Eur. Phys. J. A **15**, 175–179 (2002)
DOI 10.1140/epja/i2001-10249-1

**The European
Physical Journal A**

New insights into neutron-rich nuclei at high spin

J.H. Hamilton[1,a], A.V. Ramayya[1], J.K. Hwang[1], X.Y. Luo[1], J.O. Rasmussen[3], E.F. Jones[1,4], X.Q. Zhang[1], S.J. Zhu[1,2,5], P.M. Gore[1], T.N. Ginter[3], I.Y. Lee[3], R.V.F. Janssens[6], I. Ahmed[6], J.D. Cole[1,7], W. Greiner[8], G. Ter-Akopian[2,9], and Yu. Oganessian[9]

[1] Physics Department, Vanderbilt University, Nashville, TN 37235, USA
[2] Joint Institute for Heavy Ion Research, Oak Ridge, TN 37835, USA
[3] Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[4] Universidade de Coimbra, Coimbra, Portugal
[5] Physics Department, Tsinghua University, Beijing, PRC
[6] Argonne National Laboratory, Argonne, IL 60439, USA
[7] Idaho National Environmental and Engineering Laboratory, Idaho Falls, ID 83415, USA
[8] Institute of Theoretical Physics, Goethe University, Frankfurt am Main, Germany
[9] Flerov Laboratory for Nuclear Reactions, JINR, Dubna, Russia

Received: 21 March 2002 /

Abstract. With new high statistic data, new isotopes and new high-spin structures are observed in neutron-rich nuclei populated in the spontaneous fission of ^{252}Cf. The ^{135}Te levels are extended, and many new levels in ^{139,141}Ba observed. The coexistence of collective and single particle-hole states is found in ^{135}Te. The $N = 83$ ^{135}Te and ^{139}Ba show marked differences associated with differences in their particle and hole states. New levels in ^{141}Ba complete evidence for two opposite-parity doublets characteristic of stable octupole deformation. In ^{114,116}Pd a second backbend is observed for the first time in this mass region and the backbend in ^{118}Pd occurs earlier than in $^{112\text{-}116}$Pd because of a reduction in pairing. Gamma-type vibrational bands are seen up to 13^+ to 15^+ in ^{104,106}Mo, $^{108\text{-}112}$Ru, and $^{112\text{-}116}$Pd. Their behavior reflects prolate to triaxial shapes in these nuclei. The levels of ^{162,164}Gd are observed for the first time. As N increases toward mid-shell at 104, the moments of inertia in $N = 100$ ^{164}Gd show an unexpected decrease compared to $N = 98$ ^{162}Gd. The levels in ^{162,164}Gd form remarkable shifted identical bands with nuclei separated by 2n, 2p, α, and 2α.

PACS. 25.85.Ca Spontaneous fission – 27.60.+j $90 \leq A \leq 149$ – 27.60.+q $150 \leq A \leq 189$ – 21.60.-n Nuclear-structure models and methods

1 Introduction

The extensive new information on the structures of neutron-rich nuclei populated in spontaneous fission from small detector arrays and the first studies with Gammasphere and Eurogam were reviewed in 1995 [1]. In the next five years additional significant insights have been found, for example [2]. In 2000 we carried out γ-γ-γ coincidence studies in the spontaneous fission of ^{252}Cf with 103 detection in Gammasphere and acquired over 10 times the number of events in our three-week run of 1995. These data opened up the opportunity to study nuclei populated to higher-spin states in known bands and new side bands and to assign γ-rays to previously unidentified nuclei. In this paper we present a few selected examples of the new physics to come from such higher statistical data.

