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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 multistep Coulomb excitation. This structure is interpreted as a pairing isomer analogous to a similar band identified in ^{154}Gd, based on 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 that vary by less than 10% [1]. Contrasting with this expectation, a recent study of ^{154}Gd [2] reports a less-deformed excited band built on the 0_3^+ state at 1182 keV with a moment of inertia only 52% of that of the ground-state band (based on energy differences between states within each band and assuming a rigid rotor model).

In addition to smaller deformation than the ground-state band in ^{154}Gd, the excited band structure is remarkable because of the highly enhanced (t, p) population [3] and greatly reduced (p, t) population [4] of the 0^+ 1182- and 2^+ 1418-keV states. Based on this difference in population strength, the excited band is interpreted [2] as a pairing isomer [5], that is, an isolated structure with a smaller pairing gap than that of the ground state characterized by large two-neutron transfer cross section and a large asymmetry in (t, p) and (p, t) reaction population strength. The possibility of such a structure built on the $\frac{11}{2}^-$ [505] Nilsson orbital is implied by Peterson and Garrett [6] because of its reduced off-diagonal pairing matrix elements with nearby orbitals and is 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 neutrons into the steeply upsloping $\frac{11}{2}^-$ [505] orbital would result in a less-deformed excited structure in an even-even nucleus (where the occupancy of the orbital, $V^2 > 0.5$). If the less-deformed band in ^{154}Gd is indeed such a pairing isomer, structures like that based on the 0_3^+ state should exist in nuclei nearby.

In this rapid communication, we report the observation of a weakly deformed coexisting band structure in ^{152}Sm (cf. Fig. 1) with a moment of inertia that is 58% of that of the ground-state band. The states in ^{152}Sm, J^π (E_x keV) 0^+ (1083), 2^+ (1293), 4^+ (1613), and (6^+) (2004), shown in Fig. 1 constitute a close analog of the less-deformed band 0^+ (1182), 2^+ (1418), and 4^+ (1701) in ^{154}Gd [2]. The 0_3^+ state at 1083 keV is populated very strongly (68% of the ground-state strength) in the ^{150}Sm$(t, p)^{152}$Sm reaction [7], but is populated with less than 1% strength in the ^{154}Sm$(p, t)^{152}$Sm reaction [8]. This dramatic asymmetry in (t, p) and (p, t) population is very much like that found in ^{154}Gd, as illustrated in Fig. 2, and provides strong evidence that this band is another example of a pairing isomer at $N = 90$.

The excited band in ^{152}Sm was elucidated through detailed γ-ray coincidence spectroscopy following β decay of ^{152m,g}Eu and multiple-step Coulomb excitation. The decay experiments, ^{152m,g}Eu $\rightarrow$ ^{152}Sm, were conducted at Lawrence Berkeley National Laboratory using the 8π spectrometer [10], 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 γ-γ coincidence events were recorded concurrently. Data obtained for the decay of ^{152g}Eu(13 yr, $J^\pi = 3^-$) in a 334-h measurement contained 2×10^9 singles and 6×10^8 γ-γ coincidence events. The ^{152m}Eu(9 h, $J^\pi = 0^-$) decay data contained 2×10^8 singles and 2×10^7 γ-γ coincidence events after 85 h 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

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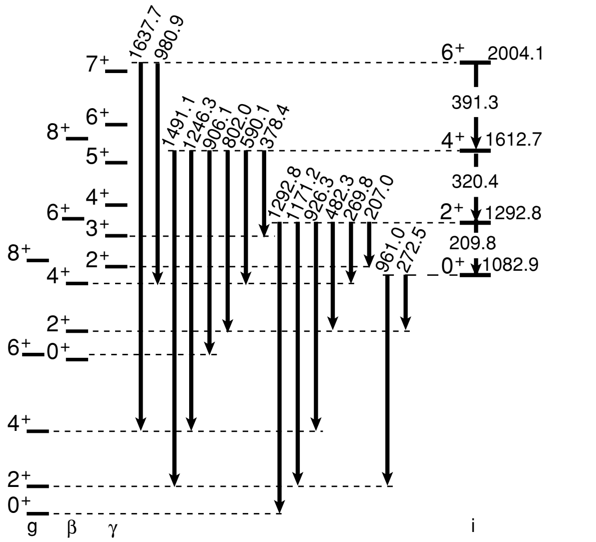

FIG. 1. Levels and transitions (in kilo-electron-volts) associated with the pairing isomeric structure in ^{152}Sm determined through γ-ray coincidence spectroscopy. The 0_i^+ (1083) and 2_γ^+ (1086) levels have been displaced for clarity. The 2004.1-keV level is newly established by this study. The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

used to populate excited states in ^{152}Sm through inverse Coulomb excitation of a three-particle-nA beam of ^{152}Sm at a "safe" energy of 652 MeV. Signals from two ions in the University of Rochester Compact Heavy Ion Counter (CHICO) [11] charged-particle detector array in coincidence with at least one "clean" γ-ray signal in the Gammasphere [12] 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 twofold (γ-γ) events, and 1×10^7 (γ-γ-γ) coincidence events were recorded in 62 h of running time.

