Decay Out of the Doubly Magic Superdeformed Band in the $N = Z$ Nucleus ^{60}Zn

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The doubly magic superdeformed band in the $N = Z$ nucleus ^{60}Zn has been identified. Linking transitions connecting this band to the yrast line provide the first spin, parity, and excitation energy measurements for superdeformed states in the $A \sim 60$ region. The stretched-$E2$ character and relatively large $B(E2)$ values of these transitions suggest a nonstatistical decay-out process. [S0031-9007(99)09006-7]

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Investigations throughout the chart of the nuclides in the past decade have led to the observation of many superdeformed (SD) rotational bands in $A \sim 190$, 150, 130, 80, and 60 nuclei [1,2]. Although it has been relatively straightforward to observe the long cascades of rotational transitions in these bands with modern γ-ray detector arrays, discrete transitions connecting SD bands to normal deformed (ND) states have been much more difficult to identify. The observation of linking transitions is, however, essential in order to determine the fundamental properties of the SD states, namely, their spins, parities, and excitation energies, and to perform spectroscopic tests of theoretical models which require a knowledge of these quantities. The properties of the linking transitions also provide crucial information about the mechanism which leads to the sudden depopulation of SD bands and to the fragmentation of the decay-out intensity over a large number of pathways.

Recently, significant progress has been made in studying the decay out of SD bands in the $A \sim 190$ region. The observation of linking transitions in ^{194}Hg [3] and ^{194}Pb [4] has led to definite quantum number assignments for SD states in these nuclei. These observations, combined with lifetime measurements for low-spin SD states [5] and decay-out γ-ray quasicontinuum studies [6], have also provided a consistent description of the decay out of $A \sim 190$ SD bands as a statistical process governed by the weak mixing of SD states with a "sea" of hot ND states separated from the SD levels by a potential energy barrier [7]. In contrast, highly deformed bands in a number of $A \sim 135$ Nd isotopes, for which no barrier is predicted at the decay-out point, mix considerably with less deformed structures and decay out while close to the yrast line [8]. The nature of the decay-out process for SD bands in other mass regions remains an open question. In this Letter we report the observation of the predicted [9,10] superdeformed band in ^{60}Zn built on the SD shell gaps at $N, Z = 30$, the doubly magic SD core in the $A \sim 60$ region. Linking transitions connecting this band to the yrast line establish the spins, parity, and excitation energies of the SD states and indicate that the decay-out process in ^{60}Zn differs substantially from that observed in heavier nuclei.

High-spin states in ^{60}Zn were studied with the Gammasphere array [11] in two experiments with thin ($\sim$0.5 mg/cm^2) ^{40}Ca targets. In the first experiment, a 125-MeV ^{28}Si beam from the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory populated ^{60}Zn via the ^{40}Ca(^{28}Si, 2α)^{60}Zn reaction, Gammasphere comprised 83 Ge detectors, and 2.5×10^9 γ-γ-γ and higher-fold coincidence events were recorded. In the second experiment, a 134-MeV ^{32}S beam provided by the ATLAS facility at Argonne National Laboratory and the ^{40}Ca(^{32}S, 3α)^{60}Zn reaction were used, Gammasphere comprised 101 Ge detectors, and 1.7×10^9 γ-γ-γ-γ and higher-fold coincidences were collected. In both experiments, charged particles were detected with the Microball [12], a 4π array of 95 CsI(Tl) scintillators, and the collimators were removed from the Ge detectors to enable γ-ray multiplicity and sum-energy measurements [13] and additional channel selectivity based on total energy conservation [14]. Although the evaporation channel leading to the $N = Z$ nucleus ^{60}Zn represented only $\sim$0.1% of the total fusion cross section in each reaction, the clean selection of these events and the very strong population of the yrast SD band in ^{60}Zn (60 $\pm$ 4% and 34 $\pm$ 3% of the channel intensity in the first and second experiment, respectively) enabled the identification of this doubly magic SD band.

Figure 1(a) shows the γ-ray spectrum obtained by summing coincidence gates set on the SD band members and Fig. 2 shows a partial decay scheme for ^{60}Zn. The six high-energy transitions shown connecting the SD band to the ground band in Fig. 2 are clearly visible in Fig. 1(a). Figure 1(b) shows the γ-ray spectrum in coincidence with the 3184 and 3656 keV transitions. All of the transitions in the ^{60}Zn ground band, as well as all of the SD band transitions above the 12^+ state, are visible in this spectrum. Note, however, that in accordance with Fig. 2 the 1376 keV SD transition is absent in this spectrum.

