Identification and Quadrupole-Moment Measurement of a Superdeformed Band in ^{84}Zr

H.-Q. Jin,[1,2] C. Baktash,[1] M.J. Brinkman,[1] C.J. Gross,[3] D.G. Sarantites,[4] I.Y. Lee,[5] B. Cederwall,[5] F. Cristancho,[6] J. Döring,[7] F.E. Durham,[8] P.-F. Hua,[4] G.D. Johns,[7] M. Korolija,[4] D.R. LaFosse,[4] E. Landulfo,[6] A.O. Macchiavelli,[5] W. Rathbun,[5] J.X. Saladin,[6] D.W. Stracener,[1] S.L. Tabor,[7] and T.R. Werner[1,9,10]

[1]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831*
[2]*Department of Physics, Rutgers University, New Brunswick, New Jersey 08903*
[3]*UNISOR, Oak Ridge Institute of Science and Education, Oak Ridge, Tennessee 37831*
[4]*Chemistry Department, Washington University, St. Louis, Missouri 63130*
[5]*Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, California 94720*
[6]*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[7]*Department of Physics, Florida State University, Tallahassee, Florida 32306*
[8]*Department of Physics, Tulane University, New Orleans, Louisiana 70118*
[9]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996*
[10]*Institute of Theoretical Physics, Warsaw University, PL-00-681, Warsaw, Poland*
(Received 14 April 1995)

High-spin states in ^{84}Zr were studied using the early implementation phase of the Gammasphere array and the "Microball" charged-particle detector system. A cascade of nine γ rays with a dynamic moment of inertia which is characteristic of superdeformed rotational bands in the $A = 80$ region has been identified and assigned to ^{84}Zr. The measured transition quadrupole moment of the band corresponds to a prolate quadrupole deformation of $\beta_2 = 0.53$ and confirms the superdeformed nature of this band. This is the first direct experimental confirmation of the existence of the predicted superdeformed shell gap at $N \simeq 44$ particle number.

PACS numbers: 21.10.Re, 21.60.Cs, 23.20.Lv, 27.50.+e

Since the observation of the first high-spin superdeformed (SD) band in ^{152}Dy [1], SD shapes have been intensively studied in nuclei in the mass $A \sim 130$, ~ 150, and ~ 190 regions [2,3]. In many instances, the large deformations of these bands have been experimentally confirmed by lifetime measurements (e.g., [4]). These findings are in excellent accord with theoretical calculations which also predicted the existence of a SD shell gap in $A \sim 80$ nuclei with proton or neutron number ~ 44 [5–7]. However, until very recently no candidate for a discrete-line SD band in the mass 80 region had been identified. Problems specific to this mass region which hinder the observation of these weakly populated bands are (a) poor photopeak efficiency for the detection of high-energy γ rays associated with these structures; (b) large velocities and angular spread of the recoiling nuclei which result in poor energy resolution; and (c) fragmentation of the yields of the fusion-evaporation products into many exit channels which produce excessive background of γ-ray transitions. Using the Eurogam-I array [8] to overcome mainly the first of these difficulties, Baktash *et al.* [9] recently reported the first observation of a discrete-line SD rotational band in the mass 80 region which was tentatively assigned to ^{83}Sr (this assignment has been confirmed in Ref. [10]). Although the dynamic moment of inertia ($\mathcal{J}^{(2)} = 27\hbar^2/\text{MeV}$) of this band corresponds to that of a SD rotational band, the large deformation attributed to this structure needs to be confirmed experimentally.

In this Letter we report identification of a discrete-line SD band in ^{84}Zr and the first lifetime measurement of such a band in the $A = 80$ region. The measured transition quadrupole moment of $Q_t = 5.2 \pm 1.0$ eb for this band corresponds to a prolate quadrupole deformation of $\beta_2 = 0.53$. This measurement provides the first direct confirmation of the long-standing prediction that a SD shell gap exists at neutron number $N \simeq 44$.

