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Static Quadrupole Moment of the First 2+ States of the Even Tin Nuclei*

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Measurements of the relative thick-target yields of γ rays deexciting the 2+ first excited states in ^{112,116,118,120,122,124}Sn, following Coulomb excitation by α particles and ^{16}O ions, have been interpreted in terms of the relative static quadrupole moments of these states. The absolute static quadrupole moment of the 2+ state in ^{120}Sn was determined to be +(0.09 ± 0.10) b. With this value it was then possible to obtain the absolute static quadrupole moments for the 2+ state in the other even tin nuclei. The resulting values are closer to the vibrational-model prediction (static quadrupole moment of zero) than to values predicted by the rotational model. A set of absolute $B(E2, 0 \rightarrow 2)$ values was also obtained with assigned errors between 2 and 3%.

I. INTRODUCTION

The Coulomb-excitation mechanism was used to investigate the static quadrupole moments of the first 2+ states of the even tin nuclei. This method is based on the facts (a) that the Coulomb-excitation cross section depends on both the dynamic quadrupole moment $[B(E2)]$ and the static quadrupole moment $[Q(2+)]$ and (b) that the relative contributions of these two moments varies with the mass of the incident projectile producing the excitation. For example, if we assume that the first 2+ state of ^{120}Sn has a $Q(2+)$ of 0.4 b (rotational value), then the differential cross sections at a backscattering angle are altered by 3% for α particles and by 12% for ^{16}O projectiles from those expected for $Q(2+)$ value of zero (phonon-vibration value). Expressed differently, the "apparent" $B(E2)$ values obtained with α particle and ^{16}O projectiles would differ 9% if $Q(2+)$ were 0.4 b. The basic Coulomb-excitation theory is given by Alder *et al.*[1]

The total cross section for Coulomb excitation also depends on $Q(2+)$ but the sensitivity is roughly only $\frac{1}{2}$ as large as that for the differential cross section at a backward angle. On the other hand, the total γ-ray yield, which is proportional to the total cross section, is a straightforward quantity to measure and can be determined quite accurately with Ge(Li) γ-ray detectors. Our initial measurements determined the "apparent" $B(E2)$ values for α particles and ^{16}O projectiles from the total γ-ray yields. These results furnished information about the relative $Q(2+)$ values of the different even tin nuclei.

It was then necessary to determine the absolute

$Q(2+)$ value for one tin nucleus in order to establish the absolute scale for the relative measurements. This was done by measuring the differential cross sections at backward angles for Coulomb excitation of ^{120}Sn for both α particles and ^{16}O ions. Two types of experiments were performed. One experiment consisted of the direct measurement of spectra of particles scattered from thin targets using surface-barrier silicon detectors. Although this method is quite direct, it suffers from poor signal-to-noise problems. To avoid this problem, another method was also used which involved the coincidence counting of deexcitation γ rays and backscattered particles.

II. EXPERIMENTAL METHOD AND RESULTS

A. "Apparent" $B(E2)$'s from γ-Ray Yields

If we assume that $Q(2+)$ is zero, then the $B(E2)$ for Coulomb excitation of the first 2+ state is given by the formula

$$B(E2; 0 \to 2) = \frac{5.554 \times 10^{-59} A_2' (CZ_2)^2 z Y(\text{exc}/\mu\text{C})}{A_1 I_{E2}} e^2\,\text{cm}^4, \tag{1}$$

where

$$I_{E2} = \int_0^{E_i} \frac{(E - C\Delta E) f_{E2}(\eta_i, \xi)}{S(E)}\, dE \,\frac{\text{MeV mg}}{\text{cm}^2}. \tag{2}$$

$zY(\text{exc}/\mu\text{C})$ is the thick-target γ-ray yield in excitations per μC of particles (z is the charge state of ions incident on the target), A_2' is the target atomic weight (normal element), A_1 and A_2 are the masses of the projectile and target in amu, Z_2 is the target nuclear charge, E_i is the incident projectile energy in MeV, ΔE is the nuclear excitation energy in MeV, $C = 1 + A_1/A_2$, and $S(E)$ in MeV cm^2/mg is the projectile stopping power in the target material. The integral I_{E2} is evaluated numerically using the $f_{E2}(\eta_i, \xi)$ values from the theory of Coulomb excitation.[1]

Inspection of relations (1) and (2) reveals that $B(E2)$ depends on the following experimental quantities: $Y(\text{exc}/\mu\text{C})$, $S(E)$, E_i, and ΔE (through ξ dependence on ΔE). Errors in these quantities will contribute error to $B(E2)$. However, if we consider the relative $B(E2)$ values of two isotopes for the same projectile, then a marked increase in accuracy is achieved. The $Y(\text{exc}/\mu\text{C})$ which depends on the efficiency of the γ-ray detector now depends on the relative efficiency rather than the absolute efficiency. The relative $B(E2)$'s are almost independent of $S(E)$ and the dependence on E_i is much reduced. The error in ΔE still contributes, but, with the high accuracy of γ-ray energies (hence ΔE) determined with Gi(Li) detectors, this source of error is already quite small.

