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EXCITATION OF THE GROUND-STATE ROTATIONAL BAND IN ^{28}Si BY INELASTIC SCATTERING OF 25.25 MeV POLARIZED PROTONS†

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ABSTRACT

Angular distribution of the analysing power and cross sections have been measured for the elastic and inelastic scattering of 25.25 MeV protons exciting the K = 0^+ ground state band in ^{28}Si. Good agreement with experiment is obtained in the coupled-channels formalism on the basis of the rotational model with a quadrupole deformation β_2 = -0.40 (oblate) and a hexadecapole deformation β_4 = +0.15. The calculations show the great sensitivity of the experimental results to both the magnitude and sign of the quadrupole and hexadecapole deformations. Equivalent fits of the data were obtained either by keeping the deformation length of the various deformed terms of the optical potential constant ($\delta_o=\beta_o R_o=\beta_1 R_1=\beta_{LS} R_{LS}$) or by increasing the deformation of the spin-orbit optical potential relative to the central potential by a factor of 1.5 (β_{LS} = 1.5 β_{cent}).

RESUME

On a mesuré les sections efficaces et les pouvoirs d'analyse par diffusion élastique et inélastique de protons de 25.25 MeV excitant la bande fondamentale K = 0^+ du ^{28}Si. De bons accords avec l'expérience (sections efficaces et polarizations) ont été obtenus dans le formalisme des équations couplées sur la base du modèle rotationnel en utilisant une déformation statique quadrupolaire β_2 = -0.40 (oblate) et une déformation hexadecapolaire β_4 = +0.15. Les calculs montrent la grande sensibilité des données expérimentales aussi bien à la grandeur qu'au

signe des déformations quadrupolaires et hexadecapolaires. On a pu obtenir des accords équivalents avec les données expérimentales soit en gardant la longueur de déformation des différents termes du potentiel optique déformé constant ($\delta_o = \beta_o R_o = \beta_1 R_1 = \beta_{LS} R_{LS}$) soit en accroissant la déformation du potentiel spin-orbit déformé par rapport à celle du potentiel central d'un facteur 1.5 (β_{LS}=1.5 β_{cent}).

I) INTRODUCTION

With the availability of polarized-ion sources at accelerator facilities in recent years, extensive polarization data have become available. Measurements of the analysing power in inelastic proton scattering have been made at different energies and for many nuclei for which cross-section data had been previously available. Analyses of the data (cross-sections and analysing powers) have been reasonably successful for collective 2^+ or 3^- states for several nuclei in the $f_{7/2}$, the $g_{9/2}$, and the s-d shells (Glashausser et al. 1967, 1968; Baugh et al. 1967; Fricke et al. 1967; Lewis et al. 1967. These distorted-wave Born approximation (DWBA) analyses with collective-model form factors provided reasonable agreement with the analysing powers only when the form factor included terms resulting from deforming the complete optical potential, i.e. the complex central and spin-orbit parts. The cross-sections had seemed well described by a deformation of the central part alone, but the analysing-power data proved the necessity of including the spin-orbit deformation as well. For simplicity, the spin-orbit form factor used was essentially phenomenological (Fricke et al. 1967; Blair et al. 1970). Later, Sherif and Blair introduced the "full Thomas" form of the spin-orbit potential in the DWBA collective-model formalism (Sherif and Blair 1968). Considerable improvement of the fits to the polarization data, particularly at forward angles, was immediately observed (Sherif 1968, 1969; Glashausser et al. 1969).

