Inelastic Scattering of Polarized Protons and a Possible Hexadecapole-Shape Transition between the Light ^{74,76,78}Se and the Heavy ^{80,82}Se Isotopes

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The ground-state band up to the 4^+ state in the even $^{74-82}$Se isotopes was studied by inelastic scattering of polarized protons at 65 MeV. Both the cross-section $\sigma(\theta)$ and the analyzing-power $A(\theta)$ measurements leading to the 4^+ state in the light ^{74,76,78}Se isotopes show quite different shapes from those in the heavy ^{80,82}Se isotopes. Coupled-channels analyses show that both the $\sigma(\theta)$ and $A(\theta)$ distributions are well reproduced with a positive deformation parameter β_4 in ^{74,76,78}Se, but with a negative β_4 in ^{80,82}Se, indicating a hexadecapole-shape transition between ^{78}Se and ^{80}Se.

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The structure of nuclei, from Ge to Sr, with neutrons in the $1g_{9/2}$ shell has been a subject of extensive experimental and theoretical investigations in recent years, and many interesting transitional behaviors in the structure have been revealed[1]; especially the ground states of ^{74,76}Kr and ^{78,80}Sr have been suggested to be strongly deformed,[2-5] while ^{72,74}Se nuclei, which also have nearly 40 neutrons, were suggested to be spherical in their ground states and deformed in the first excited 0^+ states.[6] Of particular interest in connection with these suggestions is that the large prolate deformation ($\epsilon_2 \approx 0.4$) in the ground states of ^{78,80}Sr may be reasonably well understood theoretically by invoking a hexadecapole deformation ($\epsilon_4 \sim +0.06$) in addition to the quadrupole deformation.[3]

In this Letter we suggest that the hexadecapole degree of freedom also has an important effect on the structure of the even $^{74-82}$Se nuclei; in particular we find that both the cross-section angular distribution $\sigma(\theta)$ and the analyzing power $A(\theta)$ for the inelastic scattering of 65-MeV protons to the first 4^+ state (4_1^+) in the light nuclei, $^{74-78}$Se, have very much different shapes from those in the heavier nuclei, ^{80,82}Se. Coupled-channels analyses can well reproduce the observed distributions $\sigma(\theta)$ and $A(\theta)$ only by assuming the sign of the deformation parameter β_4 to be positive for ^{74,76,78}Se, but negative for ^{80,82}Se, thus indicating a hexadecapole-shape transition between ^{78}Se and ^{80}Se.

A polarized proton beam of 65 MeV from the azimuthally-varying-field cyclotron at the Research Center for Nuclear Physics, Osaka University, was used to measure the $\sigma(\theta)$ and the $A(\theta)$ distributions for the inelastic scattering of protons to the low-lying excited states in $^{74-82}$Se. The momenta of the inelastically scattered protons from enriched $^{74-82}$Se targets (77.8%, 96.88%, 98.58%, 99.45%, and 96.81%, respectively) were analyzed with the quadrupole–double-dipole–quadrupole magnetic spectrograph RAIDEN,[7] the overall energy resolution being 20–30 keV. Momentum spectra were analyzed with a peak-fitting program. The 4_1^+ states in ^{74,76,80}Se were well separated from the 2_2^+ and 0_2^+ states. The 4_1^+ states of ^{78}Se and ^{82}Se were, however, not resolved from the 0_2^+ and the 2_2^+ states, respectively (separation energies are 4 and 3 keV, respectively). The $\sigma(\theta)$ data for the excitation of the unresolved 4_1^+ and 2_2^+ states in ^{82}Se were obtained with the following procedure: The $\sigma(\theta)$ distributions for the 4_1^+ and 2_2^+ states in ^{82}Se were assumed to be of the same shape as those of the corresponding states in ^{80}Se, and the absolute

