Evidence for Collective Oblate Rotation in $N = Z$ ^{68}Se

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A γ-ray spectroscopic measurement of the $N = Z$ nucleus ^{68}Se has been made following the ^{12}C(^{58}Ni, $2n$) reaction at 185 and 220 MeV using Gammasphere and the Argonne Fragment Mass Analyzer. Despite a very low production cross section of 200(50) μb, two distinct rotational bands were found; the ground state band consistent with oblate collective rotation, and an excited band consistent with prolate rotation. These observations support long-standing predictions that nuclear ground states with substantial oblate ($\beta_2 \sim -0.3$) deformation should exist in this region.

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Shape coexistence in nuclei has been found throughout the periodic table. From cluster structure in light nuclei to fission isomers in the heaviest, a wide variety of shapes have been theoretically predicted and experimentally observed, with configurations of different shapes often coexisting in the same nuclide. One feature, which is not trivially explained, is the rare occurrence of oblate shaped configurations when compared to the much more frequent occurrence of prolate shapes. Considerations affecting the shape of the nuclear ground state as a function of N and Z include both macroscopic (liquid drop) and microscopic effects such as the energy dependence of single particle orbitals as a function of the sign and magnitude of the deformation. Interaction effects of valence particles both with the core and with each other can also play a role. Many of these effects are symmetric in the sign of the deformation, suggesting that prolate and oblate ground states should occur with approximately equal frequency. More complete experimental information on the occurrence of oblate shapes is clearly required to provide a sound basis for understanding why they are rare. Extending shape determinations to nuclei far from stability where oblate ground states are predicted is the central motivation for the present work. Part of the lack of knowledge about oblate nuclei is experimental, as direct quadrupole moment measurements are difficult for short-lived states, and so most shape determinations are inferred indirectly from the study of rotational bands which are used to quantify the deformed configurations. In the case of collective oblate rotation perpendicular to the symmetry axis, the moment of inertia is lower than that for all other shapes, so the rotational band rapidly becomes energetically unfavored and difficult to observe. To best study collective oblate rotational bands a tightly bound oblate ground state is desirable, with competing collective configurations which are much less bound and with a low density of other noncollective states which could mix and dilute the collective motion. Such a situation may occur in light selenium nuclei.

The nuclei of interest lie very far from stability, so no direct determinations of the sign of any quadrupole moments have been made in this region. However, by studying band structure, one of the first cases of low-lying shape coexistence in nuclei was found in the selenium isotopes [1]. Here, vibrational-like spherical configurations were found to coexist with well-deformed prolate shapes, which become yrast at high spin. A great deal of theoretical and experimental work has been dedicated to measuring and understanding this coexistence [2,3]. A key outstanding prediction [2,4–8] is that the $N = Z = 34$ nucleus ^{68}Se should have a tightly bound oblate ground state with substantial deformation ($\beta = -0.27$), stabilized by a large gap in the oblate level sequence at $N, Z = 34$, and also a prolate minimum ($\beta = +0.27$) which evolves at low spin. Despite numerous experiments, only a few γ-ray transitions have been previously identified in ^{68}Se [8,9], so the issue of shape could not be properly addressed. In this Letter we present results from an experiment aimed at observing rotational bands built on these configurations and measuring their properties through γ-ray spectroscopy. Such detailed measurements of nuclei very far from stability are at the sensitivity limit of current techniques.

Studying $N = Z$ nuclei beyond the fp shell is difficult as the nuclei lie near the proton drip line and their production cross sections in all nuclear reactions are small, typically $<10^{-3}$ of the nuclear interaction cross section. We have chosen the ^{12}C(^{58}Ni, $2n$)^{68}Se fusion reaction at 185 and 220 MeV and the Daresbury technique [10] for isolation of the selenium γ rays. $A = 68$ nuclei were separated from other reaction productions using the Argonne Fragment Mass Analyzer (FMA), then stopped in an ion chamber, where the atomic number could be determined through energy loss. Gamma rays were measured in