It is generally accepted that nuclei in the first half of the 2s-1d shell exhibit a rotational character (Gove 1960, 1968). Furthermore, the large static quadrupole moments for the first excited states (Nakai et al. 1970) and the results of Hartree-Fock type calculations (Das Gupta and Harvey 1967; Ripka 1968) characterize the s-d shell as a region of permanent ground state deformation. Some of these calculations suggest also that several nuclei in this region should have a ground state hexadecapole (Brihaye and Reidemeister 1967; Goodman et al. 1970) as well as a quadrupole deformation. Recent analyses of cross-section data for the inelastic scattering of protons (De Swiniarski et al. 1969) and alpha particles (Rebel et al. 1972) from several s-d shell nuclei have definitely shown that substantial hexadecapole (Y_4) deformations were needed to fit the data for the low-lying excited states of the $K = 0^+$ band. The coupled-channels (CC) method of analysis was used because of the strong coupling among the states of the rotational band. The analyses of the proton data for ^{20}Ne, ^{28}Si and ^{32}S used the simplified form of the deformed spin-orbit potential, and good fits to these data required substantial values of both deformation parameters β_2 and β_4 . Also, the fit to the 4^+ data was much more sensitive to variations of β_4 than were the fits to the 0^+ and 2^+ angular distributions. Subsequently, measurements were made of both cross-sections and analysing powers in the scattering of 24.5 MeV polarized protons leading to the 0^+, 2^+, and 4^+ states in ^{20}Ne and ^{22}Ne (De Swiniarski et al. 1972). CC calculations, using the simplified form of the deformed spin-orbit potential as before, failed to reproduce even the shapes of the analysing-power angular distributions for the 2^+ and 4^+ states of ^{20}Ne. When the full Thomas form of the deformed spin-orbit potential, as introduced by Raynal (1969), was used in the CC program (ECIS 1971), the resulting calculations were in considerably improved agreement with the ^{20}Ne analysing-power data for the same β_2 and β_4 values deduced from the cross sections alone. Thus, as had been found in the DWBA analyses, the need for the full Thomas form was established by the polarization measurements.

Although inclusion of the full Thomas form in the calculation did not change the previously determined values of β_2 and β_4 for ^{20}Ne, it does not follow that would be the case for ^{28}Si or ^{32}S. The β_4 values were determined less accurately for those two nuclei because of the lower quality cross-section data. A theoretical calculation (Goodman et al. 1970) for ^{28}Si gives $\beta_2 = -0.25$, $\beta_4 = +0.05$ as compared with the "experimental" values $\beta_2 = -0.34$, $\beta_4 = +0.25$ (De Swiniarski et al. 1969) and $\beta_2 = -0.32 \pm 0.01$, $\beta_4 = +0.08 \pm 0.01$ (Rebel et al. 1972). Also, a recent α-γ angular correlation experiment yields a very surprising prolate ($\beta_2 > 0$) quadrupole deformation for ^{28}Si (Ahlfeld et al. 1972), so it is clear that a redetermination of the deformation parameters for ^{28}Si from both proton cross-section and analysing-power data is desirable. We report here on our measurements of the cross-sections and analysing powers for the 0^+, 2^+, and 4^+ states of ^{28}Si and on the β_2 and β_4 values resulting from a CC analysis which includes the full Thomas form of the deformed spin-orbit potential.

II) EXPERIMENTAL METHOD

The experiment was performed with a beam of 25.25 MeV protons using the polarized ion source (Clark et al. 1971) of the Berkeley 88-inch cyclotron. The experimental equipment has been described previously (Bacher et al. 1972). Scattered particles were detected by four pairs of cooled (-30^{o}C), 5mm thick, Li-drifted silicon detectors. The two detectors in each pair were placed at equal angles on opposite sides of the beam. Up to 50nA of polarized protons were delivered on target with a polarization of about 78%. The beam polarization was monitored continuously during the experiment with a ^{4}He polarimeter which has been accurately calibrated (Bacher et al.1972). Two monitor detectors placed left and right of the beam axis at a fixed scattering angle, served to monitor the incident particle flux for relative differential cross section measurements.

For each angle, alternate runs of equal length were taken with the spin vector of the incident beam oriented up and down with respect to the scattering plane. The polarization was calculated from the ratios of left and right detectors yields as described by Plattner et al. (1968). The experimental cross sections and analysing power of the states belonging to the ^{28}Si $K=0^{+}$ ground state band are shown in figures 1, 2, 3 and 4 together with calculations which will be described below. Errors shown on the figures are due to counting statistics and background subtraction. The absolute normalization of the cross-sections was deduced from comparison with results taken from the literature at about the same energy (Sandhu et al. 1971); Locard et al. 1968).

