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Static quadrupole moment of the first excited state of ^{74}Se

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The static quadrupole moment of the first 2^+ excited state of ^{74}Se was measured by using the reorientation effect in Coulomb excitation. The measurements yielded for constructive interference via the second 2^+ excited state $Q_{2+} = -0.36 \pm 0.07$ e b. This value gives a direct evidence of a prolate nuclear deformation for $N = 40$ in the even-A selenium isotopes.

[NUCLEAR REACTIONS ^{74}Se(α, α'), $E=7.3$ MeV; ^{74}Se$(^{16}$O, ^{16}O$')$, $E=33$, 34 MeV; measured Coulomb excitation ^{74}Se deduced Q_2^+, $B(E2;\ 0^+ \rightarrow 2^+)$. Enriched targets.]

A clear understanding in terms of a simple model of the nuclear structure of nuclei with the neutron number limited between 34 and 48 (or in the $1g_{9/2}$ region) has been as yet somewhat elusive. This could have been due essentially to two reasons. First, until very recently little experimental information was available on these nuclei. Second, the large number of neutrons and protons which can occupy the accessible empty orbitals make any calculation prohibitively complicated. The first point, however, is becoming obsolete very rapidly since this area of nuclei is drawing a great deal of attention and it has been the subject of extensive experimental investigations in recent years. A clear pattern is already emerging from all these studies, namely that these nuclei form, most probably, a region of permanent deformation. However, on the type of deformation and on the possible existence of an oblate to prolate shape transition around $N=40$ there is not as yet a clear consensus.[1] This point and its very important implications have been already discussed to a great extent in a recent work on the determination of the static quadrupole moments of the Se isotopes carried out in this laboratory.[2] It was found in that study that the even-A Se nuclei (from $N=42$ to $N=48$) show a nuclear deformation of prolate type. It was also remarked, however, that in order to have a better answer to the problem of the oblate-prolate shape transition at $N=40$, the Q_{2+} value of ^{74}Se should be measured together with those of the Ge isotopes spanning the region between $N=38$ to $N=44$. Thus the present work on the determination of the static quadrupole moment of the first 2^+ state of ^{74}Se is undertaken precisely with this purpose in mind. Targets of ^{74}Se (^{74}Se–82.63%; ^{76}Se–3.09%; ^{77}Se–1.55%; ^{78}Se–3.93%; ^{80}Se–6.74%; ^{82}Se–2.06%) were bombarded with a 7.3 MeV α-beam and with 33 and 34 MeV ^{16}O ions obtained from the Université de Montréal Tandem Van de Graaff accelerator. The targets were prepared by evaporating in vacuum a thin layer (between 5 and 10 μg/cm^2 for the ^{16}O bombardment and between 20 and 40 μg/cm^2 for the α beam) of metallic enriched ^{74}Se onto a 10 or 20 μg/cm^2 carbon foil. Since selenium deposited on a thin carbon backing is quickly reevaporated under moderate beam intensities, the targets were mounted on a rotating target holder[3] and strengthened by a very thin film (~1μg/cm^2) of aluminum evaporated on top of the selenium layer. The Coulomb excitation probabilities for both projectiles were measured by comparing the resolved elastic and inelastic scattered particles detected by four surface-barrier detectors placed at scattering angles of ±157.5° and ±172.5°. A typical ^{16}O spectrum is shown in Fig. 1, whereas an α spectrum is shown in Fig. 2. The ratio $R_{\text{exp}} = d\sigma_{\text{inel}}/d\sigma_{\text{el}}$ was extracted from the data after the relatively large contributions from the other Se isotopes were subtracted from the spectra (the subtraction was made using the Oak Ridge isotopic analysis given above). Particular care was also taken to search and detect possible target contaminants which could at the used bombardment energies produce elastic peaks underneath the ^{74}Se inelastic peaks. These contaminants are Ti, V, and Cr for the α beam and Ge and As for the ^{16}O ions. To this end the ^{74}Se targets were bombarded with a 3 MeV proton beam and the elements present in these targets were observed by PIXE methods and techniques developed in this laboratory.[4,5] None of the above mentioned elements were detected in the x-ray spectra and only traces of Fe, Cu, and Zn with concentrations equal to (or less than) 0.03% (Fe), 0.013%(Cu), and 0.056%(Zn) were visible. (The concentration of these isotopes is measured with respect to Se.) As a next step the measured cross-sections R_{exp}

