2 MeV recorded with an absorber composed of 0.6 cm thick lead and 0.5 cm thick cadmium, to attenuate the low energy radiations, the source-detector distance in this situation is 11 cm. The energy and relative efficiency calibrations are performed with  $^{152}\text{Eu}$  and  $^{56}\text{Co}$  sources placed at the target position. In all these sit-

uations the counting rate is controlled to be  $< 2500$  counts per second (cps) so that cascade or random summing effects are negligible. The energies and relative intensities of the  $\gamma$ -rays from the  $^{70}\text{As}$  decay are summarized in Table 1. It should be pointed out that the uncertainties of the relative  $\gamma$ -ray intensities include the contributions from counting statistics, and uncertainties of the efficiency calibrations of the spectrometers and the normalization procedure.

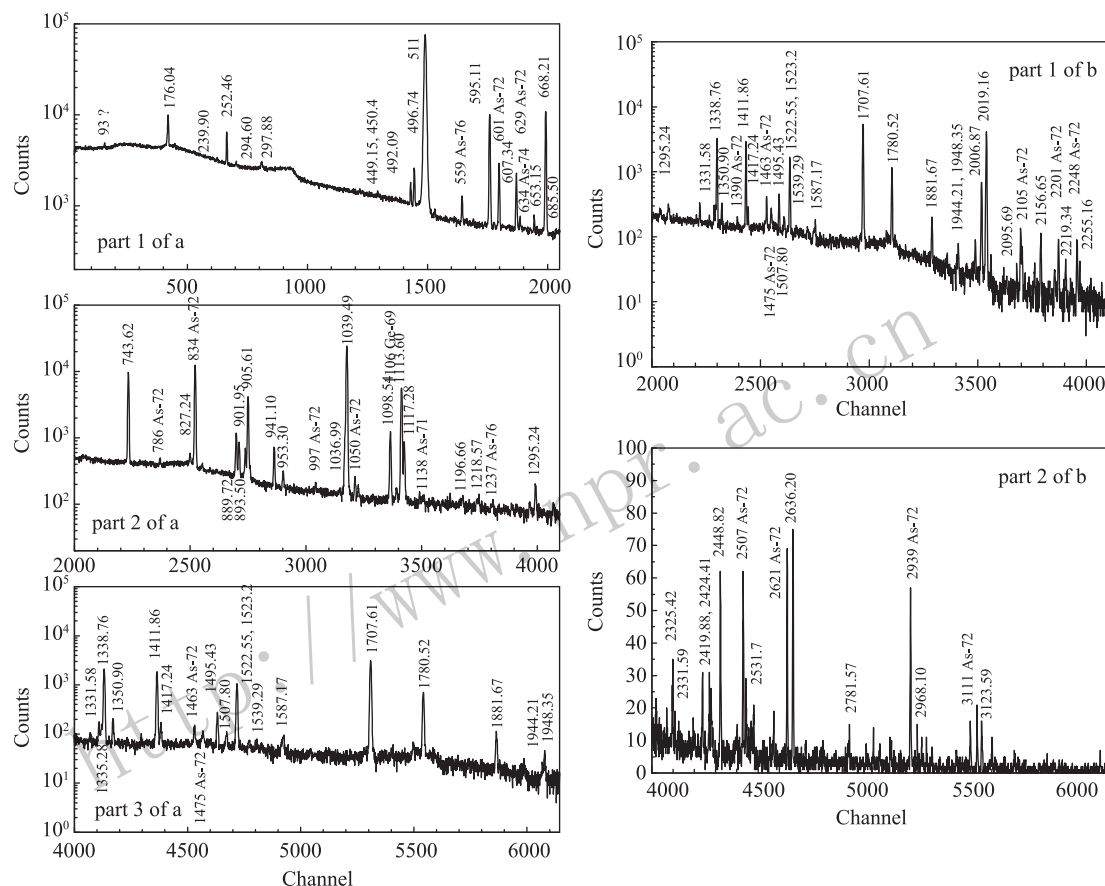


Fig. 1 Gamma-single spectra of  $^{70}\text{Ge}$  taken with an anti-Compton spectrometer. (a) The low-energy region part; (b) The high-energy region above 1.2 MeV.