Further check of this normalization was made by deducing a normalization factor from the optical model search. Good agreement between the two methods was obtained.

III) OPTICAL MODEL ANALYSIS

Optical model parameters were obtained by simultaneously fitting both the elastic cross sections and polarizations using the search code MAGALI (1969). The definition of the optical potential and search procedures employed are conventional (Glashausser et al. 1967). The absolute normalization of the data was included in the search. Corrections arising from the finite angular acceptance of the detectors were also included. Very good fits for both the elastic cross section and polarizations were obtained with a purely surface absorption W_D by searching on all nine parameters. Several sets of parameters usually used in this mass region (Blair et al. 1970; Fulling and Satchler 1968) were used as starting parameters and gave very similar results. It was also possible to get very good fits to the data with both volume absorption W_V and surface absorption W_D, with only minor changes in the other parameters. The results of the best optical model calculations are presented in Table 1 while figure 1 shows the corresponding fits to the elastic data. When the optical model parameters of set B were used as starting parameters, a search on the strength V_o, W_S, W_D, V_{LS} and on a_o, a_I, the real and imaginary diffuseness, led to a small value of the volume absorption W_V with an increase of W_D, while the diffuseness remained practically unchanged. It is interesting to point out that r_{so} remains smaller by about 20% than the real radius r_o, while the imaginary radius r_I comes out larger (~20%) than r_o. In heavier nuclei these differences are much smaller (Glashausser et al. 1967, 1968, 1969; Baugh et al. 1967; Fricke et al. 1967; Lewis et al. 1967). Finally, Table 1 shows also that better agreement with the elastic polarization is obtained using set A parameters with surface absorption alone while for the cross sections, a combination of W_V and W_D (set B) is preferable. However, the overall fits, as indicated by the total χ^2, are equivalent.

IV) COUPLED-CAHNNELS ANALYSIS

In the coupled-channels formalism the nuclear radius is defined by

$$R = R_i \left(1 + \beta_2 Y_{20} + \beta_4 Y_{40} \ldots\ldots\right)$$

where the β's are the deformations parameters determined by the experiment, the Y's are spherical harmonics and R_i corresponds to the various optical potential radii. The interaction potential arises, therefore, from the deformation of the Coulomb-potential, the complex central potential, and the spin-orbit potential. There are indications that the spin-orbit part should have a greater deformation than the central part (Satchler 1971). The coupled-channels program used for the present calculations contains the "full Thomas form" of the deformed spin-orbit term, and allows one to keep the deformation length constant ($\delta_{real} = \beta_{real} R_{real} = \delta_{Imag} = \delta_{LS}$), the deformation parameter constant ($\beta_{real} = \beta_{Imag} = \beta_{LS}$), or to make the deformation parameter β_{so} of the spin-orbit deformed potential larger than that of the central potential β_{cent}. Recent analyses by Sherif and Blair (1971, 1968, 1969) have shown that the fitting of inelastic proton scattering data for the first excited 2^+ state of ^{28}Si requires a spin-orbit deformation somewhat larger than that of the central deformation. Coupled-channels calculations are shown on figures 2, 3 and 4, together with the experimental data for the 2^+ and 4^+ states. The elastic scattering data are rather insensitive to the various calculations shown in these figures and are included only with the final results. Figure 2 presents the CC calculations using a rotational model or a vibrational model with set A parameters of Table 1. This figure shows clearly the poor fit obtained when a positive quadrupole deformation (β_2 = + 0.40) is used together with a negative hexadecapole deformation, and the agreement with the data is even worse when β_4 is set equal to zero. On the other hand the vibrational model gives a good account of the 2^+ data, but here, also, the agreement with the 4^+ data is rather poor. These calculations were done using the same deformation length for the various deformed terms of the optical potential ($\delta_o = \beta R_o = \beta_{IM} R_I = \beta_{LS} R_{LS}$). On the other hand, figure 3 shows the very good fits to the cross sections and polarizations obtained using set A parameters with a negative quadrupole deformation β_2 = -0.40 (oblate) and a positive hexadecapole deformation β_4 = +0.15 (curve 1). Curve 2 shows the extreme sensitivity of the calculations to the β_4 deformation. Although the magnitude of the analysing power for the 4^+ is not reproduced, the calculation gives the right phase while the overall agreement for all the data is very good. An improvement in the fit to the 4^+ state could possibly be obtained if the 6^+ state is included in the calculation, in the same manner as the inclusion of the 4^+ state results in a significant improvement of the coupled channel fits for the 2^+ state.

