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# QUADRUPOLE MOMENTS OF FIRST EXCITED STATES IN $^{28}$Si, $^{32}$S, AND $^{40}$Ar†

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## ABSTRACT

Static quadrupole moments of the first excited states of $^{28}$Si, $^{32}$S, and $^{40}$Ar have been measured using the reorientation effect in projectile Coulomb excitation. The results obtained are $Q(^{28}\text{Si},2^+) = +0.11\pm0.05$ b, $Q(^{32}\text{S},2^+) = -0.20\pm0.06$ b, and $Q(^{40}\text{Ar},2^+) = +0.01\pm0.04$ b.

The reorientation effect[1] in projectile Coulomb excitation provides a sensitive way to measure quadrupole moments of light nuclei. This method was successfully applied to the measurement of the quadrupole moments of $^{20}$Ne and $^{22}$Ne ($2^+$ states).[2] In the present work the first excited states in $^{28}$Si, $^{32}$S, and $^{40}$Ar have been studied using beams from the Berkeley Hilac. These measurements indicate an oblate shape for $^{28}$Si, a prolate shape for $^{32}$S, and a spherical shape, within experimental error, for $^{40}$Ar.

The method used was almost exactly the same as in the Ne experiment.[2] The γ-ray yields from excited projectile and target nuclei at two projectile-scattering angles (160° and 90°) were measured simultaneously as particle-γ coincidences between a NaI counter (7.5 cm × 7.5 cm) and a particle counter at each angle. A multidimensional-analysis program for the Hilac PDP-7 was used to store a γ-ray spectrum, a mixed particle spectrum from the two counters, and a time spectrum. In order to identify the particle counters in off-line analysis, the fast timing signals from one of the particle counters were delayed to produce two prompt peaks in the time spectra. The ratio of the excitation probability of the projectile to that of the target at each angle was deduced from the measured coincidence γ-ray spectra as: $R^{160} = (N_P^{160}/N_T^{160}) \cdot (\varepsilon_T/\varepsilon_P)$, $R^{90} = (N_P^{90}/N_T^{90}) \cdot (\varepsilon_T/\varepsilon_P)$, where $N$ is the integrated area of a photo-peak in the spectra, and $\varepsilon$ is the photo-peak efficiency of the NaI counter. Superscripts indicate the scattering angle and subscripts distinguish between projectile (P) and target (T). A double ratio, $\mathcal{R} = (R^{160}/R^{90})$, was also calculated which was less sensitive to many kinds of instrumental effects and to uncertainties in the B(E2) values of both projectile and target excitations. These ratios, after several corrections were made, were compared with calculated values using the deBoer-Winther Coulomb excitation program.[3]

This method is advantageous, because the excitation probability of the projectile is considerably more sensitive to its quadrupole moment than that of the target is to its moment. By measuring the target and projectile excitations simultaneously, several kinds of experimental uncertainties and instabilities cancel out, and by the proper choice of target nuclei, ambiguities involved in its excitation can be minimized. However, the estimation of the reorientation effect in the target excitation was more serious in the present case than in the Ne experiment, because the target nuclei were excited by heavier projectiles.

Since it was difficult to get low-energy beams of these projectiles at the Hilac, measurements have been made mainly with a $^{206}Pb$ target. In the case of $^{40}Ar$, targets of $^{120}Sn$ and $^{130}Te$ were used as well as $^{206}Pb$. Because an accurate $B(E2, 0^+ \rightarrow 2^+)$ value of $^{206}Pb$ was needed, it was determined in separate experiments by a lifetime measurement of the $2^+$ state using the Doppler-shift recoil-distance method.[4] The static quadrupole moment of the $2^+$ state in $^{206}Pb$ was assumed to be $0.0 \pm 0.5|Q_r|$.[5]

The attenuation of the γ-ray angular distribution has been corrected using attenuation factors, $G_2$ and $G_4$, determined in separate experiments. The interaction producing the attenuation was assumed to be magnetic. The correction to the γ-ray angular distribution and to the detector solid angle due to the motion of the γ-emitter was calculated by a numerical method. The higher velocities of projectile and recoiling target nuclei introduced larger corrections than was the case in the Ne experiment. However, the uncertainties due to these corrections are still only a small part of those in the final results.