Isotopically enriched metallic targets of $^{112, 116, 118, 120, 122, 124}$Sn were prepared by electrodeposition on to 5-mil nickel backings. The same targets were used for both α-particles and ^{16}O Coulomb excitation. The targets were thick to both types of projectiles. The incident projectile energies were 10 MeV for α particles and 45.5 MeV for ^{16}O ions.

The γ rays resulting from Coulomb excitation of the first 2+ state range in energy from 1.131 MeV for ^{124}Sn to 1.296 MeV for ^{116}Sn. These γ rays were detected with a 30-cc Ge(Li) detector placed at 55° to the incident beam direction. The efficiency of the detector was determined by the use of a set of calibrated γ-ray sources (^{137}Cs, ^{22}Na, ^{60}Co, ^{88}Y, etc.) obtained from the International Atomic Energy Agency Laboratories, Vienna, Austria. The source strengths are calibrated to about 1% accuracy. The same detector was used for both the α particles and ^{16}O runs, which means that the efficiency of the γ-ray detector is really not necessary to obtain ratios of "apparent" $B(E2)$'s for the two projectiles for each tin isotope. However, we also wanted to obtain an accurate set of $B(E2)$ values for the tin isotopes and for this purpose the efficiency is important.

The mean-lives of the first 2+ states of the even tin nuclei range in value from 0.5 to 1 psec.[2] Since these mean-lives are comparable to the slowing down times of the recoiling Coulomb-excited nuclei, we observe a broadening of the peak caused by the Doppler shift of the γ-ray energies. For α-particle Coulomb excitation the maximum possible shift in energy is 5 keV, and for ^{16}O ions the maximum possible shift increases to about 20 keV. In Fig. 1 we show the observed γ-ray spectra for ^{16}O Coulomb excitation; the shoulders on the right-hand side of the peak resulting from the Doppler shift are quite apparent. This Doppler broadening is an unavoidable complication which must be handled with care if good accuracy is to be maintained. Since the lifetimes are somewhat different for the different tin isotopes, the amount of Doppler broadening is variable. The ^{116}Sn peak has a larger shoulder than the ^{124}Sn peak. Because of the variable shapes of the γ-ray peaks we have not tried to fit an analytic function but have instead summed all the channels contributing counts to the peak. There is always some tailing of the γ-ray peak on the low-energy side, and the amount of tail included in the peak must be treated in a consistent way. For this reason we observed the γ rays at 55° to the incident beam direction so that the Doppler-shifted γ rays would be on the high-energy side of the peak rather than in the tail region on the low-energy side.

