Quadrupole moment of the first 2^+ excited state in ^{136}Ba through the reorientation effect

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Measurements of the Coulomb excitation probability of the first 2^+ state of ^{136}Ba were carried out using back-scattered ions of ^{4}He and ^{16}O. The static quadrupole moment Q_{2^+} and the reduced transition probability $B(E2;0^+\rightarrow 2^+)$ have been determined using the reorientation effect. It is found that $Q_{2^+}=+0.01\pm0.05$ e b ($+0.25\pm0.05$ e b) for the positive (negative) sign of the $2^{+\prime}$ interference term, and $B(E2;0^+\rightarrow 2^+)=0.399\pm0.003$ e^2b^2.

I. INTRODUCTION

The barium nuclei ($Z=56$) belong to a mass region between harmonic vibrator nuclei and those with a rotator character. The energy level spectra for low excitations of the even isotopes with $130\leq A\leq 136$ can be characterized by means of anharmonic vibrators. On the other hand, the spectrum of ^{138}Ba cannot be ascribed to either pure vibrations or rotations. The electromagnetic properties of these nuclei, which are essential for the understanding of their structure, have been the subject of a number of studies.[1–11] Nevertheless, the experimental information on the quadrupole moments of the first 2^+ excited states (Q_{2^+}), one of the important sources of information for assessing nuclear model calculations, is still conflicting.[2–6]

Several theoretical attempts[12–25] have been made to describe the barium nuclear structure. These include microscopic descriptions which consider either anharmonic effects in spherical nuclei[12,13] or axially symmetric[14] or triaxial[15] intrinsic states, using the technique of angular momentum projected quasiboson states. Some of these models make the unusual prediction of an oblate shape for the barium isotopes. These nuclei have also been treated by collective models in terms of shape variables, either with well-defined nonaxial equilibrium deformation,[16–18] or as soft nuclei.[19–22] Recently, the interacting boson approximation[23,24] has been applied to this mass region. The isotope $A=136$ ($N=80$) has also been studied by the unified semimicroscopic model considering the coupling between two neutron holes and a quadrupole core.[25]

While most of these different descriptions have succeeded in reproducing the general features of the energy spectra of the barium isotopes, they suggest different trends for Q_{2^+} with the mass number A. This fact points to the need for accurate experimental measurements of the electromagnetic properties, in order to discriminate among the existing calculations.

We present here an accurate determination of $B(E2;0^+\rightarrow 2^+)$ and Q_{2^+} for ^{136}Ba, using the reorientation effect.[26] Enough data were collected to allow for a careful check in the internal consistency of the analysis, which is essential for this kind of experiment. We also present a comparison of the available experimental information of $B(E2;0^+\rightarrow 2^+)$ and Q_{2^+} values for various barium isotopes with model predictions.

II. EXPERIMENTAL PROCEDURE

The experimental methods and procedures were essentially the same as those described in Ref. 27. Targets of ^{136}Ba were bombarded with ^{4}He and ^{16}O ions from the tandem electrostatic accelerator at the University of São Paulo. The targets consisted of thin layers (~ 8 μg/cm^2 thick for ^{16}O and ~ 15 μg/cm^2 thick for ^{4}He) of metal or $Ba(NO_3)_2$ enriched with the isotope of mass 136 (92.9%) evaporated onto ~ 10 μg/cm^2 carbon backings. The scattered ions were detected by surface barrier detectors of 100 μm thickness at various angles. At the most backward scattering angle ($\theta_{lab}\simeq 174°$), ions were recorded in an 8 mm diameter annular detector. Standard techniques were employed in order to obtain very good resolution and to reduce the background in the spectra.