Coincidence measurements are made using two high-purity Ge detectors oriented at  $90^\circ$ , one of which is a planar Ge detector (GMX-20190) with 20% efficiency and 1.85 keV resolution at 1332 keV and placed 10cm from the target, the other is a coaxial Ge detector (GEM-50195) with 50% efficiency and 2.0 keV resolution at 1332 keV and placed 15 cm from the target. The data are 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 are included. The fast-slow coincidence circuit has a time resolution of about 20 ns when gated by the  $^{60}\text{Co}$  full energy peaks. For low energy transitions it can be much larger. About  $2.1 \times 10^7$  events are stored. The

reconstruction of coincidence spectra is performed off-line. For each gate, a gross spectrum without random coincidence and background correction and a background spectrum are both obtained. Coincidence relationships are determined by comparing this pair of spectra. Almost all transitions determined in singles spectra are observed in coincidence spectra too. On the other hand, several weak peaks which can not be separated in singles spectra are also identified in coincidence spectra. Selected results for some examples of coincidence spectra are shown in Fig. 2.

The present investigation of the  $^{70}\text{As}$  decay provides an extension of the information concerning this decay. Approximately 64 transitions including 4 new

Table 1 The energies and relative intensities of  $\gamma$ -rays following the decay of  $^{70}\text{As}$

Energy/keV <sup>a</sup>				Energy/keV <sup>a</sup>				Energy/keV <sup>a</sup>			
I/% <sup>a</sup>				I/% <sup>a</sup>				I/% <sup>a</sup>			
176.04	4	3.5	2	1036.99n	4	3.0	2	1881.67x	5	0.84	4
239.90	10	0.25	7	1039.49	4	100	6	1944.21	16	0.15	2
252.46	4	3.3	2	1098.54	4	5.1	3	1948.35	11	0.35	3
294.60	16	0.10	4	1113.60	4	25.1	15	2006.87	3	3.4	1
297.88	8	0.66	10	1117.28	4	3.4	2	2019.16	2	20.2	5
449.15	10	0.17	8	1196.66n	15	0.32	6	2095.69?	14	0.07	1
450.4*	5	0.16	8	1218.57	11	0.19	4	2156.65	6	0.58	3
492.09	5	1.31	9	1295.24c	6	0.59	6	2219.34y	14	0.20	2
496.74c	4	3.1	2	1331.58	7	0.47	4	2255.16	11	0.17	2
595.11	4	22.9	13	1335.28	10	0.38	4	2325.42x	18	0.18	2
607.34	4	5.3	3	1338.76	4	11.0	7	2331.59	24	0.05	1
653.15	6	0.60	7	1350.90	6	0.57	6	2419.88	24	0.12	2
668.21	4	26.9	16	1411.86	4	10.6	6	2424.41x	20	0.14	2
685.50?	12	0.21	6	1417.24c	7	0.50	5	2448.82	9	0.36	2
743.62	4	27.0	19	1495.43	5	1.4	1	2521.75	34	0.034	9
827.24	10	0.45	5	1507.80?	13	0.83	7	2531.7n	2	0.03	1
889.72	4	3.2	2	1522.55	2	5.3	4	2636.20	7	0.48	2
893.50	4	2.3	1	1523.2*	7	1.1	2	2781.57?	25	0.14	2
901.95	5	1.19	8	1539.29n	20	0.18	5	2968.10	30	0.07	1
905.61	2	13.6	8	1587.17	12	0.39	5	3123.59?	17	0.14	1
941.10	4	2.1	1	1707.61	2	21.3	6				
953.30	7	0.53	5	1780.52	2	4.7	1				

a The reported uncertainties refer to the last significant digits.  
 n New  $\gamma$ -transition identified in the present work.  
 c  $^{70}\text{Ge}$  transition not assigned to the level scheme before, but placed into the decay scheme now.  
 x The placement of  $\gamma$ -transition is confirmed in the present work again.  
 y The placement of  $\gamma$ -transition is changed in the present work.  
 \* The energy and relative intensity of  $\gamma$ -ray are deduced from the coincidence spectrum.  
 ?  $\gamma$ -transition not placed in the decay scheme.

