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Short note

(EC+β^+) decay study of ^{128}Ce

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Abstract. The (EC+β^+) decay of ^{128}Ce was reinvestigated in the ^{116}Sn (^{16}O, 4n) reaction by using a helium-jet tape transport system. The close half-lives of ^{128}Ce and ^{129}Ce made it difficult to separate the decay γ rays of both nuclei apart. Instead of the excitation-function measurements, both reactions of ^{16}O+^{116}Sn and ^{16}O+^{117}Sn were carried out, and from their comparisons, the decay γ rays of ^{128}Ce were clearly told from those of ^{129}Ce. Based on X-γ and γ-γ coincidence measurements, a detailed (EC+β^+) decay scheme of ^{128}Ce has been proposed, which revises the previous one.

PACS. 23.20.Lv Gamma transitions and level energies – 23.40.-s β decay; electron and muon capture – 27.60.+j $90 \leq A \leq 149$

In the mass 130 region of deformed nuclei, the properties at low and medium spin are dominated by the interplay between collective and single particle motion. Experimental determinations of the spins for the band members, especially for the band head, play an important role in the detailed investigation of the band structures. For odd-odd nuclide ^{128}La, its high-spin level structures in the excited states have been extensively studied[1, 2, 3], but the spin assignments of its band members are more or less tentative because they are only estimated from theoretical predictions. Instead of the in-beam study, the β decay of ^{128}Ce has been studied in order to get some useful information on the low-lying excited states of ^{128}La[4].

The (EC+β^+) decay scheme of ^{128}Ce was proposed by Hayakawa et al., who used a pulsed beam and a tape transport system[4]. But because they didn't take the mass separation or excitation-function measurements for the radioactive products, the γ rays for the decays of ^{128}Ce and ^{129}Ce couldn't be separated apart due to the quite close experimental half-life values for the decay of ^{128}Ce and ^{129}Ce [4, 5, 6]. Whether the decay scheme of ^{128}Ce proposed by Hayakawa et al. was mingled with a component from ^{129}Ce decay has been pointed out since the decay scheme of ^{129}Ce was suggested [5, 6],[7]. With this background in mind, two experiments with different targets of ^{116}Sn and ^{117}Sn foils being bombarded by ^{16}O beam were carried out, and from their comparisons, the γ rays of ^{128}Ce were unambiguously distinguished from those of ^{129}Ce, and a revised and more detailed (EC+β^+) decay scheme of ^{128}Ce was suggested.

The experiments were carried out at the SFC accelerator of HIRFL (Heavy Ion Research Facility in Lanzhou). Two 1.8 mg/cm^2 self-supporting foils of ^{116}Sn (99% enriched) and ^{117}Sn (92.8% enriched) targets were bombarded independently by a 102MeV ^{16}O^{6+} beam with a beam intensity of 0.5 eμA. The effective beam energy on target was about 90MeV due to the energy losses in the entrance window (1.94mg/cm^2 Havar foil) and the helium gas. The pressure of the helium gas in the target chamber was about 100kPa. A helium jet in combination with a fast tape-transport system was used to move the radioactivity periodically into a shielded location, where either the X-γ or γ-γ coincidence measurements were carried out, or a chemical separation procedure was performed for further γ-singles measurements. NaCl was added to the helium for aerosol formation in order to increase the transport efficiency. Both the collection time and accumulation time used in the experiments were 10min.

Gamma rays were detected by two coaxial high purity germanium detectors with the type of GMX [HpGe (GMX)], and a planar HpGe(GLP) detector was used for X-ray measurement. Both GMX detectors or one GLP and one GMX detectors were placed on the opposite side of the tape for γ-γ or X-γ coincidence measurements, while one of the GMX detectors was shielded in a lead chamber for γ-singles measurements.