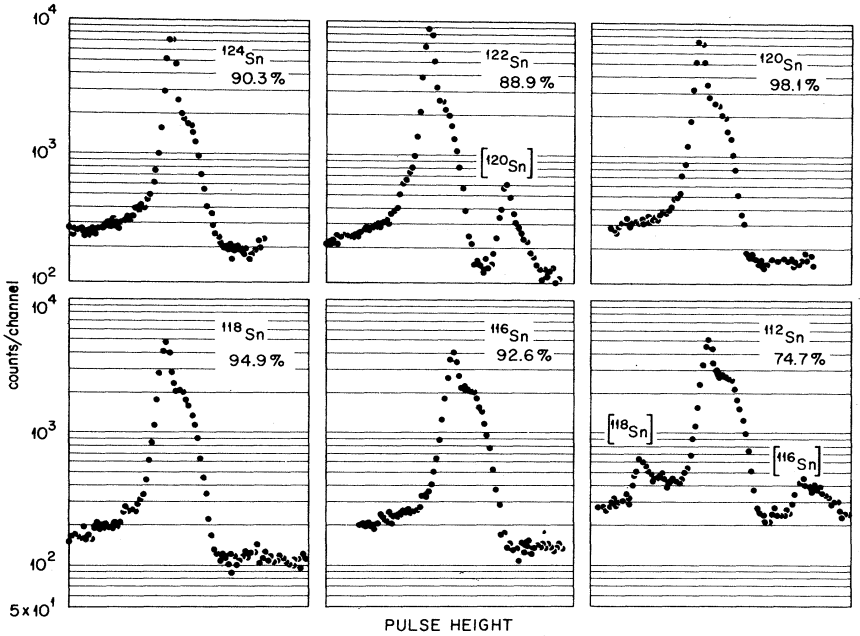

FIG. 1. Ge(Li) γ-ray spectra which result from the Coulomb excitation of the first 2+ state in the even tin nuclei by 45.5-MeV ^{16}O projectiles. γ rays were observed at an angle of 55° to the beam direction. The Doppler shifts (shoulders on the high side of the peaks) are quite apparent.

For α particles the relative γ-ray yields $I(\gamma/\mu C)$ were determined to an accuracy of about ±0.7%. The statistical error and the background-subtraction error contributed about equally to the total error. Similarly, for the ^{16}O ions, the relative $I(\gamma/\mu C)$ were determined to an accuracy of about ±0.6% with statistical and background-subtraction errors of about equal importance.

The "apparent" $B(E2)$ values are given in columns 3 and 4 of Table I. We mean by apparent $B(E2)$ those values extracted by the use of expression (1) and (2). Although not necessary, we have for convenience applied a normalization factor to the two sets of $B(E2)$ values to bring them into average agreement. The quantity of interest is given in column 5; this is the percentage difference of the "apparent" $B(E2)$ values for each isotope for α particle and ^{16}O ion excitation. We will relate these quantities to differences in the $Q(2+)$ values. We also assign an error to the percentage difference in $B(E2)$ values. This error is based on the errors in the relative γ-ray yields. As mentioned above, there are also other sources of error in obtaining the relative $B(E2)$ values. An analysis of these errors indicated that for the worst case (comparison of ^{124}Sn and ^{116}Sn) these errors are still quite small compared with the errors from the relative γ-rays yields.

According to the theory of Coulomb excitation, the influence of $Q(2+)$ on the total cross section is almost independent of the energy of the incident projectile; therefore, the use of thick targets in-

TABLE I. Summary of "apparent" $B(E2)$ values obtained from thick-target γ-ray yields with α particles and ^{16}O ions as projectiles. The percentage difference in $B(E2)$ values listed for each nucleus in column 5 is interpreted as a $\Delta Q(2+)$ value, which is listed in column 6. Taking the absolute $Q(2+)$ value for ^{120}Sn as +(0.09 ±0.10) b, we then use the $\Delta Q(2+)$ values to obtain the $Q(2+)$ values for the other tin nuclei and these values are given in the last column.

Nucleus	$E(2+)$ (MeV)	"Apparent" $B(E2)$ α particles	^{16}O ions (10^{-49} cm$^4 e^2$)	Percent difference in $B(E2)$ values	ΔQ (b)	$Q(2+)$ (b)
^{124}Sn	1.131	1.600	1.618	+(1.13 ±1.06)	+(0.12 ±0.11)	+(0.07 ±0.17)
^{122}Sn	1.140	1.931	1.890	-(2.19 ±1.04)	-(0.23 ±0.11)	-(0.28 ±0.17)
^{120}Sn	1.171	2.018	2.046	+(1.40 ±0.79)	+(0.14 ±0.08)	+(0.09 ±0.10)
^{118}Sn	1.230	2.163	2.124	-(1.82 ±0.93	-(0.18 ±0.09)	-(0.23 ±0.16)
^{116}Sn	1.293	2.132	2.157	+(1.17 ±0.91)	+(0.11 ±0.09)	+(0.07 ±0.16)
^{112}Sn	1.257	2.552	2.526	-(1.02 ±1.21)	-(0.10 ±0.12)	-(0.15 ±0.18)

troduces no essential complication. The change in cross section is proportional to Q itself (including sign) and is also approximately proportional to ΔE. For the tin nuclei a change of $\Delta Q = 0.1$ b implies about 1% change in the relative $B(E2)$ values obtained from thick-target γ-ray yields for α particles and ^{16}O ions. Column 6 lists the quantities ΔQ based on the observed percentage differences listed in column 5. The meaning of the ΔQ values is the following: For example, in comparing the $Q(2+)$ values of ^{124}Sn and ^{120}Sn we have $\Delta Q(^{124}\text{Sn}) = +(0.12 \pm 0.11)$ and $\Delta Q(^{120}\text{Sn}) = +(0.14 \pm 0.08)$; and therefore, $Q(^{124}\text{Sn}) - Q(^{120}\text{Sn}) = -(0.02 \pm 0.14)$ b.