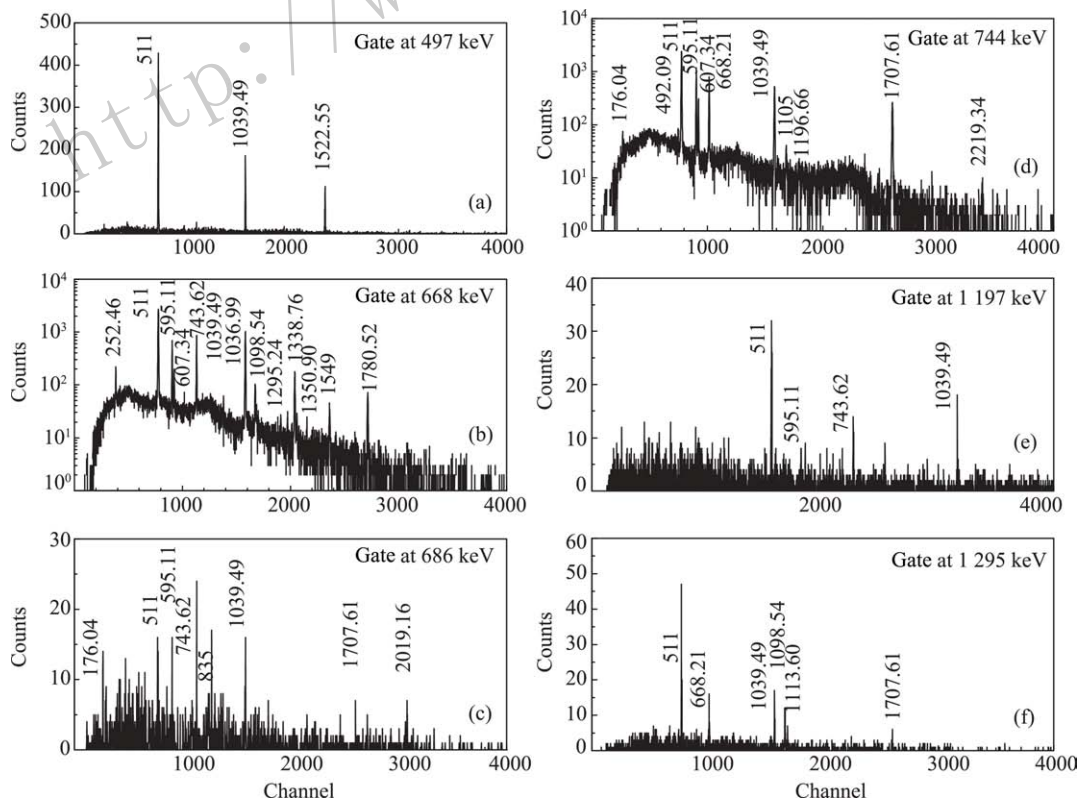


Fig. 2 Some examples of coincidence spectra gated by (a)497 keV, (b)668 keV, (c)686 keV, (d)744 keV, (e)1197 keV, (f)1295 keV  $\gamma$ -rays following the decay of  $^{70}\text{As}$ , respectively.

transitions and 2 new levels are assigned to  $^{70}\text{As}$ , based on the measured half-life and/or observation in coincidence with well-known transitions. A decay scheme, which is shown in Fig. 3, is constructed consisting of 22

excited states and 59 transitions in  $^{70}\text{Ge}$ . Additional new information is obtained on  $\gamma$ -ray branching ratios,  $\log ft$  values, spins and parities.