Angular distribution measurements confirmed the stretched-$E2$ character of the transitions in the ^{60}Zn ground and SD bands. As shown in Fig. 2, such measurements were also possible for the 3184 and 3656 keV linking transitions. Legendre polynomial fits to these data yield angular distribution coefficients $a_2 = 0.37 \pm 0.08$, $a_4 = -0.16 \pm 0.10$ and $a_2 = 0.38 \pm 0.09$, $a_4 = -0.20 \pm 0.11$ for the 3184 and 3656 keV γ rays, respectively, and favor stretched-$E2$ assignments for both of these transitions. These assignments, which are consistent with the expectation that the yrast SD band in ^{60}Zn should have positive parity and even spins, are also supported by the absence of the 6.84 MeV transition to the yrast 8^+ state which would be energetically favored if either of these links were of $\Delta I = 0$ mixed $E2/M1$ character. We therefore assign stretched-$E2$ character to these linking transitions and positive parity and the spins indicated in Fig. 2 to the SD states. The 8^+ state of the SD band is thereby established at 9.620 MeV (4.328 MeV above the yrast 8^+ state) and an extrapolation of the band to lower spin places the 0^+ SD state at an excitation energy of $\approx$7.5 MeV. Although angular distribution measurements were not possible for the other links, the above spin/parity assignments indicate that the 5464 and 5810 keV transitions are stretched $E2$'s and also favor stretched-$E2$ assignments for the 3344 and 3496 keV transitions.

We have measured the transition quadrupole moment Q_t for the ^{60}Zn SD band by the thin target Doppler shift attenuation method [15]. The fractional Doppler shift $F(\tau)$ values measured for the SD transitions are shown in Fig. 2(c). In order to extract a quadrupole moment from these measurements the decay of the band was modeled assuming a constant in-band Q_t and the feeding of the band and slowing of the recoils in the target

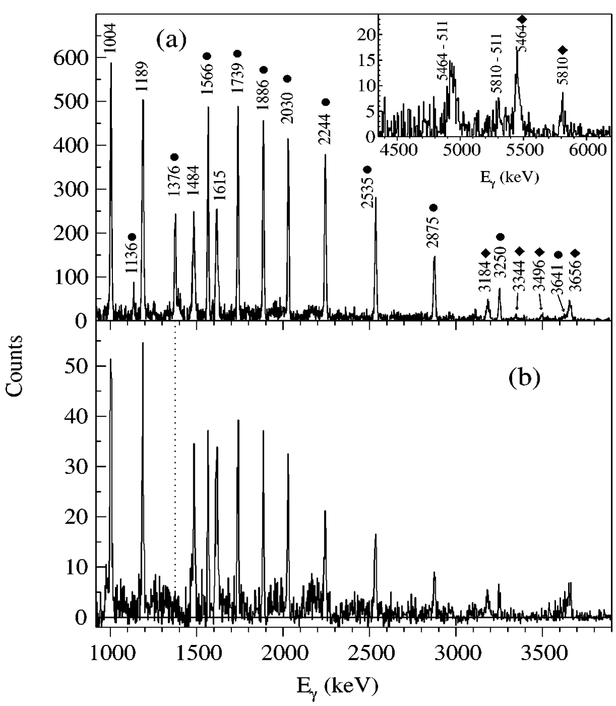

FIG. 1. γ-ray spectra in coincidence with a sum of gates on (a) the members of the ^{60}Zn SD band (circles) and (b) the 3184 and 3656 keV transitions. Diamonds in (a) label linking transitions. Note the absence of the 1376 keV γ ray in (b).

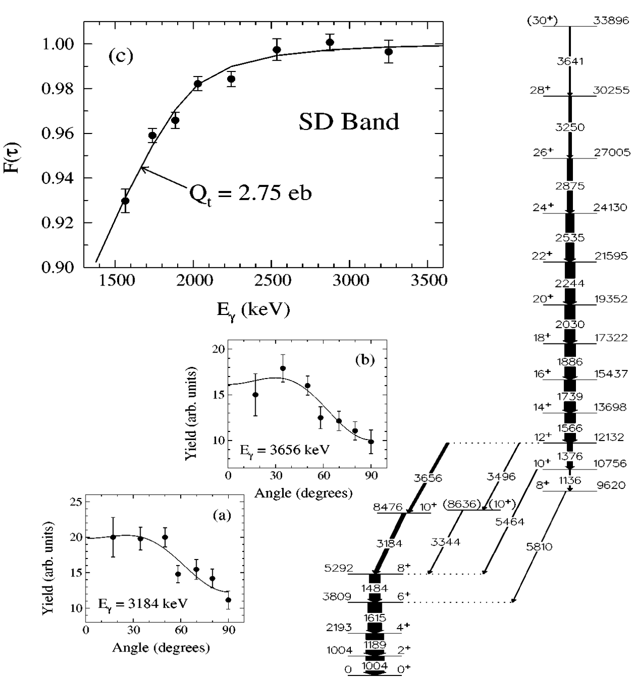

FIG. 2. Partial decay scheme for ^{60}Zn. The order of the 3496 and 3344 keV linking transitions is uncertain. Angular distributions measured relative to the beam axis are shown for the (a) 3184 keV and (b) 3656 keV linking transitions. Fractional Doppler shifts for members of the SD band and a fit giving $Q_t = 2.75$ e b are shown in (c).

