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Identification of a pairing isomeric band in ^{152}Sm

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A coexisting band structure is identified in ^{152}Sm through γ-ray coincidence spectroscopy following β decay of ^{152m,g}Eu and following multi-step Coulomb excitation. This structure is interpreted as a pairing isomer analogous to a similar band identified in ^{154}Gd, based upon relative $B(E2)$ values for transitions out of the band and two-neutron transfer reaction population of the 0^+ and 2^+ band members. Systematics for odd-A isotopes near $N = 90$ suggest that there should be a low-lying pairing isomer in ^{156}Dy, and similar structures at higher energy in ^{150}Nd and ^{158}Er.

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In the collective model for deformed nuclei [1], it is expected that excited rotational bands have the same deformation as the ground state. Indeed, observed low-lying bands typically have moments of inertia which vary by less than 10% [1]. Through detailed γ-ray coincidence spectroscopy following β decay of ^{152m,g}Eu and multiple-step Coulomb excitation, we have identified four states in ^{152}Sm which form an excited rotational band in ^{152}Sm with a moment of inertia that is ∼60% smaller than that of the ground-state band (based upon energy differences between states within each band and assuming a rigid rotor model).

The band J^π (E_x keV) 0^+ (1083), 2^+ (1293), 4^+ (1613), and (6^+) (2004), (cf. Fig. 1) is built upon the enigmatic 0^+_3 state in ^{152}Sm. The 0^+_3 state at 1083 keV, which is populated very strongly in a two-neutron transfer reaction [2], is anomalous among even-even nuclei where $L = 0$ transitions usually only significantly populate the ground state [3]. More intriguing is that the 0^+ (1083) state is populated with 68% of the ground-state population strength in the ^{150}Sm$(t,p)^{152}$Sm reaction but is populated with less than 1% strength in the ^{154}Sm$(p,t)^{152}$Sm reaction [4]. This dramatic "asymmetry" in (t,p) and (p,t) population, illustrated in Fig. 2, is further indication that the band has a character distinct from that of the ground-state band, and provides key evidence of its nature.

A similar excited band structure, with highly enhanced (t,p) population [6] (cf. Fig. 2), greatly reduced (p,t) population [7], and smaller deformation than the ground state, was recently discovered in the $N = 90$ isotone, ^{154}Gd [8]. This structure was explained [8] as a pairing isomer [9], i.e., an isolated structure with a smaller pairing gap than that of the ground state. A pairing isomer is characterized by large two-neutron transfer cross section and a very large asymmetry in (t,p) and (p,t) reaction

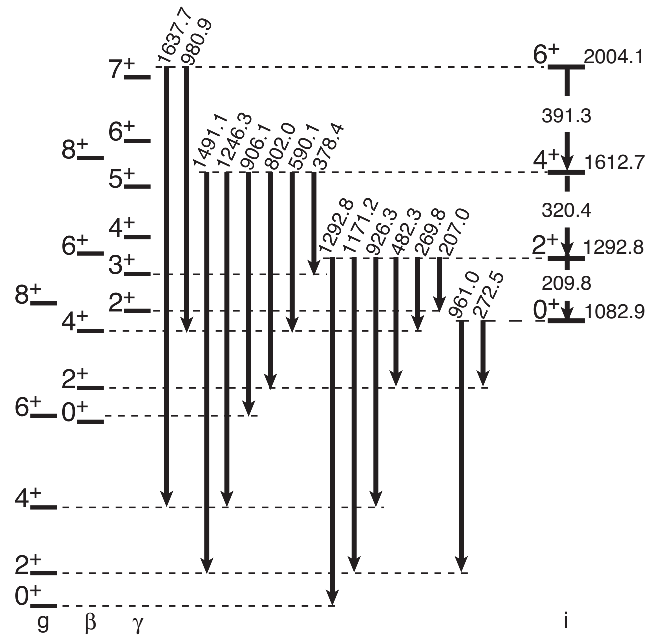

FIG. 1: Levels and transitions (in keV) associated with the pairing isomeric structure in ^{152}Sm determined through γ-ray coincidence spectroscopy. The 0^+_i (1083) and 2^+_γ (1086) levels have been displaced for clarity. The 2004.1 keV level is newly established by this study. The 1612.7 keV level previously had an ambiguous J^π and no band assignment.

