Identification of high spin states in ^{100}Zr

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Eight new high spin states and 23 new γ transitions have been identified in ^{100}Zr from studies of ^{252}Cf spontaneous fission with Gammasphere. A near-spherical excited band in ^{100}Zr based on the 331.1 keV 0^+ state is extended from 4^+ up to 12^+. A $\Delta I = 1$ band with band-head energy of 2316.1 keV is extended.

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It has recently been shown that nuclei around $A = 100$ ($36 \leqslant Z \leqslant 45$ and $54 \leqslant N \leqslant 65$) have interesting features such as coexistence of nearly spherical and well deformed shapes [1–3] and degenerate doublet bands claimed to be evidence of chirality [4]. The isotopes in this region change very rapidly from a spherical shape for nuclei with $N \leqslant 56$ to well deformed shape for nuclei with $N \sim 60$–62 because of deformation-driving orbitals such as $\nu 9/2[404]$ and the reinforcement of proton and neutron shell gaps at the same deformation in the Kr, Sr, and Zr nuclei [1,5,6]. Gamma-unstable or triaxial shapes could be built between these coexisting two deformations [4,7]. A triaxial shape, where broken chiral symmetry may occur, gives rise to a pair of nearly degenerate bands as reported in ^{104}Rh [4,7].

^{100}Zr with $N = 60$ exhibits clear coexistence of a near-spherical band built on the 331.1 keV state and a ground band with well deformed prolate shape [β_2=0.32(2)] [8]. The deformed ground band has been well established up to 20^+ from the fission work of ^{248}Cm [6] and a near-spherical band upto 4^+ from our earlier fission work of ^{252}Cf [1]. Therefore, it is interesting to identify the high spin members of the near-spherical band and also the other states that may show complexities associated with prolate, oblate, and possibly triaxial shapes.

The measurements were carried out at the Lawrence Berkeley National Laboratory with a covered ^{252}Cf source of about 60 μCi inside the reaction chamber of Gammasphere with 102 Ge detectors. The source was sandwiched between two Fe foils of thickness 10 mg/cm^2. The coincidence data (5.7×10^{11} triple and higher fold) were analyzed with the RADWARE software package [9]. The very high statistics enabled us to identify new states and transitions. The known γ transitions in ^{100}Zr and the Ce partner isotopes were used to identify the new transitions.

In the present work, a near-spherical excited band in ^{100}Zr is extended from 4^+ up to 12^+. This is the highest spin to which a coexisting near-spherical band has been observed in this region. Our new level scheme is shown in Fig. 1. In Figs. 2(a) and 2(b), parts of coincidence spectra with double gates on 275.6 and 267.3 keV transitions and 899.8 and 497.3 keV transitions, respectively, are shown. Two new transitions of energies 301.3 and 336.5 keV as seen in Fig. 2(a) are assigned to ^{100}Zr. From this coincidence spectrum and several other coincidence spectra, these two transitions are placed in band -(3) as shown in Fig. 1. Three new transitions of 440.1, 564.4, and 617.5 keV are observed as shown in Fig. 2(b). Also, a new 615.3 keV transition is observed clearly in the coincidence spectrum with the double gate on the 1331.9 and 625.5 keV transitions. Band -(2) was reported from the fission work of ^{248}Cm [6]. Only the 2754.4 and 3022.2 keV levels were known in band -(3) from our earlier fission work [1,10]. Four new states with energies of 2316.1, 2526.1, 3323.5, and 3660.2 keV in band -(3) and three new states with energies of 2579.2, 3019.3, and 3634.6 keV in band -(4) and one state with energy of 2859.7 keV in the side band are added in the present work. 23 new transitions with energies of 301.3, 336.7, 392.2, 438.8, 440.1, 496.5, 547.0, 564.4, 568.6, 615.3,617.5, 638.0, 891.8, 1172.3, 1208.1, 1254.2, 1331.9, 1397.1, 1405.6, 1434.7, 1464.2, 1698.6, and 1751.5 keV are identified. Relative intensities (I_γ) of γ transitions (keV) in ^{100}Zr are shown in Table I. The uncertainties in the intensities range from about 5% for the strong transitions to 30% for the weak transitions. Also, the $I_\gamma(I \rightarrow I\text{-}2)$ values relative to the $I_\gamma(I \rightarrow I\text{-}1)$ values in the bands -(2) and -(3) are shown in Table II. Thicknesses of the arrows indicate the relative intensities of the γ transitions.