were treated as described in Ref. [2]. Combining the statistical uncertainties with estimated uncertainties in the stopping powers, the best fit to the data is obtained with $Q_t = 2.75 \pm 0.45\ e\,\mathrm{b}$. Assuming an axially symmetric shape, the corresponding quadrupole deformation is $\beta_2 = 0.47 \pm 0.07$. Although calculations for ^{60}Zn (discussed below) predict that the Q_t of this SD band decreases from $3.05\ e\,\mathrm{b}$ at $I = 8\hbar$ to $2.06\ e\,\mathrm{b}$ at $I = 30\hbar$, the uncertainties in the $F(\tau)$ measurements for the high-energy transitions at the top of the band were too large to test this predicted spin dependence. Noting that the experimental mean Q_t value is determined almost entirely by transitions in the spin range $I = 12\text{--}22\hbar$ (where the calculated Q_t values range from 2.97 to $2.54\ e\,\mathrm{b}$), the agreement between experiment and theory is excellent.

Theoretical calculations for ^{60}Zn have been performed with both the configuration-dependent shell-correction approach with the cranked Nilsson (CN) potential [16] and the cranked relativistic mean field (CRMF) formalism [17] with the NLSH parameter set [18]. A detailed description and comparison of these calculations, which do not include pairing correlations and are thus realistic only for high-spin states, will be given in a forthcoming article [19]. Figure 3(a) shows the energies of favored configurations in ^{60}Zn relative to a rigid rotor reference from the CN calculations. At high spin the calculated yrast SD band in ^{60}Zn is separated from excited states by a large energy gap (the shaded region in Fig. 3). This band is

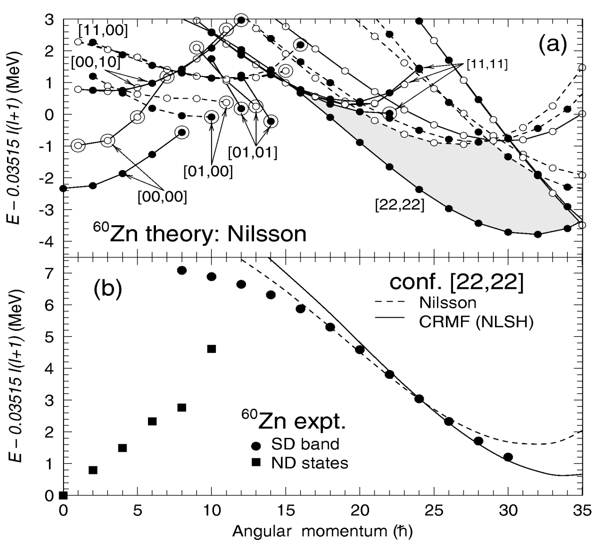

FIG. 3. Energies of states in ^{60}Zn relative to an $I(I+1)$ reference from (a) theory and (b) experiment. In (a) solid (dashed) lines denote positive (negative) parity, filled (open) symbols are used for signature $\alpha = 0$ ($\alpha = +1$), and terminating states are shown by large open circles. The configurations are labeled by $[p_1p_2, n_1n_2]$ where p_1 (n_1) is the number of proton (neutron) $f_{7/2}$ holes, and p_2 (n_2) is the number of proton (neutron) $g_{9/2}$ particles. In (b) the experimental results are compared with both cranked Nilsson and CRMF calculations for the doubly magic SD configuration [22,22].

built on the large SD shell gaps at $N, Z = 30$ corresponding to two $f_{7/2}$ holes and two $g_{9/2}$ particles in both the proton and neutron subsystems (the [22,22] configuration in the notation of Fig. 3) and represents the doubly magic SD core in the $A \sim 60$ mass region. The occurrence of the large energy gap shown in Fig. 3(a) (which also appears in the CRMF calculations) is supported by the very strong population of this SD band.

In Fig. 3(b) the experimental levels of ^{60}Zn are shown relative to the same reference and are compared with the CN and CRMF calculations for the [22,22] SD configuration (normalized to the experimental 24^+ state). At high spin, where the neglect of pairing is valid, the agreement between experiment and theory is excellent, with the CRMF calculations providing a better description of the highest-spin states [19]. At intermediate rotational frequencies ($\hbar\omega \sim 0.9$ MeV), the dynamic and kinematic moments of inertia of this SD band have pronounced upbends that are interpreted as manifestations of the alignment of the $g_{9/2}$ protons and neutrons. This alignment indicates the importance of pairing in the low-spin SD states and accounts for the low-spin divergence of the calculations and data in Fig. 3(b).