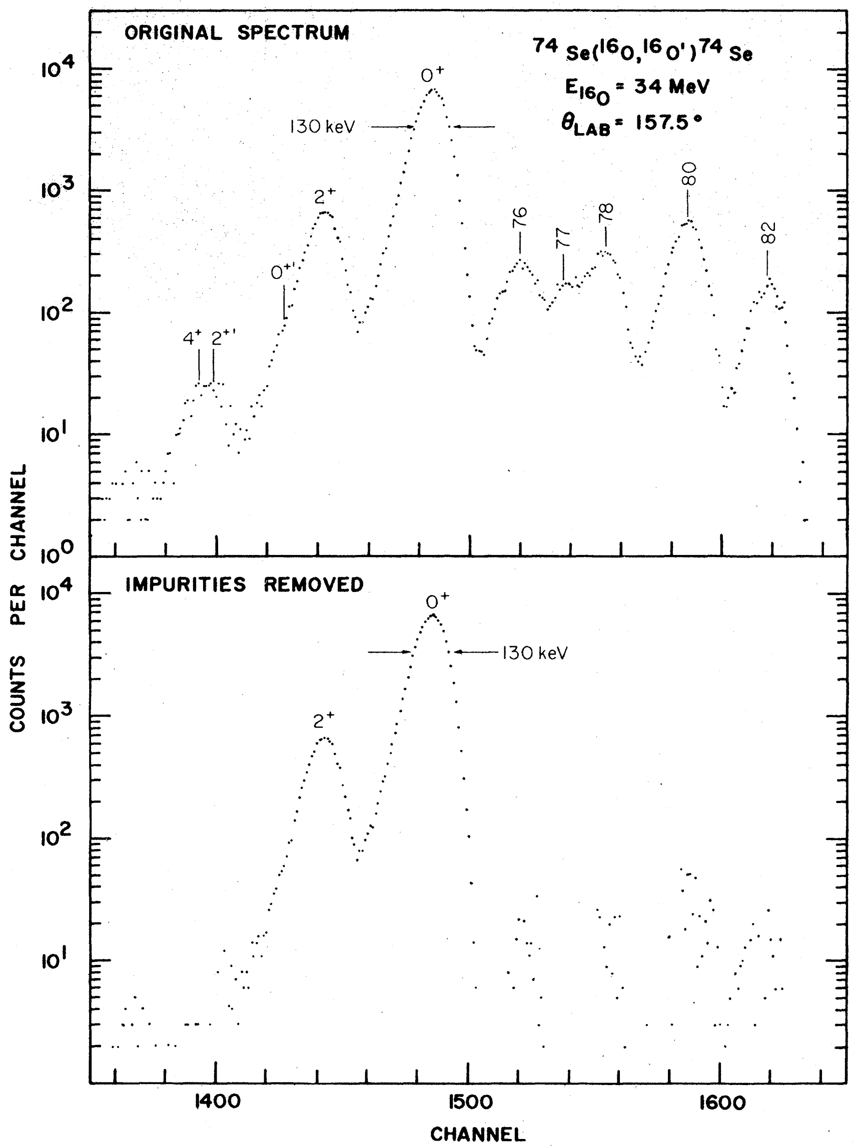

FIG. 1. The ^{16}O(34 MeV) spectrum of ^{74}Se at scattering angle $\theta_{lab}=157.5°$. Above is raw spectrum showing the elastic contributions from the Se impurities, and below is the spectrum after subtraction of the Se impurities.

were fitted with the cross-section ratios R_c calculated with the coupled-channel computer code of Winther and de Boer[6] and the results are shown in Table I. To derive the Q_{2^+} and $B(E2;0^+\rightarrow 2^+)$ values of the first excited 2^+ state in ^{74}Se, the appropriate reduced matrix elements M_{rs} of the quadrupole operator were also inserted in the program. These matrix elements were obtained from the $B(E2)$ values determined by Coulomb excitation measurements performed previously in this laboratory.[7] The energy levels and the reduced matrix elements included in the analysis are shown in Table II and the final results on the Q_{2^+} and $B(E2;0^+\rightarrow 2^+)$ values are presented in Table III. As usual, two values of Q_{2^+} are shown in Table III, since it is impossible with the experimental techniques employed here to distinguish between the constructive and destructive interference terms via the second 2^+ excited state (or $2^{+\prime}$). However, only the Q_{2^+} value due to the constructive interfer-

