Study of higher excited states in 20Ne by inelastic scattering of 24.5 MeV protons

Study of Higher Excited States in ^{20}Ne by Inelastic Scattering of 24.5 MeV Protons[1])

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(10. X. 1975)

Abstract. The angular distributions of the differential cross-sections for the inelastic scattering of 24.5 MeV protons were measured for excited states up to 9.50 MeV in ^{20}Ne. Prior to the experiment, an excitation function was measured for incident proton energies between 23 and 26 MeV to select a resonance-free region. Twenty cross-sections have been measured, generally with high precision and low statistical errors. Large variations have been found in the shapes of angular distributions for states having the same spins and parities. Some of the excited states were analyzed in the framework of the collective model using either vibrational or rotational model wave functions. Very good agreement with the cross-sections of the $K = 0^+$ ground state band have been obtained using β_2, β_4 and β_6 multipole deformations of $+0.47$, $+0.28$ and -0.10, respectively. There is definite evidence for a new state in ^{20}Ne at 9.31 MeV which we tentatively assign as a $J^\pi = 4^+$ state.

1. Introduction

The nuclear structure of low-lying $T = 0$ states in ^{20}Ne has been extensively studied in recent years. The existence of several rotational bands in ^{20}Ne has been suggested [1]. Indeed, the ground-state rotational band, $K = 0^+$, has been recently extended [2] up to the 8^+ state. Several new levels of the $K = 2^-$ band have also been found; this band is now extended up to the 8^- level [3, 4]. Several other bands have also been located in ^{20}Ne, such as the $K = 0^-$ band based on the 1^- state at 5.78 MeV; this is known up to the 9^- state [5]. Moreover, the existence of quartet states in ^{20}Ne has been suggested by several groups [5, 6]. It has been suggested for instance that the 7.20 MeV (0^+), the 7.84 MeV (2^+), and the 9.03 MeV (4^+) states could belong to the $8p$–$4h$ configuration with the basic [220] quarted configuration [6].

In the ^{16}O(^{7}Li, t)^{20}Ne reaction, Panagiotou et al. [4, 5] observed a new 0^+ level at 8.62 MeV and a 2^+ level at 10.28 MeV which are rather strongly excited in this reaction. They suggested that these two levels together with the 4^+ level at 12.77 MeV could be members of the [301] quartet configuration. It is interesting to point out

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that Arima et al. [7] have suggested that the 0^+ level of this configuration should be located around 8.8 MeV.

Besides, the successful interpretation of the states in ^{20}Ne in terms of rotational bands, there have been a considerable number of detailed shell model calculations which, in several cases, have predicted correctly the position of some low-lying states [8]. Microscopic model calculations carried out by methods such as Hartree–Fock or Hartree–Fock–Bogoliubov have predicted [9] the existence in ^{20}Ne of a large hexadecapole deformation (β_4) together with the quadrupole deformation (β_2). The existence of this large hexadecapole deformation has been confirmed from an analysis of (p, p') [10a,b,c], (α, α') [11], and (e, e') [12] experiments. While all these experiments lead to the definite existence of a large hexadecapole deformation in ^{20}Ne, the absolute value of β_4 shows considerable differences according to the type of particles used, including $\beta_4 = 0.28$ for the proton scattering experiment and 0.11 in an α-particle scattering experiment. A low energy (^{3}He, ^{3}He') experiment [13], leads to the conclusion that the value of β_4 in ^{20}Ne is close to zero. However recent high energy (^{3}He, ^{3}He') data [14] have yielded further evidence for a large hexadecapole deformation in ^{20}Ne($\beta_4 = 0.17 \pm 0.05$).