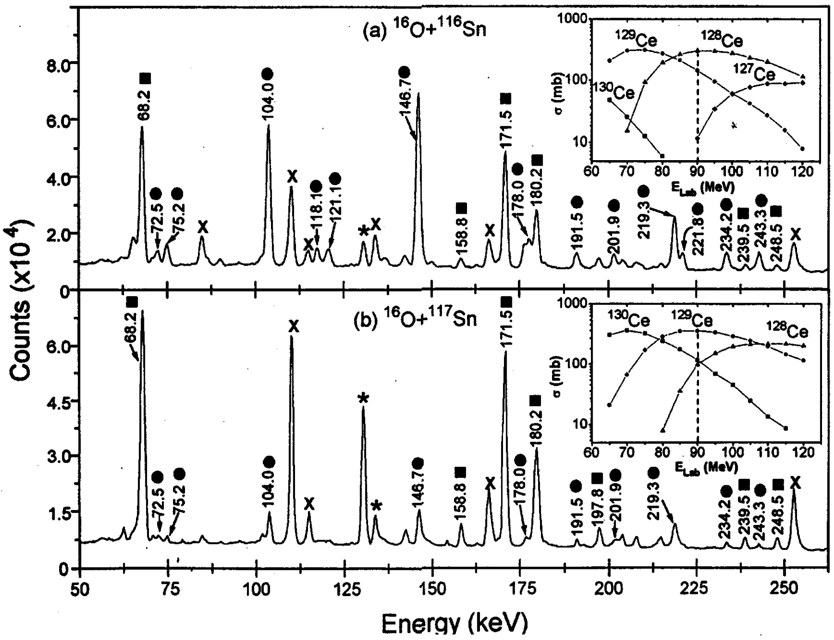

Fig. 1. The γ-ray single spectra after chemical separations in different experiments: (a) ^{16}O + ^{116}Sn and (b) ^{16}O + ^{117}Sn. The γ-rays are assigned to their β-decay parents: ^{128}Ce (solid circle), ^{129}Ce (solid square), ^{130}Ce (arista), the contaminant peaks from Lanthanum isotopes (cross). The insets are the corresponding cross sections for cerium isotopes calculated from an ALICE code

A chemical separation procedure was performed before γ-singles measurements to minimize the γ-ray contaminations from the decays of La, Ba, Cs isotopes other than the cerium. Immediately after the irradiation, the radioactive reaction products sticking on the tape were drip-washed into a beaker filled with Ce(III), La (III), Cs(I) and Ba(II) carriers and 12 Mol HNO_3. The cerium fraction was isolated rapidly by oxidation to Ce(IV) with BrO_3^- and extraction of the Ce(IV) into a 6ml 0.75M bis(2-elhylhexyl) orthophosphoric acid in n-hexane. Subsequently, the cerium was back-extracted into 5.4ml 9Mol HCl from the organic phase, and washed. Finally, the cerium activity was precapitated as oxalate, and a container with cerium-activity liquid was then prepared for γ-singles measurements. Typical separation time of the above procedure was about 5 min, and the chemical yield was close to 85%.

The main activities observed in the chemically purified cerium samples were ^{128}Ce ($\sim$4.0 min) $\rightarrow^{128}$La and ^{129}Ce (4.1min)$\rightarrow^{129}$La(11.6min). According to the calculations with the computer program "ALICE"[8], the cross sections for ^{128}Ce and ^{129}Ce are sizably different in the two experiments (see the insets of Fig. 1). This was consistent with the experimental γ-single spectra shown in Fig. 1. From the comparison of the reaction products of ^{16}O+^{116}Sn and ^{16}O+^{117}Sn in Fig. 1, the γ rays headed with 104.0keV, 146.7keV, 219.3keV etc. are from the decays of ^{128}Ce, just as Hayakawa et al. have suggested[4], while the γ rays headed with 68.2keV, 171.5keV, 180.2keV etc. should be from the decays of ^{129}Ce, as the decay study of ^{129}Ce implied[5, 6] but they were wrongly assigned to ^{128}Ce for lack of the efficient excitation-function measurements[4]. These γ rays are in coincidence with La-X rays, and the other γ rays in Fig. 1 are also assigned to different β-decay parents from X-γ coincidence measurements. The weighted average value obtained for the half-life of ^{128}Ce is 4.0$\pm$0.1 min, which agrees with the previous one of ^{128}Ce, 4.1$\pm$0.3 min[4].

By placing gates on the main γ rays of 104.0keV, 146.7keV, 219.3keV etc., the γ rays emitted from ^{128}La after ^{128}Ce β decay can be deduced from the ^{16}O+^{116}Sn reaction from their X-γ and γ-γ coincidence relationships. The observed weak γ-lines of ^{128}Ce were assigned by the coincidence measurements with La-K_α X rays and with the already assigned strong γ lines of ^{128}Ce, in some cases, using the energy sum relations as well. All the γ-γ coincidence relations found for the ^{128}Ce decay are listed in Table 1, and the relative γ-ray intensities following the decay of ^{128}Ce are also listed in Table 1. These values are based mainly on the analysis of γ-singles spectra except some weak γ-rays which were checked in terms of γ-γ coincidence spectra simutaneously. From the present experimental data given in Table 1, the (EC+β^+) decay scheme of ^{128}Ce is suggested in Fig. 2. The M1/E2 multipolarities assumed for all the transitions lower than 350keV were taken into account. Since levels of 0^+ or 1^+ in ^{128}La are preferentially populated from the ground state of ^{128}Ce (0^+), and all the γ transitions feeding the fictitious ground state of ^{128}La from these states have large intensities, a low spin isomeric state is tentatively suggested for the base state in Fig. 2, which is definitely different from the known high-spin isomeric state (5 or 6^+) in ^{128}La[4], but its half-life was not determined in this experiment.