Figure 1 shows the experimental results with best fits and calculated curves assuming $Q = 0$ and $\pm Q_r$.[5] The best fits were obtained by least-square fittings to the experimental ratios. Because only two of the three ratios ($R^{160}$, $R^{90}$, $\mathcal{R}$) are independent, a correlated weight function was used in the fitting. Results of the fittings are summarized in Table I. Effects due to other low-lying $0^+$, $2^+$, $4^+$, and $3^-$ states were estimated using experimental data[6,7,8] when available. No correction was applied unless the effect could be reliably calculated from experimental data, but additional uncertainty was given to the final values of $B(E2, 0^+ \rightarrow 2^+)$ and Q. Corrections due to the effects of E4 moments were also calculated using $\beta_2$ and $\beta_4$ from the (p,p') experiment[9] for $^{28}Si$ and $^{32}S$, but for $^{40}Ar$ only an estimated uncertainty was included. No correction was made for simultaneous excitation of projectile and target. The uncertainties introduced due to these effects were rather large, and could be appreciably reduced by further experimental information. The estimated corrections applied were small except for the case of $^{32}S$. The relatively large B(E2) values for the transitions between $0_2^+$, $2_2^+$, and $4_1^+$ states (3.78, 4.29, and 4.46 MeV) and the first excited state in $^{32}S$ made a considerable change in $Q(^{32}S)$ ($Q_{uncorr} = -0.14$ b $\rightarrow Q_{corr} = -0.20$ b).

The intrinsic quadrupole moments, $Q_0$,[10] of the $2^+$ states in the s-d shell nuclei deduced from the present projectile-excitation method are summarized in Fig. 2 together with values from other measurements.[11-15] The present result for $^{28}Si$ agrees with a previous measurement.[11] The prolate shape ($Q_0 > 0$) of $^{32}S$ was somewhat unexpected; however, in this mass region calculations have shown that the minimum Hartree-Fock energies are very close for prolate and oblate shapes,[16] so that it does not seem unreasonable that the addition of four nucleons can change the shape of a nucleus. In this regard, the different signs of the intrinsic quadrupole moments of $^{28}Si(2^+)$ and $^{27}Al(5/2^+)$ and of $^{32}S(2^+)$ and $^{33}S(3/2^+)$ are more striking. There are a number of possible reasons why the sign of $Q_0$ for an odd-A nucleus might be different from that of a neighboring even-even one. Two rather obvious possibilities are: 1) if the state is a member of a K = 1/2 band, the sign of $Q_0$ will be opposite to that shown in the figure, and 2) if two shapes lie at nearly the same energy, the one preferred could be changed by the addition or removal of a particle from an orbital whose energy depends strongly on deformation. For all odd-A nuclei in this region, the sign of the quadrupole moment is correctly given by the position of the nucleus on the Nilsson single-particle diagram as determined by its nucleon number and the ground-state spin. The small static moment of $^{40}Ar(2^+)$ (spherical shape) seems reasonable since this nucleus is quite near the doubly-closed shell.

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## FOOTNOTES AND REFERENCES

†Work performed under the auspices of the U. S. Atomic Energy Commission.

*On leave of absence from Osaka University, Osaka, Japan.

**On leave of absence from CEN de Bordeaux-Gradignan, France, NATO fellow.

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5. $Q_r$ is the quadrupole moment calculated from the B(E2, $0^+ \rightarrow 2^+$) value using the rigid rotor model.

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10. $Q_0$ is deduced from the measured Q or B(E2, $0^+ \rightarrow 2^+$) values in a model-dependent way using the formulae:

$$Q = \frac{3K^2 - I(I+1)}{(I+1)(2I+e)} Q_0, \quad \text{or} \quad B(E2,\ 0^+ \rightarrow 2^+) = \frac{5e^2}{16\pi} Q_0^{\ 2} \quad .$$

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## FIGURE CAPTIONS

Fig. 1. Typical results of the experiments and analysis. The solid lines are the best fits (corresponding to an uncorrected Q) and the dashed lines show the curves for $Q = 0$ or $\pm Q_r$. The arrows indicate the "safe energy" ($E_s$) defined in Ref. 1.

Fig. 2. Intrinsic quadrupole moments, $Q_0$,[10] in s-d shell nuclei. The circles indicate the intrinsic moments of first-excited $2^+$ states determined from measured static quadrupole moments by: the present method (double circles), the method of the Chalk River group (closed circles), and that of the group at Heidelberg (open circles). The squares indicate the values calculated from measured $B(E2,\ 0^+ \rightarrow 2^+)$ values. The intrinsic moments of odd-A

nuclei deduced from the spectroscopic quadrupole moment (assuming K = I except for $^{19}F^{*}$ (K = 1/2, I = 5/2)) are shown by the diamonds.