In the following section we will discuss the determination of the absolute $Q(2+)$ for ^{120}Sn. The observed value is $+(0.09 \pm 0.10)$ b. Using this value and the ΔQ values given in Table I, we deduce the $Q(2+)$ values for the other tin isotopes, and these are listed in the last column.

B. Absolute $Q(2+)$ for ^{120}Sn

The absolute differential cross sections at backward angles for the Coulomb excitation of the 2+ state in ^{120}Sn were measured for α-particles and ^{16}O projectiles. In one set of experiments we directly measured the elastic and inelastic scattering from thin targets using surface-barrier silicon detectors. In order to minimize the energy spread caused by kinematics, we used an annular detector to measure the ^{16}O spectra. The detector measured the scattering between the lab angles of 170 to 177°. The target was enriched (98.4%) metallic ^{120}Sn evaporated onto a thin carbon-foil backing to a thickness of about 10 μg/cm^2.

Examples of the observed ^{16}O spectra are given in Fig. 2. The peaks have an energy width of about 175 keV. A portion of the observed tails on the low-energy side of the elastic peak is caused by elastic scattering from the small amounts of lighter tin isotopes in the target. From the spectra we determine the ratio of counts in the elastic peak and in the inelastic peak due to excitation of the 2+ state in ^{120}Sn. With the assumption that the sum of the cross sections is equal to the Rutherford cross section, we can deduce the differential cross section for Coulomb excitation, and from this we can extract "apparent" $B(E2)$ values. These $B(E2)$ values are shown in Fig. 3 for the incident ^{16}O energies of 38.5, 40, 42, and 44 MeV. The errors shown for the $B(E2)$ values are about 3 to 4% and they result from the statistical error and uncertainties in the subtraction of the tail of the large elastic peak on which the 2+ peak rides. Within the errors, the four values for $B(E2)$ are in agreement. The average value for the apparent $B(E2)$ for ^{16}O is $(2.070 \pm 0.035) \times 10^{-49}$ cm$^4 e^2$.

The ratio of inelastic to elastic cross sections for α-particle Coulomb excitation of ^{120}Sn is quite small – typically, one part in 2000. There is a strong temptation to make measurements at high α-particle energies since this markedly improves the ratio of inelastic to elastic events. However, one then runs the risk of violating the basic assumption of pure Coulomb excitation. We made measurements at three α-particle energies of 10,

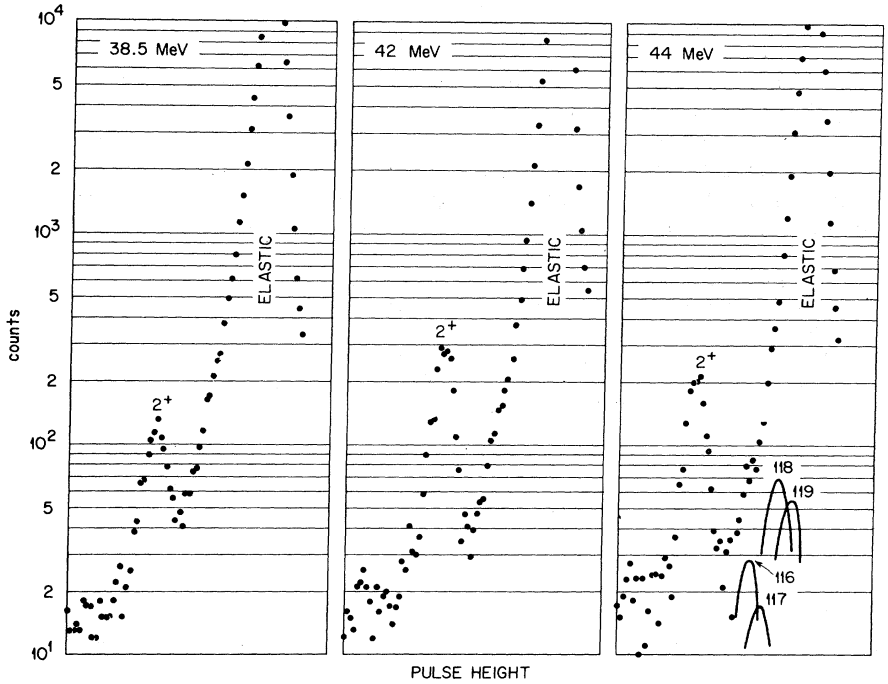

FIG. 2. Examples of ^{16}O spectra observed in an annular silicon surface-barrier detector when the beam struck a thin ^{120}Sn target.

