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ELECTRIC HEXADECAPOLE MOMENT IN ^{152}Sm*

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ABSTRACT

The Coulomb excitation of the 4^+ rotational state of a deformed nucleus can proceed by both double E2 and single E4 transitions. The excitation cross section also contains a term corresponding to the interference between the two. The Coulomb excitation of ^{152}Sm with ^4He projectiles has been carefully measured and the results were analyzed with a computer program including E4 terms. Best fits were obtained for $\langle 0^+ \| \mathcal{M}(E4) \| 4^+ \rangle = +0.35 \pm 0.11$ eb^2.

Coulomb excitation can be one of the most reliable methods for determining electric multipole matrix elements of nuclei. However, one must be careful to include all processes having effects comparable to the one being measured, and the analysis may become very complicated or even ambiguous. The present study of an E4 transition moment in ^{152}Sm began as the evaluation of a correction to measurements[1] of $B(E2; 2^+ \rightarrow 4^+)$. It became apparent that this particular correction was not very well known and could be rather large, especially when light projectiles were used so that double E2 excitation is weak. The accurate determination of the $B(E2; 2^+ \rightarrow 4^+)$ value from lifetime measurements[2] made it possible

to combine that result with the Coulomb excitation measurements and determine the E4 moment.

The experiment consisted of an accurate determination of the intensity of the $4^+ \rightarrow 2^+$ gamma-ray transition in ^{152}Sm relative to those of the $2^+ \rightarrow 0^+$ transitions in ^{152}Sm and ^{150}Sm following Coulomb excitation with ^4He ions. Targets of both natural samarium and enriched ^{152}Sm were measured at each bombarding energy. This method provides accurately-known standard peaks (122 and 334 keV) for comparison at both higher and lower energies than the peak of interest (245 keV). Gamma-ray spectra were simultaneously stored as singles events and as coincidences with ^4He ions backscattered through an angle of about 160 deg. These two types of measurement are about equally sensitive to the effect of an E4 transition moment, but differ markedly in their sensitivity to many other effects. Thus the agreement of the singles and back-scatter results greatly reduces the probability that an important effect has been overlooked.

An overall view of the possibilities for measuring E4 transition moments using this method is contained in Fig. 1. We have used the following notation:

$$\langle 0^+ \| \mathcal{M}(E4) \| 4^+ \rangle = \int \rho r^4 Y_{40} d^3r = \sqrt{B(E4; 0^+ \rightarrow 4^+)} \quad ,$$

where ρ is the nuclear charge density. The effect of an E4 moment on the cross section for populating the 4^+ level of ^{152}Sm in coincidence with back-scattered ^4He ions ($d\sigma$) is shown, normalized to the cross section with no E4 moment ($d\sigma_0$). This behavior changes very little with projectile scattering angle, so that the corresponding curve for the singles measurements differs by only a few percent. The general shape of this curve is caused by the dominance of the direct E4 transition, which depends quadratically on the moment. The weaker interference term (linear) causes the asymmetry about zero. Also shown in Fig. 1

is the relationship of the E4 moment to the deformation parameter, β_4, which will be defined below. This curve has been constructed by adjusting β_2, for each value of β_4, so that the measured $B(E2;0^+ \rightarrow 2^+)$ value in ^{152}Sm is reproduced. The asymmetry of this curve relative to zero is caused by the positive second-order contribution to the E4 moment from β_2. The asymmetries in these two curves make it unlikely that one can measure negative E4 moments by this technique, since reasonable values[3] of $\beta_4 (\geq -0.2)$ do not give rise to sufficiently large negative E4 moments to cause measurable deviations in the cross section. This situation renders improbable one of the two possibilities for the moment that would otherwise result from a given cross section measurement. Small positive values of β_4, however, should produce readily measureable effects in the cross section.