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Gammasphere, consisting of 101 70% Compton suppressed germanium detectors. ^{68}Se was produced with a cross section of 200(50) μb at 220 MeV. The first-level trigger condition consisted of all events with one or more detected γ rays and a coincident particle crossing the FMA focal plane within 1 μs. Data at 220 MeV were collected for 55 h with a 0.4 pnA beam and a 600 $\mu g/cm^2$ target. Approximately 2×10^5 ^{68}Se γ events were collected, about half of which had more than one coincident γ ray. The lower beam energy only populated bands to $J \approx 4\hbar$. Considerable care was required in the analysis to subtract time-random coincidence events and remove those events which were improperly characterized in the ion chamber [10]. Some results are shown in Fig. 1; in Fig. 1(a) the mass $A = 68$ gated spectrum is presented, dominated by ^{68}Ge γ rays with ^{68}Se indiscernible, whereas in Fig. 1(b) the best ^{68}Se γ-ray spectrum is shown, with Z gating and time-random subtraction. From the analysis of the angle dependence of the γ emission, intensities and multipolarities could be extracted. The ^{68}Se-γ-γ coincidences which were collected [Fig. 1(c)] were essential for construction of the decay scheme. The population of the nucleus at low spin was critical for tracing yrast and nonyrast structures.

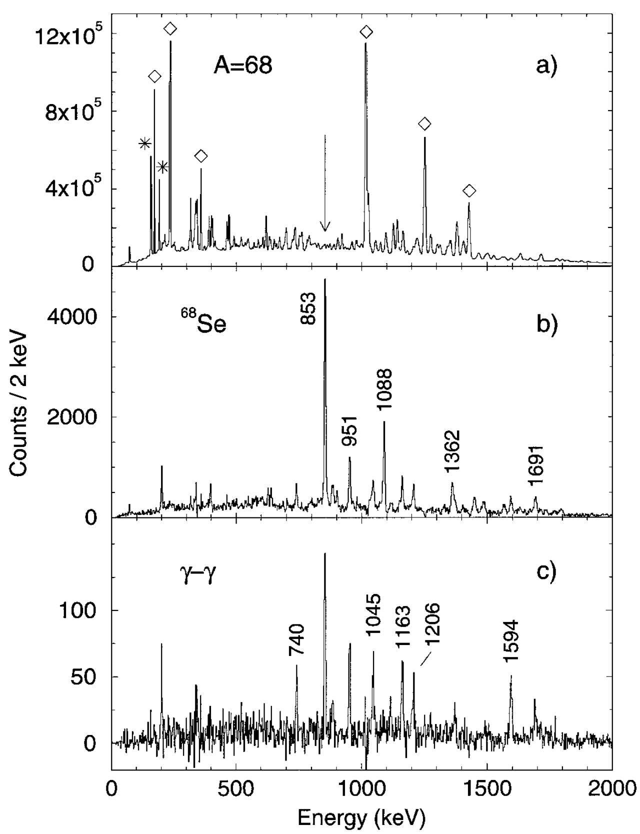

FIG. 1. Selected γ-ray spectra from this experiment. (a) shows a mass $A = 68$ gated spectrum. ^{68}Ge (◇) and ^{68}As (∗) transitions are clearly visible, but ^{68}Se is not discernible. (b) is mass and Z gated and time random subtracted and has only γ rays associated with ^{68}Se. (c) shows γ-γ coincidence data gated on 951, 1045, and 1163 keV transitions.

A synopsis of the results is given in Fig. 2. Two distinct bands are apparent. Their kinematic moments of inertia are shown in Fig. 3, compared to neighboring selenium nuclides.