Table I. Summary of the experimental results.

| Target | Basis of calculations: B(E2, ↑ target) $e^2\times10^{-50}$ $cm^4$ | Basis of calculations: Q(target) (b) | Result (projectile): B(E2, $0^+ \to 2^+$) $e^2\times10^{-50}$ $cm^4$ | Result (projectile): $Q(2^+)$ (b) |
|---|---|---|---|---|
| (a) $^{28}Si$ (1.78 MeV) | | | | |
| $^{206}Pb$ | 9.1±0.6[a] | $+0.5\|Q_r\|$ | 3.3±0.4 | 0.126±0.045 |
| | | 0.0 | 3.3±0.4 | 0.110±0.045 |
| | | $-0.5\|Q_r\|$ | 3.3±0.4 | 0.098±0.045 |
| Summary | 9.1±0.6[a] | $(0.0\pm0.5\|Q_r\|)$[b] | 3.3±0.4 | +0.11 ±0.05 |
| (b) $^{32}S$ (2.24 MeV) | | | | |
| $^{206}Pb$ | 9.1±0.6[a] | $+0.5\|Q_r\|$ | 3.3±0.5 | -0.192±0.055 |
| | | 0.0 | 3.3±0.5 | -0.202±0.055 |
| | | $-0.5\|Q_r\|$ | 3.3±0.5 | -0.215±0.055 |
| Summary | 9.1±0.6[a] | $(0.0\pm0.5\|Q_r\|)$[b] | 3.3±0.5 | -0.20 ±0.06 |
| (c) $^{40}Ar$ (1.46 MeV) | | | | |
| $^{120}Sn$ | 23.0±1.2[c] | $+0.5\|Q_r\|$ | 3.4±0.4 | 0.032±0.040 |
| | | 0.0 | 3.4±0.4 | -0.021±0.040 |
| | | $-0.5\|Q_r\|$ | 3.4±0.4 | -0.081±0.040 |
| | 23.0±1.2[c] | $(0.0\pm0.5\|Q_r\|)$[b] | 3.4±0.4 | -0.021±0.065 |
| $^{130}Te$ | 30±3[d] | -0.15±0.20[d] | 3.2±0.6 | 0.019±0.062 |
| $^{206}Pb$ | 9.1±0.6[a] | $+0.5\|Q_r\|$ | 3.0±0.5 | 0.052±0.072 |
| | | 0.0 | 3.0±0.5 | 0.040±0.072 |
| | | $-0.5\|Q_r\|$ | 3.0±0.5 | 0.022±0.072 |
| | 9.1±0.6[a] | $(0.0\pm0.5\|Q_r\|)$[b] | 3.0±0.5 | 0.040±0.075 |
| Summary | (Average) | | 3.2±0.5 | +0.01 ±0.04 |

[a]Reference 4.

[b]Assumption: $Q_r$ is the value calculated from the B(E2) using the rigid-rotor model.

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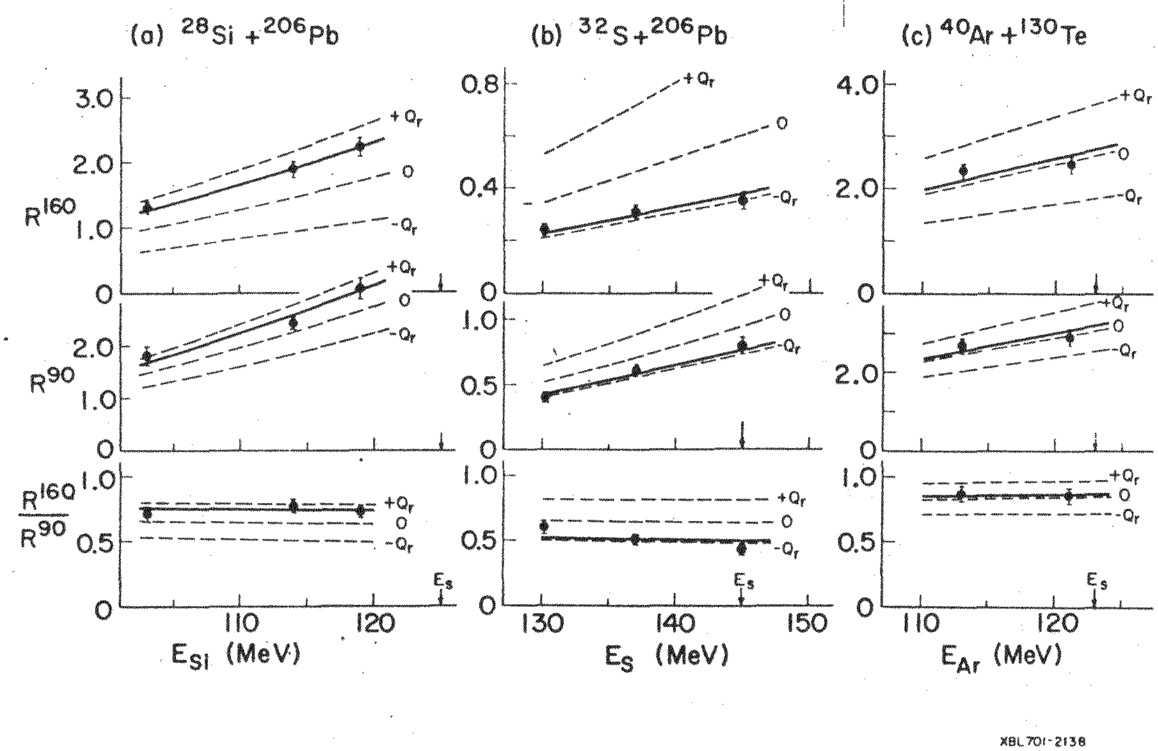
(a) 28Si + 206Pb
(b) 32S + 206Pb
(c) 40Ar + 130Te
R160
R90
R160/R90
+Qr
0
-Qr
Es
ESi (MeV)
ES (MeV)
EAr (MeV)
XBL701-2138