We have bombarded thin (≈ 2 mg/cm^2) self-supporting metallic targets of Sm with 10 to 14 MeV ^4He beams from the Lawrence Radiation Laboratory HILAC. This target thickness ensures that less than 2% of the recoiling nuclei escaped from the target. The beam energy was determined by comparison with a ^{212}Po alpha source.[4] Gamma-ray spectra were measured with a Ge(Li) detector whose relative counting efficiency was determined to an estimated accuracy of 2% using a ^{177m}Lu source.[5] The total conversion coefficients for the transitions were obtained from the tables of Hager and Selzer[6] and should result in uncertainties no greater than 1% in $1 + \alpha_T$. The spectra were recorded at a gamma-ray angle of 55 deg relative to the beam direction. The singles measurements were not very sensitive to this angle, but the back-scatter coincidence data were. In the latter case we measured the intensity of the 122 keV transition at 45 and 90 deg relative to the beam direction, and obtained an angular distribution attenuation coefficient,

G_2, of 0.93,on the assumption that the relationship between G_2 and G_4 is that given by a magnetic dipole interaction. Since the value of G_2 was near unity for this line, and since the other three transitions of interest have much shorter lifetimes, we assumed no attenuation of the anglular distributions in those cases. Finite solid angle corrections were made using the tables of Black and Gruhle.[7] A small empirically-determined correction was made for the accidental simultaneous arrival in the detector of two 122 keV photons, simulating one of 244 keV. There is also a correction of about 2% in the intensity of the 122-keV line in the natural samarium targets due to photons from ^{147}Sm. A typical gamma-ray spectrum in coincidence with back-scattered projectiles is shown in Fig. 2.

In calculating the intensity of the 245-keV line, we used a computer program[8] which took account of E2, E3, and E4 excitations. We included the rotational states up to 8^+ in ^{152}Sm, using the B(E2) values given in Diamond et al.[2] The first two of these are: $B(E2;2^+ \rightarrow 0^+) = 0.686 \pm 0.014\ e^2b^2$, and $B(E2;4^+ \rightarrow 2^+) = 1.009 \pm 0.033\ e^2b^2$. However, because double E2 excitation of the 4^+ level is weak with ^{4}He projectiles, the decay to the 4^+ level from higher levels excited by a single step can be important. The largest contributions of this kind stem from the collective vibrational levels. There is also a small effect on the calculated cross sections of the 4^+ level due to the addition of the vibrational levels. We included in the calculations four vibrational states, whose properties are summarized in Table 1. An uncertainty of 25% in the feeding from each vibrational state was assumed. Each B(Eλ) value[9,10] and branching ratio[11] has been measured. The higher rotational states also feed the 4^+ state, but very weakly. We have also shown in Table 1 all the contributions to the calculated singles (σ_0) and back-scatter ($d\sigma_0$) cross sections of

the 4^+ state at 10.38 MeV ^{4}He energy. An important feature is that the effect of the vibrational states relative to the direct population (and E4 contributions) is three times smaller in the back-scatter spectra than it is in the singles spectra. The omission of other important states of this type should therefore show up as a discrepancy between the singles and coincidence data.

A number of other effects which might influence the calculated cross-sections of the 2^+ or 4^+ states in ^{152}Sm were considered, among which were : 1) excitation of the giant dipole states; 2) the presence of an appreciable E6 transition moment; and 3) static E2 and E4 moments. None of these give rise to corrections of appreciable size. In the calculations, rigid-rotor values for $B(E4;2^+ \rightarrow 4^+)$ were used. If this were zero instead, then our measured value for $\langle 0^+ \| \mathcal{M}(E4) \| 4^+ \rangle$ would be increased by about 10%. For ^{150}Sm we used a $B(E2;2^+ \rightarrow 0^+)$ value[2] of 0.278 ± 0.010 e^2b^2 and a static moment (prolate) of half the rigid-rotor value. A variation of the static moment from zero to the full rigid-rotor value introduces a change no greater than about ±1% in the cross sections for the 2^+ state. In all cases the agreement between the $2^+ \rightarrow 0^+$ transitions in ^{152}Sm and ^{150}Sm was satisfactory. An effect that has not yet been evaluated is the possibility of quantal corrections to the semi-classical calculations used. These would be expected to lower the calculated cross sections[12] (increase our E4 moment) and could be as large as a few percent.

