Static Quadrupole Moment of the First Excited State of ^{30}Si

M. P. Fewell, D. C. Kean, R. H. Spear, and T. H. Zabel
Department of Nuclear Physics, Australian National University, Canberra 2600, Australia

and

A. M. Baxter and S. Hinds
Physics Department, Australian National University, Canberra 2600, Australia
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The static quadrupole moment, Q_{2^+}, and $B(E2; 0^+ \rightarrow 2^+)$ of the first excited state of ^{30}Si have been measured using the reorientation effect in Coulomb excitation, giving $Q_{2^+} = -5 \pm 6$ $(+1 \pm 6)$ $e \cdot \mathrm{fm}^2$ and $B(E2; 0^+ \rightarrow 2^+) = 253 \pm 30$ (261 ± 30) $e^2 \cdot \mathrm{fm}^4$ if the interference from the second excited state is constructive (destructive). The result for Q_{2^+} indicates that Hartree-Fock calculations which ignore solutions other than those with $K = 0$ are inadequate, and supports shell-model calculations and band-mixed Hartree-Fock calculations.

It has long been recognized[1,2] that a measurement[3] of the static quadrupole moment, Q_{2^+}, of the first excited state of ^{30}Si ($J^\pi = 2^+$, $E_x = 2.235$ MeV) is highly desirable. There have been numerous calculations of Q_{2^+} (Table I), but hitherto no experimental determination. The several varieties of Hartree-Fock-Bogoliubov (HFB) calculations,[4-8] mostly due to Faessler and collaborators, all suggest that ^{30}Si is oblate, and give values of Q_{2^+} in the range from $+11$ to $+21$ $e \cdot \mathrm{fm}^2$. On the other hand, the truncated shell-model calculations of Wildenthal, McGrory, and Glaudemans[1] give $Q_{2^+} = -6.6$ $e \cdot \mathrm{fm}^2$. For most other even-even nuclei in the *sd* shell, the differences between the values of Q_{2^+} predicted by HFB and shell-model calculations are too small to be resolved experimentally; see, for example, recent results for ^{24}Mg (Ref. 9) and ^{28}Si, ^{32}S, and ^{34}S (Ref. 10). Thus an experimental determination of Q_{2^+} for ^{30}Si would provide a sensitive and significant test of the various applications of these models.

The measurement of $Q_{2^+}(^{30}\mathrm{Si})$ reported herein was performed using the reorientation effect in Coulomb excitation of ^{30}Si projectiles by ^{208}Pb. Beams of up to 250 nA of $^{30}\mathrm{Si}^{8,9,10+}$ ions were obtained from the Australian National University's 14UD Pelletron accelerator at energies in the range from 106 to 136 MeV. The target consisted of ^{208}PbS evaporated onto a thin carbon foil. The isotopic enrichment of the ^{208}Pb was 99.14% and its partial thickness 8 μg/cm^2. Backscattered ions were detected by an annular silicon surface-barrier detector at a mean laboratory scattering angle of 175°. Detectors were also placed on either side of the target to detect ions scattered through ±90°. Details of the technique have been given previously.[9,11]

Typical spectra obtained at 90° and 175° are shown in Fig. 1. Procedures used for unfolding the elastic (0^+) and inelastic (2^+) groups, and hence determining the excitation probability, P_{exp}, of the 2^+ state $[P_{\mathrm{exp}} = d\sigma_{2^+}/(d\sigma_{0^+} + d\sigma_{2^+})]$, were essentially as described elsewhere.[9,11] The

TABLE I. Comparison of theory and experiment for $Q_{2^+}(^{30}\mathrm{Si})$.