Three experimental features suggest oblate deformation for the ^{68}Se ground state band. In nuclei, the measured moment of inertia is always much lower than that of the corresponding rigid shape because of the strong influence of pairing, which, at spin $J = 0$ usually reduces the measured moment to about half its rigid value for well-deformed nuclei and to the few percent level in nuclei near shell closures. The two cases can be distinguished as the deformed nuclei have rotational bands with moments of inertia which vary smoothly with spin and enhanced electromagnetic decays. With increasing angular momentum, and the associated reduction in pairing, nuclei in the mass 80 region were found to approach their rigid-body value [11]. The ground state band in ^{68}Se has a very low moment of inertia which changes smoothly with spin (Fig. 3) as is expected for a rotating oblate shape. For an $A = 68$ nucleus, with $\beta = -0.27$, the rigid body value is 14.3 MeV^{-1}, and the ground state band is found to slowly rise from 45% to 77% of this value between spin $J = 2$ to 10. Further, the ^{68}Se ground state band shows no evidence for rotational alignment arising from pair-breaking up to the highest observed rotational frequency, $\hbar\omega = 0.875$ MeV. This is unusual for the heavier even-even nuclei in this region, which are all prolate or triaxial and exhibit particle

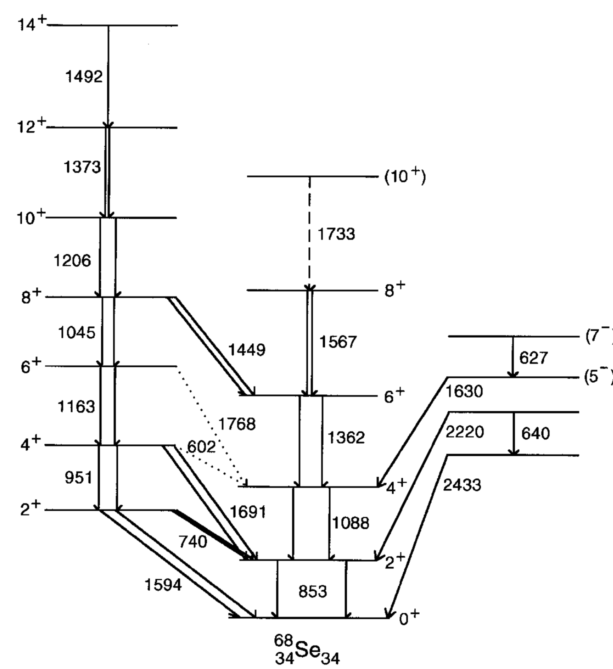

FIG. 2. The decay scheme of ^{68}Se constructed from this work. γ-ray energies are rounded to the nearest keV due to large Doppler shifts arising from the nuclei recoiling at $v/c = 0.069$. The widths of the arrows reflect relative intensities of transitions. Transitions marked (···) were observed in the ^{68}Se gated singles spectra but were too weak for rigorous coincidence placement.

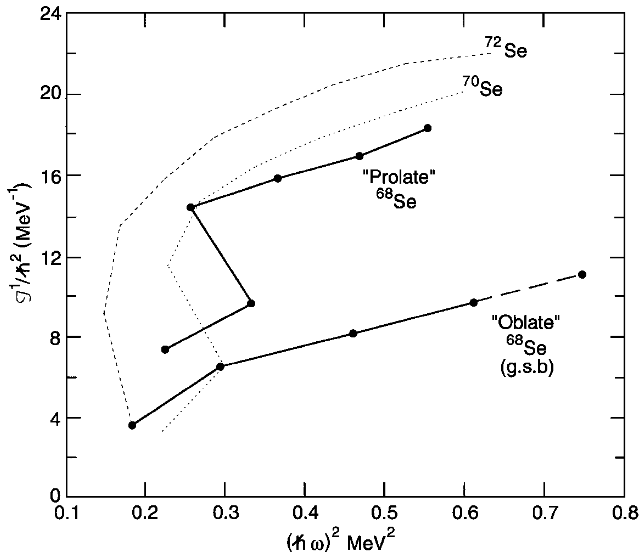

FIG. 3. The kinematic moment of inertia of the two bands in ^{68}Se compared to the yrast bands of ^{70}Se ($\cdots$) and ^{72}Se (---).