Although it seems likely that the discrepancies observed at lower energies are due to compound nucleus contributions and problems in applying the optical model at these energies, the reason for the large variation of β_4 at high energies among the different scattering experiments was until recently an open question. The discrepancy observed was particularly large between (p, p') and (α, α') results. This suggested that the effect of the size of the composite particle (α or ^{3}He) is important. Indeed, Rebel and Schweimer [15] have recently reanalyzed their 104 MeV (α) inelastic scattering ^{20}Ne data. On the basis of the deformed folding model [16] they have obtained values for the quadrupole and hexadecapole deformations of $\beta_2 = 0.42$ and $\beta_4 = 0.23$ respectively; these values are in very good agreement with the (p, p') results [10]. Using the same folding collective model Mackintosch [17] has also recently removed the discrepancy observed between β_2 obtained for ^{24}Mg by (p, p') [10a] and (α, α') [11] experiments. Mackintosch and de Swiniarski have shown that the folding collective model determines the hexadecapole moment fairly unambiguously [17] especially when ^{3}He particles are used as probes [18].

We will present in this paper the cross-sections and calculations concerning the inelastic scattering of 24.5 MeV protons on ^{20}Ne. The first goal of this experiment was to get precise data from this deformed nuclei to test a microscopic model interaction containing such terms as tensor, two-body spin-orbit forces, etc. [19]. Such calculations are still only in progress [20] and will therefore not be presented in this paper. Prior to this experiment an excitation function was measured to select a possible resonance-free region. Since some of the data which will be presented in this paper have already appeared in the literature as a separate paper [10a], emphasis will be put on the cross-sections not yet published. All the cross-sections for the states observed up to 9.5 MeV excitation energy in ^{20}Ne have been measured with good precision and low-statistical errors with the exception of some weakly excited states like the 0^+ at 6.72 MeV. We observe considerable differences in the shape and absolute value of cross-sections for states having the same spins and parities (J^π). The states belonging to the ground-state $K = 0^+$ rotational band are strongly excited as well as states which are members of the $K = 2^-$ or $K = 0^-$ bands.

After a description in Section 2 of the experimental method used to obtain the data, the experimental cross-sections are presented in Section 3. The optical model analysis and the various coupled-channels or DWBA calculations are presented in Section 4. The paper concludes with a short summary in Section 5.

2. Experimental Method

The $^{20}Ne(p, p')$ excitation function and inelastic scattering experiments were carried out using the momentum analyzed [21] beam from the Berkeley 88-inch cyclotron. Two 4 mm Li-drifted Si detectors 20° apart were used in the excitation function experiment, while four such detectors also spaced 20° apart were used in the inelastic scattering experiment. In both cases the detectors were cooled to −25°C with thermo-electric devices. Proton resolution of approximately 50 keV (FWHM) was obtained. Particle identification was not used as most proton-induced reactions on ^{20}Ne have very negative Q-values [22]. One exception is the (p, α) reaction whose alpha groups contaminate proton peaks corresponding to ^{20}Ne states at excitations $\geqslant$5.63 MeV. Fortunately these alpha groups moved through the proton spectrum rapidly and did not present a serious problem in the data analysis.

Table I
Summary of geometrical variables used in the inelastic proton scattering experiment. All values are in centimeters

Counter	ω_1	ω_2	h_2	l_1	l_2
1	0.152	0.149	0.305	7.82	24.82
2	0.148	0.126	0.290	7.82	24.82
3	0.149	0.154	0.283	7.70	24.87
4	0.153	0.141	0.286	7.62	24.93

Standard gas collimating systems were used in both experiments. Table I summarizes the geometries in the inelastic scattering experiment. The value ω_1 is the width of the front collimator, while l_1 is the distance from the target center to the front collimator and l_2 is the distance between front and rear collimators. The quantity h_2 is the vertical aperture of the rear collimator and ω_2 its width. All values are given in centimeters. The gas cell was 7.6 cm in diameter, and the windows were composed of 2.5×10^{-4} cm Havar foil. The neon gas targets were filled with ^{20}Ne enriched to $\geqslant$99.9%. The differential cross-sections were then extracted using a previously derived formula [23] for the gas target geometry.

