Measurement of the Sign of the Spectroscopic Quadrupole Moment for the 2_1^+ State in ^{70}Se: No Evidence for Oblate Shape

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Using a method whereby molecular and atomic ions are independently selected, an isobarically pure beam of ^{70}Se ions was postaccelerated to an energy of 206 MeV using REX-ISOLDE. Coulomb-excitation yields for states in the beam and target nuclei were deduced by recording deexcitation γ rays in the highly segmented MINIBALL γ-ray spectrometer in coincidence with scattered particles in a silicon detector. At these energies, the Coulomb-excitation yield for the first 2^+ state is expected to be strongly sensitive to the sign of the spectroscopic quadrupole moment through the nuclear reorientation effect. Experimental evidence is presented here for a prolate shape for the first 2^+ state in ^{70}Se, reopening the question over whether there are, as reported earlier, deformed oblate shapes near to the ground state in the light selenium isotopes.

A remarkable property of the nucleus is its ability to assume different configurations giving energy minima corresponding to different shapes of the mean field. It is often claimed that the presence of low-lying excited 0^+ states in even-even nuclei is strong evidence for such shape coexistence, since it is difficult to account for the presence of such states otherwise [1,2]. Arguably the most striking example of this is the case of ^{186}Pb [3], where both the first and second excited states have a spin parity of 0^+. These states were interpreted as the bandheads of oblate and prolate rotational configurations, in close competition with the spherical ground state expected for this singly magic ($Z = 82$) nuclear system. The region close to the $N = Z$ line from ^{56}Ni to ^{80}Zr is believed to be one of rapidly changing nuclear shape. At the upper end of this region, strongly prolate deformed shapes are found: ^{80}Zr is

suggested to have $\beta_2 \sim 0.4$ on the basis of the high moment of inertia [4], and a strongly prolate ground state, consistent with $\beta_2 \sim 0.4$, has recently been established from the Gamow-Teller strength distribution in ^{76}Sr [5]. For the midshell nuclei near $N = Z = 34$ and 36, large shell gaps exist for protons and neutrons at both prolate and oblate shape, which would favor shape coexistence near the ground state. In the light krypton isotopes, $^{72-78}$Kr, a low-lying excited 0^+ state is observed. There is good experimental evidence that this state has an oblate intruder configuration, and it most likely becomes the ground state in ^{72}Kr [6,7]. An analysis of the mixing of this state with the ground state, through consideration of their perturbed energies and the excited state lifetime, suggests an oblate ground state for ^{72}Kr [6], while the recently measured $B(E2; 0^+ \rightarrow 2^+)$ value in this nucleus,

using intermediate-energy Coulomb excitation, is consistent with theoretical calculations that assume an oblate ground state [8].

The situation regarding the light selenium isotopes is not so clear. The unusual behavior of the low-lying states of ^{72}Se, including an excited 0^+ state below 1 MeV reported over 30 years ago by Hamilton *et al.* [9], was interpreted in terms of the coexistence of near-spherical and well-deformed prolate shapes. Such an interpretation receives considerable support from lifetime measurements [10,11], which show a relatively weak $B(E2)$ value for the $2^+ \to 0^+$ transition in ^{72}Se and $B(E2)$ values 2 or 3 times larger (and consistent with members of a well-deformed rotational band) for higher spin states.

The behavior of the ground-state rotational band in ^{70}Se is strikingly different to that of neighboring ^{72}Se [12–14]. The low-lying yrast sequence is far from the expectations of a simple rotational band; indeed, plotting the kinematic moment of inertia shows a strong structural change around $I = 6$. Lifetime measurements reveal almost the opposite behavior to ^{72}Se with a comparatively strong $B(E2)$ for the $2^+ \to 0^+$ transition, which reduces successively to a third of this value for the $6^+ \to 4^+$ transition [11]. Woods-Saxon cranking [13], Yukawa macroscopic-microscopic [15], and microscopic calculations [16] predict that the most energetically favorable shape for the ground state is oblate.

The properties of the light selenium nuclei have taken on topical interest with the recent efforts dedicated toward studying the light krypton nuclei, and the results from the work by Fischer *et al.* indicating collective oblate rotation in ^{68}Se [17]. This interpretation rests on the low moment of inertia of the ground-state band, suggested to be consistent with an oblate deformed shape. A low moment of inertia could also, however, be consistent with a weakly deformed prolate shape and is an observable which can be perturbed by other factors such as mixing. No evidence for a low-lying 0^+ state is reported, which would be strong evidence for shape coexistence, nor is such a state known in the rather well-studied nucleus, ^{70}Se, where the lowest suggested state with a spin/parity of 0^+ is at 2012 keV [14]. It is interesting to note that the moment of inertia of the ground-state band in ^{70}Se mimics very closely that of the suggested oblate band in ^{68}Se at low spin, and the prolate band above $I = 6$ (see Fig. 3 of Ref. [17]).