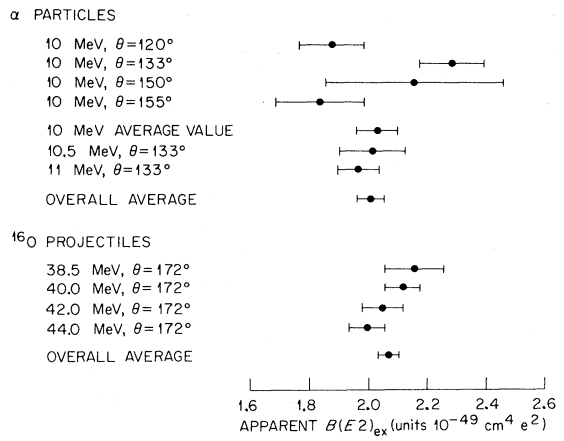

FIG. 3. Graphical summary of "apparent" $B(E2)$ values obtained from the Coulomb excitation of the first 2+ state in ^{120}Sn. Results are shown for both α particles and ^{16}O projectiles.

10.5, and 11 MeV.

Another source of difficulty is the fact that small amounts of impurities lighter than ^{120}Sn, such as iron, can give rise to an elastic peak in the vicinity of the inelastic peak for ^{120}Sn. We therefore made measurements on the α-particle spectra with a well-collimated detector which could be moved in angle in order to shift the relative positions of possible impurity peaks and the peak from inelastic scattering by ^{120}Sn. Two examples of α-particle spectra are shown in Fig. 4.

A summary of the apparent $B(E2)$ values obtained for α-particle Coulomb excitation of ^{120}Sn is shown graphically in Fig. 3. The average value of $B(E2)$ obtained from 10-MeV runs is in good agreement with the values obtained at 10.5 and 11 MeV. Combining all the runs we obtain an apparent $B(E2)$ value of $(2.010 \pm 0.045) \times 10^{-49}$ cm$^4 e^2$.

Assuming that the apparent $B(E2)$ values result from a combination of the true $B(E2)$ and the $Q(2+)$, the theory of Coulomb excitation gives the result

$$B(E2)_{\text{apparent}} = B(E2)[1 + c_1 Q(2+)],$$

where the constant c_1 is calculable for a given experimental situation. For the present case we have $c_1 = +0.292$ b^{-1} for ^{16}O ions and a weighted value (c_1 varies with angle) of $c_1 = +0.065$ b^{-1} for α particles. The two measured apparent $B(E2)$ values yield the result

$$Q(2+) = +0.14 \pm 0.13 \text{ b},$$

$$B(E2) = (1.99 \pm 0.05) \times 10^{-49} (e^2 \text{ cm}^4).$$

The second set of experiments done to measure the absolute $Q(2+)$ of ^{120}Sn involved γ-ray–backscattered-particle coincidences. By detection of the γ ray we enhance the signal-to-noise ratio for detection of the inelastic events. The incident beam passed through the annulus of a surface-barrier detector and struck a thick metallic target of ^{120}Sn.