Two experiments were performed at the 88-Inch Cyclotron at the Lawrence Berkeley Laboratory. The ^{58}Ni(^{29}Si, $2pn$) and ^{58}Ni(^{32}S, $\alpha 2p$) reactions were used to populate excited states in ^{84}Zr at bombarding energies of 128 and 135 MeV, respectively. Both experiments used a highly enriched ^{58}Ni foil with a thickness of 245 μg/cm^2. The experimental setup consisted of the early implementation phase of the Gammasphere array [11] comprising 36 Compton-suppressed Ge detectors, and the Washington University "Microball" [12], which is a 4π charged-particle detector array with 95 CsI(Tl) scintillators. The event trigger required coincidences between at least one element of the Microball and three or more Ge detectors. A total of 7.4×10^8 raw events from the ^{29}Si-induced reaction and 4.2×10^8 raw events from the ^{32}S-induced reaction were collected. The events were sorted off-line into E_γ-E_γ matrices subject to the appropriate proton (p) and alpha (α) charged-particle gates. The final $2p$-gated matrix included 3×10^8 γ-γ events, of which $\sim 25\%$ were associated with the ^{84}Zr + $2pn$, while the $\alpha 2p$-gated matrix from the ^{32}S-induced reaction had 2×10^8 γ-γ events. The exit-channel selectivity afforded by the Microball proved to be essential for the reported lifetime measurement.

From these coincidence data, a rotational band of nine γ rays with energies between 1526 and 2761 keV was established. The spectra shown in Fig. 1 were obtained by summing gates set on the 1526- through 2435-keV γ rays in panel (a) and 1526- through 2272-keV γ rays in panel (b). The 2761-keV transition in panel (a) and 2435-keV in panel (b) are not certain and are put in brackets to indicate the upper sensitivity limit in the two reactions. While double-gated spectra from the triple-coincidence data did not reveal any new transitions due to lack of statistics, they confirmed that all the labeled γ rays belong to this band. To indicate the decay pattern of the observed band into the normally deformed (ND) states, a partial level scheme of ^{84}Zr [13] is shown in Fig. 2. The following conclusions may be drawn: (1) unambiguous assignment of this band to ^{84}Zr is possible due to the fact that only γ-ray transitions between the ND states in ^{84}Zr (marked with symbols in Fig. 1) are seen in both reactions; and (2) the decay out of the band takes place from the lowest two states and feeds with comparable intensities into the ND bands 1 to 3 at an average spin of 19.5 ± 1.1, as shown in Fig. 2. However, the linking transitions could not be identified. The observed decay pattern of this band is consistent with the statistical character of the decay of the SD bands in other regions which is believed to be multistep and carries a few units of angular momentum [2,3]. Therefore, we can set an approximate limit of $\geq 21\hbar$ and $39\hbar$ for the spins of the lowest and highest states of the band, respectively.

The intensities of the band members relative to that of the $2^+ \rightarrow 0^+$ transition in ^{84}Zr are shown as an inset in Fig. 1(b). In both reactions, feeding takes place mostly into the top four states in the band. However, the population of the band saturates at $\sim 4\%$ and $\sim 2\%$ for the ^{29}Si- and ^{32}S-induced reactions, respectively. The lower angular momentum and, hence, the smaller population observed in the $\alpha 2p$ exit channel can be qualitatively explained as due to the fact that α particles carry away more angular momentum than the protons. Also, for the beam