2 High-spin levels in N = 8 ^{135}Te and ^{139}Ba

The high-spin levels in ^{135}Te have recently been independently extended, fig. 1 [3,4]. These data provide new tests of particle-hole structures around double magic ^{132}Sn as described in [3]. The band starting at 4023.3 keV has been extended to include three additional crossover transitions [4]. Note that in our scheme we have given relative intensities and, by using very precisely known transition energies in a variety of fission fragments, obtained relative energies with an accuracy of less than 0.1 keV from uncompressed spectra. That band is a good candidate for a tilted rotor band [5]. Near the lower end of the band, the neutron total angular momentum can couple at near right angles to the proton angular momentum vector. Such bands are characterized by strong $M1$ cascade transitions with weak crossovers as seen in this band. We would expect on geometrical grounds that fission fragments would prefer

---

[a] e-mail: `j.h.hamilton@vanderbilt.edu`

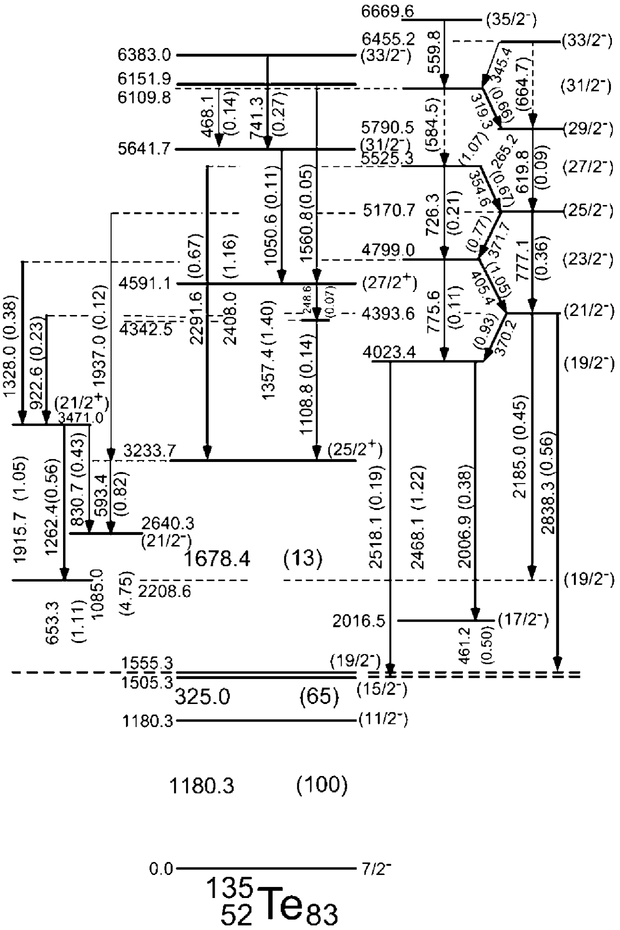

Fig. 1. Level scheme of ^{135}Te.

populating some kind of prolate bands as intermediates on the path to spherical ground states. This high-energy band in ^{135}Te is very regular. Fornal *et al.* [3] assigned it as the promotion of an $h_{ll/2}$ neutron across the 82 shell gap to pair up with the $f_{7/2}$ neutron. For a prolate deformed potential, the two protons would be in the 1/2[431] orbital and the neutrons would have a pair in the 1/2[541] and a hole in the 11/2[505]. This is the first proposal for a tilted rotor band in neutron-rich nuclei and for prolate-spherical shape coexistence in nuclei around double magic ^{132}Sn.

The levels in $N = 83$ ^{139}Ba from our new Gammasphere data are shown in fig. 2 [4]. The first two levels are from ^{139}Cs β-decay and the next three from ^{136}Xe(α, xn) work [6]. The next 10 levels are from our work. The levels in ^{139}Ba look very much like those of ^{135}Te (fig. 1). One striking difference in the cascade from the 19/2$^-$ level is that for Te it is a cascade of three stretched $E2$ transitions, while in Ba a 17/2$^-$ level occurs between the 19/2$^-$ and the 15/2$^-$. As Fornal *et al.* [3] propose by comparison with the 82-neutron neighbor ^{134}Te, the cascade from 19/2$^-$ to the ground may be mainly the $\pi(g_{7/2})^2$ multiplet of 6 → 4 → 2 → 0 stretch-coupled to the $f_{7/2}$ neutron. Recall that in odd-odd nuclei near double-closed shells, particle-particle or hole-hole nuclei have a multiplet splitting pattern that makes the stretched (maximum spin) and anti-stretched (minimum spin) multiplet mem-