population strength [9]. The possibility of such a structure built upon the $\frac{11}{2}^-$ [505] Nilsson orbital was implied by Peterson and Garrett [10] because of its reduced off-diagonal pairing matrix elements with nearby orbitals, and was suggested to act more like a hole state in the deformed rare earth region, even when the $\frac{11}{2}^-$ [505] orbital is nearly filled. Transfer of two particles into the steeply upsloping $\frac{11}{2}^-$ [505] orbital would result in a less-

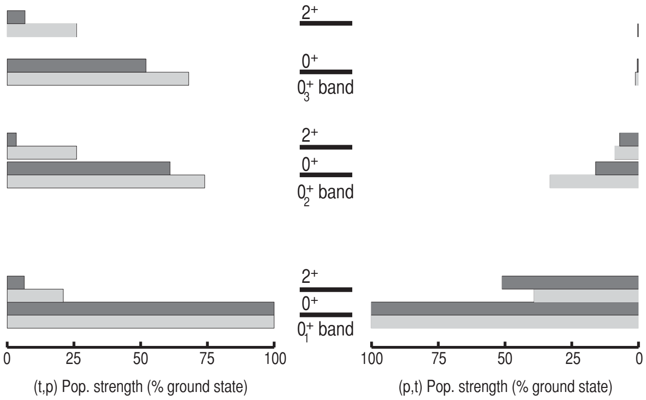

FIG. 2: A comparison of two-neutron transfer reaction strength to states in ^{152}Sm (light bands) and ^{154}Gd (dark bands). Data are from [4–7].

deformed structure in an even-even nucleus (where the occupancy of the orbital, $V^2 > 0.5$).

The 0^+ (1182), 2^+ (1418), and 4^+ (1701) band members found in ^{154}Gd [8] constitute a close analog of the 0^+ (1083), 2^+ (1293), and 4^+ (1613) levels in ^{152}Sm observed in the β decay and Coulomb excitation studies detailed here.

The decay experiments, ^{152m,g}Eu $\rightarrow$ ^{152}Sm, were conducted at Lawrence Berkeley National Laboratory using the 8π spectrometer [11], an array of 20 Compton-suppressed Ge detectors. Europium sources of $\sim$50 μCi were produced by the ^{151}Eu(n,γ) reaction in the Oregon State University reactor. Sources were mounted in the center of the detector array (22.0 cm source-to-detector distance), and scaled-down γ-ray singles and $\gamma-\gamma$ coincidence events were recorded concurrently. Data obtained for the decay of ^{152g}Eu (13 yr, $J^\pi = 3^-$) in a 334-hour measurement contained 2×10^9 singles and 6×10^8 $\gamma-\gamma$ coincidence events. The ^{152m}Eu (9 hr, $J^\pi = 0^-$) decay data contained 2×10^8 singles and 2×10^7 $\gamma-\gamma$ coincidence events after 85 hours of counting. The ^{152g}Eu source contained 0.8% ^{154}Eu, and the ^{152m}Eu sources contained 1.4% ^{152g}Eu and 0.01% ^{154}Eu, determined as decay rates in this study.

Multiple-step Coulomb excitation of ^{152}Sm was performed at the Lawrence Berkeley National Laboratory's 88-Inch Cyclotron. A 400 μg/cm^2, 99.86% enriched ^{208}Pb target was used to populate excited states in ^{152}Sm through inverse Coulomb excitation of a 3 particle-nA beam of ^{152}Sm at a "safe" energy of 652 MeV. Signals from two ions in the CHICO [12] charged-particle detector array in coincidence with at least one "clean" γ ray signal in the Gammasphere [13] array of (104) Compton-suppressed Ge detectors triggered an event. The 1° angular resolution of the CHICO array provided kinematic characterization of scattered ions and recoiling target nuclei so that Doppler corrections could be applied to the detected γ rays emitted from the Coulomb-excited beam nuclei. Approximately 7×10^8 single-γ-ray events, 8×10^7 two-fold $(\gamma-\gamma)$, and 1×10^7 $(\gamma-\gamma-\gamma)$ coincidence events were recorded in 62 hours of running time.