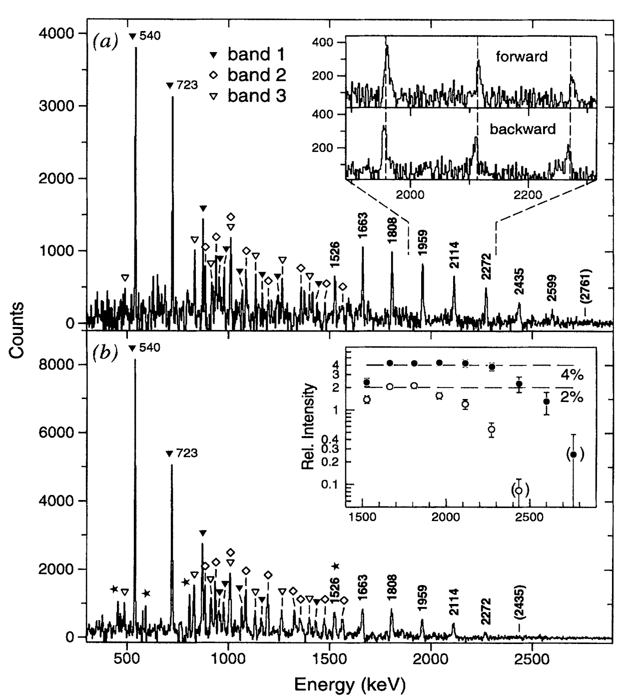

FIG. 1. γ-ray spectra created by summing coincidence gates set on transitions belonging to the SD band in ^{84}Zr from the reactions of ^{29}Si + ^{58}Ni in (a) and ^{32}S + ^{58}Ni in (b). Members of the SD band are labeled with γ-ray energies and the transitions from three normally deformed bands in ^{84}Zr are marked by symbols. The lines labeled with stars in (b) are contamination from neighboring channels. The inset in (a) shows the residual Doppler shift for three γ rays in the SD band. The inset in (b) shows the intensities of the SD transitions relative to that of the $2^+ \rightarrow 0^+$ transition (540 keV) in ^{84}Zr from the two reactions using beams of ^{29}Si (filled circles) and ^{32}S (open circles).

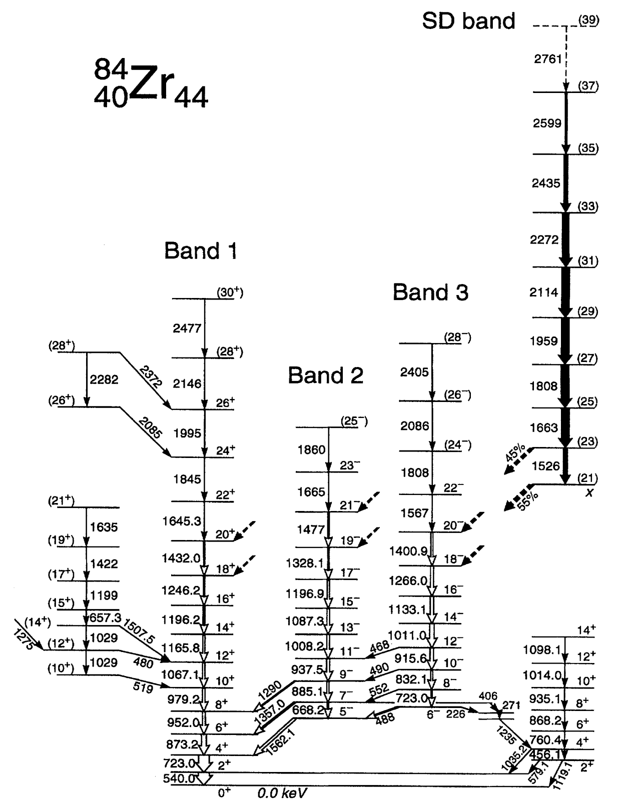

FIG. 2. A partial level scheme for ^{84}Zr established in this work and Ref. [13] that shows the decay pattern of the SD band into the ND states. The widths of the solid arrows, indicating the intra-SD transitions, are proportional to the relative intensities of the γ rays. The widths of the dashed arrows indicate the relative intensities of the (unobserved) transitions that feed out of the SD band and into the three ND bands. The uncertainty in the energies of those transitions shown with decimal points is ≤ 0.5 keV, and for those shown without decimal points is ~ 1 keV.