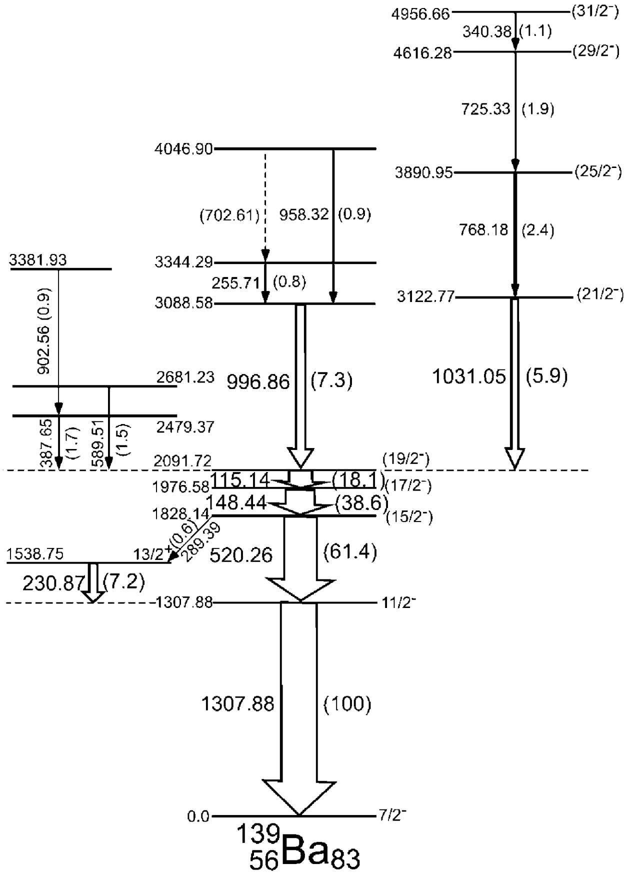

Fig. 2. Level scheme of ^{139}Ba.

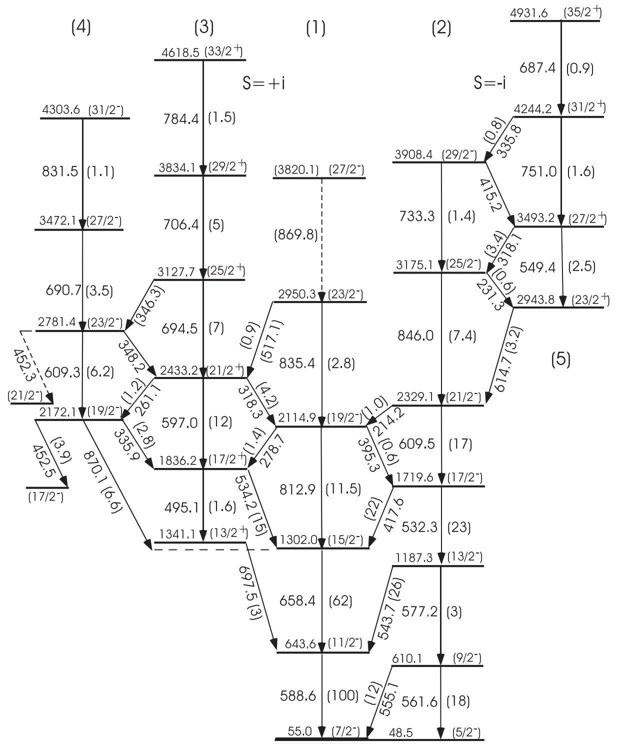

Fig. 3. Level scheme of ^{141}Ba.