Fig. 1

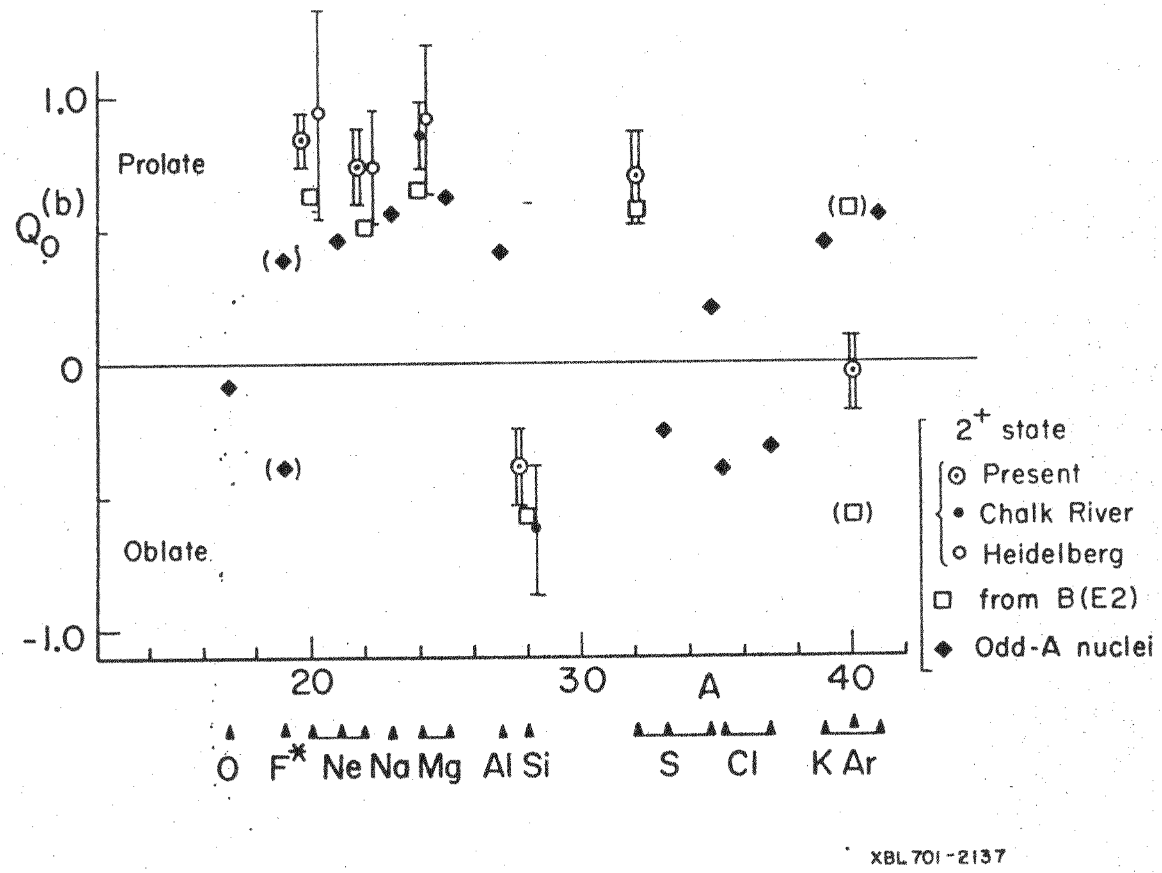
1.0
Prolate
$Q_0$(b)
0
Oblate
-1.0
20
30
A
40
2+ state
Present
Chalk River
Heidelberg
from B(E2)
Odd-A nuclei
O F* Ne Na Mg Al Si S Cl K Ar
XBL 701-2137

Fig. 2