Measurement of the Quadrupole Moment of the First Excited 2^+ State of ^{18}O

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(Received 15 September 1975)

We measured the static electric quadrupole moment (Q_{2^+}) and $B(E2, 0_1^+ \rightarrow 2_1^+)$ of the first excited state of ^{18}O at 1.98 MeV. The values obtained were $(-0.19 \pm 0.02$ b$)e$ (for the positive sign of the interference term involving the 2_2^+ state) and $(0.0048 \pm 0.0002$ b$^2)e^2$ for Q_{2^+} and $B(E2, 0_1^+ \rightarrow 2_1^+)$, respectively. For these values the ratio $|Q_{2^+}|/[B(E2, 0_1^+ \rightarrow 2_1^+)]^{1/2}$ is about 3, whereas for no other nucleus does it exceed unity by more than 30%.

A considerable amount of experimental information relating to the structure of ^{18}O is now available. Measurements of γ-ray transition probabilities,[1-5] the magnetic moment of the 1.98-MeV 2_1^+ state,[6] and spectroscopic factors from transfer reactions[7] have recently been performed. Together with the known energy levels much of this data can be understood within the framework of a shell model built on a spherical basis.[8,9] In these calculations the states of ^{18}O are essentially $(sd)^2$ neutron states mixed with particle-hole excitations of the ^{16}O core. However to account for the strong $E2$ transitions such as the one between the 2_1^+ and the 0_2^+ level at 3.63 MeV, states composed of spherical particle components $(sd)^2$ plus deformed four-particle, two-hole components (in the Nilsson-model sense) are necessary.[10,11] A similar interpretation[12] has been given for ^{42}Ca which parallels ^{18}O in many respects. The recent measurement of the quadrupole moment of the first 2^+ state[13] presents strong evidence for the coexistence of a deformed intrinsic state with spherical $(fp)^2$ states. By the same token a measurement of Q_{2^+} would provide a crucial test for this picture in ^{18}O.

In the present work we report on a measurement of the Q_{2^+} and $B(E2, 0_1^+ \rightarrow 2_1^+)$ values of the first excited state of ^{18}O, using the reorientation effect.[14] A beam of ^{18}O ions with energies between 58 and 63 MeV, produced by the Universität zu Köln FN tandem accelerator, was excited by scattering from ^{209}Bi. The target was composed of a 10-μg/cm^2 layer of ^{209}Bi vacuum evaporated onto a 5-μg/cm^2 layer of carbon, or a 15-μg/cm^2 layer of carbon and copper. Elastically and inelastically scattered ^{18}O ions were detected in 100-μm-thick surface-barrier detectors positioned at laboratory angles between 45 and 175°. The energy resolution of the system was better than 250 keV full width at half-maximum for all scattering angles. This was sufficient to separate clearly ^{18}O ions elastically scattered from ^{209}Bi and those Coulomb excited into the 1.98-MeV level of ^{18}O. Spectra taken with this experimental arrangement are shown in Fig. 1. The peak corresponding to the 2^+ state exhibits appreciable (about ± 140 keV) Doppler broadening due to the large recoil velocity of $v/c \sim 0.07$ and γ decay energy of 1.98 MeV.

The aim of the experiment was to determine, as accurately as possible, the excitation probability R, defined as the ratio of the inelastic $[^{18}\mathrm{O}(2^+)]$ peak intensity to the sum of the inelastic and elastic intensities. Aside from the question of counting rate, the maximum precision is obtained when the ratio of the inelastic peak height to background is maximum. This is particularly difficult in the present case since the excitation probabilities range between 10^{-4} and 10^{-3}. However, as seen in Fig. 1, it was possible to achieve acceptable peak-to-valley ratios guided, principally, by the methods of Berant *et al.*[16] The line-shape fits shown in Fig. 1 were used to determine the contribution of the background of the 2^+ peak and assure that the shapes