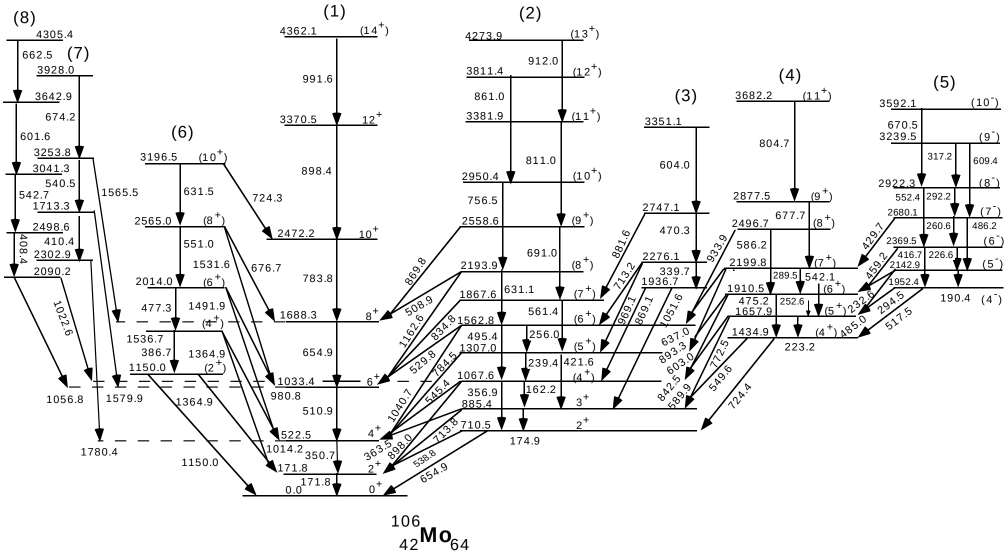

Fig. 4. Level scheme of ^{106}Mo.

Table 1. Gamma-band energy differences.

	^{104}Mo	^{106}Mo	^{108}Ru	^{110}Ru	^{112}Ru	^{112}Pd	^{114}Pd	^{116}Pd	^{118}Pd
2-3	216	175	267	247	224	359	317	329	370
3-4	186	182	208	224	233	266	309	307	417
4-5	260	239	312	291	255	397	310	345	441
5-6	249	256	268	309	234	243	353	382	
6-7	312	305	370	337	270	480	306	392	
7-8	290	326	288	376	423	209	365	347	
8-9	356	365	422	380	272	393	251	417	
9-10	323	391		456	499		432	304	
10-11	391	432		394	258		166	246	
11-12	357	429			580		583		
12-13	410	463			226		119		
13-14					669				
14-15					186				

bers 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, the particle-hole coupling in ^{139}Ba can have the 17/2$^-$ lying below the 19/2$^-$ in the multiplet of $\pi(g_{7/2})_6^{-2}\nu f_{7/2}$. The analogous 17/2$^-$ state in ^{135}Te is probably the state 462 keV above the 19/2$^-$. The 996.9 and a 1031 keV transitions can be the strong $E3$ transitions with similar energies seen in ^{135}Te. The analogies between the Ba and Te isotopes again may break down above the 19/2$^-$ level because the proton configuration in Ba ($Z = 56$) can form higher-spin states at modest cost in energy by promoting proton pairs from $g_{7/2}$ to the nearby $d_{5/2}$ subshell. That is not possible for Te ($Z = 52$).

3 Octupole collectivity in ^{141}Ba

Our new level scheme for $N = 85$ ^{141}Ba is shown in fig. 3 [4]. We observed five bands, and suggested their spins and parities. The two positive-parity bands extend to the highest excitation energies and spins among all the $N = 85$ isotones. Bands 2-3 are extended from our earlier work [7], and their parity assignments were inverted. Bands 1 and 2 may be predominantly based on the neutron $(f_{7/2})^3$ and $(f_{7/2})^2h_{9/2}$ configurations. In analogy with the higher-Z $N = 85$ isotones, it seems logical to assign band 3 as the odd $f_{7/2}$ neutron stretch-coupled to an octupole phonon. Band 4, likewise, fits the isotone systematics of the odd $f_{7/2}$ neutron stretch-coupled to two octupole phonons. Band 5 may result from the coupling of an octupole phonon to band 2. The structure of ^{141}Ba appears to be intermediate between the spherical-shell-model–type observed in ^{139}Ba and the stable pear shapes found in the heavier Ba isotopes.