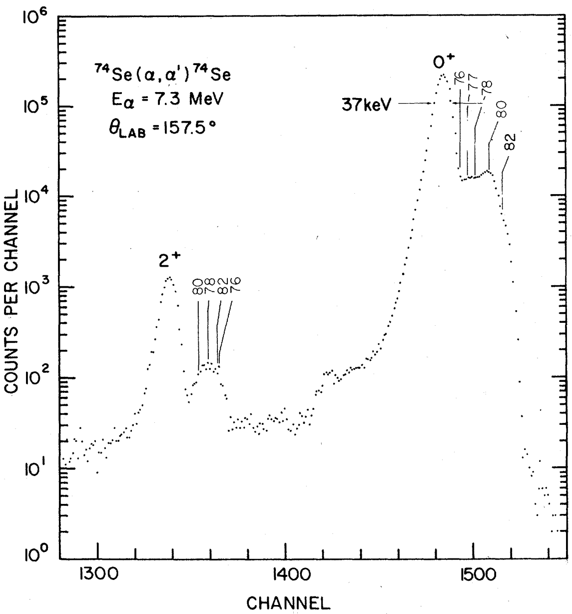

FIG. 2. The α(7.3 MeV) spectrum of ^{74}Se at scattering angle θ_{lab} = 157.5°.

TABLE I. Value of the experimental and least-squares fitted ratios.

Beam energy (MeV)		Lab angle (deg)	$R_{exp}\times 10^3$ [a]	$R_c \times 10^3$ [b]
7.26	(^{4}He)	157.5	5.675 (1.5)	5.702
		172.5	5.909 (1.3)	5.898
7.28	(^{4}He)	157.5	5.818 (1.5)	5.755
		172.5	5.932 (1.4)	5.954
7.28	(^{4}He)	157.5	5.796 (1.1)	5.755
		172.5	5.877 (1.3)	5.954
32.9	(^{16}O)	157.5	88.82 (1.0)	88.29
		172.5	91.45 (0.9)	90.31
33.9	(^{16}O)	157.5	100.4 (1.1)	102.0
		172.5	103.7 (1.2)	104.4

[a] The experimental error for R_{exp} are statistical only and are quoted in percent.
[b] The fitted ratios are those obtained for a positive value of $P_3 = M_{02'}M_{22'}M_{02}$.

ence term ($P_3 > 0$ in our notation) will be considered in the following since this is the value which is strongly favored (when Q_{2^+} is negative) from experimental and theoretical considerations.[1] The negative value of Q_{2^+} would imply a prolate nuclear deformation also in ^{74}Se. Thus there is no evidence of an oblate to prolate shape transition at $N = 40$ in the even-A Se nuclei. This was not totally unexpected since previous work on the ^{75}Se nucleus showed that its low lying positive parity levels could be adequately described only by considering a single neutron coupled to a deformed prolate ^{74}Se core.[14,15] Furthermore, it is expected from theor-

TABLE II. Energy levels of ^{74}Se and reduced $E2$ matrix elements (in eb) used in the analysis.

Energy (keV) [a]	J^π	Level number	Matrix elements [b] 1(0$^+$)	2(2$^+$)	3(0$^{+'}$)	4(2$^{+'}$)	5(4$^+$)
0	0^+	1	0	M_{12}	0	−0.093	0
634.8	2^+	2	M_{12}	M_{22}	−0.389	±0.775	−1.166
854.1	$0^{+'}$	3	0	−0.389	0	0	0
1269.2	$2^{+'}$	4	−0.093	±0.775	0	0	0
1363.2	4^+	5	0	−1.166	0	0	0