Equivalent fits can also be obtained when the spin-orbit deformation is made greater than that of the central deformation. Figure 4 presents the CC calculations using set A parameters, $\beta_2 = -0.40$, $B_4 = +0.15$ and various values of the ratio β_{LS}/β_{cent} of the spin-orbit deformation to the central deformation. Best agreement with the data is obtained when this ratio is equal to 1.5 (curve 1, fig. 4). This figure shows also that a good fit to the 4^+ analysing power can be obtained by increasing this ratio to 2.0 and decreasing slightly β_4 from 0.15 to 0.10. However, this makes the agreement with the 2^+ data rather poor, and the calculation then underestimates the 4^+ cross section.

Finally the use of set B optical model parameters gives equivalent fits to those reported here, and, therefore, they are not presented. Table 2 gives the final deformation parameters obtained from this study in comparison with some recently reported values.

V) CONCLUSION

In summary, coupled-channels calculations are in reasonably good agreement with our measurements of inelastic scattering of polarized protons exciting the K = 0^+ ground state rotational band in ^{28}Si. The best agreement is obtained using negative quadrupole deformation β_2 = −0.40 (oblate) and a positive hexadecapole deformation, β_4 = +0.15. Therefore the oblate shape of this nucleus is confirmed, and it is found that the β_4 deformation is considerably smaller than previously determined from inelastic proton scattering cross-sections alone (De Swiniarski 1969). Also it is in better agreement with the β_4 value deduced from the very impressive fits to the alpha-particle scattering data (Rebel et al. 1972). Although the inelastic scattering data might be equally well described by a vibrational model with different values of β_2 and β_4, the measured static quadrupole moment of the 2^+ state (Nakai et al. 1970) rules out this interpretation.

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TABLE 1

	V_o (MeV)	r_o (fm)	a_o (fm)	W_V (MeV)	W_D (MeV)	r_I (fm)	a_I (fm)	V_{LS} (MeV)	r_{LS} (fm)	a_{LS} (fm)	χ^2_σ	χ^2_p	$\sigma_R^{theor.}$
Set A	48.20	1.15	0.65	0.00	5.14	1.33	0.67	6.55	0.92	0.52	138	87	823
Set B	48.95	1.15	0.65	2.01	4.33	1.33	0.60	6.97	0.94	0.57	88	134	757

TABLE 2

Deformation parameters of ^{28}Si

Experimental and Theoretical Results

β_2	β_4	Ref.	Method
-0.40	+0.15	This work	$(\vec{p},p')$CC
-0.32±0.01	+0.08±0.01	Rebel,H. et al. 1972	(α,α')CC
-0.34	+0.25	De Swiniarski et al. 1969	(p,p')CC
-0.39	+0.10	Horikawa,Y. et al. 1971	(e,e')CC
-0.55	+0.33	Blair,A.G. et al. 1970	$(\vec{p},p')$CC
0.36		Craig,R.M. et al. 1966	$(\vec{p},p')$CC
-0.25	+0.05	Goodman,A.L. et al. 1970	H F B

FIGURE CAPTIONS

Figure 1 Optical model prediction for the elastic cross section and polarization. The two sets of parameters of Table 1 were used.

Figure 2 Coupled-channels calculations for the experimental cross section and analysing power of the 2^+ and 4^+ states in ^{28}Si.
(1) CC rotational model prediction with $\beta_2 = +0.40$ $\beta_4 = -0.15$;
(2) CC rotational model with $\beta_2 = +0.40$ $\beta_4 = 0.00$;
(3) CC vibrational model $\beta(2^+) = 0.40$ $\beta(4^+) = 0.15$. Set A optical model parameters were used.