Typical spectra are shown in Fig. 1. The resolution (FWHM) obtained was about 30–40 keV for ^{4}He and 140–160 keV for ^{16}O projectiles. The ^{16}O spectra have ratios greater than 10:1 between the inelastic peak height and the valley between peaks. The procedures used for unfolding the elastic and inelastic groups, and for determining the excitation probability of the first 2^+ state [$R_{exp}=(d\sigma/d\Omega)^{2^+}_{lab}/(d\sigma/d\Omega)^{0^+}_{lab}$], were essentially those described elsewhere.[27,28]

Table I presents the experimental excitation probabilities and their uncertainties. The statistical plus fitting uncertainties in R_{exp} are, for most of the data, of the order of 1–2 %

The validity of the adopted analysis is based on the assumption that the contribution to the 2^+ intensities from sources other than pure Coulomb excitation (i.e., nuclear reactions) are negligible. The data considered in the present analysis (Table I) correspond to bombarding energies below the "safe values": 46.4 MeV for the ^{16}O beam and 11.5 MeV for incident alpha particles. The "safe energy" domains were obtained using the criterion that half the distance of the closest approach in a head-on collision must be greater than or equal to the sum of the two nuclei radii [$1.25(A_1^{1/3}+A_2^{1/3})$] plus 6 fermis. This requirement