energies used, EVAPOR [14] Monte Carlo calculations indicate that the maximum angular momentum brought into the compound system is 49 $\hbar$ and 52 $\hbar$ in the ^{32}S and ^{29}Si reactions, respectively. This difference can cause an additional lowering of the spin at which the band is fed. Surprisingly, the point at which the population intensity reaches its maximum is lower by $\sim 4\hbar$ in the ^{32}S-induced reaction. It has been commonly assumed that this saturation point marks the approximate spin at which the yrast ND and SD bands cross each other and, therefore, may be used to estimate the spin and excitation energy of the SD bands [2]. (In the case of the ^{29}Si-induced reaction here, this assumption gives an estimated excitation energy of $E_x \sim$ 13 MeV for the lowest-lying level in the SD band, or nearly 3.5 MeV above the ND yrast line.) The present data indicate that the exact location of this saturation point is reaction dependent and is sensitive to the entry-state distribution (which is presumably at a lower energy in the $\alpha 2p$ channel than the $2pn$).

The answer to the important question as to whether the observed band is superdeformed should come from direct lifetime measurements. Lifetime measurements of the SD states in the $A = 80$ region are difficult, primarily due to the large transition energies and, hence, very short lifetimes (less than tens of femtoseconds). Most of the SD states decay before the recoils have moved out of a thin target. Thus, the conventional Doppler shift attenuation method of measuring line shapes in a backed target is not possible. However, very short lifetimes can be estimated by a technique [15] based on the residual Doppler shifts from the slowing down of recoil nuclei in a thin target. Here we present such an analysis for the data from the ^{58}Ni(^{29}Si, $2pn$)^{84}Zr reaction.

The high-spin normally deformed states in ^{84}Zr have lifetimes of $\sim$100 fs [16], which are significantly larger than the $\sim$30 fs that it takes for the ^{84}Zr recoils to travel through the 245 μg/cm^2 Ni target. Therefore, γ rays from the ND states are mostly emitted after the recoiling nuclei exit the target with a well-defined velocity distribution. This average recoil velocity may be used to correct for the Doppler shift of the γ rays from the ND states. However, SD states have much shorter lifetimes and, consequently, a much larger fraction of them decay while the recoiling nucleus is slowing down in the target. The fast γ rays in the SD band should then have larger Doppler shifts resulting in higher (lower) energies in the forward- (backward-) angle detectors. The gains of the germanium detectors were matched so that the strong transitions from the ND states in ^{84}Zr had the same energy calibration. With these gains, the SD spectra for the 15 forward ($\overline{\theta} = 32°$ relative to the beam direction) and 15 backward ($\overline{\theta} = 148°$) detectors clearly showed additional Doppler shifts [see the inset in Fig. 1(a)]. The observed differences were converted into the average fractional shift $F = \langle v/v_0 \rangle$, where v is the recoil velocity of the nucleus as deduced from $\langle (v/c)\cos\theta \rangle = \Delta E_\gamma / E_\gamma$. (The maximum recoil velocity v_0/c was 0.0324 in this experiment.) The results are shown as open squares in Fig. 3. For comparison, five points (filled circles) corresponding to transitions in the normally deformed band of ^{84}Zr are also included.

The slowing down of the recoiling nuclei in the target was modeled using the electronic stopping powers given by Ziegler, Biersack, and Littmark [17]. The velocity distribution of the recoiling nuclei was calculated as a function of the decay time by integrating over the target material and averaging over three different reaction points in the target. A side feeding of rotational cascades of two transitions was used according to the experimental feeding pattern. The decay of the nuclei was then modeled by assuming the same transition quadrupole moment Q_t value for both the in-band and side-feeding transitions. In Fig. 3, the calculated F values are plotted as a function of γ-ray energies for five Q_t values of 3, 4.5, 5.2, 6, and 8 e b. The constant velocity of the recoils outside the target is indicated by the horizontal dotted line which corresponds to an average recoil velocity of 3.07%. Within the experimental error bars and with the exception of the weak transition at 2435 keV, the residual shifts of the SD band clearly fall between the two calculated curves of $Q_t = 4.5$ and 6.0 e b. This is in contrast to the trend for the transitions from the ND bands that fall very close to the dotted line.