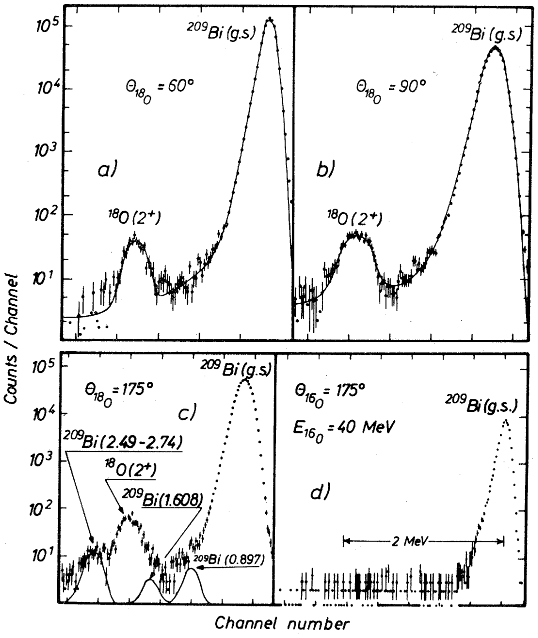

FIG. 1. (a)–(c) Spectra of the reaction ^{209}Bi(^{18}O, ^{18}O*)^{209}Bi obtained at a bombarding energy of 63 MeV. In (c) are shown the contributions due to the Coulomb excitation of ^{209}Bi calculated by use of the electric matrix elements of Broglia *et al.* (Ref. 15), which were subsequently subtracted from the spectrum. (d) A spectrum of the reaction ^{209}Bi(^{16}O, ^{16}O)^{209}Bi obtained under similar conditions as the ^{18}O spectra. One count has been added to all channels, and data points with errors that would reach below 1 have been drawn without error bars.

were consistent with single peaks. The validity of this procedure was confirmed by obtaining spectra [Fig. 1(d)] of ^{16}O scattered from identical targets and, except for the bombarding energy, for identical experimental conditions as used in the ^{18}O measurements. This spectrum demonstrates that the low-energy tail of the ^{209}Bi elastic peak varies smoothly in the region corresponding to the 2^+ state of ^{18}O. Incorporation of the Doppler broadening into the fit to the line shapes was accomplished by constructing the inelastic peak from the elastic peak folded with a square distribution with a width of about 280 keV. Excellent fits [Figs. 1(a) and 1(b)] were obtained by use of functions for the elastic peak shapes similar to those used in Ref. 16. Statistical plus fitting errors in the evaluation of R ranged, for the most part, between 3 and 10%.

Contributions due to the Coulomb excitation of levels in ^{209}Bi at 0.897 and 1.608 MeV and of the $3^- \otimes h_{9/2}$ septuplet of levels between 2.491 and 2.740 MeV have been subtracted out of the spectra [Fig. 1(c)], by use of the $B(E2)$ and the $B(E3)$ values of Ref. 15. Since the relative contributions of these excitations were about the same at all angles a change in the $B(E2)$ and $B(E3)$ values has a negligible effect on Q_{2^+}. For 175° where the relative influence of the septuplet was most important, a decrease in the total $B(E3)$ by 40% will decrease R by less than 3%.

In the measurement method used in the present work an unresolved contamination in the forward-angle inelastic peaks would tend to increase the observed Q_{2^+}. Such effects are particularly important in the present case since the excitation probabilities at forward angles are so small ($\sim 1\times10^{-4}$ at 45° to 15×10^{-4} at 90°). Hence trace impurities in the target at about the 1×10^{-4} level (which is the limit which can be set from the ^{16}O spectra) might appreciably affect the results. According to the supplier the Bi purity was 5 ppm. In addition, calculations of the scattering kinematics indicate that a mass distribution between $A \sim 145$ and 175 would be required to affect the 2^+ intensity between 45 and 90°. It is therefore very unlikely that elastic scattering from impurities is present. Similar calculations of the kinematics of light-mass-transfer reactions for ^{18}O on ^{209}Bi (very sub-Coulomb) leading to low-lying or gound states in the reaction products would seem to rule out contamination from this source as well. In order to ascertain the contribution from reactions with the carbon-plus-Cu backings additional measurements on the backing itself were performed at 63 MeV. Contributions to the relevant part of the ^{209}Bi spectra were found only at 45 and 60° and were subtracted out by normalizing the spectra to the Cu elastic peaks.

Since the excitation probabilities are very sensitive functions of the scattering angle (e.g., the change in R at 45° is about 11% per degree), a careful determination of the detector angles was warranted. In this regard, the scattering chamber used in this experiment, for which detectors could be positioned only at fixed angles (every 15°) proved to be of considerable advantage. Several independent determinations of the scattering angles were performed including an electro-optical measurement.[17] All measurements gave consistent results and the error in the scattering angles is conservatively reckoned to be ± 0.2°.

The question of the maximum or "safe" bombarding energy compatible with pure Coulomb excitation has been carefully considered. The excitation probabilities at 175° are consistent

TABLE I. The measured Q_{2^+} and $B(E2, 0_1^+ \rightarrow 2_1^+)$ values for ^{18}O. In the present work two values were obtained corresponding to the + or − sign of the interference term involving the 2_2^+ state at 3.92 MeV. The experimental methods used were Coulomb excitation (CE), Doppler-shift attenuation (DSA), and recoil distance (RD).