By comparing the level structures of the neighboring odd-A nuclei ^{127}Ba and ^{127}La[9, 10], this low-spin isomeric state in ^{128}La was suggested to be 2^+ or 1^+ with the configurations of $\pi[422]3/2\otimes\nu[411]1/2$ or $\pi[411]3/2\otimes\nu[411]1/2$[4]. In case of 2^+, the β-feeding from ^{128}Ce ground state (0^+) to the base state of ^{128}La in Fig. 2 could be ignored due to the selection rules. While in case of the 1^+ isomeric base state, the ground-to-ground β feeding must be considerable but its intensity was undeter-

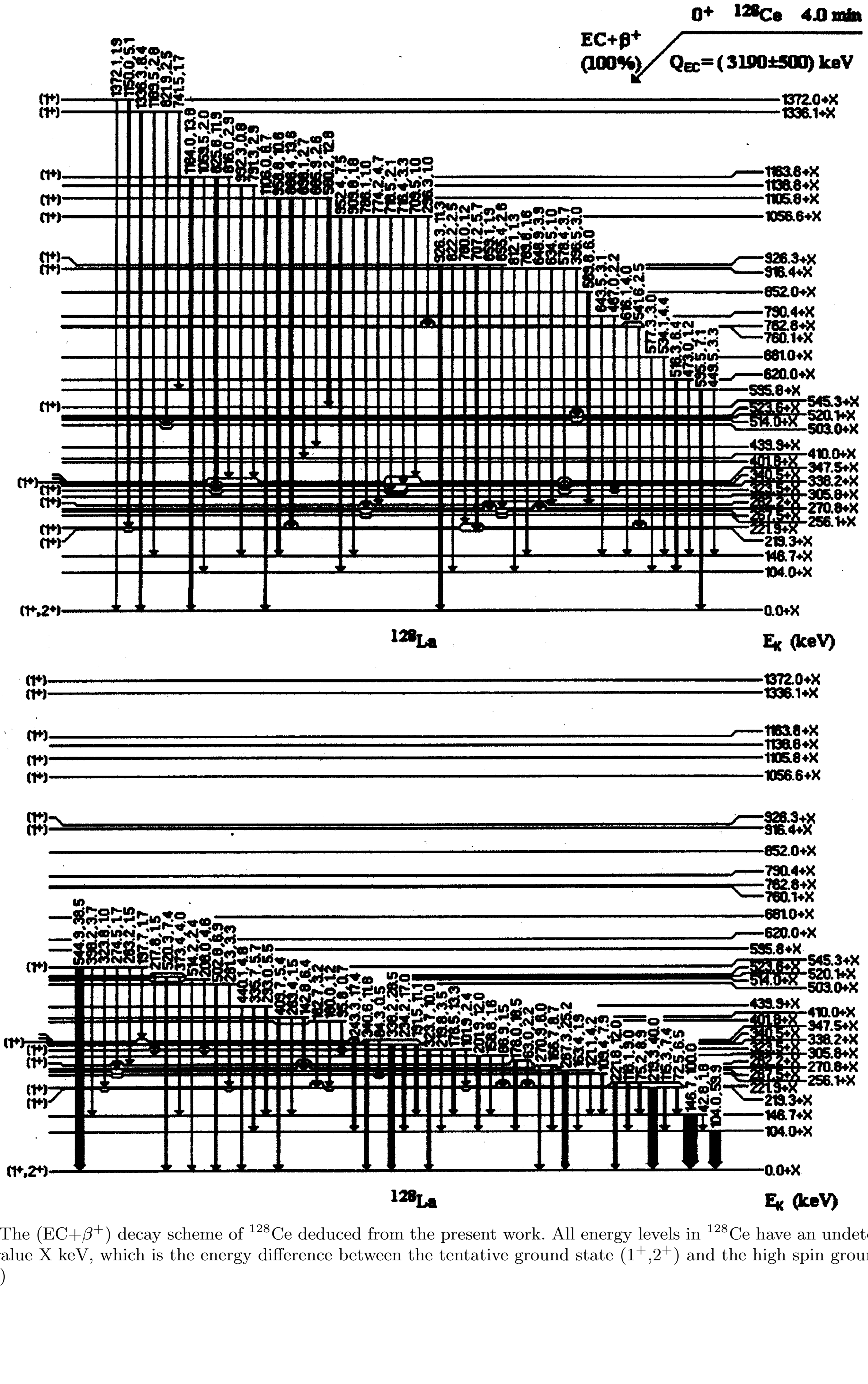

Fig. 2. The (EC+β^+) decay scheme of ^{128}Ce deduced from the present work. All energy levels in ^{128}Ce have an undetermined energy value X keV, which is the energy difference between the tentative ground state (1^+,2^+) and the high spin ground state (5 or 6^+)