alignments near $\hbar\omega \sim 0.5$ MeV. However, it is a feature expected for high-j, high-K orbits in oblate nuclei, where the crossing of the ground state band by an "s band" is not energetically favored. We performed a cranked shell model calculation which indicated that for oblate shapes, particle alignment should be very gradual, and the first crossing should not occur until $\hbar\omega \sim 1.0$ MeV. Finally, the sign of the quadrupole moment of a nucleus can often be inferred from the properties of bands in neighboring odd-A nuclei. In ^{69}Se, a band based on the intruder $g_{9/2}$ orbital has been inferred to be oblate deformed, based on measurements of the sign of the $E2/M1$ mixing ratio of the lowest band member [12]. Thus, the ground state band of ^{68}Se has all the characteristics expected of a rotating oblate shape. It is worth noting parenthetically that ^{68}Se was originally suggested to be a candidate "bubble nucleus" with a low-density interior [13]. Were this the ground state configuration, the transfer of mass to large radius would lead to bands with enhanced, not diminished, moments of inertia.

In contrast, the excited band has the characteristics of the many prolate bands known in the region. For a rigid nucleus with $A = 68$ and prolate deformation ($\beta = +0.27$) the moment of inertia is 17.2 MeV^{-1}, 20% higher than for an oblate shape, qualitatively consistent with our observation of the low-spin part of the bands shown in Fig. 3. The excited band has a moment of inertia which is always larger than the ground state band and has a sharp backbend at $\hbar\omega = 0.57$ MeV. The alignment partially matches the predictions of [4,8] and our cranked calculations for a prolate configuration. In Ref. [4] a gradual alignment of protons at low frequency, centered at $\hbar\omega = 0.45$ MeV followed by a sudden alignment of neutrons at $\hbar\omega = 0.50$ MeV was predicted. We find a gain in alignment, about $4\hbar$, similar to that measured for $(g_{9/2})^2$ aligned configurations measured in neighboring nuclei, but half that which would be expected for simultaneous alignment of protons and neutrons. However, there seem to be other inconsistencies in high-spin alignment in prolate selenium and krypton nuclei which need resolving as a separate issue. At high spin, above the alignment region, ^{68,70,72}Se show similar characteristics, with rather constant moments of inertia, which increase with mass faster than the expected $A^{5/3}$ dependence. This is consistent with the predicted increase in deformation with mass of $\beta = +0.27$, 0.30, and 0.32 driven increasingly strong by the prolate shell gap at $N = 38$. Thus, the excited band has characteristics expected of a rotating prolate shape.

The close proximity of the $J = 8$ states, separated by only 119 keV, allows the degree of band mixing to be quantified using a simple two-level mixing approach. It is clear from Fig. 3 that the interaction has not strongly perturbed the positions of the $J = 8$ states. This is most clear in the oblate band, where the $J = 8$ state lies very close to a smooth interpolation between the $J = 6$ and $J = 10$ states. A parametrization of this band indicates that the interaction has elevated the $J = 8_2$ state by 8 ± 4 keV. This corresponds to an interaction strength of $V_{\mathrm{op}} = 20 \pm 10$ keV. The γ-decay pattern of the two $J = 8$ states appears to be quite different, the yrast state having near-equal in-band and out-of-band decays, and the yrare state having an out-of-band decay of $<10\%$. However, the branching ratios are strongly biased by the relative phase spaces, and a calculation of the $B(E2)$ ratios indicates that the in-band to out-of-band rates are also consistent with mixing with $V_{\mathrm{op}} = 20$ keV if the bands are equally collective. The $J = 4$ and 6 branchings are also consistent with a small interaction, which is less perturbing as the states lie further apart. For $J < 2\hbar$ the situation is less clear due to our failure to identify an excited $J^\pi = 0^+$ bandhead. The modest interaction between the yrast and excited band further indicates their structure is quite different, as may be expected from two configurations of different shape with a significant barrier between them, and the gamma branching ratios indicate the bands have similar transitional quadrupole moments, as expected from the predicted shapes of $\beta_2 = +0.27$ and -0.27.