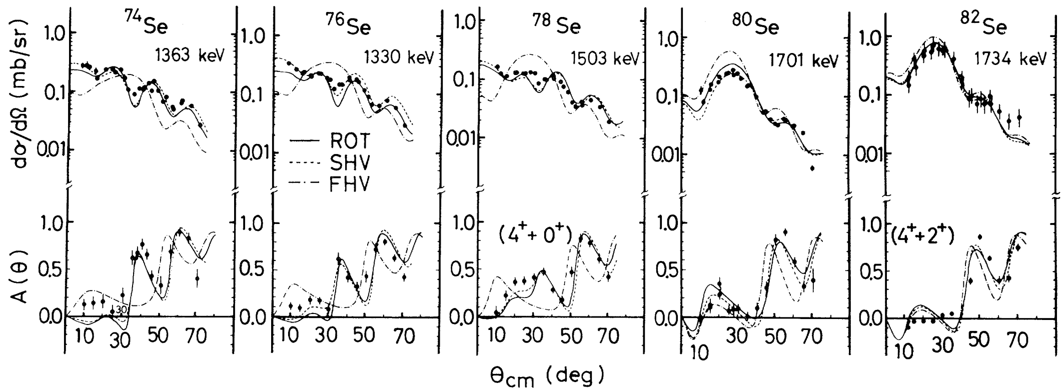

FIG. 1. The cross section $d\sigma/d\Omega$ and the analyzing power $A(\theta)$ for the 4_1^+ state in $^{74-82}$Se. Lines are CC predictions with three models described in the text.

values were determined so as to reproduce the unresolved, summed angular distributions by a linear combination of the two assumed distributions for the 2_2^+ and 4_1^+ states with a χ^2-fitting criterion. The ratio of the yield of the 4_1^+ state to that of the 2_2^+ state thus obtained for each angle was then used to resolve summed yields into individual distributions of the 2_2^+ and 4_1^+ states.[8] A similar procedure was also applied[8] to the unresolved 4_1^+ and 0_2^+ states in ^{78}Se.

The $\sigma(\theta)$ and the $A(\theta)$ data for the 4_1^+ state in $^{74-82}$Se thus obtained are shown in Fig. 1. The distributions $\sigma(\theta)$ and $A(\theta)$ for the 4_1^+ state in ^{74,76,78}Se are similar in shape to each other, while they are much different from those in the heavier isotopes ^{80,82}Se. In particular, $\sigma(\theta)$ for $^{74-78}$Se increases at forward angles (up to $\sim 8°$) and has small bumps at $\sim 20°$ and $\sim 32°$, in contrast to rather smoothly decreasing distribution $\sigma(\theta)$ at forward angles in ^{80,82}Se. The corresponding differences in $A(\theta)$ between the light $^{74-78}$Se and the heavier ^{80,82}Se are also seen clearly in the forward region.

The distributions $\sigma(\theta)$ and $A(\theta)$ for the 4_1^+ state in the light nuclei ^{74,76,78}Se cannot be reproduced with distorted-wave Born-approximation calculations which always predict shapes similar to the experimental distribution in the heavier nuclei, ^{80,82}Se. We performed coupled-channels (CC) calculations with several models: the axially symmetric rotational model (ROT) with 0_g^+-2_1^+-4_1^+ coupling, and the first- and second-order harmonic vibrational models (FHV and SHV) in which the 4_1^+ state consists of the mixing of two quadrupole-phonon and one hexadecapole-phonon states, and is coupled to both the 0_g^+ state and the one-quadrupole-phonon 2_1^+ state. The CC calculations were performed with the code ECIS.[9]

A set of optical-potential parameters evaluated recently[10] for a wide range of nuclear mass at the present incident energy was adopted as an initial set of parameters, and slightly varied to get the best fits to $\sigma(\theta)$ and $A(\theta)$ for the elastic scattering. With these parameters fixed, the deformation parameters β_2 and β_4 were varied to get the best fits to all the experimental $\sigma(\theta)$ and $A(\theta)$ data for the three relevant coupled states.