In Fig. 3 we have plotted the ratio of the observed cross section (σ) to those calculated including all feedings (σ_0), against the bombarding energy. The error bars on the data points do not include any of the systematic uncertainties involved in the analysis. The dashed and solid lines show the values for the backscatter and singles data, respectively, corresponding to an E4 moment of

(The other possible solution, -0.7 eb^2, seems improbable.) +0.35 eb^2./ This is the best fit to the data below 11 MeV, and would not be changed appreciably if we included the 11.1 MeV data and/or all the data from the enriched ^{152}Sm target. The results from the natural samarium target are high at 14 and 12.2 MeV, and possibly at 11.1 MeV also. While we do not fully understand this, it is clear that interference from nuclear inelastic scattering will affect the backscatter results in this direction at sufficiently high energies (almost certainly at 14 MeV). Furthermore, at 14 MeV the singles results from the natural samarium target were not evaluated due to the appearance of a shoulder on the 245 keV peak. This shoulder might also be affecting the results from this target at somewhat lower bombarding energies, although no complexity could be detected. Due to the unambiguous consistency of all types of results below 11 MeV, we have chosen to evaluate the E4 moment from these data.

The largest single source of uncertainty in the result is due to the $B(E2;4^+ \rightarrow 2^+)$ value which is known to an accuracy of ±3.3%. This is true largely because it affects both the singles and back-scatter results in the same way. The uncertainties in the $B(E2;2^+ \rightarrow 0^+)$ values are less important here because there are two independent quantities (^{150}Sm and ^{152}Sm). The feeding corrections from the vibrational states cause a large uncertainty in the singles results (3.8%), but only a relatively small one (1.4%) in the back-scatter results. Conversely the angular distributions cause much larger uncertainties in the back-scatter results (2.9%) than in the singles (0.5%). In both cases the uncertainties due to the peak-area determinations are smaller than ∿2%, as are those from other individual sources. The best value for the E4 moment, with the known uncertainties taken into account is +0.35 ± 0.11 eb^2. This error limit does not include/the possible quantal corrections or the possibility of omitted corrections. We cannot set a real upper limit

on these, but it is reassuring that the two types of experiments, whose sensitivity to the various corrections is generally different, yield consistent results. The present experiments have also given information on ^{154}Sm, but a more accurate value for $B(E2;4^+ \rightarrow 2^+)$ is needed before a meaningful analysis is possible.

If we assume the nucleus to be a rigid, uniformly-charged rotor with a sharp surface defined by:

$$R = R_0 (1 + \beta_2 Y_{20} + \beta_4 Y_{40}),$$

we can evaluate β_2 and β_4 from the measured E2 and E4 transition moments. Taking the charge radius to be $R_0 = 1.2\ A^{1/3}$f., we find $\beta_2 = (+)\ 0.254$ and $\beta_4 = +0.058 \pm 0.032$ in ^{152}Sm. The sign of β_2 has been assumed to be positive in this analysis. These values of β_λ depend on the radius used and change roughly as $R_0^{-\lambda}$. The inclusion of still higher moments would probably affect the deduced deformation parameters slightly. It is interesting to try to compare this shape of the charge field with the shape of the nuclear field measured by Hendrie et al.[13] who found $\beta_2 = +0.246$ and $\beta_4 = +0.048$ for the above value of R_0. These appear to be quite similar, but it is not really clear that this is the proper way to compare these two sets of results. The present value of β_4 is also in reasonable accord with theoretical estimates[3] of nuclear shapes.

We believe the present work shows that it is possible to find experimental conditions where E4 transition moments can be reliably determined in Coulomb-excitation measurements. This is true in spite of the fact that many different processes contribute to the observed cross sections and must be taken into account for accurate evaluations. Conversely the presently measured E4 moment produces sizeable effects that must be included in the precise determination of other matrix elements from Coulomb-excitation studies on ^{152}Sm.

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FOOTNOTES AND REFERENCES

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FIGURE CAPTIONS

Fig. 1. Relationship between the E4 moment and a) the normalized cross section (backscatter) for populating the 4^+ state of ^{152}Sm with 10.4 MeV ^4He ions, and b) the deformation parameter, β_4, using a radius of $R_0 = 1.2\ A^{1/3} f$. (see text).

Fig. 2. Gamma-ray spectrum in coincidence with 10.4 MeV ^4He projectiles backscattered from a natural samarium target. Accidental coincidences have been subtracted.