The band-head of band -(2) at 2259.8 keV in ^{100}Zr was tentatively assigned the spin and parity of 6^+ in Refs. [6,11] and 5^- in Refs. [1,12] because of transitions to the known 4^+ and 6^+ but not to 2^+ levels. The 2259.8 keV state was assigned a configuration of $\nu 9/2[404]\times\nu 3/2[411]$ [11] based on the fact that the experimental $(|g_K - g_R)/Q_0|$ value $(0.12\,(e\text{b})^{-1})$ [6] is consistent with the calculated one $[0.13\ (e\text{b})^{-1}]$ [6]. However, the 6^+ assignment to band -(2) raises two objections. First, a $\Delta K = 6$ transition to the ground band would result in a very long half life as observed for the $17/2^+$ state with 8.6(8) μs half-life in ^{99}Y [13]. However, the half-life of the band-head of band -(2) is not more than several ns. Secondly, the energy

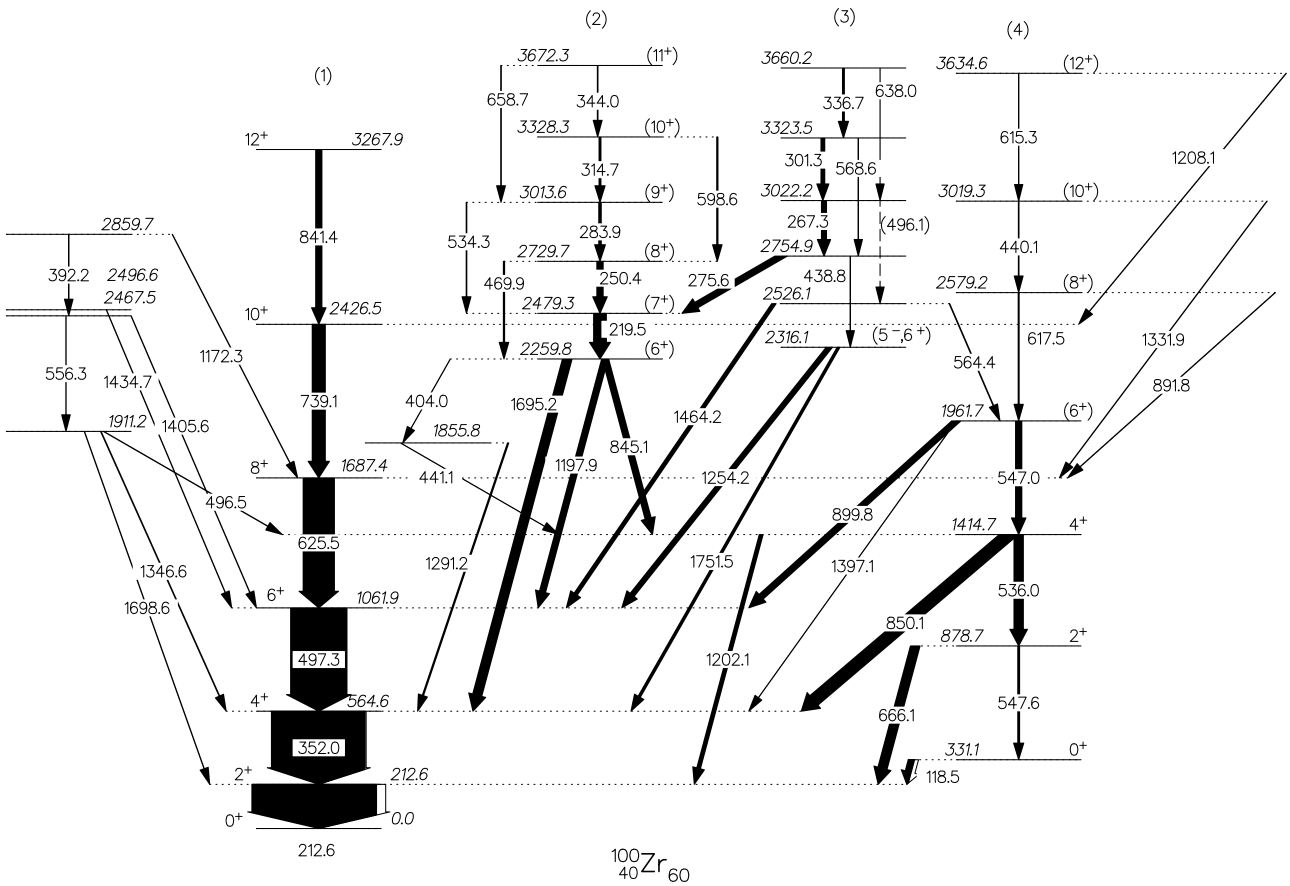

FIG. 1. Level scheme of ^{100}Zr observed from the spontaneous fission of ^{252}Cf. The transition patterns do not exclude the spin and parity of 5^- for band-head of bands -(2). Eight new states and 23 new transitions are added in the present work.

splitting (695.8 keV) of the Gallagher-Moskowski interaction observed for a similar band in ^{98}Sr [14] is too large compared with the average value of 400 keV in this region [14]. A spin and parity of 5^- for the band head of band -(2) was proposed based on the proton configuration of $\pi 5/2[303]\times 5/2[422]$ [1, 12]. The short half-life of the 2259.8 keV state does not exclude $\Delta K = 5$ K-forbidden $E1$ transitions with $K = 5$ as a good quantum number. The spins and parities to the levels of band -(3) have never been assigned before.