The calculated $\sigma(\theta)$ and $A(\theta)$ distributions for the 4_1^+ states are shown in Fig. 1 together with the experimental data. As seen clearly in the figure, the FHV model fails to reproduce the experimental data, while both the SHV and the ROT models reproduce well the overall trend of the distributions $\sigma(\theta)$ and $A(\theta)$.[11] The values of the deformation parameters β_2 and β_4 finally obtained are shown in Table I. The sign of the β_2 value is consistent with the sign of the quadrupole moment[12] for all the isotopes.[13] Of particular inter-

TABLE I. Deformation parameters β_2 and β_4 for the 2_1^+ and 4_1^+ states, respectively, in $^{74-82}$Se deduced from the present analyses. ROT denotes the axially symmetric rotational model, SHV the second-order harmonic vibrational model with one- and two-phonon mixing in the 4_1^+ state. Errors are estimated to be less than ±15% and ±30% for the β_2 and β_4 values, respectively.

^{A}Se	β_2		β_4	
A	ROT	SHV	ROT	SHV
74	0.256	0.269	0.019	0.017
76	0.267	0.281	0.014	0.012
78	0.255	0.256	0.002	0.001
80	0.194	0.196	−0.026	−0.034
82	0.155	0.163	−0.049	−0.050

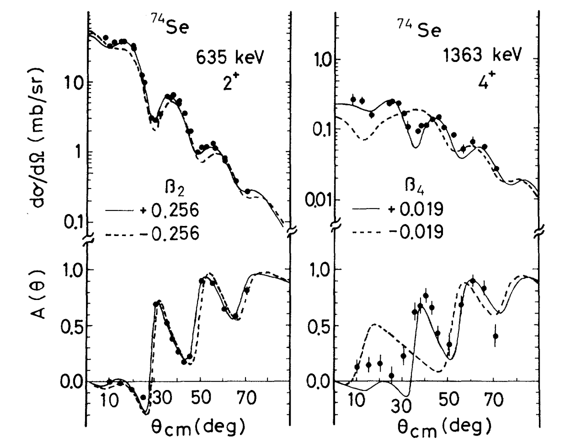

FIG. 2. The cross sections and the analyzing powers for the $2_1{}^+$ and the $4_1{}^+$ states in ^{74}Se. Lines are CC predictions with the axially symmetric rotational model.

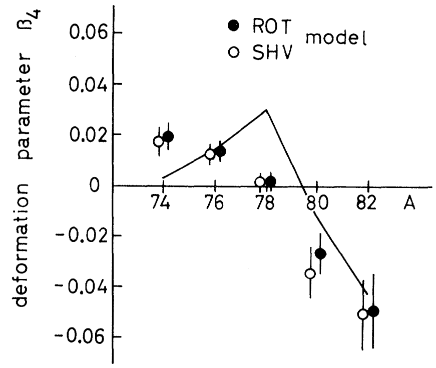

FIG. 3. Deformation parameters β_4 for the $4_1{}^+$ state in $^{74-82}$Se obtained from the present CC analyses with the ROT and the SHV models described in the text. The solid line is a prediction based on the Nilsson model with Harada's method (Ref. 15).

est are the signs of the deformation parameters β_4 which are positive in the light isotopes ^{74,76,78}Se but negative in the heavier isotopes ^{80,82}Se. The CC calculations with β_4 of the same magnitude but opposite sign to those adopted in the calculation in Fig. 1 are in definite disagreement with the experiment as shown, for example, in Fig. 2, where $\sigma(\theta)$ and $A(\theta)$ for the $2_1{}^+$ state in ^{74}Se are also shown for comparison.

Furthermore, the SHV and ROT models predict essentially the same β_4 in sign and magnitude for each isotope studied. It is worthwhile to mention that the straightforward meaning of the sign of the parameter is somewhat different between those models: In the rotational model, a nonzero β_4 value implies a static hexadecapole deformation in the ground state, while in the present second-order harmonic vibrational model, the sign of β_4 implies the definite relative sign of the hexadecapole to the quadrupole vibrations; thus such a vibration may be called a dynamical hexadecapole deformation associated with a transition, as is often used to treat vibrational as well as rotational motions in a unified way.[14]