The SD data are best fitted by a Q_t of 5.2 $\pm$ 0.8 e b which corresponds to a $B(E2)$ strength of 440 W.u. Uncertainties in the slowing-down process, the modeling of the side feedings, and the target thickness may contribute

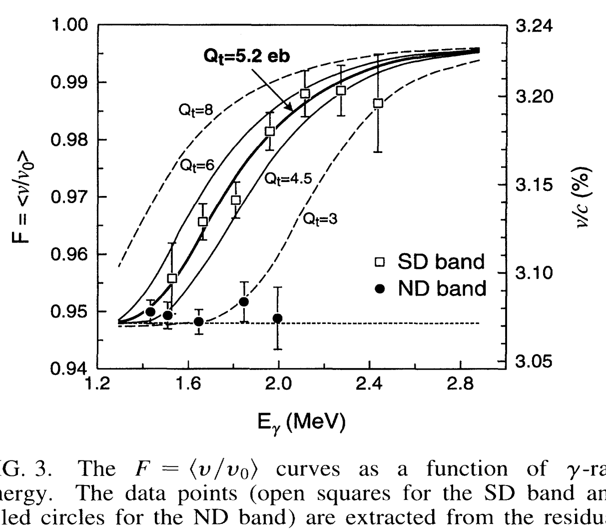

FIG. 3. The $F = \langle v/v_0 \rangle$ curves as a function of γ-ray energy. The data points (open squares for the SD band and filled circles for the ND band) are extracted from the residual Doppler shifts of the γ rays detected in the forward and backward detectors. Calculated F curves with different Q_t values are shown as lines. Most of the experimental SD data fall between the two curves of $Q_t = 6.0$ and 4.5. The dotted horizontal line corresponds to zero residual Doppler shift, appropriate for the transitions (1432, 1508, 1645, 1845, and 1995 keV) of the ND bands.

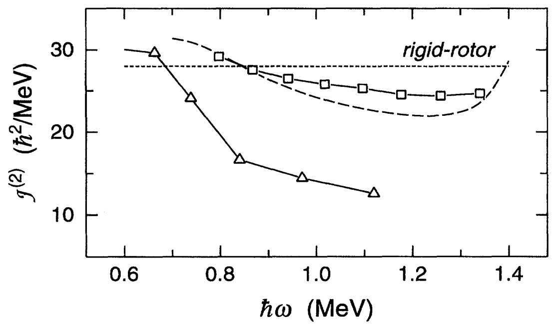

FIG. 4. Comparison of the experimental $\mathcal{J}^{(2)}$ of the SD band (open squares) with values from a cranked Woods-Saxon calculation for the lowest-lying SD band (dashed line) in ^{84}Zr. For comparison, the $\mathcal{J}^{(2)}$ for the ND band 3 (triangles) and a prolate rigid rotor with a deformation of $\beta_2 = 0.53$ (dotted line) are also indicated.

an additional ± 0.5 e b to the estimated error. Nevertheless, it is clear that the resulting Q_t is much larger than 3 e b which is an upper limit for the ND states in the $A = 80$ region [16,18]. The measured value of Q_t corresponds to a quadrupole deformation of $\beta_2 = 0.53$ assuming an axially symmetric prolate shape for the nucleus.