TABLE I. Relative intensities (I_γ) of γ transitions (keV) in ^{100}Zr. Intensity errors range between about 5% for the strong transitions and 30% for the weak transitions.

γ transition	I_γ	γ transition	I_γ	γ transition	I_γ	γ transition	I_γ
212.6	100	441.1	0.9	638.0	0.1	1331.9	1.1
219.5	5.5	469.9	0.1	666.1	7.0	1346.6	2.9
250.4	2.4	496.5	0.9	739.1	5.2	1397.1	0.7
267.3	1.0	497.3	65	841.4	2.1	1405.6	1.1
275.6	2.6	534.3	0.5	845.1	8.8	1434.7	0.1
283.9	2.1	536.0	6.8	850.1	9.5	1464.2	1.8
301.3	0.8	547.0	3.0	891.8	1.0	1695.2	4.9
314.7	1.0	556.3	0.5	899.8	2.3	1698.6	0.1
336.7	0.3	564.4	0.3	939.8	0.5	1751.5	1.7
344.0	0.5	568.6	0.1	1172.3	0.8		
352.0	84	598.6	0.2	1197.9	1.8		
392.2	0.3	615.3	0.1	1202.1	1.9		
404.0	0.5	617.5	0.6	1208.1	0.5		
438.8	0.1	625.5	26	1254.2	2.0		
440.1	0.4	658.7	0.2	1291.2	0.2		

TABLE II. Relative intensities (I_γ) of γ transitions (E_γ keV) in bands -(2) and -(3).

Level energy (keV)	γ transition (keV)	I_γ
2729.7	469.6	4
	250.4	100
3013.6	534.3	24
	283.9	100
3323.5	568.6	13
	301.3	100
3328.3	598.6	20
	314.7	100
3660.2	638.0	33
	336.7	100
3672.3	658.7	40
	344.0	100

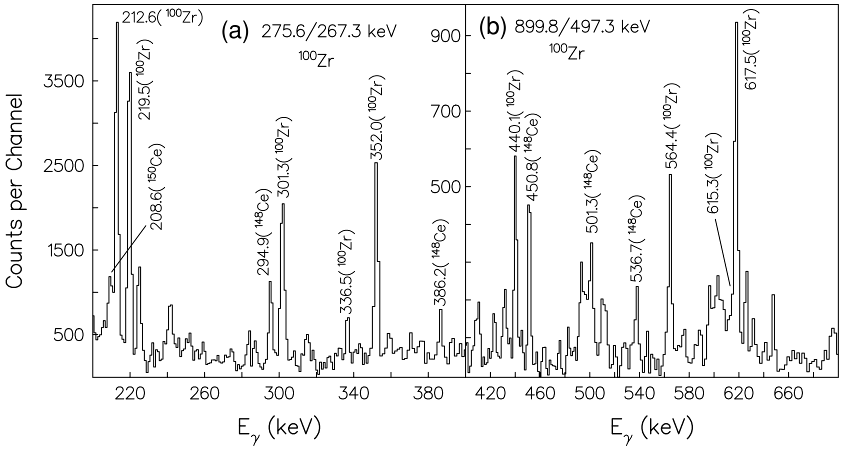

FIG. 2. (a) Coincidence spectrum with double gates on 275.6 and 267.3 keV transitions and (b) coincidence spectrum with double gates on 899.8 and 497.3 keV transitions in ^{100}Zr. The new 615.3 keV transition can be seen clearly in the coincidence spectrum with the double gate on 1331.9 and 625.5 keV transitions.