The $^{20}Ne(p, p')$ excitation function was carried out between 23 MeV and 26 MeV proton energy in approximately 500 keV steps. The beam energy width was approximately 10 keV, and the calibration of the analyzing magnets by nuclear resonant scattering of accelerated molecular hydrogen ions [24] indicates that the beam energy is known to the order of its width. However, since this careful calibration was not done at the time of the excitation function work, a more realistic estimate in the beam energy error would be $\pm$50 keV. The energies used were 23.10 MeV, 23.56 MeV, 23.97 MeV, 24.65 MeV, 25.11 MeV, 25.63 MeV and 26.09 MeV. The excitation functions were taken at 30°, 50°, 140° and 160°. Data for twelve proton groups up to 8.46 MeV excitation in ^{20}Ne were extracted. These results are given in Figure 1. The J^π values listed in parenthesis are taken from the literature [25]. These data were taken with 59.6 cm Hg pressure of ^{20}Ne in the gas cell.

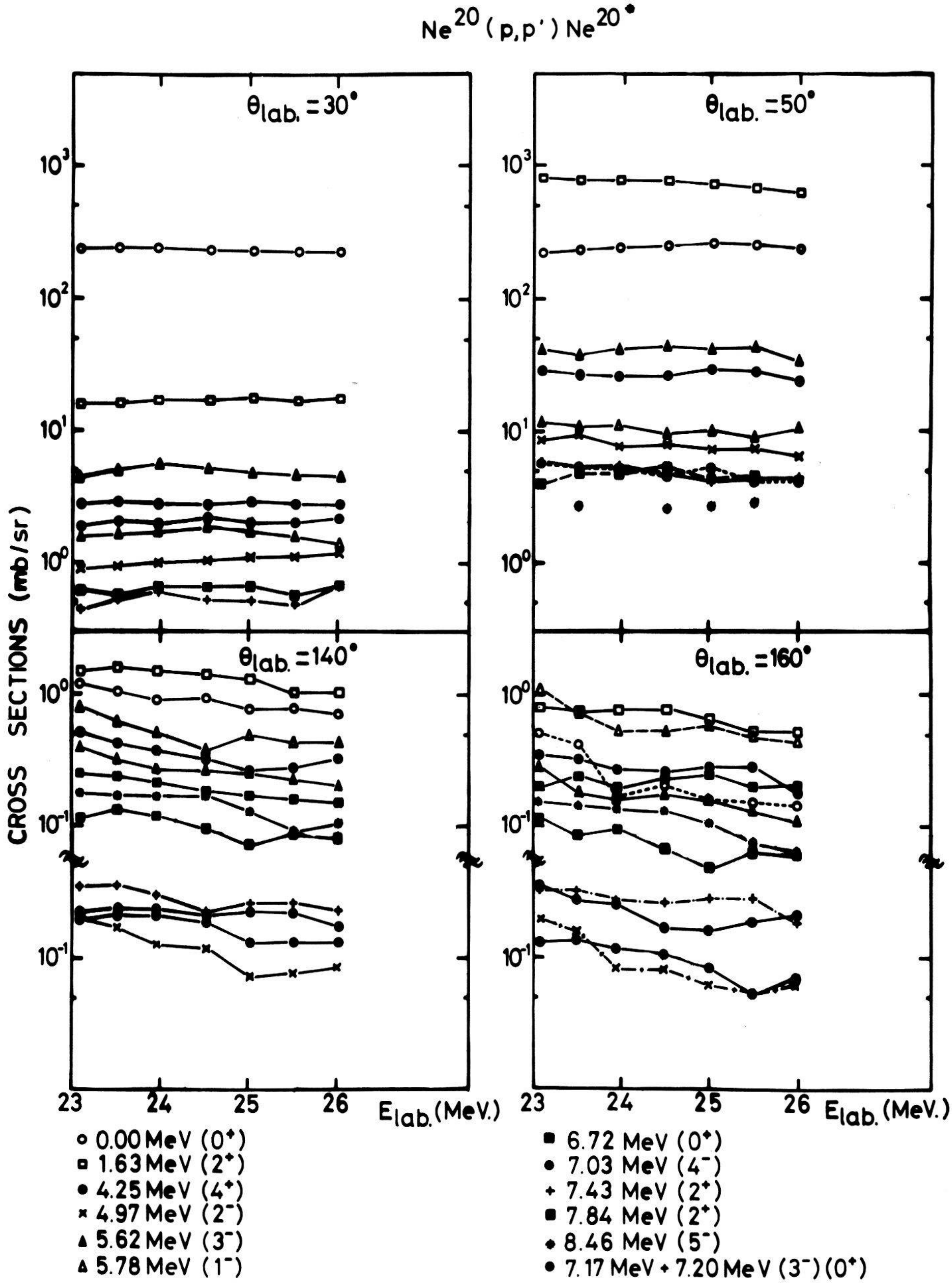

Figure 1
Excitation functions for the low-lying states in ^{20}Ne.

On the basis of the excitation function results, a beam energy of 24.50 MeV was chosen for the ^{20}Ne inelastic scattering experiment. Data were taken every 2.5° from 12.5° to 90° lab angle, and then in 5° steps from 90° to 165° lab angle. At forward angles the gas cell pressure was 11.0 ± 0.1 cm Hg with a temperature of $294° \, ^{+1°}_{-2°}$ K. In order to increase the counting rate at back angles, the ^{20}Ne pressure was increased to 20.4 ± .1 cm Hg. Temperature and pressure were monitored throughout the experiment and the errors given above indicate the observed drifts. Energy calibration of the proton spectra was achieved by comparing the proton spectra with the two-body kinematics appropriate for the states in ^{20}Ne. During this experiment, up to 1μA of analyzed protons were delivered on the target.