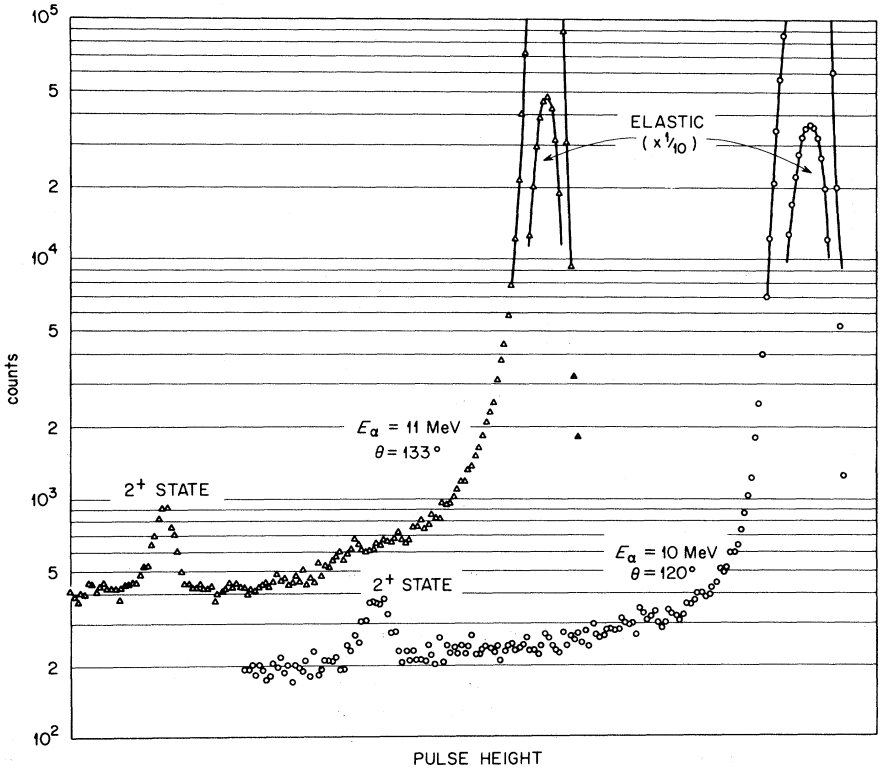

FIG. 4. Examples of α-particle spectra observed in a silicon surface-barrier detector when the incident beam struck a thin ^{120}Sn target.

Scattered particles, both elastic and inelastic, between the lab angles of 155 and 171° were detected in the annular detector. The γ rays resulting from Coulomb excitation were detected by a 7.6×7.6-cm NaI detector located at 55° to the incident beam direction and with a distance of 2.15 cm from the face to the target spot. At this distance the calculated values for $W(\theta = 55°)$ are 1.0775 and 1.0805, respectively, for α particles and for ^{16}O ions.

The use of a thick target avoids the strong attenuations of angular correlations which result when ionized atoms recoil through vacuum.[3,4] However, we now have to deduce the effective target thickness from the lower bias level set on the pulse from the annular detector. It was therefore important to accurately determine the energy response of the detector for both α particles and ^{16}O ions. This was done by variation of the beam energy incident on the target and, in the case of ^{16}O ions, by using a series of targets of different atomic weight.

The accurate knowledge of the target thickness is important to the experiment because the elastic scattering cross section increases with decreasing particle energy, whereas the inelastic scattering cross section decreases with decreasing particle energy. Hence, we need to know the target thickness in energy units. It turns out that we do not need to know the thickness in atoms/cm^2, since we assume the Rutherford cross section is valid and this normalizes out the product of the incident flux and the atoms/cm^2. It follows that although the absolute value of the stopping power $S(E)$ is not essential, the shape of $S(E)$ is important.

The observed shape of the particle spectrum in the annular detector can be compared with the calculated shape based on a given $S(E)$. For α particles, which have a well-established shape for $S(E)$, we calculated the expected energy spectrum in the annular detector and we compared this with the observed spectrum in the top of Fig. 5. It is seen that the calculated shape agrees well with what is observed. On the other hand, the shape of $S(E)$ for ^{16}O ions is not very well known. In Fig. 6 we have plotted four possible $S(E)$ shapes for ^{16}O ions in tin. The values represented by A have been discussed previously.[5] The values represented by B are taken from Booth and Grant[6] for ^{16}O energies below 24 MeV and extrapolated to higher energies. The values represented by C were chosen to give an $S(E)$ shape between those represented by A and B. Finally, set D are values recently recommended by Northcliffe and Schilling.[7]