In other words, around the excitation energy of bands -(2) and -(3), two quasi-particle bands of $\pi 5/2[303]\times 5/2[422](K = 5^-)$ and $\nu 9/2[404]\times 3/2[411]$ $(K = 6^+)$ are possible in ^{100}Zr [15]. Therefore, bands -(2) and -(3) may come from two kinds of quasi-particle excitations. However, the absence of K forbiddenness and inconsistency of the Gallagher-Moskowski interaction value may suggest that these two bands are not from an axially symmetric shape, but from a possible triaxial shape where K is not a good quantum number. Let us examine a single particle level diagram for axial shapes, such as Fig. 1 of Skalski *et al.* [17]. We can identify regions of quadrupole deformation and particle number with levels near Fermi energy that will be mixed by Y_{22} shape matrix elements. For $^{100}_{40}Zr_{60}$ those candidate two quasipaticle configurations for bands -(2) or -(3) which have $\nu 1/2[411]$or $\nu 3/2[411]$ will be subject to triaxial shape driving, as the system can minimize energy through Y_{22} mixing between the above two orbitals. The nearby 5/2[413] orbital can also mix and help drive toward Y_{22} deformation. Also, another two-quasiparticle excitation with the configuration of $\nu 1/2[411]\times 9/2[404]$ could produce a rotational band with $K^\pi = 5^+$. Therefore, the spins and parities of bands -(2) and -(3) are consistent with several internal configurations which need further study. The spins and parities of band -(2) in ^{100}Zr in Fig. 1 were tentatively assigned by Durell *et al.* [11] up to 11^+ based on the cascade to crossover ratios. In band -(3), only band-head spin and parity were assigned tentatively as $(5^-,6^+)$ in the present work. The cascade transitions in bands -(2) and -(3) dominate over the $E2$ crossover transitions except for the first two states in band -(3). The dominance of $M1/E2$ cascade transitions over $E2$ crossover transitions in ^{100}Zr can be explained by smaller quadrupole moments of the bands -(2) and -(3) that reduce the $E2$ crossover transition rate and the $E2$ admixture in the $M1/E2$ cascade transition. This means that the nuclear shape of bands -(2) and -(3) is much less deformed than $\beta_2 = 0.32(2)$ [8] of the ground band.

We carried out the deformed HF+BCS calculations for ^{100}Zr with a Skyrme interaction SIII [16]. These predict a coexistence of the prolate shape ($\beta_2 = 0.365$) at the ground state and an oblate shape ($\beta_2 = -0.195$) at 560 keV as shown in Fig. 3. A similar result was reported by Skalski *et al.* [17] suggesting the coexistence of the prolate shape ($\beta_2 = 0.34$) at the ground state and an oblate shape ($\beta_2 = -0.21$) at 0.85 MeV using the Nilsson-Strutinsky-BCS method [17]. The calculated values of $|\beta_2| \approx 0.37$ for the ground state and $|\beta_2| \approx 0.12$ for the excited 0^+ state at 331.1 keV were obtained by using a band mixing theory [2]. These ground state deformations are reasonably close to the experimental value of $\beta_2 = 0.32(2)$ [8]. However, whether the band -(4) starting at 331.1 keV has an oblate shape remains in question. The larger rotational spacing in the excited 0^+ band is consistent with the ground band being prolate and the excited 0^+ band being oblate. There is evidently considerable band mixing between them, giving rise to strong cross band transitions. The likely coexistence of the prolate and oblate shapes of the 0^+ bands in ^{100}Zr could lead to a possible coexistence of the prolate and oblate as well as triaxial shapes at the highly excited 2 quasiparticle bands such as bands -(2) and -(3).

In summary, eight new high spin states and 23 new γ transitions are identified in ^{100}Zr. A near-spherical excited band -(4) in ^{100}Zr is extended from 4^+ up to 12^+. A $\Delta I = 1$ band -(3) is proposed.

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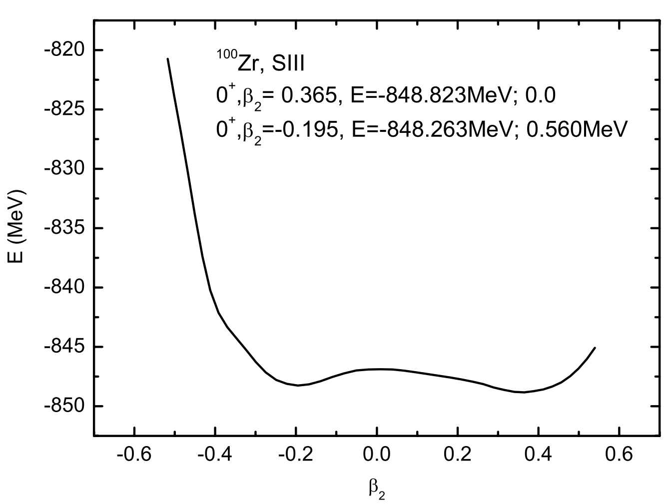

FIG. 3. The deformed HF+BCS calculations with a Skyrme interactions SIII.

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