Fission γ spectra and levels in ^{139}Ba

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Analysis of ^{252}Cf recent spontaneous-fission γ data from Gammasphere has enabled the discovery of transitions in ^{139}Ba in coincidence with those of its Molybdenum fission partner. A new level scheme going up to ≈ 5 Mev includes 11 new transitions and 10 new levels. We make analogies with the 83-neutron isotone ^{135}Te and discuss possible configurations in the spherical single-particle shell model. We suggest a band as a possible magnetic rotation band of the type treated by tilted-axis cranking theory.

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I. INTRODUCTION

It is now more than three decades since the first spectroscopic studies of prompt fission γ rays using cryogenic germanium detectors. The earliest such work, published in 1964, measured γ spectra in coincidence with fission fragments, detected in silicon particle detectors [1]. Later work used coincidence measurements among two or more germanium γ detectors with spontaneous fission sources of ^{252}Cf with backing and cover foils sufficiently thick to stop fission fragments and α decay particles, thus minimizing Doppler smearing in all transitions delayed by more than the fission-fragment stopping time of a few picoseconds. The next two decades saw much progress, as larger-volume germanium detectors became available. A disadvantage of "thick-source" work, which has no explicit coincidence with fission fragments, is that γ rays following β decay of fission products are admixed with the prompt γ rays, giving highly complex spectra for two-fold coincidence work. Nevertheless, progress was made, especially on yrast and near-yrast γ cascades in even-even nuclei, since fission tends initially to feed levels of average spin greater and equal to 6 [2], and β decay, except for cases with a few high-spin parents, mostly feeds lower spins. Furthermore, prompt fission γ's are usually in coincidence with prompt fission γ's from the complementary fission fragment partner.

This work complemented γ spectroscopy from β decay of fission product nuclei and enabled construction of nuclear level schemes including higher spins. With the construction of multidetector Compton-suppressed germanium γ detector arrays in the 1980's new progress was made possible, as multiplicity tagging of events facilitated a good discrimination between prompt fission γ's and those following β decay. β decay, with a few exceptions, is not followed by cascades of three or more γ rays, whereas prompt fission γ cascades, which are in coincidence with cascades in the partner nucleus, give a rich sampling of greater and equal to three-fold events in multidetector arrays. A great achievement in spontaneous fission γ spectroscopy was the discovery of a second island of pear-shaped nuclei a few nucleons beyond the double closed shell of ^{132}Sn [3]. This island is analogous to that just beyond ^{208}Pb, where the combination of quadrupole and octupole deformation produces shapes lacking reflection symmetry about the equatorial plane. In the 1990's the larger arrays, like Eurogam and Gammasphere, have provided yet more powerful tools for such studies [4]. There is no real answer for how much data is enough. The better the array and the more events gathered, the better one can search for and resolve weaker transitions and do the harder work of exploring nuclear types other than even-even.

In a recent paper some of us reported on reanalysis of our 1995 data to give the barium-molybdenum yield matrix [5]. Since ^{139}Ba had not been identified in prompt fission γ analysis, we had to interpolate between ^{138}Ba and ^{140}Ba yields to form the contour plot of yields. Thus, it was with real excitement that with the 2000 data, which have more than four times the number of events in midenergy peaks, we were able to identify two of the ^{139}Ba γ rays from β decay work [6] as in coincidence with the molybdenum complementary fragment ^{108}Mo. We then found further matching γ rays with Rossendorf work [7] using the reaction ^{136}Xe $(\alpha,n)^{139}$Ba.

II. DATA ACQUISITION AND ANALYSIS

The ^{139}Ba work reported here is mainly based on thick-source ^{252}Cf measurements in Gammasphere over a month of running time in the year 2000. The source strength was 62 μ Ci of α decay on 1 August 2000. The ^{252}Cf was de-

TABLE I. Gamma transitions assigned to ^{139}Ba.