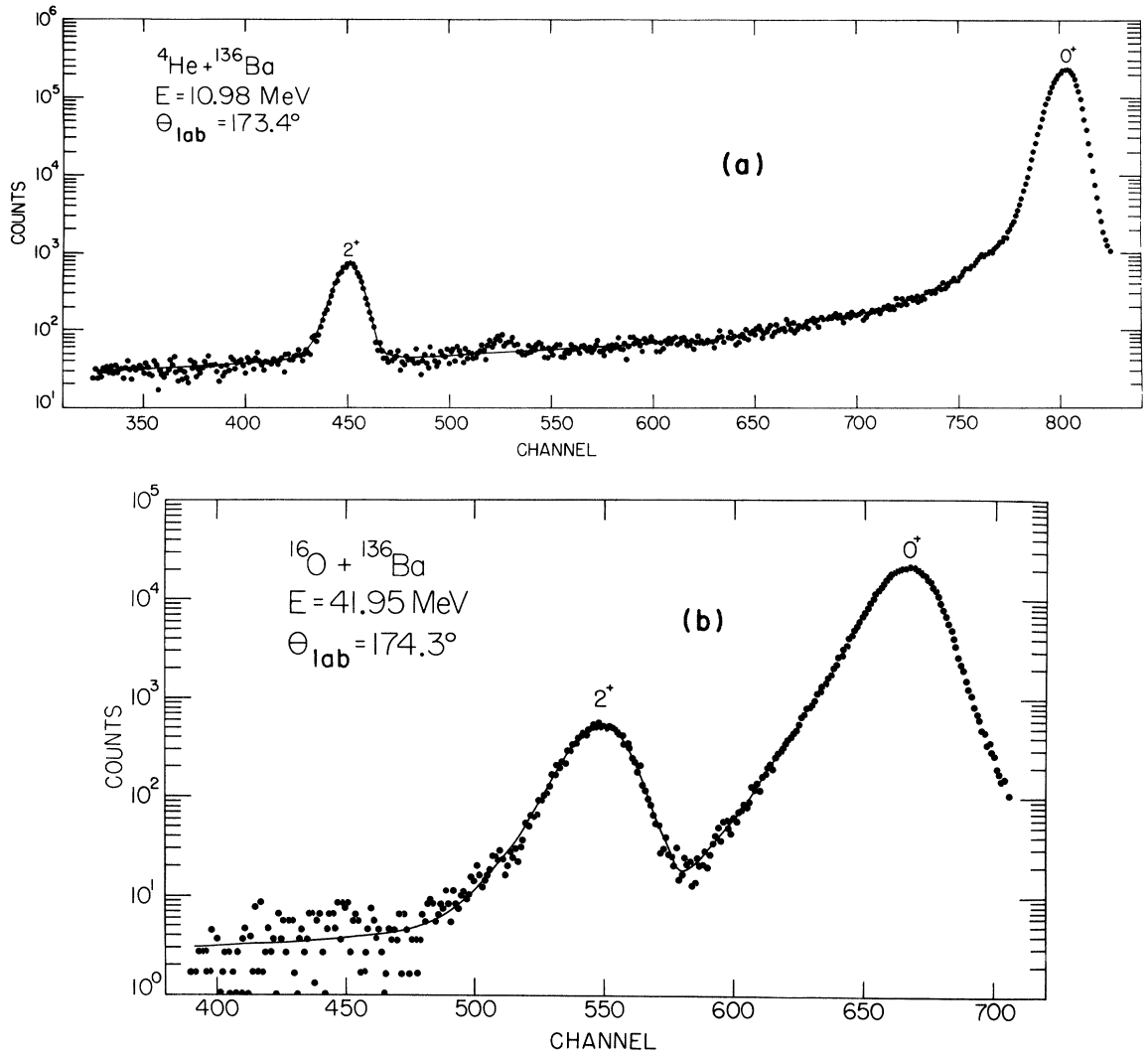

FIG. 1. Spectra of ^{4}He ions (a) and ^{16}O ions (b) back-scattered from ^{136}Ba. The lines passing through the experimental points represent the fits to the spectra from which the contributions of scattering from contaminants were subtracted.

was fulfilled for the cases where experiments have been performed.

The Q_{2^+} and $B(E2;0^+\rightarrow 2^+)$ values were determined from a comparison of the experimental ratios R_{exp} with the results of a semiclassical coupled-channel calculation for multiple Coulomb excitation (MCE),[29] in which the electric quadrupole matrix elements $M_{12}=[B(E2;0^+\rightarrow 2^+)]^{1/2}$ and $M_{22}=1.319Q_{2^+}$ were treated as free parameters. The coupling between the first four levels in ^{136}Ba was considered in this analysis. Their excitation energies, J^π values, and associated electric quadrupole matrix elements ($M_{ij}=\langle I_j||M(E2)||I_i\rangle$) are given in Table II.

In cases where measured $B(E2)$ values were lacking, explicit values for M_{ij} were calculated from the available experimental information [$B(E2;2^{+\prime}\rightarrow 0^+)/B(E2;2^{+\prime}\rightarrow 2^+)=0.029\pm0.006$ (Ref. 30) and $B(E2;0^+\rightarrow 2^+)=0.418\pm0.011$ (Ref. 3)] with the help of predictions by the asymmetric rotor model of Davydov *et al.*[19,20] This model has been chosen since it reproduces fairly well the energy spectra of several transitional nuclei and since its predictions for the electromagnetic properties of ^{134}Ba are in good agreement with the experimental results.[6] The electric quadrupole matrix elements have been calculated with the help of the branching ratios listed in Ref. 20. The adiabaticity parameter $\mu=0.5$ and the asymmetry parameter $\gamma=27°$ which better reproduce both the ^{134}Ba and ^{136}Ba energy spectra have been adopted.

The parameters adopted by Kerns and Saladin[3] had the values $\mu=0.5$ and $\gamma=26.5°$. The $E2$ matrix elements considered in their analysis differ from those listed in Table II by less than 7%.

The dependence of the $B(E2;0^+\rightarrow 2^+)$ and Q_{2^+} determined values on the matrix elements $M_{ij}(E2)$ used in the MCE calculation has been investigated. This has been done by setting M_{34} equal to zero and varying all the other matrix elements listed in Table II by 40%. These variations reflect the degree of agreement of the model predictions with the experimental $M_{ij}(E2)$ values[6] for ^{134}Ba. The largest observed change in $B(E2;0^+\rightarrow 2^+)$ was of

TABLE I. Experimental excitation probabilities (R_{exp}) and the corresponding errors.

Projectile	E_{lab} (MeV)	θ_{lab} (deg)	R_{exp} (10^{-3})	Errors (%)
^{4}He	9.98	173.4	1.59	1.1
		130.0	1.28	3.4
		110.0	1.03	3.1
	10.48	173.4	2.16	0.6
		110.0	1.38	1.9
	10.73	173.4	2.48	1.4
		150.0	2.21	2.0
		120.0	1.77	1.5
	10.98	173.4	2.80	1.2
		120.0	2.05	1.3
^{16}O	41.95	174.3	25.0	0.9
		130.0	21.0	3.7
		110.0	18.3	3.2
	42.43	174.3	26.4	1.1
		130.0	23.1	4.3
		110.0	18.5	3.9
	42.92	174.3	27.3	1.4
	43.47	173.4	30.6	1.3
	43.97	173.4	33.6	1.1
	44.43	173.4	34.9	0.8

0.08% due to the M_{13} matrix element. The Q_{2^+} value was affected mainly by the M_{13} and M_{23} matrix elements. The systematic uncertainty in Q_{2^+} related to the matrix elements errors is estimated to be ± 0.01 e b.