Turning to a discussion of the band and its elucidation, the 0^+ (1083) and 2^+ (1293) levels were first associated with each other due to their very strong population in the ^{150}Sm$(t,p)^{152}$Sm reaction [2] (cf. Fig. 2). Observation of the 1293 $\rightarrow$ 1083 intraband 210 keV γ ray in the decay of ^{152m,g}Pm with an absolute quadrupole transition $B(E2; 1293 \rightarrow 1083) = 184(100)$ W.u. has suggested that the 1083 and 1293 keV states are part of a collective band [14]. In coincidence spectroscopy following the decay of ^{152g}Eu, we confirm the placement of the 210 keV (1293 $\rightarrow$ 1083) transition, and observe additional γ-ray transitions from the 1293 keV level to 0^+, 1^-, 2^+, 3^-, and 4^+ states which establish a definite $J^\pi = 2^+$ for this level.

The level at 1613 keV is newly assigned as the 4^+ member of the band [15] built on the 0^+ level at 1083 keV. Previously, only two γ-ray transitions were assigned to de-excite the 1613 state in the adopted gammas for this level [15]: the 906 ($1613 \rightarrow 6_g^+ 707$) and 572 ($1613 \rightarrow 3_1^- 1041$). Coincidence gates from the decay of ^{152g}Eu, shown in Fig. 3, reveal the presence of new transitions at 590 ($1613 \rightarrow 4_\beta^+ 1023$) and 320 ($1613 \rightarrow 2_i^+ 1293$) keV. The 320 keV transition is observed for the first time in ^{152}Sm and is the primary indication that the 1613 keV state is associated with the 1293 keV state. Other new transitions de-exciting the 1613 keV level are established by coincidence gating as feeding the 122 (2_g^+), 367 (4_g^+), 811 (2_β^+), 1221 (5_1^-, see Fig. 4), and 1234 (3_γ^+) levels, from the decay of ^{152g}Eu. The decays from the 1613 keV level to 2^+, 3^+, 3^-, 4^+, 5^-, and 6^+ states establish a definite $J^\pi = 4^+$ for this state.

Figure 4 shows triple γ-ray coincidences for transitions out of the 4^+ level at 1613 keV obeserved in the Coulomb excitation study. The resulting spectra reveal the 391 keV transition from the (6^+) 2004.1 keV level. (The presence of a 7^- level at 2003.6 keV [15] prevents definite assignment of γ-ray transitions to positive-parity levels of spin > 5 due to lack of energy resolution.) We assign the 2004 level as the 6^+ member of the pairing isomeric band built on the 0_3^+ (1083) state. No other candidates for higher-spin members of the band have been identified in either the β decay or Coulomb excitation studies.

The coincidence spectroscopy for transitions out of the 1083, 1293, 1613, and 2004 keV levels and the relative $B(E2)$ values for the observed γ rays, presented in Table I, strongly support interpreting these states as a band built upon the 0_3^+ (1083) state. In Table I, transitions out of each level are listed in decreasing order of relative $B(E2)$ values in ^{152}Sm, where negligible $M1$ admixtures are assumed in calculating the relative $B(E2)$ values. The strongest collective transitions are observed to be the in-band 210 (1293 $\rightarrow$ 1083), 320 (1613 $\rightarrow$ 1293),