Method	Q_{2^+} ($e \cdot \mathrm{fm}^2$)	Ref.
Shell model	-6.6	1
Triaxial rotor	$+4.6$	2
HF	$+21$	4
HFB	$+11.7$	5
HFB	$+21$	6
HFB (Particle no. projection)	$+11.9$	7
Multiconfigurational HF	$+20$	8
This experiment	-5 ± 6 (constructive interference)	
	$+1 \pm 6$ (destructive interference)	

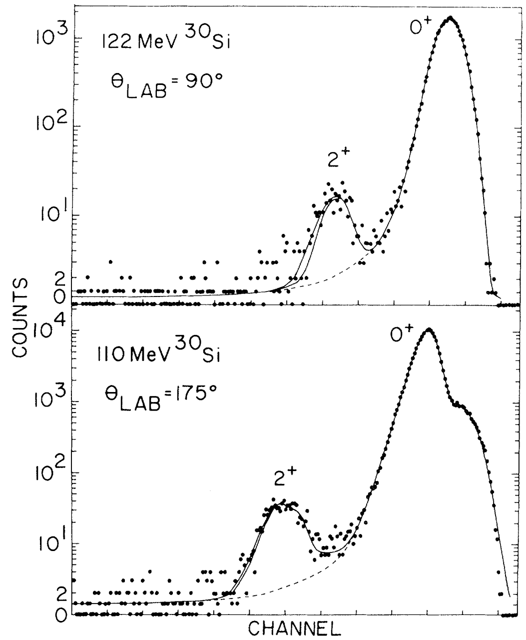

FIG. 1. Spectra obtained at 90° and 175° for ^{30}Si ions scattered from ^{208}Pb. The full curves are fits to the data. In each case the difference between the two full curves indicates the calculated contribution from target excitation of the 2.61-MeV 3^- state of ^{208}Pb. The dashed curve shows the tail of the 0^+ peak resulting from the analysis. The structure on the high-energy side of the 175° spectrum is a detector artifact.

elastic and inelastic groups are not as well resolved as in our previous work with lighter nuclei. In the worst case, the ^{30}Si inelastic peak height is 3 times the minimum in the valley between the elastic and inelastic peaks. The errors assigned to P_{exp} include, in addition to statistical uncertainties, a 15% uncertainty in estimating the intensity of the background under the inelastic peak; a greater error would cause a discernible discrepancy between the line-shape fits and the experimental spectra. The peak due to excitation of the 2.61-MeV 3^- state of ^{208}Pb was not resolved from the ^{30}Si 2^+ peak. It was subtracted using the known values[12] of $B(E3; 0^+ \rightarrow 3^-)$ and Q_{3^-}, assuming pure Coulomb excitation. The probability of target excitation is calculated to be between 10.5 and 12.3% of that of projectile excitation in the energy range of interest for 90° scattering, and between 3.7 and 5.3% for 175° scattering. The consequent uncertainties in P_{exp} are negligible compared with statistical uncertainties.

Elastic scattering from target impurities in the mass ranges $A = 195$ to 202 and $A = 187$ to 197 could contribute peaks to the spectrum in the region of the ^{30}Si inelastic peak at 175° and 90°, respectively. Analysis of a spectrum obtained at 55 MeV and 175° showed that, at the level of two standard deviations of the background, upper limits of 4 and 1% could be placed on contributions of such impurities to P_{exp} at 175° and 90°, respectively. These are negligible compared with other experimental uncertainties.

The 175° spectra obtained at energies from 128 to 136 MeV showed substantial contributions from the neutron-transfer reaction ^{208}Pb(^{30}Si, ^{31}Si)^{207}Pb and the proton-transfer reaction ^{208}Pb(^{30}Si, ^{29}Al)-^{209}Bi. Some of the groups from the neutron-transfer reaction occur at energies corresponding to the 2^+ inelastic peak. The cross sections for the various transfer peaks observed showed an exponential increase with energy in the range from 128 to 136 MeV, as expected for such reactions near the Coulomb barrier.[13,14] This energy dependence was used to infer the transfer cross sections at lower energies. The resulting percentage corrections to the 2^+ peak intensity were 6 ± 6, 9 ± 7, 10 ± 7, 14 ± 7, and 21 ± 7 at 106, 110, 112, 116, and 122 MeV, respectively. The errors correspond to uncertainties in the least-squares extrapolation. At beam energies of 116 MeV and below, for which the calculated transfer contribution to the region of the inelastic peak is less than 15%, the spectra show no evidence of transfer peaks and are consistent with the assumed extrapolation. Consistent with the well-known backward peaking of transfer-reactions near the Coulomb barrier,[14] no indication of transfer reactions was observed in any of the 90° spectra.