Figure 3 CC rotational model predictions for the 0^+, 2^+ and 4^+ cross sections and analysing power; (1) $\beta_2 = -0.40$ $\beta_4 = +0.15$; (2) $\beta_2 = -0.40$ $\beta_4 = 0.00$. Calculations were done using set A (table 1) optical model parameters and keeping the same deformation length for the different terms of the deformed optical potential (βR = cte).

Figure 4 CC rotational model predictions for the 2^+ and 4^+ states in ^{28}Si using parameters set A (table 1) and increasing the spin-orbit deformation parameter relative to the central deformation from 1.0 to 2.0.

(1)	$\beta_2 = -\ 0.40$	$\beta_4 = +\ 0.15$	$\beta_{LS} = 1.5\ \beta_{cent}$
(2)	$\beta_2 = -\ 0.40$	$\beta_4 = +\ 0.15$	$\beta_{LS} = \beta_o = \beta_I$
(3)	$\beta_2 = -\ 0.40$	$\beta_4 = +\ 0.15$	$\beta_{LS} = 2\ \beta_{cent}$

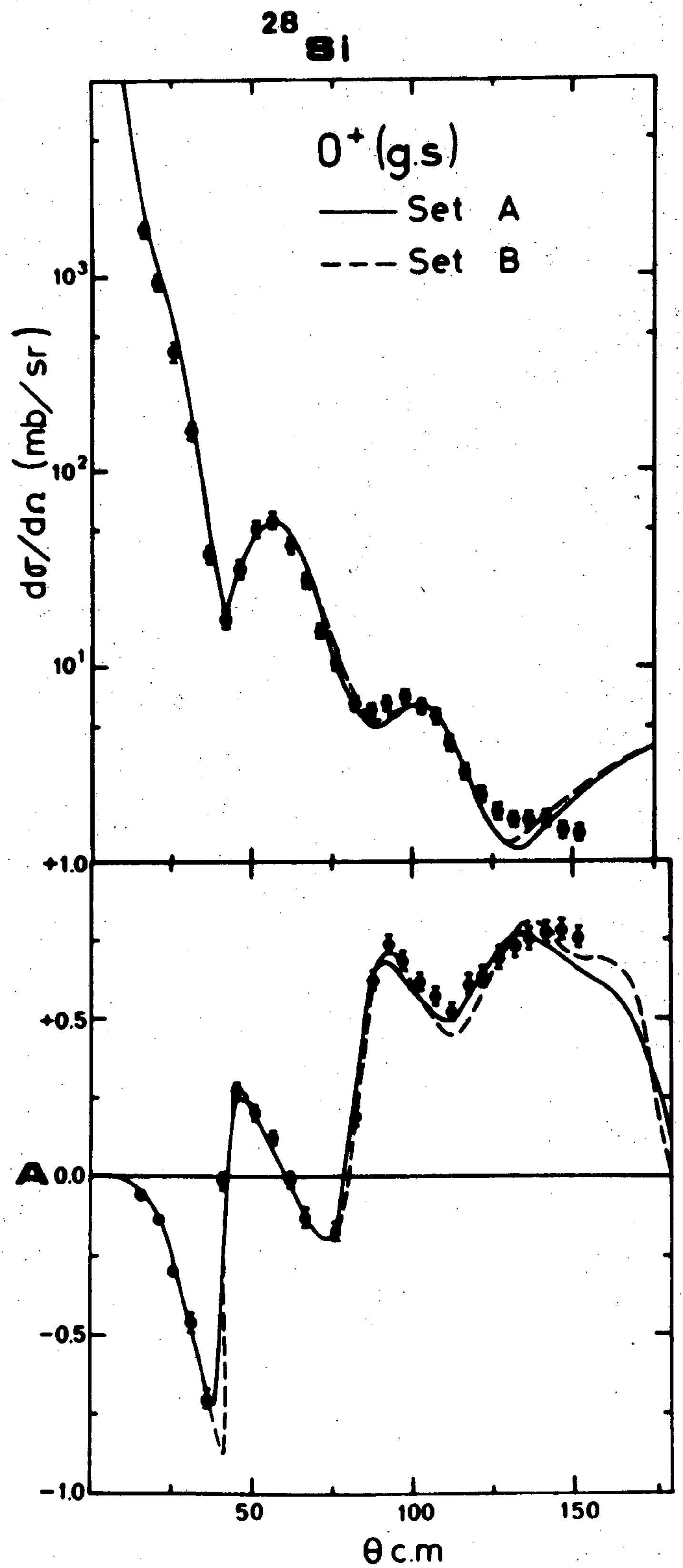

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Fig. 1