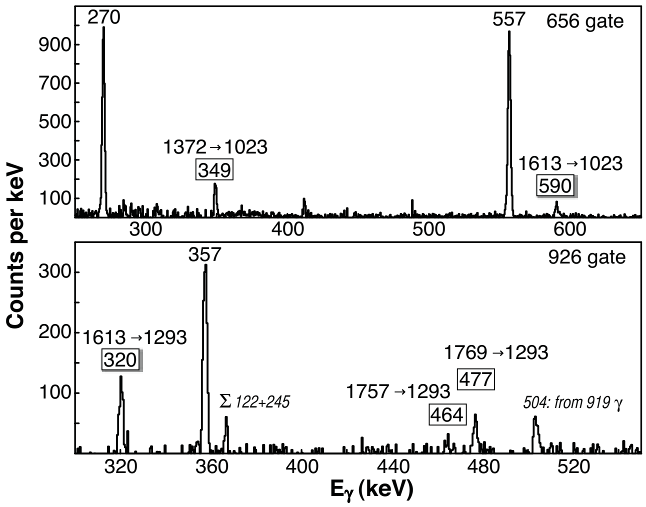

FIG. 3: The 656 (1023 → 367; $4^+_\beta \to 4^+_g$) and 926 (1293 → 367; $2^+_i \to 2^+_g$) keV γ-ray coincidence gates for the ^{152g}Eu → ^{152}Sm decay show several new transitions (in boxes). Two of the new γ rays feeding the 2^+_i and 4^+_β states, at 320 and 590 keV, respectively, are from the 4^+ band member at 1613 keV. Other new γ rays are from established [15] levels. The 270, 357 and 557 keV transitions have established assignments [15] from previous work.

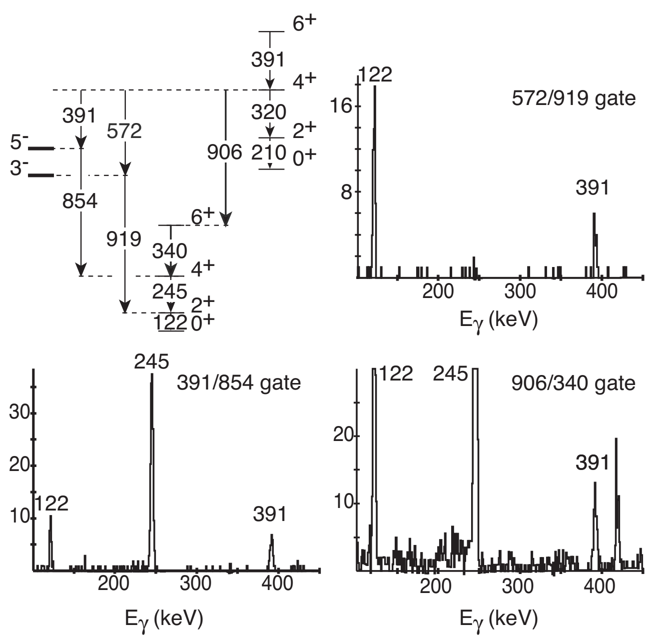

FIG. 4: Triple γ-ray coincidence gates for the multi-step Coulex experiment locate the (6^+) state of the band.

and 391 keV (2004 → 1613) transitions. Relative $B(E2)$ values for the analog transitions in ^{154}Gd are presented for comparison with the ^{152}Sm values in Table I.

In addition to the comparable deformation, $\Delta E(0^+ \leftrightarrow 2^+) = 210$ keV in ^{152}Sm and 237 keV in ^{154}Gd, and two-neutron transfer reaction data (Fig. 2), the very similar

TABLE I: Relative $B(E2)$ values for transitions out of states in the pairing isomer band in ^{152}Sm compared with relative $B(E2)$ values for analog transitions in ^{154}Gd. Data for ^{154}Gd are extracted from [16]. Relative $B(E2)$ values assume negligible $M1$ admixtures for all transitions.