E_γ (keV)	Statistical σ (keV)	Relative intensities	Assignment
1307.877	0.017	100	$11/2^- \rightarrow 7/2^-$
520.258	0.009	61.4	$(15/2^-) \rightarrow 11/2^-$
148.443	0.005	38.6	$(17/2^-) \rightarrow (15/2^-)$
115.137	0.006	18.1	$(19/2^-) \rightarrow (17/2^-)$
996.860	0.046	7.3	
1031.049	0.021	5.9	$(21/2^-) \rightarrow (19/2^-)$
387.653	0.005	1.7	
255.710	0.021	0.8	
958.325	0.056	0.9	
768.177	0.030	2.4	$(25/2^-) \rightarrow (21/2^-)$
725.334	0.027	1.9	$(29/2^-) \rightarrow (25/2^-)$
340.378	0.024	1.1	$(31/2^-) \rightarrow (29/2^-)$
589.513	0.030	1.5	
902.564	0.034	0.9	
230.872	0.034	7.2	$13/2^+ \rightarrow 11/2^-$
289.386	0.035	0.6	$(15/2^-) \rightarrow 13/2^+$

posited on iron foil of thickness 10 mg/cm^2 with iron cover foil of 10 mg/cm^2. The experiment ran for two weeks in August and two weeks in November. The source was surrounded by a polyethylene sphere of diameter 7.72 cm that absorbed β rays and conversion electrons, as well as partially moderating and absorbing fission neutrons. The additional foil absorbers before the detectors used in most Gammasphere runs were removed so as to give good efficiency for lower-energy γ rays. For most of the run ≈ 100 detectors were operating, as compared with ≈ 70 in our 1995 run. The standard Hevimet absorbers in front of the anti-Compton bismuth germanate (BGO) detectors were in place. The efficiency for γ rays under 100 keV was much improved over 1995, due mostly to improvement in the coincidence timing in the electronics. We recorded data in standard mode with 16 k bins (0.333 keV/bin) for analog-to-digital converter γ-energy pulse heights and 1024 bins (1 nsec/bin) for TAC timing signals. The Gammasphere data acquisition system ran for us at $\approx 90\%$ of the full rate possible for the six event-formatter modules when events were restricted to three fold or higher. For completeness we took a small amount of data as singles and greater and equal to two-fold events.

For first analyses we created a ''Radware cube'' three-dimensional histogram without specifying time-to-amplitude converter timing gates. This gives us triple-coincidence events with ≈ 1 μs resolving time. We have examined various double-gated spectra with least-squares peak-fitting codes PK and FT2 of David Radford's GF3 program, which determine energy, width, and intensity along with their statistical standard deviations.

We have taken special care to do the energy calibration with peaks of previously well-determined energies in the fission spectra of our actual data set. From least-squares fitting of these chosen standard peaks, we use a linear calibration with slope of 0.333 318 keV/channel and offset of $-0.154\,88$ keV. We estimate a systematic standard deviation of about ± 0.1 keV besides the statistical standard deviation reported by the fitting codes. When determining energies of ^{139}Ba transitions, we make least-squares fitting of a given peak with as many different double-gate combinations as possible. We then make a weighted average of these independent determinations using the standard deviations from the fittings. In Table I we list these energies and their statistical standard deviations, rounded to the nearest electron volt. (In the case of the very weak transition of 289.39 keV and its standard deviation, we have presented the values given by subtraction of the stronger following cascade γ energy from the energy of the cross-over transition. The independent direct determination of energies gives 289.51 keV with statistical standard deviation of 0.14 keV—within one standard deviation of the more precise tabulated energy value from differences.) We realize that a common practice in nuclear spectroscopy literature is to give a conservative estimate of the standard deviation and round energies to 0.1 or 0.01 keV. However, this conservative practice means a loss of information, especially about energy differences among successive members of a rotational band. Such differences are usually better measured than the absolute transition energy. Thus, we do less rounding and give both statistical and systematic standard deviations to avoid loss of information. This approach has long been used by the community building level schemes from neutron capture γ rays. In this way, one can test whether cascade transitions sum to presumed cross-over transitions. Likewise the search for small irregularities in rotational band spacings needs transition energy differences, which are better known than absolute transition energies.