Fig. 3. The measured cross sections for populating the 4^+ level of ^{152}Sm normalized to the appropriate calculated value with no E4 moment, plotted against the bombarding energy. The solid points are for enriched ^{152}Sm targets and the open ones for natural samarium targets. The triangles and circles are backscatter and singles results, respectively. The dashed and solid lines are the calculated results for back-scatter coincidences and singles, respectively, with $\langle 0^+ \| \mathcal{M}(E4) \| 4^+ \rangle = +0.35\ eb^2$.

Table 1. Calculated Population of the 4^+ State

Level I^π	K	E(MeV)	$B(E\lambda; 0^+ \rightarrow I^\pi)$ e^2b^λ	$f(4^+)$[a]	E_α = 10.38 MeV $f(4^+)\sigma_{IK}$	$f(4^+)d\sigma_{IK}$
2^+	0(β)	0.811	0.023	0.21	57	2.6
	2(γ)	1.087	0.083	0.013	5	0.3
3^-	0	1.042	0.14	0.30	29	1.9
	1	1.578	0.078	0.73	9	0.5
6^+	0	0.7067	b	1.00	0.6	0.14
4^+	0	0.3665	b	1.00	328	53.4
$\sigma_0(d\sigma_0)\mu b$					429	58.8

[a] Fraction of the decay which goes to the 4^+ level.

[b] Only multiple E2 excitation is considered here. The B(E2) values used are given in the text.