Positive parity bands can occur in deformed nuclei due to β- and γ-collective shape vibrations, and should be considered as an alternative interpretation of our data. Several observables should, in principle, resolve the difference between vibrational excitations and separate potential minima. In well-deformed nuclei the β- and γ-vibrational bands have moments of inertia similar to their ground state bands. This is clearly not the case here. β-shape vibrations and two-shape nuclei should have low-lying $J^\pi = 0^+$ bandheads which would probably be isomeric. Unsuccessful searches for isomers in ^{68}Se have been made [8,9,14]. A $J^\pi = 0^+$ isomer decaying by internal conversion could easily have been missed in the present experiment, since a change in charge state during the 400 ns flight time through the FMA would have prevented the recoil reaching the focal plane and generating an event trigger. However, very low-lying $J = 0$ isomers are known in this region, including a recently discovered shape isomer in ^{74}Kr [15]. Clearly, a dedicated isomer search of ^{68}Se would be useful. A $K = 2$ γ-vibrational band should have odd-spin members with a $J = 2, 3, 4, 5$ sequence. In neighboring ^{64}Ge, a candidate $J = 3, 5$ cascade is known which is consistent with maximal γ softness [16]. We could not find a corresponding set of states in ^{68}Se, at least indicating reduced γ softness. This observation is supported by the decay of the second $J = 2$ state in these two nuclei, which lie at similar excitation energies. In ^{64}Ge the decay is mainly to the $J = 2$ state and weakly to the ground state, whereas in ^{68}Se the situation is reversed. If one assumes that the decays are of pure $E2$ multipolarity, the $B(E2; 2_2 \to 2_1)/B(E2; 2_2 \to 0_1)$ ratio is lower in ^{68}Se by a factor of 16, again indicating reduced γ softness. However, the $J = 2 \to 2$ decays have a dipole $M1$ component which needs to be subtracted, as it could be different in the two nuclei. Because of poor statistics and low alignment this subtraction cannot be done with sufficient precision to allow the relative γ softness to be reliably quantified. Theory also predicts this change along the $N = Z$ line: Comparing the (β, γ) potential energy surfaces [8,10], ^{64}Ge has a valley across the triaxial landscape, allowing free γ-shape vibration, whereas ^{68}Se has distinct oblate and prolate minima, each of which should support a rotational band. Thus, while a two-minima potential energy surface is more consistent with our measurements, a vibrational interpretation cannot be rigorously excluded.

In conclusion, we have produced the $N = Z$ nucleus ^{68}Se and made detailed spectroscopic measurements. Two distinct rotational bands were found, the ground state band having properties consistent with collective oblate rotation, and the excited band having characteristics consistent with prolate rotation. Calculations [2,4–8] suggest the lowest barrier between oblate and prolate shapes lies in the triaxial plane at constant quadrupole deformation ($\beta = 0.27$) with a height of 250–650 keV. The bands found in this work interact rather weakly indicating the barrier may be higher. Our observations support the long-standing predictions of a tightly bound oblate configuration, with a separate prolate configuration about 600 keV less bound. The conditions for supporting sizable oblate deformation seem to be just satisfied, with enough particles in the shell to support considerable deformation, polarized by a large gap in the oblate single particle sequence for both protons and neutrons at $N, Z = 34$. However, this stabilization is delicate; removal of particles leads to ill-defined shapes of low collectivity, as found in germanium and zinc nuclei at low spin, while the addition of particles builds collectivity which is driven by bulk effects and the $N, Z = 38$ shell gap to the more normal prolate shapes found in strontium and zirconium isotopes. Only in the light lead-mercury region and in the neutron deficient iodine region are similar balances found although with considerably smaller deformations. We hope these observations will reinvigorate the discussion of the conditions required to support substantial oblate deformation in general and encourage self-consistent microscopic calculations with the projected Hartree Fock [17] or Monte Carlo shell model [18].

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