Before assigning transitions to a particular nucleus and determining relative intensities, we shift each of the two gates separately off-peak to a nearby valley region of the spectrum. This affords a background subtraction to take account of unwanted gating by residual Compton scattering distribution of higher-energy γ rays, not completely suppressed by the BGO Compton suppression. Our methodol-

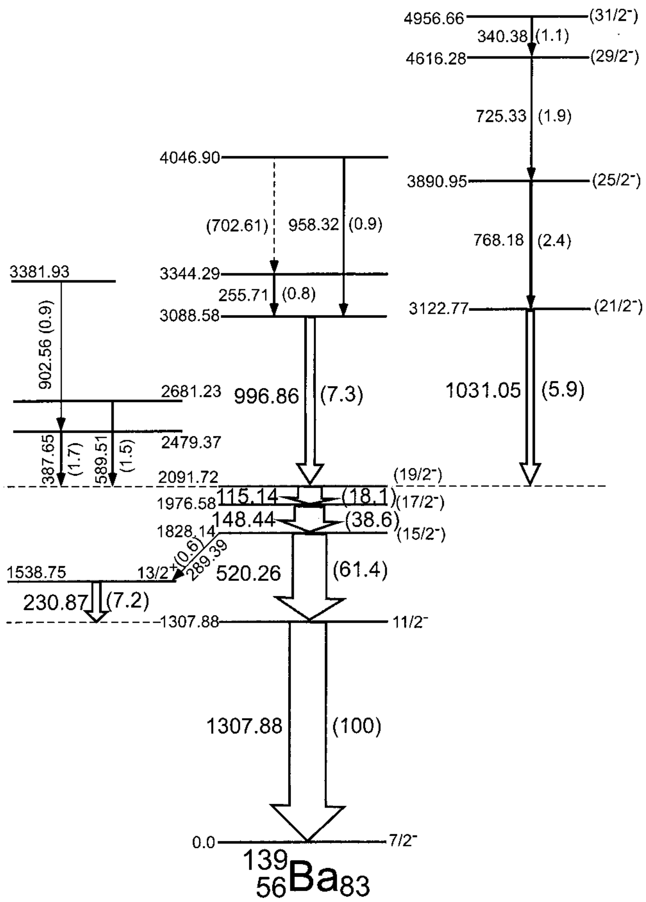

FIG. 1. New level scheme of ^{139}Ba proposed in this paper for levels populated by prompt fission of of ^{252}Cf. Note that levels below the 1308 keV $11/2^-$, seen in β decay and (α,n) studies, were not observed here.