The linking transitions observed in ^{60}Zn account for only $37 \pm 3\%$ of the decay-out intensity. It can also be noted from the intensities of the γ rays in the ^{60}Zn ground band in Fig. 1(a) that much of the unobserved decay-out intensity bypasses the yrast 8^+ and 6^+ states and feeds into the ground band at the 4^+ and 2^+ levels. These observations indicate that the majority of the decay-out intensity is fragmented over a large number of weak multistep pathways and, at first, suggest that the statistical decay-out model [7] used in the $A \sim 190$ mass region might also provide a successful description of the decay out of the ^{60}Zn SD band. One striking difference between these mass regions, however, is that all of the observed linking transitions in ^{60}Zn are assigned stretched-$E2$ character, whereas the decay out of SD bands in the $A \sim 190$ region is dominated by the $E1$ transitions expected in a statistical decay process. Although stretched-$E2$ decay-out transitions have been observed for a number of highly deformed bands in Nd isotopes [8], in these nuclei a considerable mixing of the highly deformed ($\beta_2 \sim 0.3\text{--}0.4$) and ND ($\beta_2 \sim 0.2\text{--}0.3$) bands is understood in terms of their similar deformations and the absence of a well-defined barrier between these shapes at the decay-out point. In ^{60}Zn, the deformation change is larger and the observation of the SD band to 4.328 MeV above the yrast line suggests a substantial barrier between the ND and SD minima, as in the $A \sim 190$ region. A weak mixing of the ND and SD states and a statistical decay out in which $E1$ transitions compete favorably would thus be expected. It should be noted, however, that the suppression of isoscalar dipole transitions in $N = Z$ nuclei may influence the competition between $E1$ and $E2$ decay-out transitions in ^{60}Zn.

Additional information about the decay-out process in ^{60}Zn can be obtained from transition strengths. If the mean Q_t of 2.75 $\pm$ 0.45 e b is used to estimate the in-band strength during the decay-out process, the measured branching ratios give $B(E2)$'s of 0.8(2) and 0.04(2) Weisskopf units (W.u.) for the 3656 and 5464 keV linking transitions and, assuming stretched-$E2$ character, a decay-out $B(E2)$ of 0.2(1) W.u. for either order of the 3496 and 3344 keV γ rays. If a γ-ray energy of 900 keV and the upper limit of $\sim$4% of the SD band intensity are assumed for the unobserved $8^+ \rightarrow 6^+$ SD transition, a lower limit of 0.01 W.u. is obtained for the 5810 keV transition. All of these $B(E2)$ values are much larger than the upper limit of $\sim 10^{-4}$ W.u. (before correcting for the weak SD/ND mixing amplitudes) set on the decay-out $E2$ strengths in ^{194}Pb [5]. Although in a statistical description of the decay-out process the mixing between SD and ND states, and hence the degree to which the decay-out transition strengths are suppressed, depends strongly on the height (and shape) of the potential energy barrier separating the SD and ND wells, we note that the "large" $B(E2)$ of 0.8(2) W.u. for the 3656 keV linking transition is particularly difficult to reconcile with a statistical decay-out model.

The important role of pairing in the decay-out process for SD bands in heavier nuclei has been discussed by a number of authors [20]. In ^{60}Zn, the doubly magic [22,22] SD configuration and the ground-band configuration differ only by the movement of a pair of protons and a pair of neutrons from the $f_{7/2}$ to the $g_{9/2}$ orbital. The mixing of these configurations in the presence of pairing correlations at low spin is thus expected to be more significant than in heavier nuclei where the SD and ND configurations differ by the rearrangement of a substantial number of nucleon pairs. Clearly, a detailed theoretical study of the decay out of $A \sim 60$ SD bands which includes a full treatment of pairing correlations is required to determine if such pairing-mediated configuration mixing can account for the decay-out properties observed in ^{60}Zn.

In summary, we have observed the doubly magic SD band in the $N = Z$ nucleus ^{60}Zn. Linking transitions connecting this band to the yrast line provide the first spin, parity, and excitation energy measurements for $A \sim 60$ SD states. The stretched-$E2$ character and relatively large $B(E2)$ values of the linking transitions suggest a nonstatistical decay-out mechanism. Future experimental studies of the decay out of SD bands in $A \sim 60$ nuclei, as well as theoretical studies of the decay-out process tailored specifically to this mass region, will undoubtedly lead to a more complete understanding of both superdeformation in these light nuclei and the decay out of SD bands in general.

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