Q_{2^+}/e (b)	$B(E2, 0_1^+ \rightarrow 2_1^+)/e^2$ (b^2)	χ^2	Method	Reference
-0.19 ± 0.02	0.0048 ± 0.0002	0.93	CE	Present (+ intf.)
-0.16 ± 0.02	0.0048 ± 0.0002	0.91	CE	Present (− intf.)
-0.11 ± 0.05	0.0039 ± 0.0004	...	CE	19
...	0.0046 ± 0.0013	...	DSA	1
...	0.0038 ± 0.0002	...	RD	2
...	0.0040 ± 0.0002	...	RD	3
...	0.0048 ± 0.0002	...	DSA	4
...	0.0047 ± 0.0002	...	RD	5

with pure Coulomb excitation for energies up to and including 63 MeV. Furthermore, the elastic scattering of ^{18}O on ^{208}Pb was measured from 63 up to 68 MeV and no evidence was found for deviations of the back-angle elastic cross sections from Rutherford cross sections in this energy range.

Determination of the Q_{2^+} and $B(E2, 0_1^+ \rightarrow 2_1^+)$ values was accomplished by comparing the measured R values with those ($R_{\rm comp}$) calculated by use of the de Boer–Winther program.[18] The first five energy levels of ^{18}O and their associated electric quadrupole matrix elements[3] were used in the calculation. For the purpose of a best-fit comparison $R_{\rm comp}$ was expressed[16] as

$$R_{\rm comp}(Q) = R_{\rm comp}(Q')[1 + (Q - Q')\rho_{\rm comp}], \qquad (1)$$

where the sensitivity parameter $\rho_{\rm comp}$ is defined by this expression. Our final results together with the χ^2 values for the fits are summarized in Table I. Both the experimental R values and the best-fit values normalized with respect to $R(Q=0)$ are plotted in Fig. 2. The presentation of the data in this manner emphasizes the very large size of the effect. Indeed, it is the extreme sensitivity of R to Q_{2^+} [about 30% per (0.1 b)e] which in spite of the small values of R, makes this measurement feasible.

Because of the large values (~ 1) of the adiabaticity parameter ξ encountered in this work the influence of higher-lying levels on the evaluation of Q_{2^+} and $B(E2, 0_1^+ \rightarrow 2_1^+)$ is small. From Table I it is seen that changing the sign of the interference term involving the 2_2^+ state (usually the most important such effect) changes Q_{2^+} by less than 15%. The influence of levels other than the first five, or the effect of multipolarities other than $E2$, has not been thoroughly investigated. It is expected that because of the large size of ξ together with the weak coupling of the 2_1 and higher levels, such effects are negligible in comparison with the size of the reorientation effect. We have, however, considered the question of the influence of the giant $E1$ resonance more closely. Using the corrected expression of equation 57 of Ref. 14 and taking $\eta_0 = 0.27$, which is

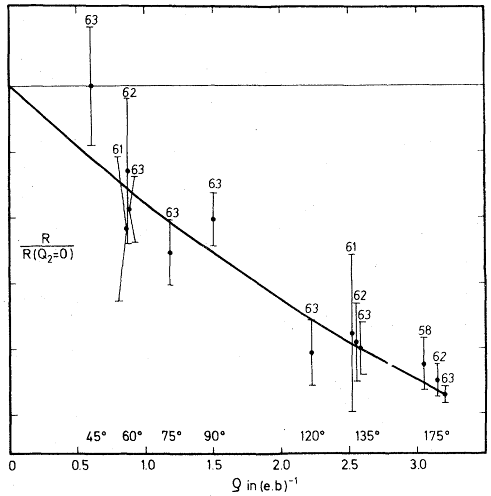

FIG. 2. The experimental excitation probabilities R normalized by the values calculated with the de Boer–Winther program using $Q_{2^+} = 0$. These ratios are plotted as a function of the sensitivity parameter, and are shown together with their corresponding scattering angles and bombarding energies. The solid line is the fit corresponding to the values given in Table I for the positive interference sign.

the estimate[20] for heavy deformed nuclei, we find that Q_{2^+} is lowered by $(0.024\text{ b})e$ but $B(E2, 0_1^+ \to 2_2^+)$ is increased by about $(0.0004\text{ b}^2)e^2$. In addition, since the validity of the heavy-deformed-nucleus estimate of η_0 for ^{18}O is not evident and since a more reliable estimate is not available, we have not corrected our results for the effect of the $E1$ resonance. We note that the $B(E2, 0_1^+ \to 2_1^+)$ values obtained from lifetime measurements (see Table I) set an upper limit of $\eta_0 \sim 0.15$.