Figure 2 shows the energy dependence of the double ratio $P_{\text{exp}}/P_{\text{Coul}}$, where P_{Coul} is the excitation probability of the 2^+ state calculated assuming a pure Coulomb interaction. It appears that data for energies greater than 112 MeV at 175° and 128 MeV at 90° are significantly affected by nuclear interference. These data were therefore not used in the calculation of Q_{2^+} and $B(E2; 0^+ \rightarrow 2^+)$, which has performed using the Winther–de Boer multiple Coulomb-excitation program. The 3.499-MeV 2_2^+ state of ^{30}Si was included in the analysis using matrix elements computed from data in Ref. 3. Effects of other states up to 5 MeV excitation were investigated and found to be negligible. A number of small corrections[11] were applied, their net effect being to increase Q_{2^+} by 0.2 $e \cdot \text{fm}^2$ and to decrease $B(E2; 0^+ \rightarrow 2^+)$ by 24 $e^2 \cdot \text{fm}^4$. The static $E4$ moment of the 2^+ state is not known; however, even if β_4 had the improbably

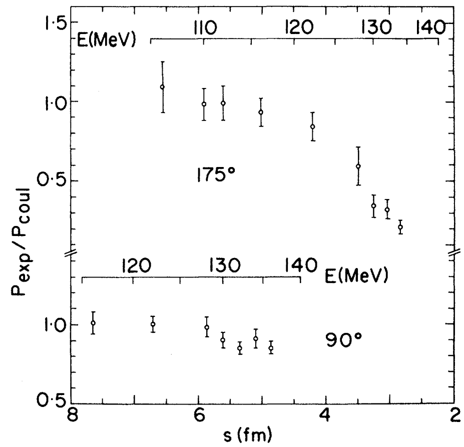

FIG. 2. Plots of the double ratio P_{exp}/P_{Coul} against beam energy E and the distance of the closest approach of the nuclear surfaces s, as defined in Ref. 11.

large value[15] of 0.3, its effect would be to change Q_{2^+} by less than 1.1 $e\cdot\text{fm}^2$ and $B(E2; 0^+ \to 2^+)$ by less than 3 $e^2\cdot\text{fm}^4$. A correction for the effect of the giant-dipole resonance was applied using $\sigma_{-2} = 3.5A^{5/3}$ μb MeV^{-1} (Ref. 16); this increased Q_{2^+} by 1.1 $e\cdot\text{fm}^2$ and increased $B(E2; 0^+ \to 2^+)$ by 17 $e^2\cdot\text{fm}^4$. An estimate of relativistic effects was made using the modified adiabaticity parameter suggested by Winther and Alder.[17] This decreased $B(E2; 0^+ \to 2^+)$ by 4 $e^2\cdot\text{fm}^4$ and Q_{2^+} by 0.2 $e\cdot\text{fm}^2$. Since the magnitudes of relativistic corrections are not well established, these corrections have not been applied, but have been included as contributions to the estimated uncertainties. The results obtained are $Q_{2^+} = -5 \pm 6$ $(+1 \pm 6)$ $e\cdot\text{fm}^2$ and $B(E2; 0^+ \to 2^+) = 253 \pm 30$ (261 ± 30) $e^2\cdot\text{fm}^4$ for constructive (destructive) interference from the 2_2^+ state. As indicated below, there is some theoretical support for believing that the interference is constructive. The errors quoted take account of uncertainties in relativistic corrections, spectrum analysis, subtraction of transfer-reaction contributions, beam energy, and the scattering angles. The last two effects contribute negligible uncertainty to Q_{2^+} and $B(E2; 0^+ \to 2^+)$.