[a] The energy values are taken from Ref. 7.
[b] The matrix elements are defined by $M_{rs} = \langle s \| i^\lambda \mathfrak{M}(E\lambda) \| r\rangle$, where $\mathfrak{M}(E\lambda)$ is the multipole operator, $\lambda = 2$, and $M_{rs}^2 = (2I_r + 1)B(E2; r \to s)$. The $B(E2)$ values have been obtained from Ref. 7. It should remarked, however, that the $B(E2; 2^{+'} \to 2^+)$ and $B(E2; 2^{+'} \to 0^+)$ values used to calculate the respective matrix elements are slightly different from those given in Ref. 7. In the present work the determination of $B(E2; 2^{+'} \to 2^+)$ and $B(E2; 2^{+'} \to 0^+)$ was carried out considering the more precise intensity values of the 634.5 and 1269.2 keV transitions as given in Ref. 8 (see Ref. 7 for more details).

TABLE III. Results for $B(E2; 0^+ \rightarrow 2^+)$ and Q_{2^+} values obtained for ^{74}Se.

$P_3 = M_{02'}M_{22'}M_{02}$	Interference	$B(E2; 0^+ \rightarrow 2^+)(e^2b^2)$	$Q_{2^+}(eb)$ [a]	$\chi^2/d.f.$
+	Constructive	0.388 ± 0.005	-0.36 ± 0.07	0.9
−	Destructive	0.386 ± 0.005	-0.14 ± 0.07	0.9

[a] The errors in the measured values of Q_{2^+} have been calculated using the procedures given in Refs. 9 and 10. The possible correction due to the giant dipole resonance (Refs. 11 and 12) was not considered, whereas the small quantum mechanical correction (Ref. 13) was included in the Q_{2^+} values.

etical and experimental considerations that a prolate deformation characterizes also the ^{72}Se nucleus.[16] It is probable that ^{74}Se as well as the other Se nuclei exhibit a marked triaxial shape as indicated by the values of the intrinsic deformation parameters γ_0 and γ_2, obtained using the sum rule method of Kumar.[17] These values are 23.1° and 22.0°, respectively.

[1] M. Vergnes, Institut de Physique Nucléaire, 91406 Orsay Report IPNO-PHN-78-05 (unpublished); talk given at the Winter School of Zakopane, 1977 (unpublished); and private communication.

[2] R. Lecomte, P. Paradis, J. Barrette, M. Barrette, G. Lamoureux, and S. Monaro, Nucl. Phys. A284, 123 (1977).

[3] E. H. Woodburn, M. Barrette, J. L. Foster, and G. Lamoureux, Nucl. Instrum. 109, 561 (1973).

[4] M. Barrette, G. Lamoureux, E. Lebel, R. Lecomte, P. Paradis, and S. Monaro, Nucl. Instrum. 134, 189 (1976).

[5] R. Lecomte, P. Paradis, S. Monaro, M. Barrette, G. Lamoureux, and H. A. Ménard, Nucl. Instrum. 150, 289 (1978).

[6] A. Winther and J. de Boer, in *Coulomb Excitation*, edited by K. Alder and A. Winther (Academic, New York, 1966).

[7] J. Barrette, M. Barrette, G. Lamoureux, S. Monaro, and S. Markiza, Nucl. Phys. A235, 154 (1974).

[8] A. Coban, J. C. Lisle, G. Murray, and J. C. Willmott, Part. Nucl. 4, 108 (1972).

[9] J. Barrette, M. Barrette, R. Haroutinian, G. Lamoureux, and S. Monaro, Phys. Rev. C 10, 1166 (1974).

[10] P. Paradis, G. Lamoureux, R. Lecomte, and S. Monaro, Phys. Rev. C 14, 835 (1976).

[11] J. Eichler, Phys. Rev. 133, B1162 (1964).

[12] A. C. Douglas, and N. McDonald, Phys. Lett. 24B, 447 (1967).

[13] K. Alder and K. A. Pauli, Nucl. Phys. A128, 193 (1969).

[14] N. E. Sanderson, Nucl. Phys. A226, 173 (1973).

[15] N. E. Sanderson and R. G. Summers-Gill, Nucl. Phys. A261, 93 (1976).

[16] K. P. Lieb and J. J. Kolata, Phys. Rev. C 15, 939 (1977).

[17] K. Kumar, *The Electromagnetic Interactions in Nuclear Physics*, edited by W. D. Hamilton (North-Holland, Amsterdam, 1974).