A disturbing problem is the comparison with the $B(E2, 0_1^+ \to 2_1^+)$ values obtained from the measured lifetimes, as shown in Table I. Although the latest measurements are in excellent agreement with the present work, the reason for discrepancy among the various lifetime measurements is not fully understood. If, e.g., we had performed our analysis using the average of the pre-1975 $B(E2, 0_1^+ \to 2_1^+)$ values obtained from lifetimes[3] and our own $R(175°)$ data, we would have obtained a value for Q_{2^+} of $(-0.07 \pm 0.010\text{ b})e$. Though still large, this value is a factor 3 smaller than that quoted in Table I. Finally, we should mention the unpublished measurement of Disdier *et al.*[19] Although the quoted Q_{2^+} value is not inconsistent with our results, the disagreement between the $B(E2, 0_1^+ \to 2_1^+)$ values makes this comparison unreliable. It should be noted that our earlier results,[21] which were based on a preliminary analysis of a subset of all the data, are in good agreement with the results reported here.

For the purpose of discussion it is useful to deal with the ratio $|Q_{2^+}|/[B(E2, 0_1^+ \to 2_1^+)]^{1/2}$ which in the present measurement was found to be 2.7 ± 0.3. On the other hand the value obtained for ^{42}Ca, for which similar results might be expected, is ~ 1.[13] To our knowledge no other nuclei have been discovered for which this ratio is appreciably greater than 1.[22] This implies either that the 2_1^+ state is more deformed than the ground state or that there is appreciable cancelation in the 2_1^+ to 0_1^+ $E2$ transition. In any case our results suggest that there must be a significant amount of deformed component in the 2_1^+ state.

Although the very large size of the effect we obtain makes it difficult to conceive of additional influences which might appreciably affect our results, the measurement does stretch (as reflected in the large errors for the R values) the limit of applicability of this method. Added to the discrepancies associated with the lifetimes it is clear that further lifetime and reorientation-effect measurements are needed.

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[1] J. W. Olness *et al.*, Phys. Rev. C 7, 2239 (1973).

[2] Z. Berant *et al.*, Nucl. Phys. A225, 55 (1974).

[3] A. B. McDonald *et al.*, Can. J. Phys. 52, 1381 (1974).

[4] J. A. J. Hermans *et al.*, to be published.

[5] J. Asher *et al.*, to be published.

[6] K. H. Speidel *et al.*, Phys. Lett. 57B, 143 (1975).

[7] H. T. Fortune and S. C. Headley, Phys. Lett. 51B, 136 (1974).

[8] T. Engeland and P. J. Ellis, Nucl. Phys. A181, 368 (1972).

[9] J. B. McGrory and B. H. Wildenthal, Phys. Rev. C 7, 974 (1973).

[10] G. E. Brown, in *Proceedings of the International Congress for Nuclear Physics, Paris, France, 1964,* edited by P. Gugenberger (Centre National de la Recherche Scientifique, Paris, France, 1964), Vol. 1, p. 129.

[11] H. G. Benson and B. H. Flowers, Nucl. Phys. A126, 332 (1969).

[12] W. J. Gerace and A. M. Green, Nucl. Phys. A93, 110 (1967).

[13] C. W. Towsley *et al.*, Nucl. Phys. A204, 574 (1973).

[14] J. de Boer and J. Eichler, Adv. Nucl. Phys. 1, 1 (1968).

[15] R. A. Broglia *et al.*, Phys. Rev. C 1, 1508 (1970).

[16] Z. Berant *et al.*, Nucl. Phys. A196, 312 (1972).

[17] A. Bockisch *et al.*, to be published.

[18] A. Winther and J. de Boer, in *Coulomb Excitation,* edited by K. Alder and A. Winther (Academic, New York, 1966), p. 303.

[19] D. L. Disdier *et al.*, private communication [as quoted by A. Christy and O. Häusser, Nucl. Data Tables 11, 281 (1973)].

[20] H. Nebel and D. L. Lin, Phys. Rev. 156, 1133 (1967).

[21] A. M. Kleinfeld, K. P. Lieb, D. Werdecker, and U. Smilansky, in *Proceedings of the International Conference on Reactions Between Complex Nuclei, Nashville, Tennessee, 1974,* edited by R. L. Robinson *et al.* (North-Holland, Amsterdam, 1974), Vol. 1, p. 27.

[22] Christy and Häusser, Ref. 19.