I	F	^{152}Sm	^{154}Gd
0^+_i	2^+_β	100	100
	2^+_g	4	2
2^+_i	0^+_i	100	100
	4^+_β	30	26
	3^+_γ	-	36
	2^+_γ	10	4
	2^+_β	7	16
	4^+_g	2	2
	0^+_β	-	0.4
	0^+_g	0.2	0.1
	2^+_g	0.1	0.1
4^+_i	2^+_i	100	100
	3^+_γ	8	1
	4^+_β	3	9
	6^+_g	3	1
	2^+_β	0.2	0.2
	4^+_g	0.03	0.2
	2^+_g	0.01	0.01
	2^+_γ	-	0.1
6^+_i	4^+_i	100	-
	4^+_g	0.2	-
	4^+_β	0.02	-

patterns of relative $B(E2)$ values presented in Table I indicate that the 0^+_3 bands in ^{152}Sm and ^{154}Gd have the same structure. While the $B(E2)$ values reflect some differences in the lower-lying states of each nucleus, basic trends emerge in Table I. These trends may be useful in recognizing analogous bands in nearby nuclei where the transfer reaction data is unclear (as may be the case in ^{150}Nd, see below) or not available.

As a result of the proximity of the $\frac{11}{2}^-$ [505] Nilsson orbital to the Fermi surface [10], the pairing isomeric band should not be confined to just ^{154}Gd and ^{152}Sm, but should be a feature in other nearby rare-earth nuclei. Band-head systematics for $\frac{11}{2}^-$ [505] in odd-neutron nuclei are shown in Fig. 5. While caution is needed in using Fig. 5 to estimate excitation energies of unobserved pairing isomers because, e.g., the energies plotted in Fig. 5 will contain effects of pairing correlation blocking,the systematic trend in the odd-A isotopes suggests that there should be a low-lying pairing isomer in ^{156}Dy, probably at a slightly higher excitation than observed in ^{154}Gd and ^{152}Sm. Figure 5 also indicates that such bands should appear at slightly higher energy (than in ^{152}Sm and ^{154}Gd) in ^{150}Nd and ^{158}Er.

Figure 5 suggests an explanation for why the pairing isomer was not observed in a study of the ^{148}Nd$(t,p)^{150}$Nd reaction [17, 18]. The trend in Fig. 5 indicates the 0_3^+ state in ^{150}Nd should be slightly higher in energy than the 0_3^+ (1083) state in ^{152}Sm, assuming blocking effects are comparable in these nuclei. The population of the 0_3^+ states in ^{152}Sm and ^{154}Gd through the (t,p) reaction (cf. Fig. 2) implies that the analog state in ^{150}Nd should have been very strongly populated. However, a large peak from ^{18}O covers the region ∼900 - 1300 keV in the proton spectrum [18], obscuring where a peak corresponding to the 0_3^+ state in ^{150}Nd is expected.

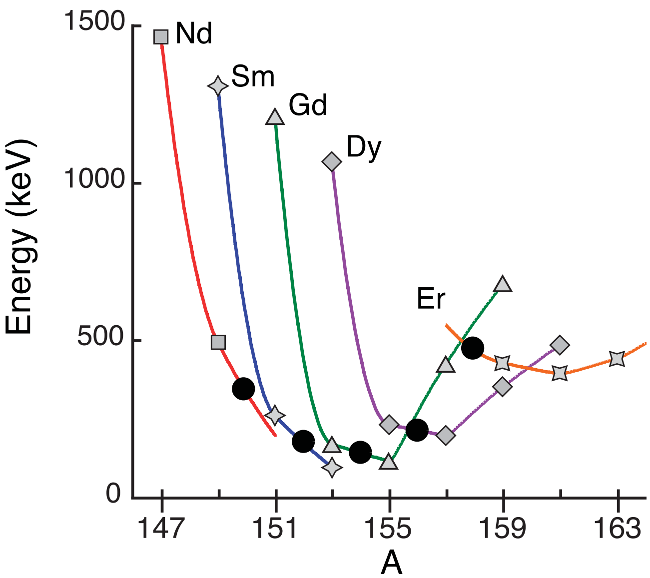

FIG. 5: The $\frac{11}{2}^-$ [505] band-head energies in the odd-mass $87 \le N \le 97$ isotones extracted from the ENSDF database [19] exhibit a systematic trend. Relative values interpolated at $N = 90$ (circles) show that the [505] pairing isomer approaches a minimum excitation energy near ^{152}Sm and ^{154}Gd, where bands are identified at 1083 and 1182 keV, respectively.