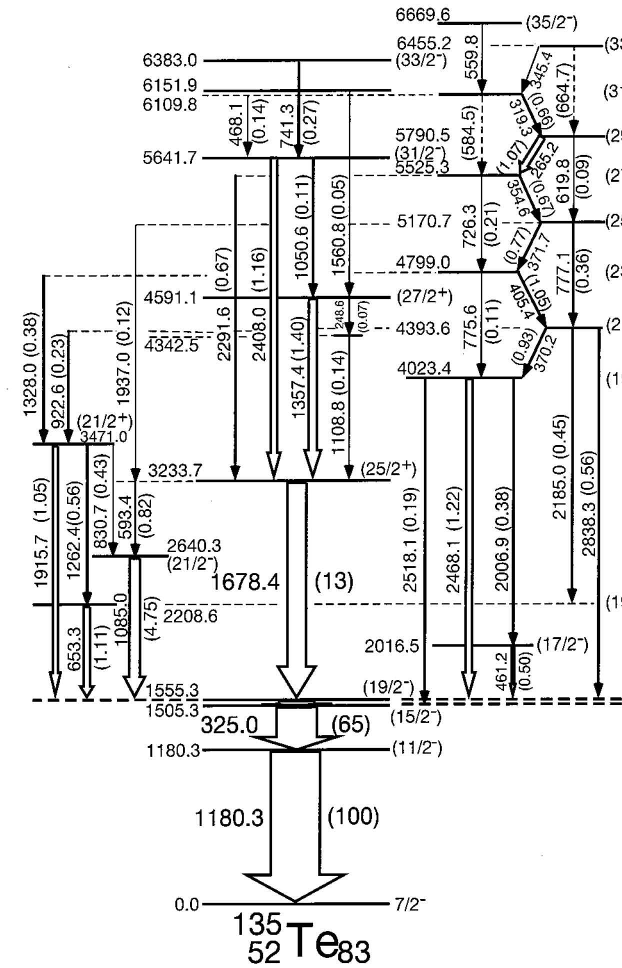

FIG. 2. Level scheme of ^{135}Te prompt fission γ population. This scheme is similar to that of Fornal *et al.* [9] except that we present relative intensities, as well as energy values to an additional significant figure. The intensities of the two lowest transitions of 325.0 and 1180.3 keV have not been corrected by a factor of $\approx$0.75. This correction is needed because the isomeric decay lifetime of the 1555.3-keV level is approximately half of the experimental coincidence resolving time.

ogy on this background correction for triple-coincidence data is discussed in detail in our recent publication [8]. Our relative intensities in Table I have been corrected for efficiency by dividing the net counts in the peak by the product of the efficiencies for the energies of the two gates and the concerned peak. We have corrected for internal conversion only on the four cascade transitions to ground from the $19/2^-$ level, since we generally are not certain of multipolarities. We assume that the 115.14 keV and 148.44 keV transitions are purely $M1$. However, for the other γ transitions here, expected to be dipole and quadrupole multipolarities, given the coincidence resolving time of ≈ 1 μs, the internal-conversion coefficient corrections should be small.

III. LEVEL SCHEME AND DISCUSSION

We concur with the Rossendorf reaction work concerning the ground cascade up to the $19/2^-$ level. We see a 289.39 keV weak branching transition not previously reported. This goes from the $15/2^-$ to the $13/2^+$ level. Figure 1 shows our proposed level scheme for ^{139}Ba. It is interesting to compare features with those in the isotone ^{135}Te. They both have 83 neutrons, one beyond the closed shell. The protons beyond $Z=50$ are expected first to fill the $g_{7/2}$ subshell. Tellurium will have a pair of protons in this subshell, and barium will have a pair of holes. A level scheme and shell-model configuration assignments for ^{135}Te have recently been published by Fornal *et al.* [9] based on Gammasphere work with spontaneous fission of ^{248}Cm. We can see the ^{135}Te quite strongly and have verified generally their level scheme. For the reader's convenience, for comparisons, and because we present for the first time relative intensities, we give in Fig. 2 our proposed level scheme for ^{135}Te. Our scheme is quite similar to that of Fornal *et al.* [9], but we have a few differences in our scheme. For the regular band built on the 4023.5-keV level (the neutron-core-excited states) we observed the 775.6 keV cross-over transition depopulating the 4799.0-keV level. The 620-keV dashed cross-over transition depopulating the 5791-keV level reported by Fornal *et al.* [9] is now confirmed and its energy is measured to be 619.8 keV. The 371.7-keV and 370.2-keV transitions were resolved with their energies and intensities determined by least-squares peak fitting for coincidence spectra with selective gating. The 1026-keV and 829-keV transitions, which depopulate the 3234- and 5171-keV levels, respectively, are not observed by us. The two 512-keV transitions, depopulating the 2017- and 6153-keV levels of the Fornal *et al.* level scheme are not reported by us because they are too close in energy to positron annihilation. We have not yet found time to employ the clever coincidence time gating they made to exploit the time delay at the 19/2- isomeric level with 0.5 μs half-life at 1555.3 keV, and the 50-keV transition is too low in energy to use as an energy gate. Thus, we cannot with confidence resolve their lower 512-keV transition nor can we distinguish between transitions populating the 1505.3-keV and 1555.3-keV isomeric level.