It is well known that the computed excitation probabilities are sensitive to the sign of the interference term $M_{12}M_{2s}M_{1s}$ arising from the direct excitation of the first 2^+ level and the excitation through a higher lying intermediate 2^+ state s. Therefore, the values of $B(E2;0^+\rightarrow 2^+)$ and Q_{2^+} were computed for both signs of the matrix elements product $P_3 = M_{12}M_{13}M_{23}$.

Table III lists the $B(E2;0^+\rightarrow 2^+)$ and Q_{2^+} values and their respective errors. The tabulated results include small corrections for effects of atomic screening[31] and vacuum polarization.[32] Corrections arising from the semiclassical approximation have also been taken into account, but no corrections have been made for the effects of excitation modes other than $\lambda = 2$. The Q_{2^+} values are strongly affected by the sign of the product P_3, whereas that of $B(E2;0^+\rightarrow 2^+)$ shows no dependence on it. The quoted errors have been calculated from a quadratic combination of statistical uncertainties with errors in spectrum fitting, incident energy, scattering angle, and in the adopted values for the matrix elements $M_{ij}(E2)$.

The results of the analysis are presented in a graphical form in Fig. 2, where the ratio $R_{exp}/R_{comp}(Q=0)$ has been plotted against the sensitivity parameter ρ defined[26] by

$$R_{comp}(Q) = R_{comp}(Q=0)(1+\rho Q) .$$

In this expression, $R_{comp}(Q=0)$ is the computed excitation probability for the static quadrupole moment Q equal to zero. In the MCE calculation of $R_{comp}(Q)$ and $R_{comp}(Q=0)$, the value of the $B(E2;0^+\rightarrow 2^+)$ determined in the present work was used.

The full lines in Fig. 2 are the best fits to the present data (closed circles), and the dashed line is the best fit to Pittsburgh's data[3] (open triangles). The experimental points of the present experiment for $\rho < 0.06$ correspond to back-scattered ^{4}He ions. The Pittsburgh datum for $\rho \simeq 0.06$ was obtained with ^{16}O ions scattered at a forward angle of 60.6° with the beam direction. The differences between the results of both experiments will be discussed in Sec. III.

III. RESULTS AND DISCUSSION

Table III presents the available experimental $B(E2;0^+\rightarrow 2^+)$ and Q_{2^+} for ^{136}Ba. The results of the present work correspond to a value of $B(E2;0^+\rightarrow 2^+)$ which is smaller than the previous ones and has greater precision.

The values for Q_{2^+} listed in Table III indicate different shapes for the nucleus [slightly prolate[3] or oblate[4] or quasispherical (present work) for $P_3 > 0$]. Nevertheless, we cannot consider them as being in complete disagreement since they lie within the standard deviations. The error of Q_{2^+} estimated in this work is 0.05 e b. The weighted average of the experimental results yields for the quadrupole moment a value of $\langle Q_{2^+} \rangle = -0.002 \pm 0.067$ e b and $\langle Q_{2^+} \rangle = +0.23 \pm 0.06$ e b for the positive and negative sign of the interference term, respectively.

In order to try to understand the difference between our results and those of Ref. 3 we refer to Fig. 2, where the two measurements are compared in a plot of

TABLE II. Energy levels and matrix elements (M_{ij}) of the $E2$ operator (in e b) used in the multiple Coulomb excitation calculations (see the text).

Level	J^π	Excitation energy (MeV)	1	2	3	4
1	0^+	0	0	M_{12}	0.128	0
2	2^+	0.818	M_{12}	M_{22}	0.751	0.903
3	$2^{+\prime}$	1.551	0.128	0.751	0	0.132
4	4^+	1.867	0	0.903	0.132	0

TABLE III. The $B(E2;0^+\rightarrow 2^+)$ and Q_{2+} experimental values of ^{136}Ba.