Turning to a discussion of the band, the 0^+ (1083) and 2^+ (1293) levels were first associated with each other because of

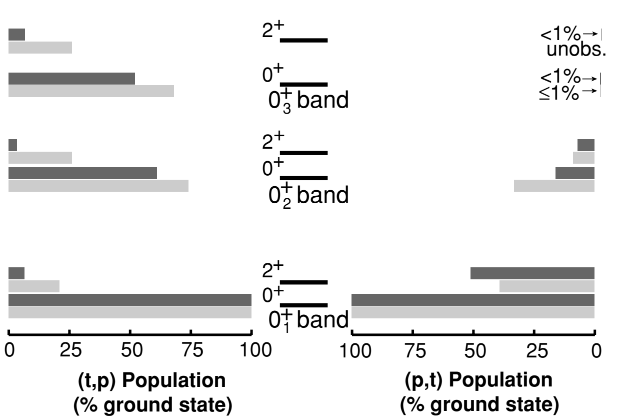

FIG. 2. A comparison of two-neutron transfer reaction strength to states in ^{152}Sm (light bands) and ^{154}Gd (dark bands). Data are from Refs. [3,4,8,9].

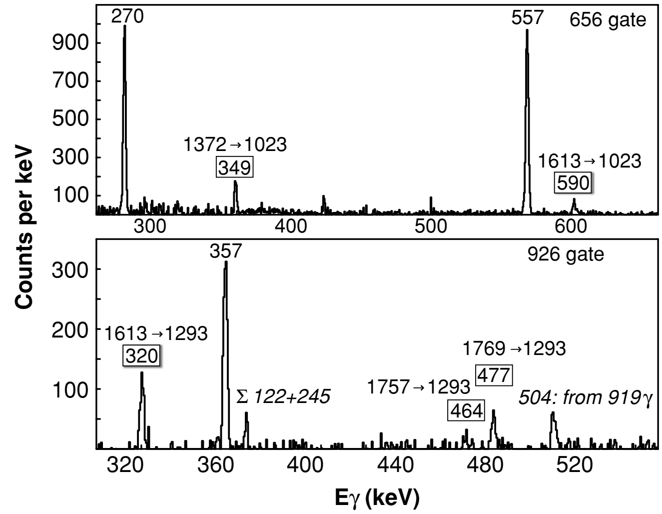

FIG. 3. The 656- (1023 → 367; $4_\beta^+ \to 4_g^+$) and 926- (1293 → 367; $2_i^+ \to 2_g^+$) keV γ-ray coincidence gates for the ^{152g}Eu → ^{152}Sm decay show several new transitions (in boxes). Two of the new γ rays feeding the 2_i^+ and 4_β^+ states, at 320 and 590 keV, respectively, are from the 4^+ band member at 1613 keV. Other new γ rays are from established [14] levels. The 270-, 357-, and 557-keV transitions have established assignments [14] from previous work.

their very strong population in the ^{150}Sm$(t, p)^{152}$Sm reaction [7] (cf. Fig. 2). Observation of the 1293 → 1083 intraband 210 keV γ ray in the decay of ^{152m,g}Pm with an absolute quadrupole transition $B(E2; 1293 \to 1083) = 184(100)$ W.u. has suggested that the 1083- and 1293-keV states are part of a collective band [13]. In coincidence spectroscopy following the decay of ^{152g}Eu, we confirm the placement of the 210-keV (1293 → 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 [14] built on the 0^+ level at 1083 keV. Previously, only two γ-ray transitions were assigned to deexcite the 1613 state in the adopted gammas for this level [14]: the 906- (1613 → 6_g^+707) and 572- (1613 → 3_1^-1041) keV transitions. Coincidence gates from the decay of ^{152g}Eu, shown in Fig. 3, reveal the presence of new transitions at 590 (1613 → 4_β^+1023) and 320 (1613 → 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 deexciting 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 [14] prevents definite assignment of γ-ray transitions to positive-parity levels of spin >5 because

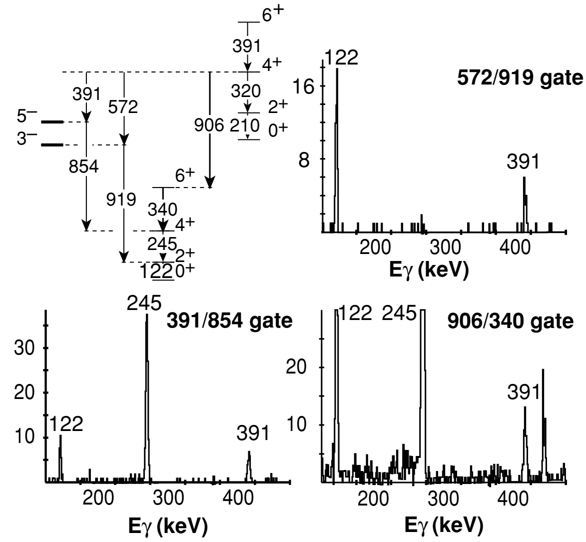

FIG. 4. Triple γ-ray coincidence gates for the multistep Coulex experiment locate the (6^+) state of the band.

of 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.