In the lower part of Fig. 5 we have compared

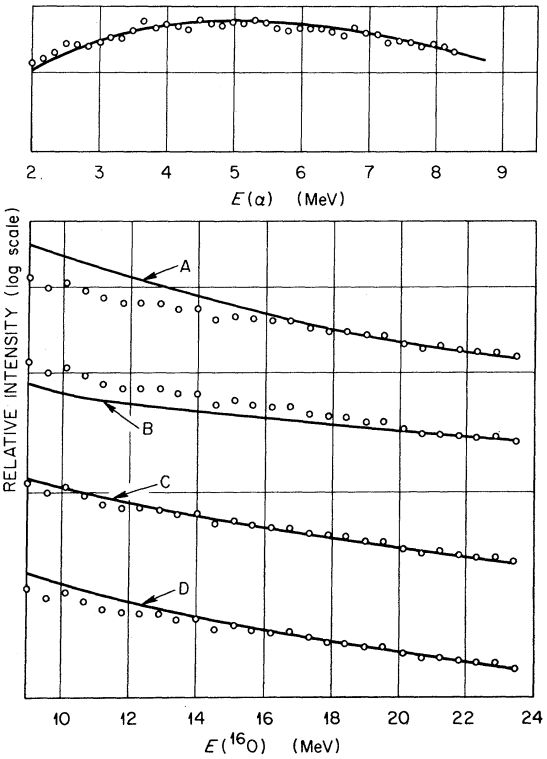

FIG. 5. Observed and calculated shapes of particle spectra backscattered from a thick ^{120}Sn target into an annular surface-barrier detector. The solid curves are calculated shapes for different shapes taken for the stopping power $S(E)$. The upper curve is for α particles and the lower curves are for ^{16}O ions.

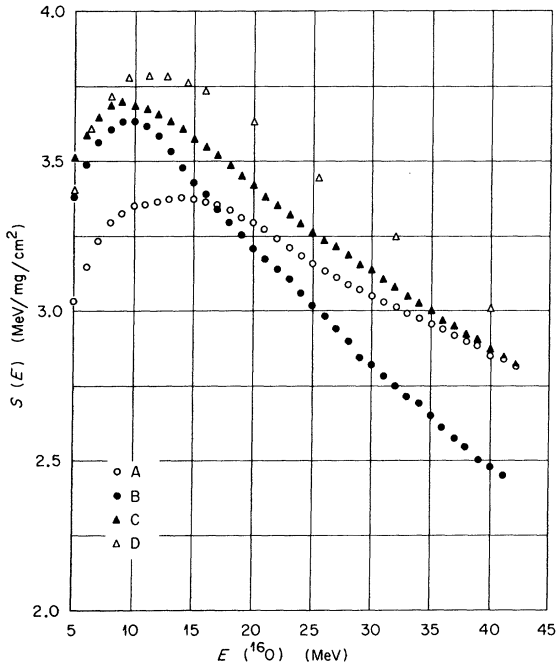

FIG. 6. Four different sets of stopping powers for ^{16}O ions in tin (see text).

the calculated shapes of the particle energy spectra for different $S(E)$ shapes with what is observed experimentally. Shapes A and B for $S(E)$ produce calculated spectra which differ appreciably from what is observed, whereas $S(E)$ represented by shapes C and D agree quite well with the observed spectrum. We have therefore used the $S(E)$ shape represented by C to calculate the target thickness.

For the α-particle runs, the incident energy was 10.0 MeV and the target thicknesses were 2.70 and 2.15 MeV, respectively, for elastic and inelastic scattering. For the ^{16}O ion excitation, the incident energy was 42 MeV and the target thicknesses were 8.85 and 8.35 MeV, respectively, for elastic and inelastic scattering. Our subsequent analysis of the experimental results indicates that we would have reduced the systematic errors due to uncertainties in $S(E)$ if we had used a somewhat thinner target for the ^{16}O ions.

The statistical accuracy of the ratio of probabilities for Coulomb excitation with α particles and ^{16}O ions was ±2%, which implies an error of ±0.11 b for $Q(2+)$ of ^{120}Sn. Because of a possible systematic error caused by uncertainty in the shape of $S(E)$ for ^{16}O ions, we have increased the error on $Q(2+)$ to ±0.16 b. Therefore, the result of this experiment is

$$Q(2+) = +0.02 \pm 0.16 \text{ b},$$

$$B(E2) = (2.07 \pm 0.05) \times 10^{-49} (e^2 \text{ cm}^4).$$

This result is in resonable agreement with +0.14 ± 0.13 b obtained from the first experimental method. Combining the two results we have a final value of