$B(E2;0^+\rightarrow 2^+)$ (e^2b^2)	Q_{2+} $(e\,b)$	Sign of interference term[a]	Ref.
0.399±0.003	+0.01±0.05	+	present work
0.399±0.003	+0.25±0.5	−	present work
0.418±0.011	−0.19±0.17	+	Ref. 3
0.417±0.012	+0.02±0.18	−	Ref. 3
0.50 ±0.07	+0.43±0.52	+	Ref. 4
0.53 ±0.16			Ref. 1

[a]Sign of the matrix elements product $P_3=M_{12}M_{13}M_{23}$.

$R_{exp}/R_{comp}(Q=0)$ versus the sensitivity parameter ρ.

While the two ^{16}O measurements at the backward scattering angles ($\rho>0.17$) are in good agreement, the Pittsburgh forward angle ^{16}O datum[3] (triangle with $\rho\simeq 0.06$) exhibits an excitation probability which is about 5% larger than the ^{4}He measurements at backward angles (closed circles with $\rho\lesssim 0.06$) of the present work. The difference in R_{exp} for small ρ data seems to be the reason why the Pittsburgh value for $B(E2)$ is larger than ours. Also, the slope of the straight line which best fits their data (open triangles) and their Q_{2+} result depend strongly on only one excitation probability for small ρ, as shown by the dashed line in Fig. 2. An error in this datum could drastically change their $B(E2)$ and Q_{2+} values, whereas the reliability of our results is ensured by the existence of many experimental data (ten points) with $\rho\lesssim 0.06$. The reason for the large difference between our results and those reported by Towsley *et al.*[4] has not been determined.

Figure 3 displays the available experimental information on $B(E2;0^+-2^+)$ (the present work and Refs. 1, 3, 4, 6, 33, and 34) for the even barium isotopes with $130\leq A\leq 138$ together with the results of some theoretical calculations (Refs. 14, 16, and 23). The various models

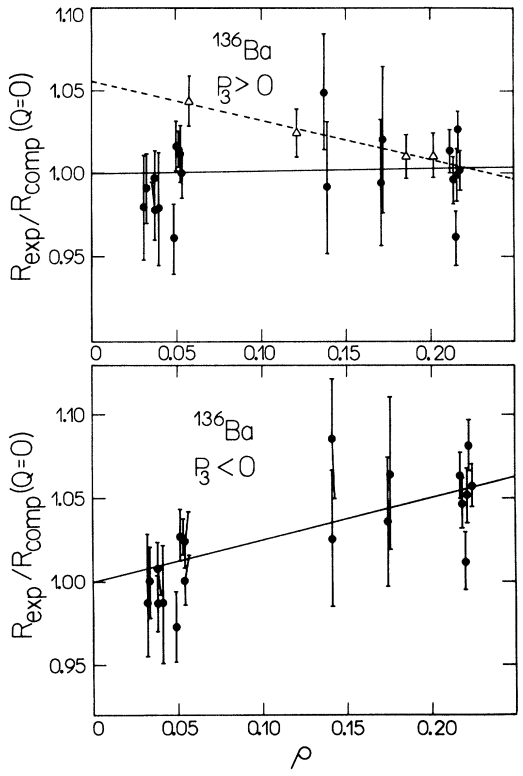

FIG. 2. The ratio $R_{exp}/R_{comp}(Q=0)$ as a function of the sensitivity parameter ρ, calculated for both signs of the interference term $P_3\equiv M_{12}M_{23}M_{13}$ (see the text). The full lines are the best fits to our data (closed circles) and the dashed line is the fit to the Pittsburgh data (triangles, Ref. 3) using the $B(E2;0^+\rightarrow 2^+)$ value from the present work (see Table III).