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 [15]. 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	—

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 on 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 → 1083), 320- (1613 → 1293), 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 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. Although differences in the lower lying states of these nuclei are reflected in the $B(E2)$ values in Table I, basic trends emerge that not only show the close similarities of the 0_3^+ structures in ^{152}Sm and ^{154}Gd but also may be useful in recognizing analogous bands in nearby nuclei. These trends will be particularly helpful in nuclei where the (t, p) population is not as remarkable as that illustrated in Fig. 2 (for a 0_3^+ state in ^{150}Nd, a population limit of $\leqslant$10% of the ground state strength is reported in the ^{148}Nd$(t, p)^{150}$Nd reaction [16,17]) or in nuclei where transfer reaction data are not available.

As a result of the proximity of the $\frac{11}{2}^-$ [505] Nilsson orbital to the Fermi surface [6], 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, plotted in Fig. 5, show a

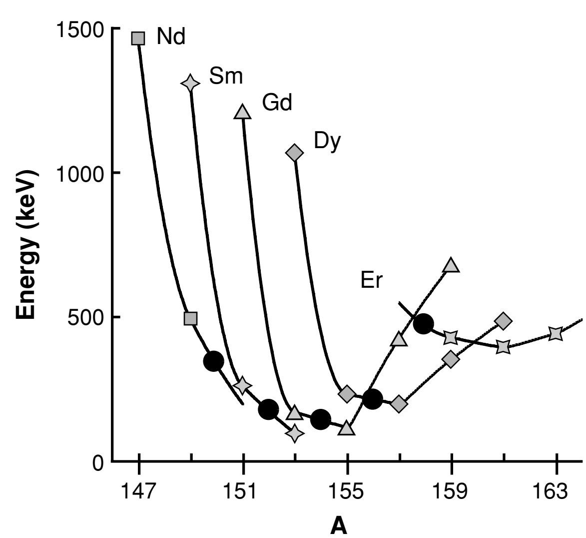

FIG. 5. The $\frac{11}{2}^-$ [505] band-head energies in the odd-mass $87 \leqslant N \leqslant 97$ isotones extracted from the ENSDF database [18] exhibit a systematic trend. Relative values interpolated at $N = 90$ (circles) show that the [505] pairing isomer approaches a minimum excitation energy near ^{152}Sm and ^{154}Gd, where bands are identified at 1083 and 1182 keV, respectively.

minimum near $A = 153$. The interpolated energies for the $N = 90$ nuclei, illustrated as solid circles, indicate that the relative values for these even-even nuclei are lowest near ^{152}Sm and ^{154}Gd. Although caution is needed in using Fig. 5 to estimate excitation energies of unobserved pairing isomers because, for example, the plotted energies 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. Similarly, Fig. 5 indicates analogous structures in ^{150}Nd and ^{158}Er should appear at higher excitation energies than the observed bands at 1182 keV in ^{154}Gd and 1083 keV in ^{152}Sm.

In summary, using γ-ray coincidence spectroscopy following the β decay of ^{152m,g}Eu and multiple-step Coulomb excitation, we have identified four states that consititute an excited rotational band that 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 [2]. This result suggests a systematic behavior of the underlying $\frac{11}{2}^-$ [505] Nilsson configuration that gives rise to the pairing isomerism [6] 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] 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).
[3] M. A. M. Shahabuddin, D. G. Burke, I. Nowikow, and J. C. Waddington, Nucl. Phys. **A340**, 109 (1980).
[4] D. G. Fleming, C. Gunther, G. Hagemann, B. Herskind, and P. O. Tjom, Phys. Rev. C **8**, 806 (1973).
[5] I. Ragnarsson and R. A. Broglia, Nucl. Phys. **A263**, 315 (1976).
[6] R. J. Peterson and J. D. Garrett, Nucl. Phys. **A414**, 59 (1984).
[7] S. Hinds, J. H. Bjerregaard, O. Hansen, and O. Nathan, Phys. Lett. **14**, 48 (1965).
[8] P. Debenham and N. M. Hintz, Nucl. Phys. **A195**, 385 (1972).
[9] J. H. Bjerregaard, O. Hansen, O. Nathan, and S. Hinds, Nucl. Phys. **86**, 145 (1966).
[10] 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*., Nucl. Instrum. Meth. Phys. Res. A **257**, 301 (1987).
[11] 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).
[12] 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, 1996), p. 50.
[13] H. Mach, M. Hellstrom, B. Fogelberg, D. Jerrestam, and L. Spanier, Phys. Rev. C **46**, 1849 (1992).
[14] A. Artna-Cohen, Nucl. Data Sheets **79**, 1 (1996).
[15] 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).
[16] R. Chapman, W. McLatchie, and J. E. Kitching, Phys. Lett. **B31**, 292 (1970).
[17] R. Chapman, W. McLatchie, and J. E. Kitching, Nucl. Phys. **A186**, 603 (1972).
[18] 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.