3. Experimental Cross-sections

The $^{20}\mathrm{Ne}(p, p')^{20}\mathrm{Ne}^*$ spectrum taken at $E_p = 24.5$ MeV and at $\theta_{\mathrm{lab}} = 150°$ is shown in Figure 2. As can be seen from this figure, the states belonging to the ground state rotational band ($K = 0^+$) are strongly excited as well as the states belonging to the $K = 2^-$ band based on the 2^- state at 4.97 MeV and the states of the 0^- band based on the 1^- state at 5.78 MeV. Because of the very good resolution achieved in this experiment, many cross-sections for states up to 9.5 MeV could be obtained. These results are given in Figures 3, 4 and 5. Again J^π values are taken from published work [25]. There is definite evidence for a new state at 9.31 MeV which has not yet been seen in any scattering experiment but is strongly excited in this experiment. The existence of this state had, nevertheless, been suggested some time ago from reactions like $^{12}\mathrm{C}(^{12}\mathrm{C}, \alpha)^{20}\mathrm{Ne}$ [26] or $^{19}\mathrm{F}(d, n)^{20}\mathrm{Ne}$ [27]. We observe also a very weak state around 8.6 MeV which could be the 8.6 MeV (0^+) found in a heavy-ion experiment [4, 5]. Unfortunately no cross sections could be extracted for this state. The Figures 3, 4 and 5 which present the measured differential cross sections[5]) show considerable differences among states characterized by the same angular momentum. A typical comparison between cross-sections for several states having the same spins and parities can be seen in Figure 6 where a continuous line has been drawn through the experimental points as a visual guide. The experimental errors shown on the curves are purely statistical but background was generally subtracted and taken into account in the total errors calculations. All the data were reduced using a fitting program [28] and show consistent results.