Table 1. Gamma-ray energies, relative γ-ray intensities, and coincidence relationships observed for the decay of ^{128}Ce

E_γ* (keV)	I_γ	Coincidence γ (keV)	E_γ* (keV)	I_γ	Coincidence γ (keV)	E_γ* (keV)	I_γ	Coincidence γ (keV)
42.8	1.8(2)	104.0	197.7	1.7(4)	104.0, 243.3			544.9
63.0	2.2(2)	72.5, 115.3, 219.3	201.9	12.0(2)	95.8, 104.0, 208.0,	569.8	6.0(4)	104.0, 146.7, 178.0
72.5	6.5(1)	63.0, 146.7, 182.7,			217.8	577.3	3.0(7)	104.0
		541.6, 886.4	208.0	4.6(2)	86.9, 104.0, 115.3,	578.4	3.7(4)	146.7, 191.5, 234.2,
75.2	8.9(1)	101.9, 146.7, 180.0,			201.9, 219.8, 821.9			338.2
		281.3, 323.8	217.8	1.5(4)	86.9, 104.0, 115.3,	595.5	7.1(4)	741.5
84.3	0.5(2)	109.4, 146.7			201.9, 219.8	616.1	4.0(4)	146.7
86.9	1.5(2)	72.5, 146.7, 208.0,	219.3^D	40.0(6)	63.0, 86.9, 104.0,	634.5	1.0(6)	104.0, 178.0
		219.3			182.7, 541.6, 707.2,	643.5	3.1(6)	146.7
95.8	0.7(1)	201.9			886.4	648.9	3.9(4)	267.3
101.9	2.4(2)	75.2, 118.1, 146.7	219.8^D	3.5(6)	104.0	655.4	2.6(4)	146.7, 293.0
104.0	59.9(2)	42.8, 63.0, 101.9,	221.8	12.0(2)	101.9, 323.8, 1150.0	659.1	1.9(6)	267.3
		115.3, 118.1, 163.4,	234.2	17.0(2)	104.0, 718.5	665.9	2.6(4)	146.7, 293.0
		166.7, 178.0, 201.9,	243.3	17.4(2)	104.0, 197.7, 709.5,	696.1	2.7(4)	142.8
		219.8, 234.3,243.3,			791.3, 816.0	707.2	5.7(4)	72.5, 104.0, 146.7,
		335.7, 516.3, 560.2,	263.2^D	1.5(4)	104.0, 178.0			219.3
		577.3, 569.8, 634.5,	263.4^D	1.5(4)	146.7	709.5	1.0(5)	104.0, 243.3
		709.5, 774.2, 812.1,	267.3	25.3(2)	142.8, 648.9, 659.1	716.4	3.3(7)	340.6
		816.0, 821.9, 825.6,	270.9	6.0(2)	655.4	718.5	2.1(7)	234.2
		886.4, 952.4, 1059.5	274.5	1.7(2)	166.7, 270.9	741.5	1.7(6)	595.5
109.4	7.9(5)	84.3, 146.7	281.3	3.3(2)	75.2, 115.3, 118.1,	769.8	1.6(4)	146.7
115.3	7.4(2)	104.0, 182.7, 281.3,			146.7	774.2	4.7(4)	104.0, 178.0
		541.6	293.0	5.5(2)	146.7	780.0	1.2(4)	146.7
118.1	9.0(1)	101.9, 104.0, 281.3,	296.3	1.0(3)	104.0, 541.6	786.1	1.0(6)	166.7
		323.8	323.7^D	10.0(4)		791.3	2.9(4)	243.3
121.1	4.2(5)	146.7	323.8^D	1.0(4)	75.2, 221.8	812.1	1.3(4)	104.0
142.8	6.4(2)	267.3, 696.1	335.7	5.7(3)	104.0, 665.9	816.0	2.9(4)	104.0, 243.3
146.7	1000	72.5, 75.2, 101.9,	338.2	28.5(3)	578.4, 825.6	821.9^D	2.5(4)	514.2
		109.4, 121.1, 158.8,	340.6	11.8(3)	716.4	822.2^D	2.5(4)	104.0
		176.5, 191.5, 263.4,	373.4	4.0(5)	146.7	825.6	11.9(4)	104.0, 146.7, 191.5,
		281.3, 293.0, 373.4,	396.5	3.0(7)	520.3			234.2, 338.2
		398.2, 449.5, 473.0,	398.2	3.7(7)	146.7	886.4	13.6(4)	72.5, 104.0, 219.3
		534.1, 560.2, 616.1,	409.7	5.4(3)		909.8	1.8(4)	146.7
		643.5, 769.8, 780.0,	440.1	4.8(7)		926.3	11.3(4)	
		886.4, 909.8, 958.8,	449.5	3.3(3)	146.7	952.4	7.5(4)	104.0
		992.3, 1189.5	467.0	2.2(7)	176.5	958.8	10.6(4)	146.7
158.8	1.6(4)	146.7	473.0	1.2(5)	146.7	992.3	0.8(4)	146.7
163.4	1.9(1)	104.0	502.8	6.9(3)		1059.5	2.0(4)	104.0
166.7	8.7(8)	104.0, 274.5, 786.1	514.2	2.4(8)		1106.0	6.7(5)	
176.5	13.3(2)	146.7, 467.0	516.3	6.4(3)	104.0	1150.0	5.1(5)	75.2, 104.0,146.7,
178.0	18.5(2)	104.0, 263.2, 569.8	520.3	7.4(5)	396.5			221.8
		634.5, 774.2	534.1	4.4(3)	146.7	1164.0	13.8(5)	
180.0	1.2(6)	75.2	541.6	2.5(3)	72.5, 115.3, 146.7,	1189.5	2.8(5)	146.7
182.7	3.2(2)	72.5, 115.3, 219.3,			219.3	1336.3	8.4(6)	
		696.1	544.9	38.5(4)	560.2	1372.1	1.9(6)	
191.5	11.1(2)	146.7, 578.4, 718.5	560.2	12.8(4)	146.7, 219.3, 243.3,			