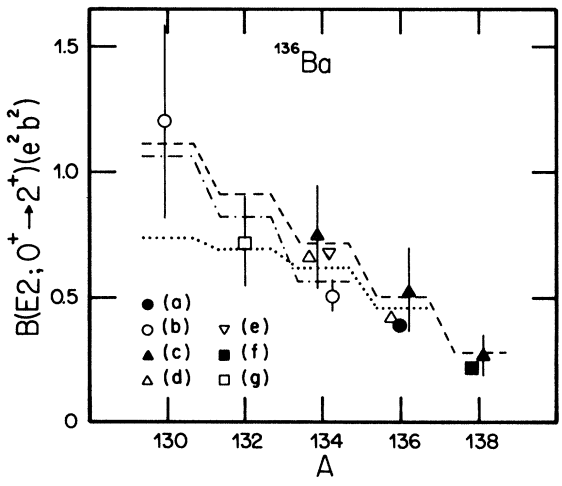

FIG. 3. $B(E2;0^+\rightarrow 2^+)$ experimental values for the even barium isotopes compared to some model predictions. The experimental data are from the following: (a) the present work, (b) Ref. 4, (c) Ref. 1, (d) Ref. 3, (e) Ref. 6, (f) Ref. 34, and (g) Ref. 33. The dashed line represents the results of an angular momentum projected quasiboson calculation including axially symmetric intrinsic states (Ref. 14). The dotted line is from a collective model where the barium isotopes are treated as having nonaxial equilibrium deformation (Ref. 16). The "dashed-dotted" line is an interacting boson approximation calculation (Ref. 23).

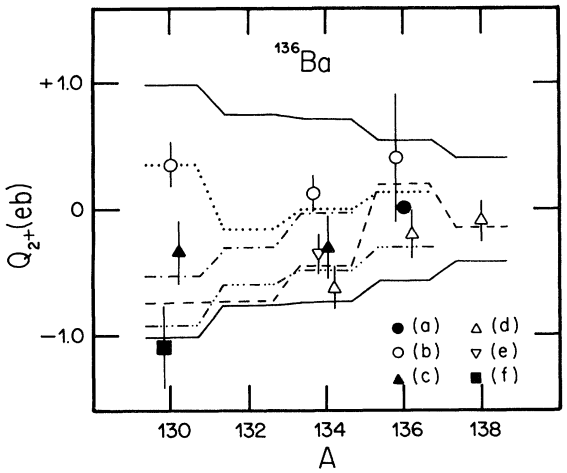

FIG. 4. Q_{2^+} experimental values determined for constructive interference ($P_3>0$) compared with some model predictions. The experimental data are from the following: (a) the present work, (b) Ref. 4, (c) Ref. 5, (d) Ref. 3, (e) Ref. 6, and (f) Ref. 2. The full line represents the rigid rotor model values. The dotted line is the prediction of a collective model which uses nonaxial equilibrium deformation (Ref. 16). The dashed line represents an angular momentum projected quasiboson state calculation for axially symmetric intrinsic states (Ref. 14). The "dashed-three dotted" line is from a microscopic model which takes in account the anharmonic effects in spherical nuclei (Ref. 13). The "dashed-one dotted" line is an interacting boson approximation result (Ref. 23).

reproduce the tendency of decreasing $B(E2;0^+\rightarrow 2^+)$ values as the neutron number increases towards the magic neutron number $N=82$

In Fig. 4, the experimental values determined for the constructive interference ($P_3>0$) (the present work and Refs. 2–6) are compared with some model predictions recently applied to the even barium isotopes with mass number $130\leq A\leq 138$ (Refs. 13, 14, 16, and 23). This figure shows the marked discrepancy among the various experiments, most of them with large errors. The relevant difference between the theoretical predictions is the existence or nonexistence of shape transition(s) in the mass region considered. The Q_{2^+} determined in the present work for isotope 136 would favor the models which indicate a slightly oblate shape for such a nucleus. While the plotted Q_{2^+} value ($P_3>0$) from the present work is nearly zero, the Q_{2^+} determined for the negative interference term ($P_3<0$) has a moderate positive value (see Table III). However, in order to make any meaningful statement on which model provides the best description for the nuclear structure of the even barium isotopes, accurate experimental Q_{2^+} values are still badly needed.

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[1]D. G. Alkhazov, D. S. Andreev, V. D. Vasil'ev, Yu. P. Gangrskii, I. Kh. Lemberg, and Yu. I. Udralov, Izv. Akad. Nauk. SSSR, Ser. Fiz. 27, 1285 (1963) [Bull. Acad. Sci. USSR, Phys. Ser. 27, 1263 (1963)].

[2]J. J. Simpson, D. Eccleshall, M. J. L. Yates, and N. J. Freeman, Nucl. Phys. A94, 177 (1967).