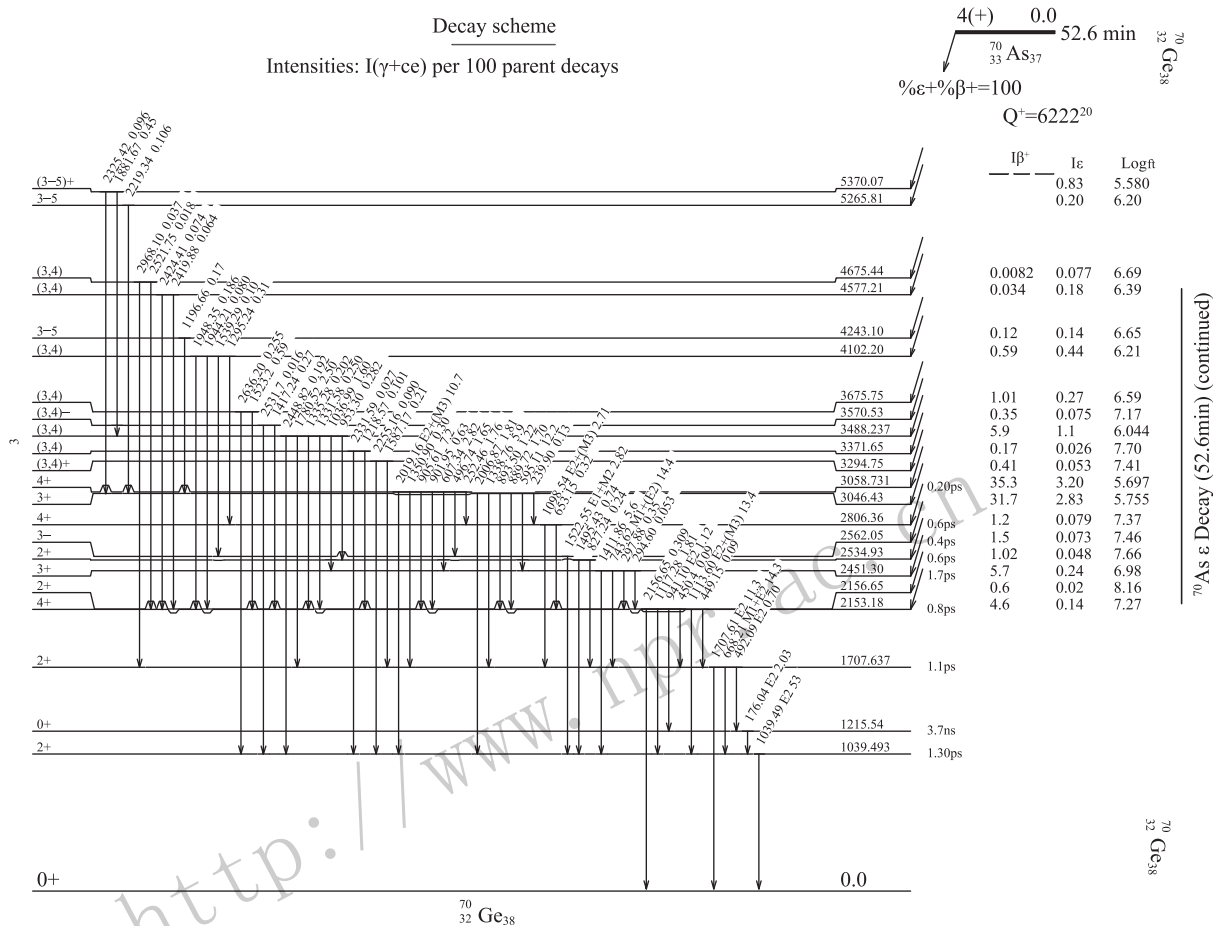


Fig. 3 Decay scheme of  $^{70}\text{As}$  proposed in this experiment.

### 4 Discussion of the decay scheme

The relative  $\gamma$ -ray intensities are normalized to give 100 for the total feeding of the ground state, thus excluding a direct feeding of the ground state because of spin arguments. The intensity of the E2 176.04 keV  $\gamma$ -ray is corrected for internal conversion<sup>[4]</sup>. From the studies of the (p, p $\gamma$ ) reaction<sup>[5]</sup>, it was concluded that the 1215.54 keV level decays for only about 1% by internal conversion to the ground state directly by compared with the transitions of 176.04 keV  $\gamma$ -ray. From the  $\gamma$ -ray and internal conversion electron intensities<sup>[2,3]</sup>, the intensities of the direct ( $\beta^+$ +EC) feeding of the levels are deduced by balancing the populating and depopulating intensity of each level here. Finally the  $\log ft$  values and the intensities of the  $\beta^+$  and electron-capture branches to the  $^{70}\text{Ge}$  levels are calculated by using the ENSDF (Evaluated Nuclear Structure Data File) analysis and checking program

offered by NNDC (National Nuclear Data Center) at Brookhaven National Laboratory. The result is presented in the decay scheme (Fig. 3).

The discussion below is limited to levels which have not been observed before, to those for which the population and depopulation mode, spin or parity assignment has been revised significantly with respect to previous works.

The 3570.53 level: This level is based on the observation of the 1113.60 ~ 1417.24 cascade and 1039.49 ~ 2531.7 cascade. The  $\log ft$  value indicates that the  $\beta^+$ (EC) transition to the level is allowed or once-forbidden. The possible spin assignments are, therefore, 3-5. In addition, an energy level at 3568±3 keV was found in the nuclear reaction studies<sup>[2,3]</sup>, and the spin and parity of 2<sup>-</sup>-4<sup>-</sup> are adopted in those works. Therefore they can be considered as identical levels, and in the present work the possible spin and parity assignments of this level are 3<sup>-</sup>-4<sup>-</sup>.