In summary, using γ-ray coincidence spectroscopy following the β decay of ^{152m,g}Sm and multiple-step Coulomb excitation, we have identified four states which consititute an excited rotational band which is less deformed than the ground state in the nucleus ^{152}Sm. The structure in ^{152}Sm is interpreted as a pairing isomeric band analogous to a recently discovered band in ^{154}Gd [8]. This result suggests a systematic behavior of the underlying $\frac{11}{2}^-$ [505] Nilsson configuration which gives rise to the pairing isomerism [10], and implies similar bands should be present in neighboring rare earth nuclei.

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[1] A. Bohr and B. R. Mottelson, *Nuclear Structure*, vol. 2: Nuclear Deformations (World Scientific, Singapore, 1998), 2nd ed.
[2] S. Hinds, J. H. Bjerregaard, O. Hansen, and O. Nathan, Phys. Letters **14**, 48 (1965).
[3] R. A. Broglia, O. Hansen, and C. Riedel, in *Adv. in nuclear physics*, edited by M. Baranger and E. Vogt (Plenum Press, New York, 1973), vol. 6, p. 287.
[4] P. Debenham and N. M. Hintz, Nucl. Phys. A **195**, 385 (1972).
[5] J. H. Bjerregaard, O. Hansen, O. Nathan, and S. Hinds, Nuclear Phys. **86**, 145 (1966).
[6] M. A. M. Shahabuddin, D. G. Burke, I. Nowikow, and J. C. Waddington, Nucl. Phys. A **340**, 109 (1980).
[7] D. G. Fleming, C. Gunther, G. Hagemann, B. Herskind, and P. O. Tjom, Phys. Rev. C **8**, 806 (1973).
[8] W. D. Kulp, J. L. Wood, K. S. Krane, J. Loats, P. Schmelzenbach, C. J. Stapels, R. M. Larimer, and E. B. Norman, Phys. Rev. Lett. **91**, 102501 (2003).
[9] I. Ragnarsson and R. A. Broglia, Nuclear Phys. **A263**, 315 (1976).
[10] R. J. Peterson and J. D. Garrett, Nuclear Phys. **A414**, 59 (1984).
[11] J. P. Martin, D. C. Radford, M. Beaulieu, P. Taras, D. Ward, H. R. Andrews, G. Ayotte, F. J. Sharp, J. C. Waddington, O. Hausser, et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **257**, 301 (1987).
[12] M. W. Simon, D. Cline, C. Y. Wu, R. W. Gray, R. Teng, and C. Long, Nucl. Instrum. Methods Phys. Res. A **452**, 205 (2000).
[13] I. Y. Lee, in *Proceedings of the Workshop on Gammasphere Physics*, edited by M. A. Deleplanque, I. Y. Lee, and A. O. Machiavelli (World Scientific, Singapore, Berkeley, CA, 1996), p. 50.
[14] H. Mach, M. Hellstrom, B. Fogelberg, D. Jerrestam, and L. Spanier, Phys. Rev. C **46**, 1849 (1992).
[15] A. Artna-Cohen, Nucl. Data Sheets **79**, 1 (1996).
[16] W. D. Kulp, J. L. Wood, K. S. Krane, J. Loats, P. Schmelzenbach, C. J. Stapels, R. M. Larimer, and E. B. Norman, Phys. Rev. C **69**, 064309 (2004).
[17] R. Chapman, W. McLatchie, and J. E. Kitching, Phys. Letters **31B**, 292 (1970).
[18] R. Chapman, W. McLatchie, and J. E. Kitching, Nucl. Phys. A **186**, 603 (1972).
[19] M. R. Bhat, in *Nuclear Data for Science and Technology*, edited by S. M. Qaim (Springer-Verlag, Berlin, Germany, 1992), p. 817, data extracted from the ENSDF database, file revised as of October, 2004.

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