The key question which emerges, therefore, is whether there is any clear evidence for a well-deformed oblate minimum in the light selenium nuclei. An answer may be obtained by making use of the reorientation effect in low-energy Coulomb excitation to infer shapes. This technique has been used in tracing transitions from prolate to oblate deformation across the middle of the *sd* shell (revealing the oblate shape of ^{28}Si [18]) and more recently investigating deformed intruder states in ^{70}Ge [19]. With the advent of relatively intense radioactive-ion beams, this method can

now be used to probe the structure of nuclei far from stability. In this Letter, we report such a reorientation measurement using a radioactive beam of ^{70}Se accelerated by the REX-ISOLDE facility at CERN. This has allowed the sign of the electric quadrupole diagonal matrix element of the first excited 2^+ state in ^{70}Se to be measured, from which the shape of this nucleus in its first excited state can be directly inferred.

With a few exceptions, isobaric contamination is a common feature of ISOL beam experiments [20]. To produce an isobarically pure beam of ^{70}Se, the particular stability of the selenium carbonyl molecule was exploited. The ^{70}Se atoms were produced by spallation in a ZrO_2 fiber target bombarded by $\sim 2 \times 10^{13}$ 1.4-GeV protons/s from the CERN PS Booster. The ^{70}Se atoms diffused to the target surface, and readily formed SeCO molecules at the CO partial pressures found in the target-ion source [21]. The ^{70}Se^{12}C^{16}O molecules were then ionized in an ISOLDE-type FEBIAD ion source [22] to singly charged ^{70}SeCO$^+$, accelerated to 30 keV, separated in a magnetic sector field according to A/q ($A = 98$), and delivered to a Penning trap, REX-TRAP, at a rate of around 6×10^5 ions/s at the entrance. Inside REX-TRAP, the singly charged ions were accumulated and cooled, being kept in the trap by a relatively flat potential between entrance and exit barriers. At intervals of 58 ms, the potential barrier was lowered allowing bunches of cooled ions to escape into an electron-beam ion source, REX-EBIS. Here, the 1^+ molecular ions were broken up by a high-density electron beam, allowing the selenium ions to undergo further charge breeding. Almost 90% of the $q = 19^+$ ions were extracted within 100 μs, and mass separated according to their mass/charge ratio prior to injection into a linear accelerator, REX-LINAC [23]. The ^{70}Se beam at an energy of 206 MeV with an average intensity of about 10^4 ions/s was delivered to a secondary Coulomb-excitation target comprising a 2.0-mg/ cm^2 ^{104}Pd foil. The beam was dumped downstream of the target in a tantalum beam-stopper, viewed by a germanium detector. This detector revealed only γ-decay lines in the β-decay products of ^{70}Se ($T_{1/2} = 41.1$ min): ^{70}As and ^{70}Ge. It was estimated that the accelerated beam contained less than 1% of $A \approx 70$ impurities since such contaminants would have had to pass through two very different mass/charge separations. The Coulomb-excitation target was surrounded by the highly efficient, highly segmented MINIBALL array of high-purity germanium detectors [24] resulting in a total efficiency of about 7% for 1.3-MeV photons, including reconstructed γ-ray events from cluster addback [20]. The array comprised eight triple cluster detectors with each crystal sixfold segmented, giving rise to 144 discrete detector elements. With a target-detector distance of around 12 cm, the crystals in the array covered polar angles in the laboratory from around 35° to 80° and 105° to 150°. The scattered beam and recoiling target particles were detected in a double-

sided 500-μm thick silicon CD detector [25]. The CD detector is subdivided into four quadrants. Each front-face quadrant is further segmented by 16 annular strips and the respective back-face quadrant by 24 sector strips. The detector covers a range of forward angles in the laboratory between $16.2°$ and $53.3°$.