The 4 102.20 level: The 4 103.2 keV level has been reported in the  $^{70}\text{Ge}(\text{d}, 2\text{n})^{70}\text{As}$  reaction<sup>[1]</sup>, but its assignment has not been confirmed. The new evidence for this level is that the new two  $\gamma$ -rays at 1 295.24 and 1 539.29 keV depopulate from this level and feed to the 2 806.36 and 2 562.05 keV levels from the coincidence data analysis, respectively. In the decay study of  $^{70}\text{As}$ <sup>[1]</sup>, an assignment of (3, 4) was indicated. These are compatible with the present  $\log ft$  value.

The 4 243.10 level: This level is based on the observation of the new 1 196.66 keV transition and the 595.11-743.62-1196.66 cascade. The  $\log ft$  value indicates that the  $\beta^+(\text{EC})$  transition to the level is allowed or once-forbidden. The possible spin assignments are, therefore, 3-5.

The 5 265.81 level: The 2 219.3 keV  $\gamma$ -ray is previously assigned as between the 4 672.3 and 2 452.3 keV levels<sup>[1]</sup>. In the present work, we find the 2 219.34-595.11 cascade. So we add this new level. The  $\log ft$  value indicates that the spin of the level is 3-5.

The 5 370.07 level: The 5 373.2 keV level has been reported in the  $^{70}\text{Ge}(\text{d}, 2\text{n})^{70}\text{As}$  reaction<sup>[1]</sup>. But the uncertainty of the two  $\gamma$ -rays at  $2\,326.6 \pm 1.0$  and  $4\,327.9 \pm 3.0$  keV, which depopulated from this level, is rather large due to poor energy resolution. This level is established in the present work by the observation of two  $\gamma$ -rays at 1 881.67 and 2 325.42 keV. The 4 327.9 keV transition previously attributed to depopulation this level is not confirmed. The  $\log ft$  value indicates that the  $\beta^+(\text{EC})$  transition to the level is allowed. The possible spin assignments are, therefore, (3-5)+.

In addition,  $\gamma$ -rays at 496.74, 685.50, 1 295.24, 1 417.24, 1 507.80, 2 095.69, 2 781.57 and 3 123.59 keV

have been reported in Refs. [2] and [3]. In the present work, the transition positions of 496.74, 1 295.24 and 1 417.24 keV  $\gamma$ -rays have been assigned for the first time. The  $\gamma$ -rays at 685.50, 1 507.80, 2 095.69, 2 781.57 and 3 123.59 keV are also observed in the present work, and their relative intensities are given in Table 1, but their placements are not assigned. The  $\gamma$ -ray at 685.50 keV probably is the double-escape peak of 1 707.61 keV  $\gamma$ -ray, and the 1 507.80 keV  $\gamma$ -ray probably is the single-escape peak of 2 019.6 keV  $\gamma$ -ray.

## 5 Summary

In the present work, in order to study the  $\beta^+ + \text{EC}$  decay of  $^{70}\text{As}$ , the source of  $^{70}\text{As}$  is produced through the  $^{70}\text{Ge}(\text{p}, \text{n})^{70}\text{As}$  reaction. The decay of  $^{70}\text{As}$  to levels in  $^{70}\text{Ge}$  are studied using a NaI-HPGe Compton-suppressed spectrometer and a three-parameter ( $\gamma$ - $\gamma$ -t) coincidence system of HPGe-HPGe detectors. Approximately 64 transitions including 4 new transitions and 2 new levels are assigned to  $^{70}\text{As}$ . A decay scheme is constructed consisting of 22 excited states and 59 transitions in  $^{70}\text{Ge}$ . In addition, new information is obtained on  $\gamma$ -ray branching ratios,  $\log ft$  values, spins and parities.

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## $^{70}\text{As}(\beta^++\text{EC})$ 衰变到 $^{70}\text{Ge}$ 的低自旋激发态

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**摘要:** 通过 $^{70}\text{As}$ 的放射性衰变研究了 $^{70}\text{Ge}$ 的激发态, 新发现能量为 1036.99, 1196.66, 1539.29 和 2531.7 keV 的四条新 $\gamma$ 射线, 重新确认了 2219.34 keV  $\gamma$ 射线的跃迁位置, 新确认 496.74, 1295.24 和 1417.24 keV 这三条 $\gamma$ 射线首次放入衰变纲图, 本工作证实了 1881.67, 2325.42 和 2424.41 keV  $\gamma$ 射线的跃迁位置, 建议了能量为 4243.10 和 5265.81 keV 的两个新能级, 建立了新的衰变纲图, 基于比较半衰期和 $\gamma$ 跃迁分支比建议了一些能级的自旋-宇称。

**关键词:** 衰变;  $\gamma$ 射线; 能级; 符合

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