The present value for $B(E2; 0^+ \to 2^+)$ is in reasonable agreement with most previous determinations,[3] although it is significantly larger than the value of 201 ± 11 $e^2\cdot\text{fm}^4$, the result of the Doppler-shift-attenuation method measurement[18] with the smallest stated error. Our value for Q_{2^+} is in excellent agreement with the shell-model calculations of Wildenthal, McGrory, and Glaudemans.[1] It is in clear disagreement with the HFB calculations.[4-8] Recent HF calculations by Morrison[19] suggest that the previous calculations for ^{30}Si gave inadequate consideration to the effects of band mixing. Morrison finds a $K = 2$ band, the lowest state of which lies below the 2^+ state of the oblate $K = 0$ band. He obtains a low-lying level scheme with spectroscopic features which are in good agreement with experiment; in particular, he found that $Q_{2^+} = -6.0$ $e\cdot\text{fm}^2$, and that interference from the 2_2^+ state is constructive. The lowest 2^+ state obtains its largest component from the $K = 2$ band, whereas the 2_2^+ state is dominated by the oblate $K = 0$ intrinsic state. The large positive value of Q_{2^+} obtained in previous HFB calculations,[5-8] which were specifically restricted to $K = 0$ solutions, would appear to be that appropriate to the 2_2^+ state. The possibility of a large $K = 2$ component in the 2^+ state appears to be a novel consideration for nuclei in the *sd* shell; this severely complicates the deduction of intrinsic shape from Q_{2^+}.

The value of Q_{2^+} presented in this paper depends on the assumption of an exponential energy dependence for the neutron-transfer cross sections. However, as indicated above, there is substantial evidence that the exponential assumption is valid to a degree consistent with the presently quoted uncertainty. It should be noted that deviation of the transfer cross section from an exponential energy dependence would not affect our main conclusions. If the contribution of transfer reactions were zero, the value for Q_{2^+} would be -0.3 ± 3.0 (5.7 ± 3.1) $e\cdot\text{fm}^2$, still in poor agreement with the HFB calculations. On the other hand, if the contribution from transfer reactions has been underestimated, then the value of Q_{2^+} would be less than -5 $e\cdot\text{fm}^2$ and the disagreement would be even greater. In either case, it remains true that the experimental value for $Q_{2^+}(^{30}\text{Si})$ reveals the inadequacy of HFB calculations which ignore solutions other than those with $K = 0$, and supports the band-mixed HF calculations of Morrison[19] and the shell-model calculations of Wildenthal, McGrory, and Glaudemans.[1]

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[1]B. H. Wildenthal, J. B. McGrory, and P. W. M. Glaudemans, Phys. Rev. Lett. 26, 96 (1971).
[2]D. Kurath, Phys. Rev. C 5, 768 (1972).