The kinematics of the reaction were such that it was not possible to distinguish scattered projectile and recoiling target events via their energy as a function of laboratory angle. Coincidence spectra were therefore generated without labeling the particles recorded in the CD detector; a small component of $^{22}Ne^{6+}$ in the beam from the REX-TRAP buffer gas is removed by particle-energy gating. Figure 1 shows γ-ray energy spectra following 62 h of data collection corresponding to particle-γ coincident events arriving within the prompt event window for projectile- and targetlike species. The angular dependence of the differential cross section for excitation of the lowest 2^+ state in either scattered or recoil nucleus is such that the optimum line shapes were obtained assuming that γ rays are emitted from the detected particles in the case of ^{70}Se [see Fig. 1(a)] and, in the case of ^{104}Pd assuming no Doppler shift [see Fig. 1(b)]. The numbers of counts recorded for the $2_1^+ \rightarrow 0_{gs}$ transition in ^{70}Se and ^{104}Pd were, respectively, 139 ± 13 and 540 ± 40. For the latter, the yield comes mostly from slowed ($\beta < 1.5\%$) or stopped recoils. In-flight ($\beta > 0$) and stopped ($\beta = 0$) contributions to the Coulomb-excitation photopeaks were accounted for in the peak integration, the result of which is independent of any Doppler correction procedure.
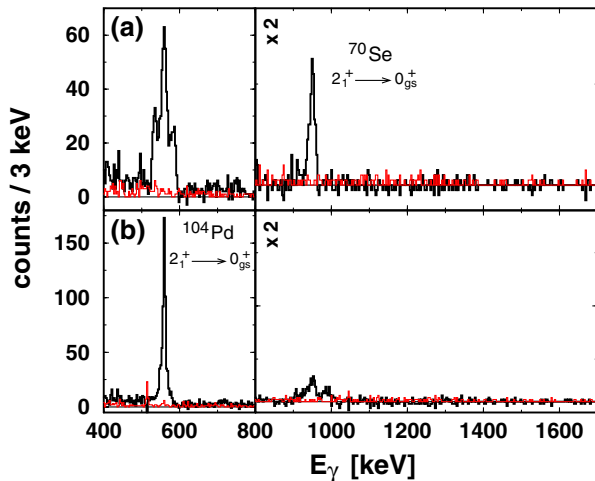
At the bombarding energy employed in this experiment, excitation of both projectile and target can occur following collisions at surface distances greater than ~ 7 fm. In this case, very little excitation is expected ($<2\%$) of states other than the lowest 2^+ in each nucleus, and the population of the 2_1^+ state relative to that of the ground state can be calculated knowing the magnitude of the $E2$ matrix element coupling the ground state and the 2_1^+ state, the diagonal $E2$ matrix element of the 2_1^+ state, and the sign of the diagonal matrix element, with small corrections arising from couplings to higher excited states. It follows that the yield of the $2_1^+ \rightarrow 0_{gs}^+$ transition in ^{70}Se relative to that of the corresponding transition in ^{104}Pd can be deduced for assumed values of ^{70}Se matrix elements provided that the ^{104}Pd matrix elements are known. The multiple Coulomb-excitation code GOSIA [26] was used to carry out the calculations. To determine the yield of the $2_1^+ \rightarrow 0_{gs}^+$ transition in ^{104}Pd, the matrix elements were obtained from $B(E2)$ [27] and quadrupole moment [28] measurements. All significant couplings to states up to the second excited 2^+ state in ^{104}Pd, in particular, the sign ambiguity in the triple product of $E2$ couplings between the ground state, 2_1^+ state, and 2_2^+ state, were taken into account. For ^{70}Se the transitional and diagonal matrix elements, $\langle 2_1^+ ||E2|| 0_{gs}^+ \rangle$ and $\langle 2_1^+ ||E2|| 2_1^+ \rangle$ were treated as unknown variables. All significant couplings between states up to the first and second excited 4^+ states in the ground-state band and the γ band were taken into account, based on previous lifetime measurements [11] where possible, or estimated using the
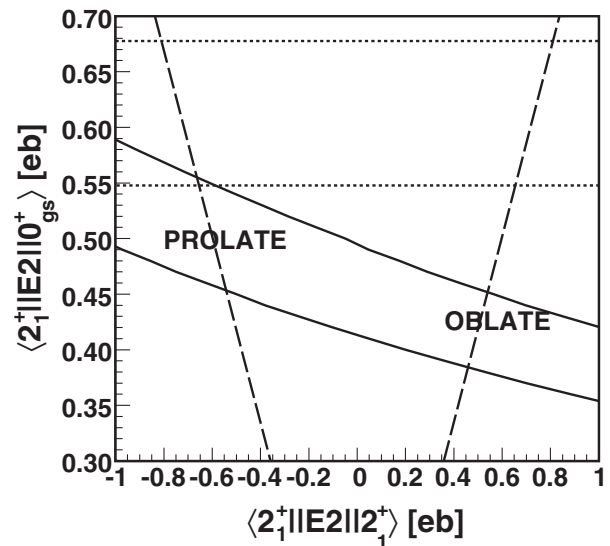

FIG. 1 (color online). Coincident, random-subtracted γ-ray energy spectra observed following the reaction $^{104}Pd(^{70}Se, ^{70}Se^*)$ at $E_{\text{beam}} = 206$ MeV. The spectrum in (a) has been Doppler corrected assuming detection of ^{70}Se, while that in (b) is the uncorrected spectrum. The 945-keV transition in ^{70}Se and the 556-keV transition in ^{104}Pd are observed, corresponding to the $2_1^+ \rightarrow 0_{gs}^+$ transitions in these nuclei. The random spectrum having a time window equal to that of true coincidences is shown as a red (or gray) line.