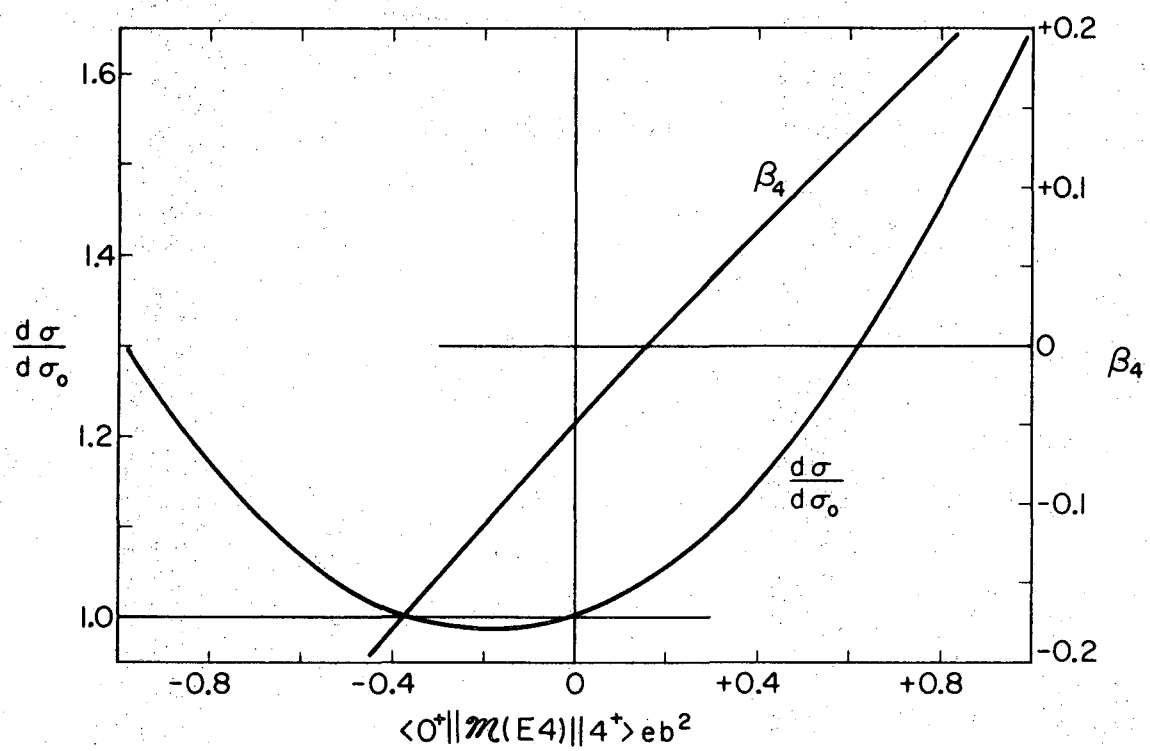

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Fig. 1

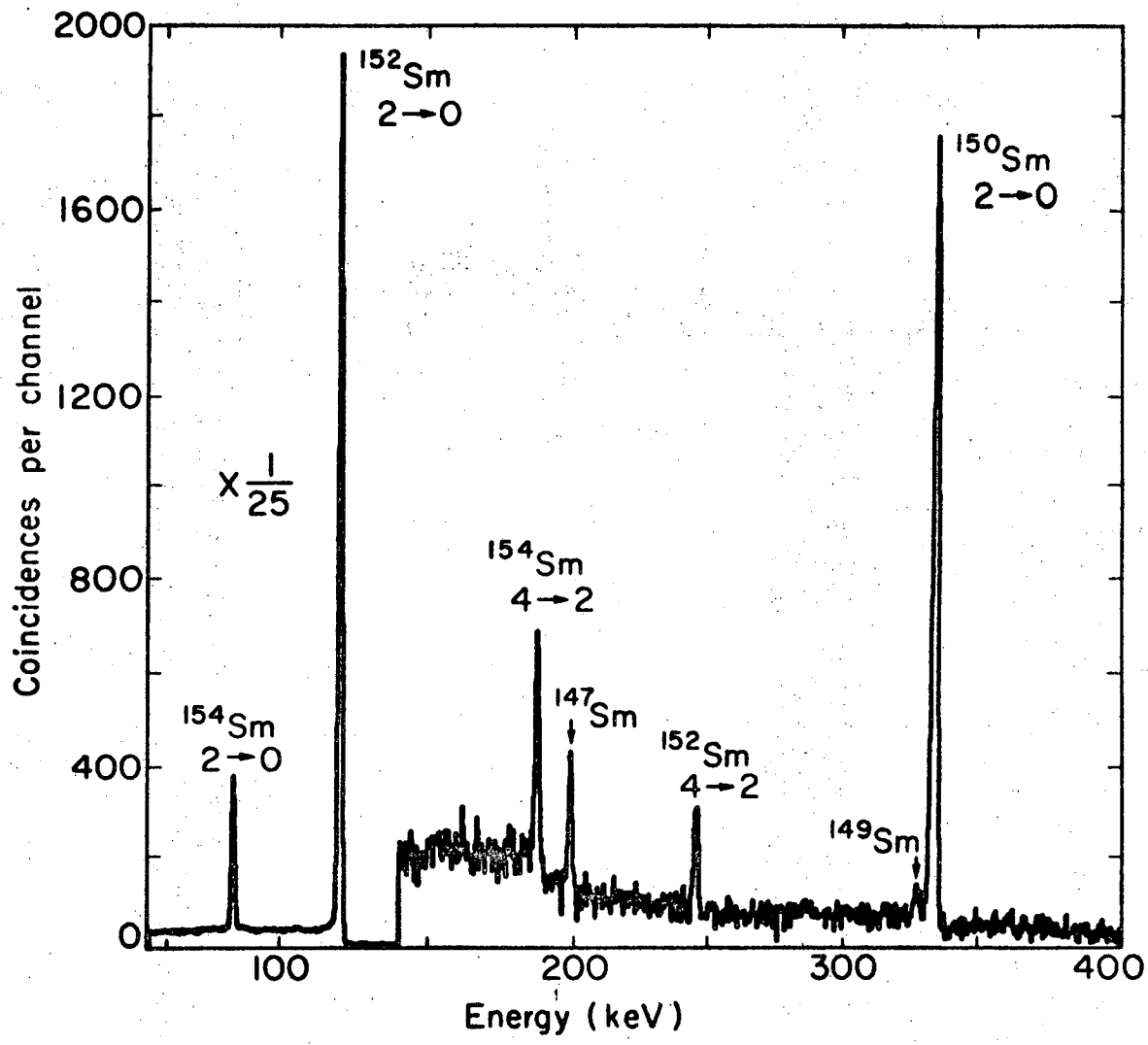

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Fig. 2