[3]P. M. Endt and C. van der Leun, Nucl. Phys. A310, 1 (1978).
[4]B. Castel and J. C. Parikh, Phys. Lett. 29B, 341 (1969).
[5]K. Goeke, A. Faessler, and H. H. Wolter, Nucl. Phys. A183, 352 (1972).
[6]K. Goeke, H. Müther, and A. Faessler, Nucl. Phys. A201, 49 (1973).
[7]K. Goeke, J. Garcia, and A. Faessler, Nucl. Phys. A208, 477 (1973).
[8]K. W. Schmid, L. Satpathy, and A. Faessler, Z. Phys. 267, 345 (1974).
[9]M. P. Fewell, S. Hinds, D. C. Kean, and T. H. Zabel, Nucl. Phys. A319, 214 (1979).
[10]G. C. Ball, O. Häusser, T. K. Alexander, W. G. Davies, J. S. Forster, and D. Horn, Bull. Am. Soc. 24, 613 (1979).
[11]M. P. Fewell, A. M. Baxter, D. C. Kean, R. H. Spear, and T. H. Zabel, Nucl. Phys. A321, 457 (1979).
[12]A. M. R. Joye, A. M. Baxter, M. P. Fewell, D. C. Kean, and R. H. Spear, Phys. Rev. Lett. 38, 807 (1977).
[13]K. G. Nair, J. S. Blair, W. Reisdorf, W. R. Wharton, W. J. Braithwaite, and M. K. Mehta, Phys. Rev. C 8, 1129 (1973).
[14]M. A. Franey, J. S. Lilley, and W. R. Phillips, Nucl. Phys. A324, 193 (1979).
[15]H. Rebel, G. W. Schweimer, G. Schatz, J. Specht, R. Löhken, G. Hauser, D. Habs, and H. Klewe-Nebenius, Nucl. Phys. A182, 145 (1972).
[16]O. Häusser, A. B. McDonald, T. K. Alexander, A. J. Ferguson, and R. E. Warner, Nucl. Phys. A212, 613 (1973).
[17]A. Winther and K. Alder, Nucl. Phys. A319, 518 (1979).
[18]J. A. J. Hermans, G. A. P. Engelbertink, L. P. Ekström, H. H. Eggenhuisen, and M. A. van Driel, Nucl. Phys. A284, 307 (1977).
[19]I. Morrison, private communication.

Doubly Coherent Production of π^- by ^{3}He Ions of 910 MeV

E. Aslanides, P. Fassnacht, and F. Hibou
Centre de Recherches Nucléaires and Université Louis Pasteur, Strasbourg, France

and

E. Chiavassa, G. Dellacasa, M. Gallio, and A. Musso
Istituto di Fisica Superiore dell'Università di Torino, Torino, Italy, and Instituto Nazionale di Física, Sezione di Torino, Torino, Italy

and

T. Bressani and G. Puddu
Istituto di Fisica dell'Università di Cagliari, Cagliari, Italy, and Instituto Nazionale di Física, Sezione di Torino, Torino, Italy

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The inclusive pion spectrum from the reaction $^3\mathrm{He} + {}^6\mathrm{Li} \to \pi^- + X$ at 910 MeV was measured at 0° with moderate resolution up to the kinematic limit of the two-body final-state reaction. A first analysis shows that the production of high-energy pions cannot be explained by the $NN \to NN\pi$ process using conventional nucleon momentum distributions. At the end of the spectrum a clear deviation from the general falloff slope is observed and attributed to the doubly coherent reaction $^3\mathrm{He} + {}^6\mathrm{Li} \to {}^9\mathrm{C} + \pi^-$.

In this Letter we report the first results on the search for the reaction

$$^3\mathrm{He} + {}^6\mathrm{Li} \to {}^9\mathrm{C} + \pi^-, \tag{1}$$

which we will call in the following "doubly coherent" to express the fact that the nucleons of both the target and projectile nuclei interact coherently to produce a two-body final state. The experiment was carried out at the CERN synchrocyclotron and took advantage of the high intensity (~ 2 $\times 10^{12}$ pulses per second) and good duty cycle (30–50%) of the extracted ^{3}He beam at 910 MeV. The search for the doubly coherent process was based on the measurement of the inclusive pion spectrum from the reaction $^3\mathrm{He} + {}^6\mathrm{Li} \to \pi^- + X$ performed at 0°. Such experiments should lead to a better understanding of high-momentum components in nuclei and may reveal, through high-energy pion production, new forms in the interaction between complex nuclei.

The determination of the pion momenta up to 800 MeV/c, with a momentum acceptance of ± 1.6%, was done using a secondary beam-transport line, tuned as an achromatic spectrometer.