* The energy error is ±0.3keV ^{D} Doublet peak, whose intensity is determineded from γ-γ coincidence spectra

mined. A branching ratio of 50% was tentatively assumed for this ground-to-ground β decay and used in the calculations. This will bring out an uncertainty of less than 0.3 in the log *ft* values for the excited states in ^{128}La except of the ground state when the ground-to-ground β feeding changes from 0 to 75%. With the above assumptions, the upper limit of β-feeding of the levels and the lower limit of log *ft* values were calculated using the table of Gove and Martin[11]. The Q_{EC} value 3.19 MeV used here is taken from the systematic mass evaluation given by Audi et al.[12]. Because the beta transition with log $ft \leq 5.9$ are allowed according to the empirical rules given by Raman and Gove [13], the 0^+ ground state of ^{128}Ce suggests that the states in ^{128}La with log *ft* value$\leq$5.9 should have the spins and parities of 1^+, just as they are shown in Fig. 2.

It should be pointed out that base state of ^{128}La in Fig. 2 is not the same as that given by Hayakawa et al.. In Fig. 4 of [4], the 23-keV γ ray deexciting to the "ground" state of ^{128}La is an escape peak of La-K_α-X rays which is coincident with all γ rays of cerium decay, and should not be placed in the decay scheme of ^{128}Ce. This naturally resulted in the wrong level energies of ^{128}La in [4] which are 23-keV higher than the corresponding ones in Fig. 2. The decay scheme of ^{128}Ce suggested by us kicks out the γ rays belonging to the decay of ^{129}Ce. It accounts for 37 excited states in ^{128}La and more than 100 γ lines, and about half of the excited states and γ rays are new compared to the old one given by Hayakawa et al.[4].

In the decay of ^{128}Ce, more than 13 1^+ states with excitation energies less than 1.5MeV in ^{128}La are populated. In principle, if the interactions between the simple (one particle-one hole) excitations and more complicated (two particles-two holes, ...) ones are taken into account, more than one 1^+ states can be formed in the low-energy region for the odd-odd daughter nucleus, and the Gamow-Teller strength of β^+ decay could be fragmented among them[14]. Since the residual interaction in the transitional nucleus is rather complicated, we expected more low-lying 1^+ states in ^{128}La than in a near spherical odd-odd nucleus. However, we are not able to reproduce so many low-lying 1^+ states in ^{128}La quantitatively by a model calculation yet. How to interpret them is still an open question.

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