It is interesting to note in connection with these observations that a theoretical prediction of the value of β_4 deformation in $^{74-82}$Se, based on the Nilsson model with Harada's method,[15] is in reasonable agreement with the experimental results regarding the trend of the change of β_4 values with the isotopes as shown in Fig. 3, thus suggesting a static hexadecapole deformation in the ground state of the isotopes $^{74-82}$Se. The onset of a static prolate deformation in $^{74-82}$Se has been suggested from[12] the negative quadrupole moment of the $2_1{}^+$ state and also from[16] the unusually large $B(E1)$ value of the lowest octupole vibrational state to the $2_2{}^+$ state in ^{74,76,78}Se. However, the recent results of the intraband $B(E2)$ values in the ground-state band and the level-energy systematics in $^{74-82}$Se are not always consistent with the axially symmetric rotational-model predictions,[6,17] requiring further investigations[18] to clarify the nuclear shape in detail in the low-lying states of $^{74-82}$Se.

In conclusion, the present results of the polarized-proton inelastic scattering strongly demonstrate that both the $\sigma(\theta)$ and the $A(\theta)$ measurements for the $4_1{}^+$ state in $^{74-82}$Se are very sensitive to the sign of the hexadecapole moment, as is the case in the scattering of vector-polarized deuterons.[19] The present analyses also clearly indicate that a static or dynamic hexadecapole-shape transition occurs between the light ^{74,76,78}Se and the heavy ^{80,82}Se isotopes. The results thus emphasize the important role played by the hexadecapole degree of freedom in the structure of the even $^{74-82}$Se nuclei.

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[7]H. Ikegami, S. Morinobu, I. Katayama, M. Fujiwara, and S. Yamabe, Nucl. Instrum. Methods 175, 335 (1980).

[8]The $\sigma(\theta)$ distributions for the $2_2{}^+$ states in ^{74,76,78,80}Se are very similar to each other in shape. This result makes it reasonable to assume a similar shape also for the $2_2{}^+$ state in ^{82}Se. We compared the χ^2 values resulting from two cases; $\sigma(\theta)$ for the $4_1{}^+$ state in ^{82}Se was assumed to be similar to that (a) in ^{80}Se, and (b) in ^{76}Se. The χ^2 value obtained for case (a) is an order of magnitude smaller than that for case (b), justifying the assumptions in the resolving procedure described in the text. Similar comments can also be made for the case of ^{78}Se. The cross sections for the $4_1{}^+$ state in ^{82}Se resulting from the χ^2-fitting procedure are more than twice as large as those for the $2_2{}^+$ state at $\theta_{lab} > 22.5°$, and those for the $4_1{}^+$ states in ^{78}Se are 8-10 times larger than those for the $0_2{}^+$ state at all angles measured.

[9]J. Raynal, private communication.

[10]H. Sakaguchi *et al.*, Phys. Lett. 89B, 40 (1979).

[11]In the harmonic vibrational model, the $4_1{}^+$ state was assumed to have mixed components of one- and two-phonon states in the form $|4_1{}^+\rangle = \cos\varphi|1\text{-phonon}\rangle + \sin\varphi|2\text{-phonon}\rangle$. The mixing parameters φ chosen are 65°, 65°, 60°, 45°, and 40° for ^{74,76,78,80,82}Se, respectively.

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[13]The effect of the spin of the β_2 on the $\sigma(\theta)$ and the $A(\theta)$ distributions for the $2_1{}^+$ state is not as large as in the case of vector-polarized deuterons [see J. H. Hamilton, A. V. Ramayya, and R. L. Robinson, in *Nuclear Interactions*, edited by B. A. Robson (Springer-Verlag, Berlin, 1979), p. 253, and references cited therein; T. Matsuzaki and H. Taketani, Nucl. Phys. A390, 413 (1982)], but the χ^2 value resulting from the fitting procedure can be used to determine which sign of β_2 is probable for the $2_1{}^+$ state.

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[17]Hamilton, Ramayya, and Robinson, Ref. 13; Matsuzaki and Taketani, Ref. 13.

[18]The $\sigma(\theta)$ and the $A(\theta)$ distributions for the $2_2{}^+$ state were found to be also well described with both the SHV and the asymmetric rotational (or the rotation-vibration) models, thus preventing us from distinguishing between these models for the $^{74-82}$Se iostopes. It is noted also that the data for the $2_2{}^+$ state are insensitive to the sign of β_4.

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