Using the Woods-Saxon cranking model, Dudek, Nazarewicz, and Rowley have performed extensive calculations for the band structures in ^{84}Zr which are discussed in detail in Ref. [7]. According to these calculations, SD bands form the lowest-lying states for spins greater than $I = 28\hbar$. In Fig. 4, the dynamic moment of inertia $\mathcal{J}^{(2)}$ of the experimental SD band is compared with the calculated values for the lowest-lying SD band which has two neutrons and one proton occupying the $h_{11/2}$ orbital from the $\mathcal{N} = 5$ higher shell. (Experimentally, the $\mathcal{J}^{(2)}$ values were obtained as $4/\Delta E_\gamma$, where ΔE_γ is the difference between the energies of two consecutive γ rays.) The calculated deformation of this band (negative parity, odd spin) is $\beta_2 = 0.53$, $\beta_4 = -0.03$, $\gamma = 0°$. The agreement is fairly good. For comparison, the $\mathcal{J}^{(2)}$ of a prolate spheroidal rigid rotor with $\beta_2 = 0.53$ (dotted line) and the ND band 3 (triangles) which is typical of band termination in this region are also shown. As pointed out in Refs. [5–7], the onset of superdeformation in this region is due to the presence of a large shell gap at neutron number $N \simeq 44$ in the single-particle spectra.

In summary, taking advantage of the high selectivity of the Microball and the high efficiency of Gammasphere, we have identified a discrete-line SD band in ^{84}Zr which consists of nine transitions and extends up to a tentative spin of $39\hbar$. The large value of the experimentally deduced quadrupole moment of this band (5.2 ± 1.0 e b) provides the first direct evidence for the presence of a SD shell gap at neutron number $N \simeq 44$. Significant differences were observed in the feeding saturation point of this SD band in two reactions that involved evaporation of different types of particles. This points to an important new factor that influences the population of SD bands.

This work was supported in part by the U.S. Department of Energy under Contracts No. DE-AC05-84OR21400 (ORNL), No. DE-AC05-76OR00033 (UNISOR), and No. DE-AC03-76SF00098 (LBL), and by Grant No. DE-FG05-88ER40406 (Washington University). The ORNL Postdoctoral Research Associates program is administered by the ORNL and the Oak Ridge Institute for Science and Education. This work was also supported in part by the National Science Foundation under Grants No. PHY-9319934 (University of Pittsburgh) and No. PHY-9210082 (FSU). One of us (T. R. W.) was partially supported by the Polish State Committee for Scientific Research under Contract No. 2 P03B 034 08.

[1] P.J. Twin *et al.,* Phys. Rev. Lett. **57**, 811 (1986).
[2] P.J. Nolan and P.J. Twin, Annu. Rev. Nucl. Part. Sci. **38**, 533 (1988).
[3] R.V.F. Janssens and T.L. Khoo, Annu. Rev. Nucl. Part. Sci. **41**, 321 (1991).
[4] M.A. Bentley *et al.,* Phys. Rev. Lett. **59**, 2141 (1987).
[5] I. Ragnarsson, S.G. Nilsson, and R.K. Sheline, Phys. Rep. **45**, 1 (1978).
[6] W. Nazarewicz *et al.,* Nucl. Phys. **A435**, 397 (1985).
[7] J. Dudek, W. Nazarewicz, and N. Rowley, Phys. Rev. C **35**, 1489 (1987).
[8] P.J. Nolan, Nucl. Phys. **A520**, 657c (1990); C.W. Beusang *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **313**, 37 (1992).
[9] C. Baktash *et al.,* Phys. Rev. Lett. **74**, 1946 (1995).
[10] D.R. LaFosse *et al.,* Phys. Lett. B (to be published).
[11] Gammasphere Proposal No. LBL-PUB-5202, 1988; I.Y. Lee, Nucl. Phys. **A520**, 361 (1990).
[12] D.G. Sarantites *et al.* (to be published).
[13] A.A. Chishti *et al.,* Phys. Rev. C **48**, 2607 (1993).
[14] J.R. Beene and N.G. Nicolis (private communication).
[15] B. Cederwall *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **354**, 591 (1995).
[16] H.G. Price *et al.,* Phys. Rev. Lett. **51**, 1842 (1983).
[17] J.F. Ziegler, J.P. Biersack, and U. Littmark, *The Stopping and Ranges of Ions in Matter* (Pergamon, London, 1985), Vol. 1.
[18] S.L. Tabor *et al.,* Phys. Rev. C **49**, 730 (1994).