4 Gamma vibrational bands to high spin in ^{104,106}Mo, $^{108\text{-}112}$Ru, and $^{112\text{-}118}$Pd

With our new much higher statistical data, we have extended the gamma vibrational bands from 3 to 10 higher-spin states in ^{104,106}Mo, $^{108\text{-}112}$Ru and $^{112\text{-}118}$Pd [8,9] (see fig. 4 and table 1). The level energy differences are compared in table 1. The γ-bands in both ^{104,106}Mo are remarkably regular in energy spacings up to 13^+ to support their axial symmetric interpretation. Bands beginning at 1583.4 and 1434.9 keV in ^{104,106}Mo are proposed as two gamma phonon bands [10]. We extended these bands to 8^+ to 11^+. The transition energies are strinkingly close in every case for the same spin (11^+–9^+, 9^+–7^+, etc.) transitions in the one- and two-phonon bands (see fig. 4). In ^{108}Ru, the odd-spin members are pushed up somewhat compared to the even-spin members while the band energies smoothly increase until 11^+ in ^{110}Ru. In ^{112}Ru, there is marked staggering with the even-spin members pushed up nearer the odd-spin members, the reverse of ^{108}Ru. In ^{112}Pd, there is again marked staggering with the odd-spin member nearer the even-spin member as in ^{108}Ru, while ^{114}Pd has reverse staggering with the even-spin states pushed up. In ^{116}Pd, the spacings are regular in general up to 9^+ with some staggering above that. These data provide new insights into the continued rotational behavior of these nuclei to high spin and open up new tests of collective models.

5 Backbending in ^{112,114,116,118}Pd

The low-lying levels to 6^+ in ^{118}Pd were recently identified in beta-decay [11]. With this piece of information, we have identified higher-spin states in ^{118}Pd [12]. The new feature is that the ground band in ^{118}Pd backbends earlier than those in ^{112,114,116}Pd (fig. 5). This earlier backbend can be reproduced by a $\nu h_{11/2}$ band crossing with about 40% reduction in the neutron pairing gap to 0.9 MeV from 1.39 and 1.27 MeV in ^{112,114}Pd. Thus, $^{112\text{-}118}$Pd exhibit prolate shapes. These band crossings explain the higher frequencies of the band crossings in the $h_{11/2}$ odd neutron bands in ^{113,115,117}Ru [13] (fig. 5) as a blocking effect of the odd $h_{11/2}$ particle. Second backbendings are seen in ^{114,116}Pd, the first such examples in neutron-rich nuclei. Note the second backbend frequency 0.42 MeV is the same as that seen in ^{107,109,111}Pd. This second backbend is likely the crossing of a $\pi g_{9/2}$ pair.

6 Identification of levels in ^{162,164}Gd and unexpected reduction in $J_1 J_2$

We reported at the last ENAM conference the identification of levels in ^{162}Gd. With our new data we confirmed and extended ^{162}Gd to higher spin and identified levels in ^{164}Gd at 73.7, 242.5, 503.9, 852.7, 1284.6, 1794.6 and 2376.9 keV (2^+–14^+). We extended to higher spins the levels in ^{84,86}Se and identified transitions in ^{88}Se.