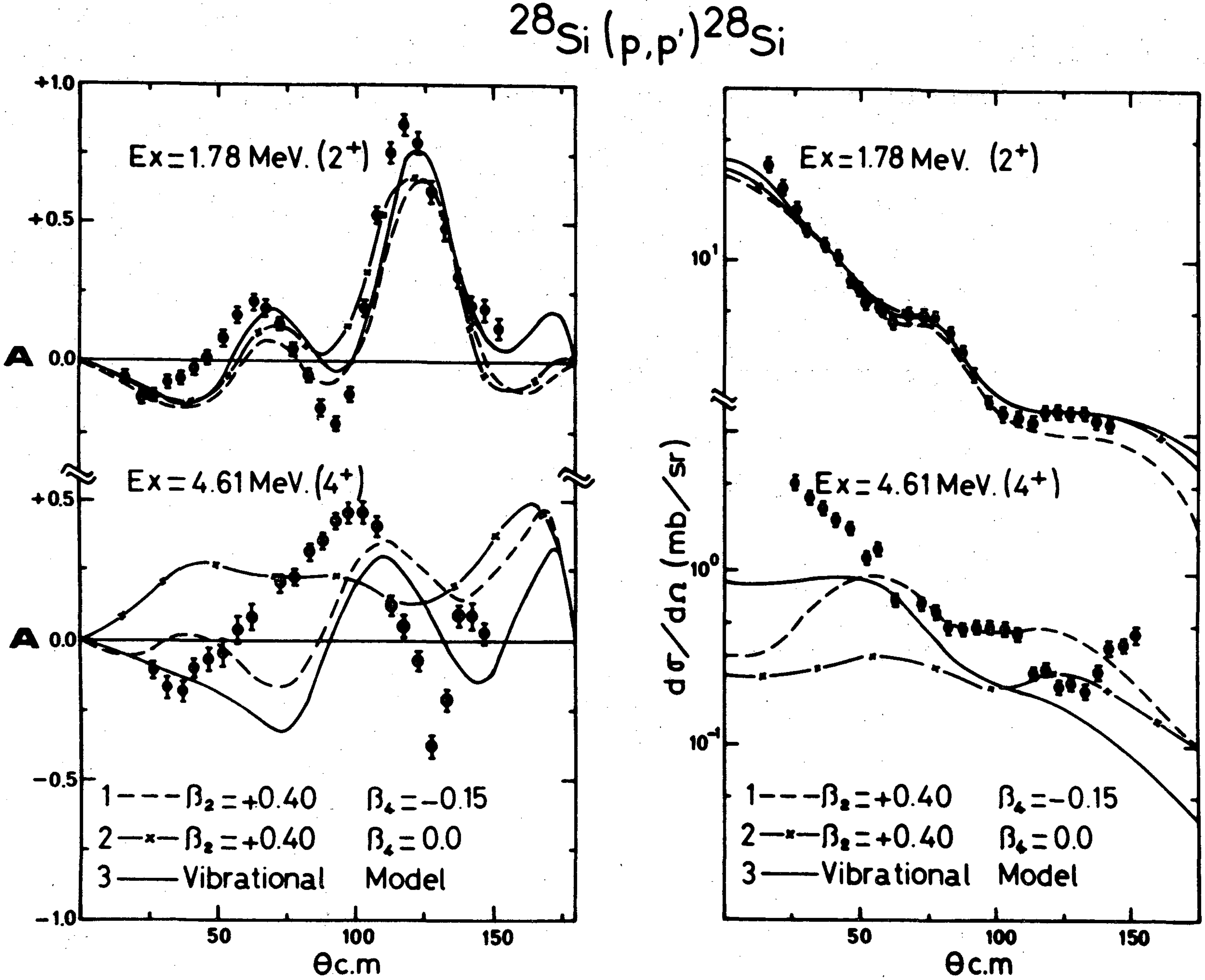

Fig. 2

XBL 732-130

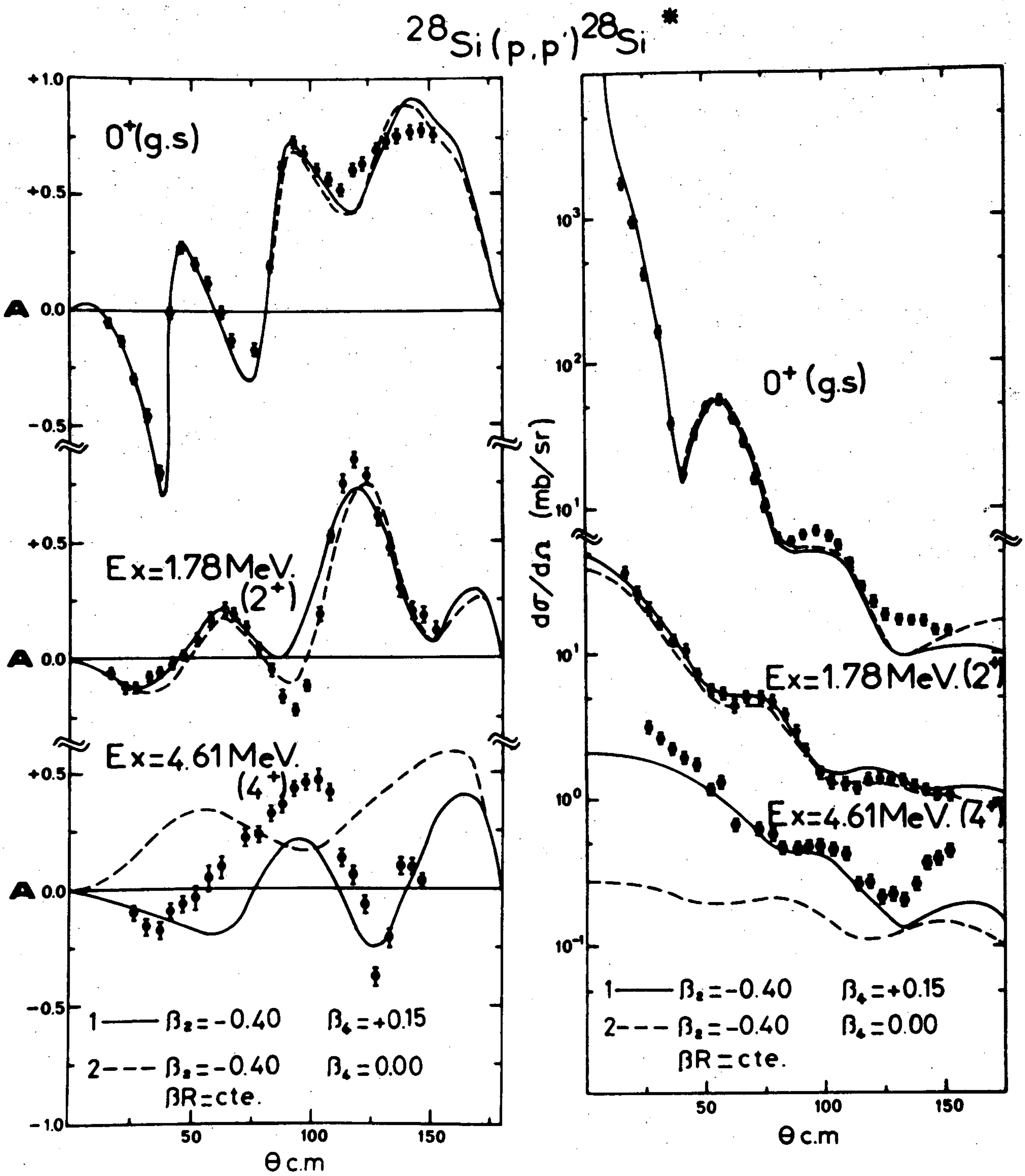

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Fig. 3

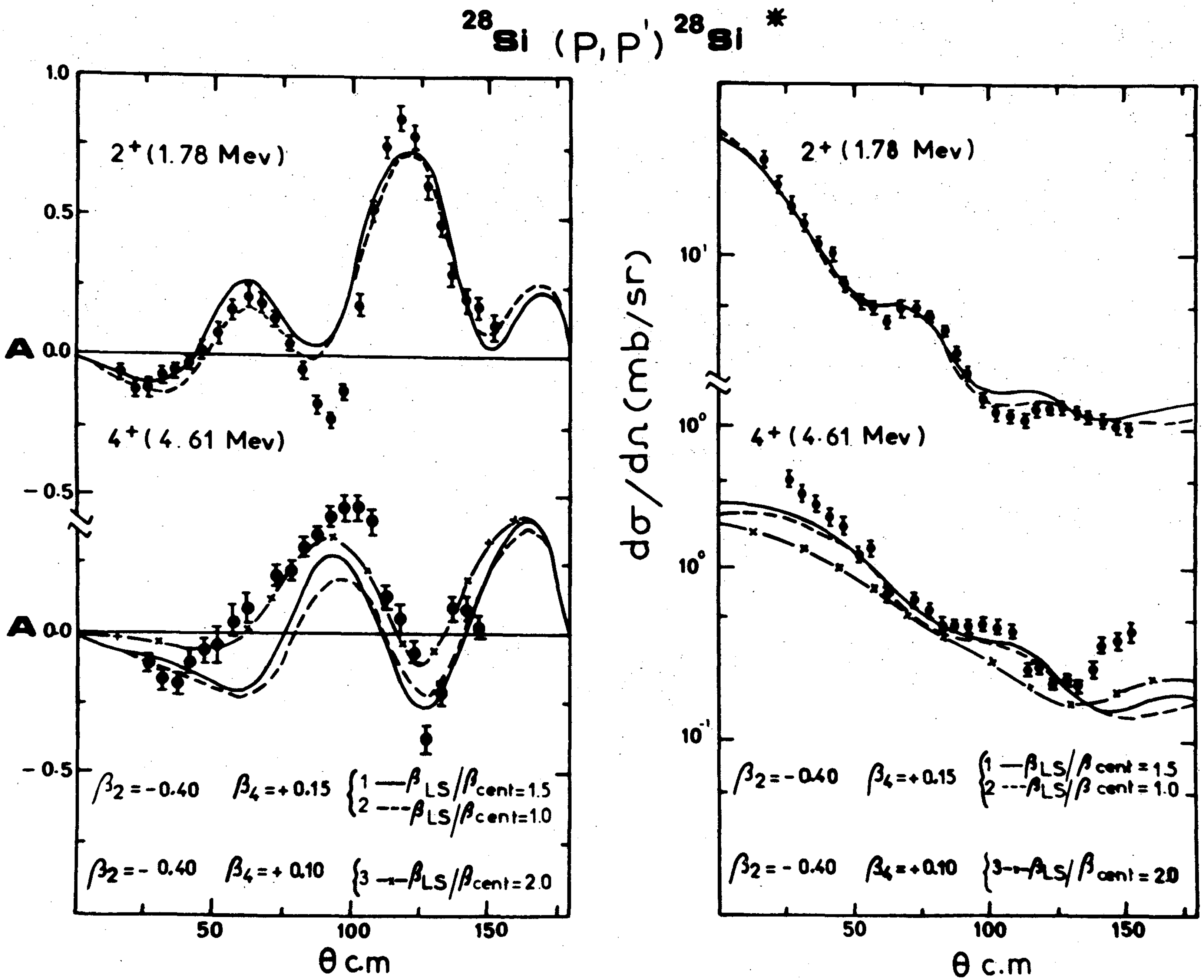

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Fig. 4

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