FIG. 2. Variation of the transitional matrix element as a function of the diagonal matrix element for the 2_1^+ state in ^{70}Se. The two solid lines are the extreme values of these matrix elements consistent with the yield of the $2_1^+ \rightarrow 0_{gs}^+$ transition in ^{70}Se (see text). The horizontal dotted lines represent the 1-σ boundary for $\langle 2_1^+ ||E2|| 0_{gs}^+ \rangle$ derived from a previous lifetime measurement [11]. The rotational model values assuming a pure prolate rotor or a pure oblate rotor, are also given (dashed lines).

rotational model. In both cases, the γ-ray yield of the 945-keV transition in ^{70}Se and the 556-keV transition in ^{104}Pd in the experiment was then calculated by (i) integrating the bombarding energy dependence over the target thickness and integrating over the range of scattering angles corresponding to the acceptance of the CD detector for the (indistinguishable) target recoils and scattered beam, and (ii) taking into account the γ-ray angular distribution, including deorientation effects, for the response of the MINIBALL array.

We have measured the cross section for the $2_1^+ \rightarrow 0_{gs}^+$ transition in ^{70}Se by measuring its yield relative to ^{104}Pd, providing two extreme values $\pm\sigma$ from the mean value. The major contributions to the uncertainty in this quantity are from the statistical uncertainty in the measured yields, and from the systematic uncertainties in magnitudes and signs of matrix elements in ^{104}Pd. All other contributions, such as from the uncertainty in the measured relative γ-ray efficiencies and from the effect of higher state couplings in ^{70}Se, are much less significant. By varying the $\langle 2_1^+ || E2 || 0_{gs}^+ \rangle$ and $\langle 2_1^+ || E2 || 2_1^+ \rangle$ matrix elements (both signs in the latter case) in ^{70}Se, the two extremes of the loci for the two matrix elements were calculated using GOSIA, see Fig. 2. The effects of changing the signs and magnitudes (to $\pm\sigma$) of other matrix elements in ^{70}Se were also included, but found to be small. The 1-σ boundary in $\langle 2_1^+ || E2 || 0_{gs}^+ \rangle$ derived from an earlier lifetime measurement of 1.5(3) ps for the 2_1^+ state in ^{70}Se [11] is also shown in Fig. 2. The figure shows that to achieve consistency between the present measurement and the earlier lifetime measurement at the 1-σ level, requires $\langle 2_1^+ || E2 || 2_1^+ \rangle < -0.5 eb$. Such a value would imply a negative sign for the spectroscopic quadrupole moment and, hence, a prolate shape. Indeed, the measured Coulomb-excitation yield and the measured lifetime are also consistent with the rotational model prediction for the two matrix elements, expected for a deformation of $\beta_2 \approx 0.25$. There still remains a small probability ($<5\%$) that the reorientation matrix element is positive if the transition matrix element were 2σ below its adopted value. This ambiguity might be resolved by a more accurate measurement of the 2_1^+ lifetime.

As a validation of the present methodology, a short Coulomb-excitation run was performed under identical experimental conditions using a beam of the lightest stable isotope, ^{74}Se, obtained also by breaking a carbonyl molecule, simply by changing the A/q settings on the respective separators. Adopting a value for $\langle 2_1^+ || E2 || 2_1^+ \rangle$ from an earlier measurement [29], the measured yield implies a $B(E2; 0_{gs}^+ \rightarrow 2_1^+)$ value of $0.36(2)e^2$b^2 in agreement with the adopted value of $0.387(8)e^2$b^2 [30].

The present measurement favors the association of a modestly deformed prolate shape with the first 2^+ state in ^{70}Se. In a simplistic picture, if the 2_1^+ and 0^+ ground state in ^{70}Se had very different intrinsic structure and associated shape, then the transition matrix element connecting the states would be very strongly suppressed. As the matrix element is relatively large, the ground state of ^{70}Se is, most likely, prolate. Given the evidence presented for oblate shapes in ^{68}Se [17] and ^{72}Kr [6,8], and the theoretical predictions of an oblate ground state for ^{70}Se [13,15,16], it is perhaps surprising that the latter nucleus does not appear to have an oblate shape near the ground state. Further work is clearly needed, both to renew the search for low-lying 0^+ states in the light selenium nuclei, and to extend the methodology of the present work to the neighboring $N = Z$ nuclei, ^{68}Se and ^{72}Kr. The latter aspect will be extremely challenging given the very low yield (~ 100 times less than for ^{70}Se) of such nuclei at present ISOL facilities.

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