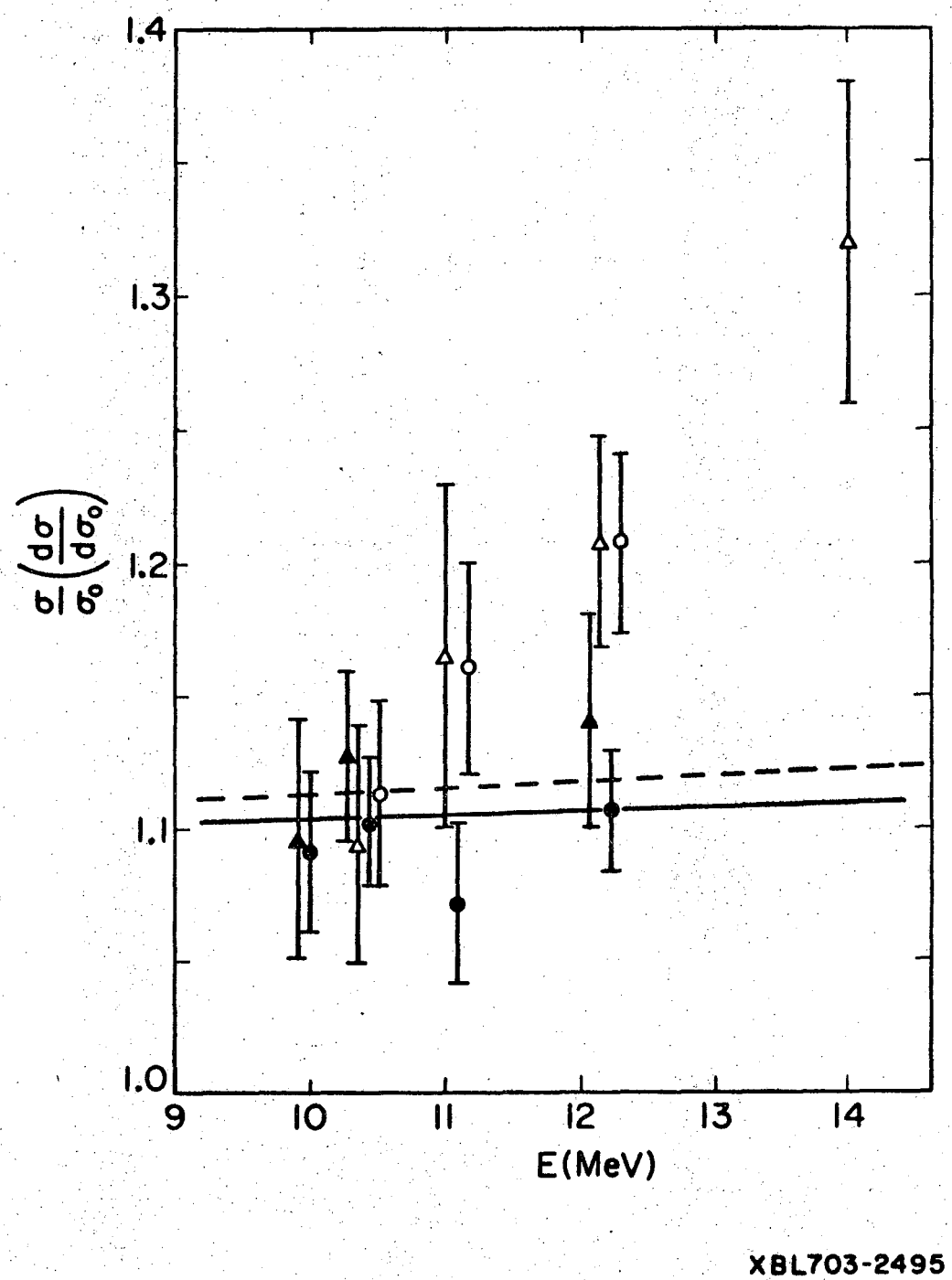
1.4
1.3
1.2
1.1
1.0
9
10
11
12
13
14
E(MeV)
$\left(\frac{d\sigma}{d\sigma_0}\right)_{\theta}$
XBL703-2495

Fig. 3

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