[3]J. R. Kerns and J. X. Saladin, Phys. Rev. C 6, 1016 (1972).

[4]C. W. Towsley, R. Cook, D. Cline, and R. N. Horoshko, J. Phys. Soc. Jpn. 34, 442 (1973).

[5]N. Neiman, R. Kalish, D. R. S. Somayajulu, and B. Herskind, Phys. Lett. 52B, 189 (1974).

[6]A. M. Kleinfeld, A. Bockisch, and K. P. Lieb, Nucl. Phys. A283, 526 (1977).

[7]P. H. Stelson, S. Raman, J. A. McNabb, R. W. Lide, and C. R. Bingham, Phys. Rev. C 8, 368 (1973).

[8]J. R. van Rise, D. C. Camp, and R. A. Meyer, Z. Phys. A 274, 383 (1975).

[9]J. Burde, S. Eshhar, A. Ginsburg, and A. Molchadzki, Nucl. Phys. A250, 141 (1975).

[10]M. Behar, R. M. Steffen, and C. Telesco, Nucl. Phys. A192, 218 (1972).

[11]R. A. Meyer, R. D. Griffioen, J. Graber Lefter, and W. B. Walters, Phys. Rev. C 14, 2024 (1976).

[12]S. R. Almoney and G. J. Borse, Nucl. Phys. A171, 660 (1971).

[13]G. Watanuki, Y. Miyanishi, and M. Yasuno, Prog. Theor. Phys. 59, 790 (1978).

[14]G. M. Ewart and N. de Takacsy, Phys. Rev. C 17, 303 (1978).

[15]G. M. Ewart and N. de Takacsy, Phys. Rev. C 20, 1145 (1979).

[16]D. Habs, H. Klewe-Nebenius, K. Wisshak, R. Löhken, G. Nowicki, and H. Rebel, Z. Phys. 267, 149 (1974).

[17]J. Meyer-Ter-Vehn, Nucl. Phys. A249, 141 (1975).

[18]H. Toki and A. Faessler, Nucl. Phys. A253, 231 (1975).

[19]A. S. Davydov and A. A. Chaban, Nucl. Phys. 20, 499 (1960).

[20]A. S. Davydov and V. I. Ovcharenko, Yad. Fiz. 3, 1011 (1966) [Sov. J. Nucl. Phys. 3, 740 (1966)].

[21]J. Dobaczewski, S. G. Rohozinski, and J. Srebrny, Z. Phys. A 282, 203 (1977).

[22]S. G. Rohozinski, J. Dobaczewski, B. Nerlo-Pomorska, K. Pomorska, and J. Srebrny, Nucl. Phys. A292, 66 (1977).

[23]G. Puddu, O. Scholten, and T. Otsuka, Nucl. Phys. A348, 109 (1980).

[24]O. Castaños, P. Federman, A. Frauk, and S. Pittel, Nucl. Phys. A379, 61 (1982).

[25]M. Meyer-Lewi and V. Lopac, Phys. Rev. C 8, 829 (1973).

[26]J. de Boer and J. Eichler, in *Advances in Nuclear Physics,* edited by M. Baranger and E. Vogt (Plenum, New York, 1968), Vol. I, p. 1.

[27]M. J. Bechara, O. Dietzsch, M. Samuel, and U. Smilansky, Phys. Rev. C 17, 628 (1978).

[28]Z. Berant, R. A. Eisenstein, Y. Horowitz, U. Smilansky, P. N. Tandon, J. S. Greenberg, A. M. Kleinfeld, and H. G. Maggi, Nucl. Phys. A196, 312 (1972).

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

[30]W. Gelletly, J. A. Moragues, M. A. J. Mariscotti, and W. R. Kane, Phys. Rev. 181, 1682 (1969).
[31]J. X. Saladin, J. E. Glenn, and R. J. Pryor, Phys. Rev. 186, 1241 (1969).
[32]L. L. Foldi and E. Erikson, Phys. Rev. 95, 1048 (1954).
[33]L. W. Fagg, Phys. Rev. 109, 100 (1958).
[34]G. Kindleben and Th. W. Elze, Z. Phys. A 286, 415 (1978).