Generally, deformation is expected to have a maximum around mid-shell which in rare-earth nuclei is $N = 104$. Indeed this is the case for Er, Yb and Hf nuclei where the lowest-energy 2^+ state is at $N = 104$. Surprisingly, for $N = 100$ ^{164}Gd, the 2^+ energy and the transitions from every other excited state in ^{164}Gd are larger than they are in $N = 98$ ^{162}Gd. The same effect is seen between $N = 98$ ^{164}Dy and $N = 100$ ^{166}Dy. So the J_1 and J_2 moments of inertia of the $N = 100$ nuclei fall between those for $N = 96$ and $N = 98$. The J_1 and J_2 values for $N = 100$ Gd, Dy increase more slowly to cross those for $N = 96$ and fall below them at about 12. Thus the $N = 100$ nuclei are stiffer, more resistant to stretching. In addition, the new levels in ^{164}Gd provide a number of new examples of shifted identical bands, bands where $J_1(1 \pm \kappa)_a = J_{1b}$ with constant κ for every spin state from 2^+ to 8^+ up to 14^+ for neighboring nuclei separated by 2n, 2p, 4n, α and 2α.

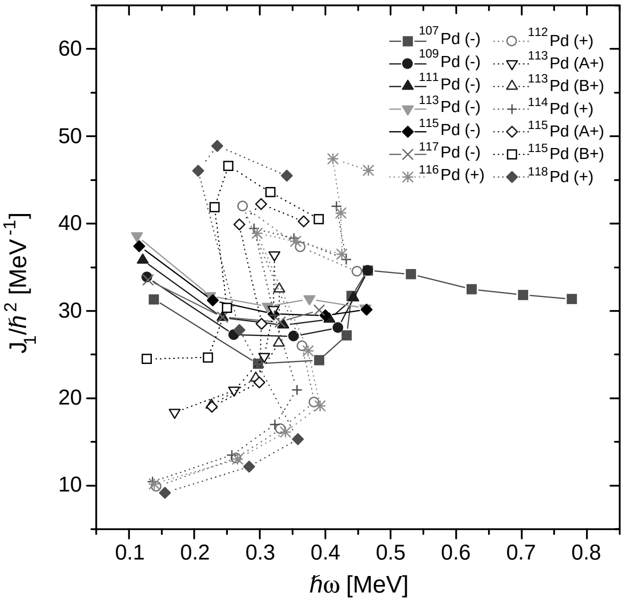

Fig. 5. Backbends in e-e and e-o Pd nuclei.

The work at Vanderbilt University, Lawrence Berkeley, Lawrence Livermore and Argonne National Laboratories is supported by the U.S. Department of Energy under Grant DE-FGO5-88ER40407 and Contract W-7405-ENG48, DE-ACO3-76SFOOO98, and W-31-109-ENG-38, respectively. The Joint Institute for Heavy Ion Research is supported by University of Tennessee, Vanderbilt University and U.S. DOE. J.H.H. thanks the Alexander von Humboldt Foundation for their support of the Vanderbilt-Frankfurt collaboration.

References

1. J.H. Hamilton *et al.*, Prog. Part. Nucl. Phys. **35**, 635 (1995).
2. J. Hamilton *et al.* (Editors), *Fission and Neutron Rich Nuclei* (World Scientific, 2000).
3. B. Fornal *et al.*, Phys. Rev. C **63**, 024322-1 (2001).
4. Y.X. Luo *et al.*, Phys. Rev. C **64**, 054306 (2001); **66**, 014305 (2002).
5. S. Franendorf, Nucl. Phys. A **677**, 115 (2000).
6. H. Prade *et al.*, Nucl. Phys. A **472**, 381 (1987).
7. S.J. Zhu *et al.*, J. Phys. G **23**, L77 (1997).
8. Li-Ming *et al.*, Chin. Phys. Lett. **18**, 24 (2001).

9. The Vanderbilt Collaboration, in preparation.
10. A. Guessous *et al.*, Phys. Rev. Lett. **75**, 2280 (1995); Phys. Rev. C **53**, 1191 (1996).
11. J. Äystö *et al.*, in ref. [2], p. 297.
12. X.Q. Zhang *et al.*, Phys. Rev. C **63**, 027302-1 (2001).
13. X.Q. Zhang *et al.*, Phys. Rev. C **61**, 014305 (2000).