There is a superficial similarity of these two 83-neutron isotones, though our weakly populated barium nucleus cannot be as well investigated as its tellurium isotone. Thus, above the lowest $19/2^-$ level the barium level scheme is quite sparse. One striking difference in the main cascade down from the $19/2^-$ level is that for tellurium it is a cascade of three stretched $E2$ transitions, while in barium a $17/2^-$ level has interposed itself between the $19/2^-$ and the $15/2^-$. As Fornal *et al.* propose by comparison with the 82-neutron neighbor ^{134}Te, the cascade from the $19/2^-$ to ground may be mainly the $\pi g_{7/2}^2$ multiplet of $6\rightarrow4\rightarrow2\rightarrow0$ stretch coupled to the $f_{7/2}$ neutron. Recall that the odd-odd nuclei near double-closed-shell particle-particle or hole-hole nuclei have a multiplet splitting pattern that makes the stretched (maximum spin) and antistretched (minimum spin) multiplet members lower in energy than intermediate-spin members. For the particle-hole cases the lowest energy member is usually of spin one less than the stretched maximum. Thus, we would expect that the particle-hole coupling in ^{139}Ba would have the $17/2^-$ lying below the $19/2^-$ in the multiplet of $\pi[g_{7/2}^{-2}]_6\ \nu f_{7/2}$. The analogous $17/2^-$ state in ^{135}Te is probably the state 461 keV above the $19/2^-$.

We have looked carefully to see if ^{139}Ba has one or both of the spectacular cascading stretched $E3$ transitions of ^{135}Te that lie just above the lowest $19/2^-$. We do not see evidence of them and believe that the particle-hole coupling again has lowered states of spin one less than that of the fully stretched configuration. The interposed level effectively "short circuits" the possible analogous $E3$ transitions with lower multipolarity transitions.

The analogies between the barium and tellurium isotones again may break down above the $19/2^-$ level because the proton configuration in barium ($Z=56$) can form higher spin states at modest cost in energy by promoting proton pairs from the $g_{7/2}$ to the nearby $d_{5/2}$ subshell. That is not possible for tellurium ($Z=52$). We have also looked for but not found any band corresponding to the close-spaced band from 4.023–6.670 MeV, which Fornal *et al.* attribute to promotion of a neutron across the 82 shell from $h_{11/2}$ to the $f_{7/2}$ subshell. With the regular spacing of this band in ^{135}Te and its strong cascade transitions (presumably $M1$) and weak crossover transitions, we suggest that this band is an example of "Tilted rotation" of a weakly deformed nucleus ("shears band") of which Frauendorf [10] has written much recently. The $h_{11/2}$ neutron hole will have its angular momentum vector tilted but mainly along the long axis of the weakly deformed core, while the proton and neutron particle pairs beyond the closed shell will contribute to an angular momentum vector tilted but mainly perpendicular to the long axis. These two angular momentum vectors will have considerably different magnetic g factors, giving rise to strong $M1$ transitions.

IV. SUMMARY

Despite the low yield of ^{139}Ba in spontaneous fission of ^{252}Cf the higher statistics in Gammasphere data taken last year made possible the extension of its high-spin level scheme by 11 new transitions and 10 new levels. We present transition energies and intensities determined by least-squares analysis, along with statistical standard deviations of the energies besides an estimated ± 0.1 keV systematic standard deviation. Similarities and differences in structure with the ^{135}Te isotone are also discussed.

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[1] H.R. Bowman, S.G. Thompson, and J.O. Rasmussen, Phys. Rev. Lett. **12**, 195 (1964).
[2] J.B. Wilhelmy *et al.*, Phys. Rev. C **5**, 2041 (1972).
[3] W.R. Phillips, R.V.F. Janssens, I. Ahmad, H. Emling, R. Holzmann, T.L. Khoo, and M.W. Drigert Phys. Lett. B **212**, 402 (1988).
[4] J.H. Hamilton *et al.*, Prog. Part. Nucl. Phys. **35**, 635 (1995).
[5] S.C. Wu *et al.*, Phys. Rev. C **62**, 041601(R) (2000).
[6] R.B. Firestone and V.S. Shirley, *Table of Isotopes*, 8th ed. (Wiley, Inc., New York, 1996), and CD-ROM 1998 Update.
[7] H. Prade *et al.*, Nucl. Phys. **A472**, 381 (1987).
[8] S.C. Wu *et al.*, Nucl. Inst. Methods Phys. Res. (to be published).
[9] B. Fornal *et al.*, Phys. Rev. C **63**, 024322 (2001).
[10] S. Frauendorf, Nucl. Phys. **A677**, 115 (2000). See also Z. Phys. A **358**, 163 (1997).