$$Q(2+) = +0.09 \pm 0.10 \text{ b}.$$

The above interpretation attributes the whole observed deviation in $B(E2)$ values to the influence of the $Q(2+)$. However, we know that other interference processes in Coulomb excitation can influence the $B(E2)$ ratio. In particular, interference due to the virtual excitation of higher 2′+ states can be important. The magnitude of such an interference depends on the term $[B(E2, 0 \rightarrow 2')B(E2, 2' \rightarrow 2)]^{1/2}$. We do not know these $B(E2)$ values for the even tin nuclei. To assess the importance of such an interference we will assume representative values found for other vibrational-type nuclei.[8] We take the single-particle value for $B(E2, 0 \rightarrow 2')$, viz. 1.8×10^{-50} cm$^4 e^2$ and we take $B(E2, 2' \rightarrow 2) = B(E2, 2 \rightarrow 0)$. With these values we have used the Winther-deBoer computer program[9] to calculate the amount of interference in the $B(E2)$ values caused by the virtual excitation of a higher 2′+ state. The result is that such an interference could alter the $Q(2+)$ value by ±0.1 b, which is about equal to the present experimental accuracy. Since we do not know the actual numbers for the $B(E2, 0 \rightarrow 2')$ and $B(E2, 2' \rightarrow 2)$ transitions in the tin nuclei, we cannot easily assign a meaningful uncertainty to the measured $Q(2+)$ due to such an interference. It should be borne in mind that the measured $Q(2+)$ could eventually be altered by possibly ±0.10 b when these $B(E2)$ values become available.

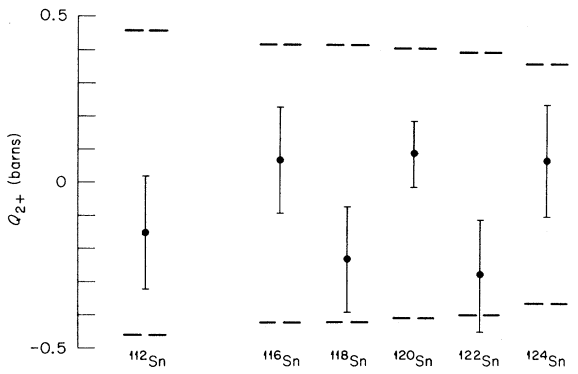

FIG. 7. The observed $Q(2+)$ values for the different even tin nuclei. The dashed lines indicate the rotational limits (prolate and oblate). The familiar parameter β_2 is approximately 0.12 for the even tin nuclei.

Taking the absolute value for $Q(2+)$ of ^{120}Sn as +0.09± 0.10 b we can use the ΔQ values in Table I to calculate the $Q(2+)$ values for the other even tin isotopes. These values are given in the last column of Table I.

It is instructive to compare the observed $Q(2+)$ values with those predicted for a rotational 2+ state. In this case the $Q(2+)$ is related to the $B(E2, 0 \rightarrow 2)$ by the relation

$$eQ(2+) = \frac{8}{7}\left\{\frac{\pi}{5}[B(E2, 0 \rightarrow 2)]\right\}^{1/2}.$$

In Fig. 7 we show the measured $Q(2+)$ values and the rotational values (oblate and prolate values for each nucleus indicated by dashed lines). We see that four of the nuclei have $Q(2+)$ values which are consistent with zero (expected vibrational value). ^{118}Sn and ^{122}Sn have values which are approximately midway between vibrational and prolate

TABLE II. Summary of absolute $B(E2)$ values for the even tin nuclei.

Nucleus	$B(E2, 0 \rightarrow 2)$ (10^{-49} cm$^4 e^2$)
^{112}Sn	2.56 ±0.06
^{116}Sn	2.16 ±0.05
^{118}Sn	2.16 ±0.05
^{120}Sn	2.03 ±0.04
^{122}Sn	1.96 ±0.04
^{124}Sn	1.61 ±0.04

rotational values. The errors shown are standard deviations.

The present experimental results produce a rather accurate set of $B(E2)$ values for the first 2+ states of the even tin nuclei. The results are based on the absolute $B(E2)$ for ^{120}Sn obtained in the two experiments described above and on the relative $B(E2)$ values for the different tin isotopes given in Sec. A. These values are given in Table II. We had previously published[10] a similar set of $B(E2)$ values which we thought had a relative accuracy of ±2% and an absolute accuracy of ±5%. The relative values of the numbers given in Table II agree well with the previous values but the absolute values do not. The average difference between the two sets of values is 12%. We have uncovered a systematic 8% error in the γ-ray efficiencies of the detector used in making the previous measurements. The absolute values of the $B(E2)$'s given in Table II are to be perferred to those previously given.

Curtis *et al.*[11] have studied the quadrupole excitations of the even tin isotopes by inelastic electron scattering. The $B(E2)$ values they obtain are model dependent. The Tassie model and the "best-fit" model give $B(E2)$'s which differ by about 25%. Our old set of $B(E2)$ values agreed quite well with the Tassie-model values from electron scattering. The smaller $B(E2)$ values of Table II move in the direction of the "best-fit" values from electron scattering but are still somewhat closer to the Tassie-model $B(E2)$'s.

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