4. Analysis

4.1 Optical model calculations

The optical model potential between the incident proton and the target nucleus has the usual form

$$V(r) = -\left[V_0 f(r, r_0, a_0) - 4ia_I W_D \frac{d}{dr} f(r, r_I, a_I)\right] + \frac{\hbar}{m_\pi c} \frac{V_{LS}}{r} \frac{d}{dr} f(r, r_{LS}, a_{LS}) \mathbf{L} \cdot \boldsymbol{\sigma}$$

to which is added the Coulomb potential from a uniformly charged sphere of radius

[5]) The tabulated cross sections are available on request at the LBL, Bldg 88 (Dr. D. L. Hendrie) or at I.S.N. Grenoble (Information Service – Mme TUR).

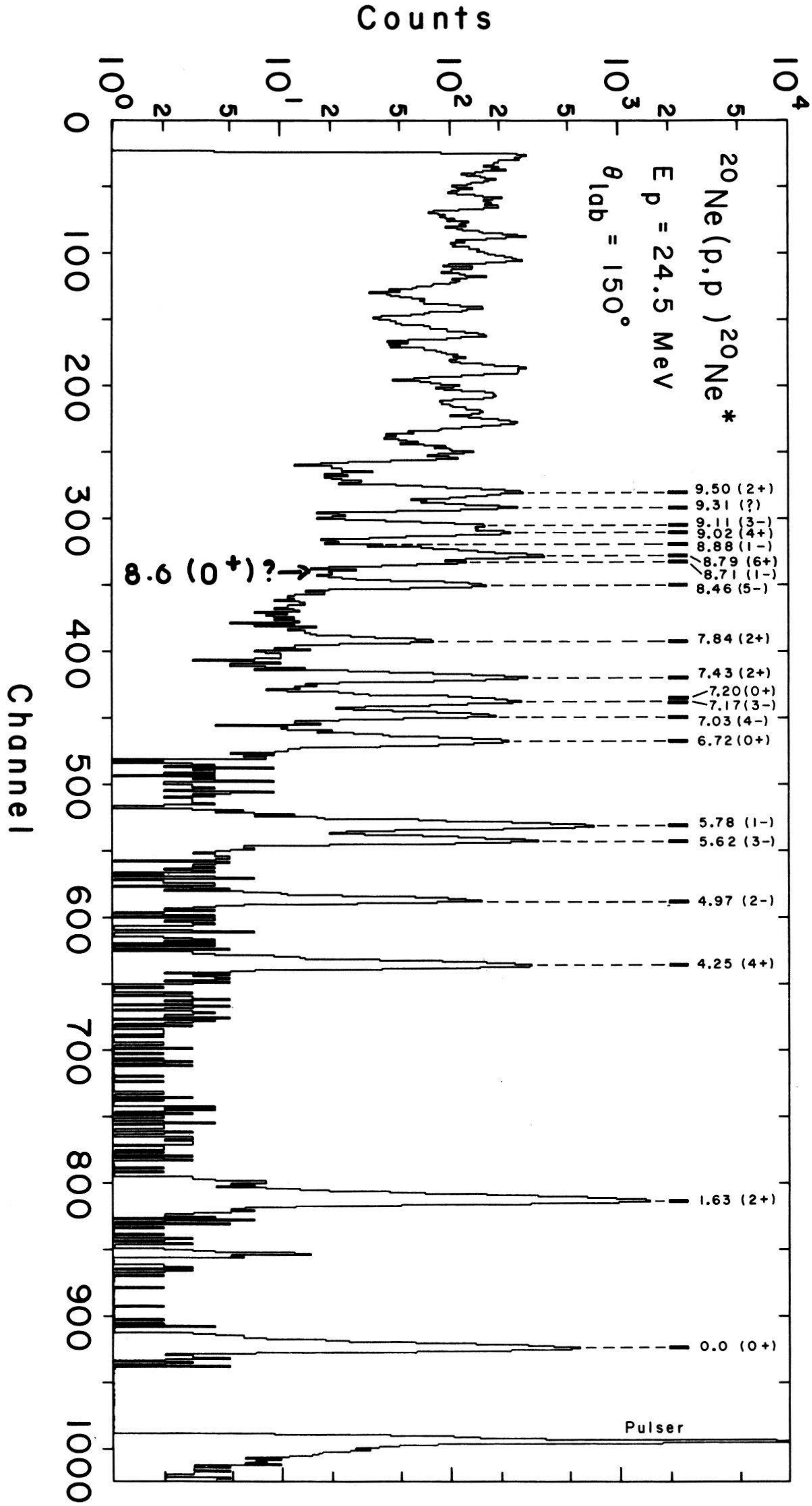

Figure 2
Experimental spectrum at $\theta_{lab} = 150°$.

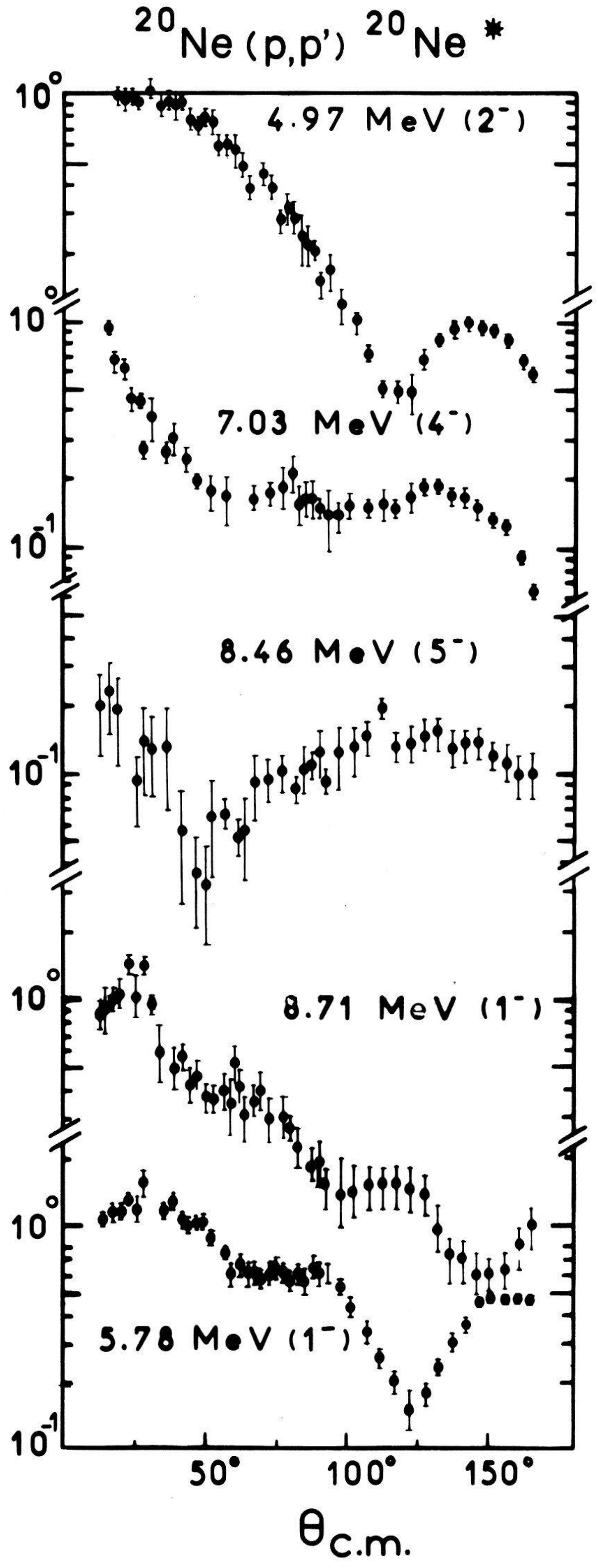

Figure 3
Experimental cross-sections for several negative parity states in ^{20}Ne.

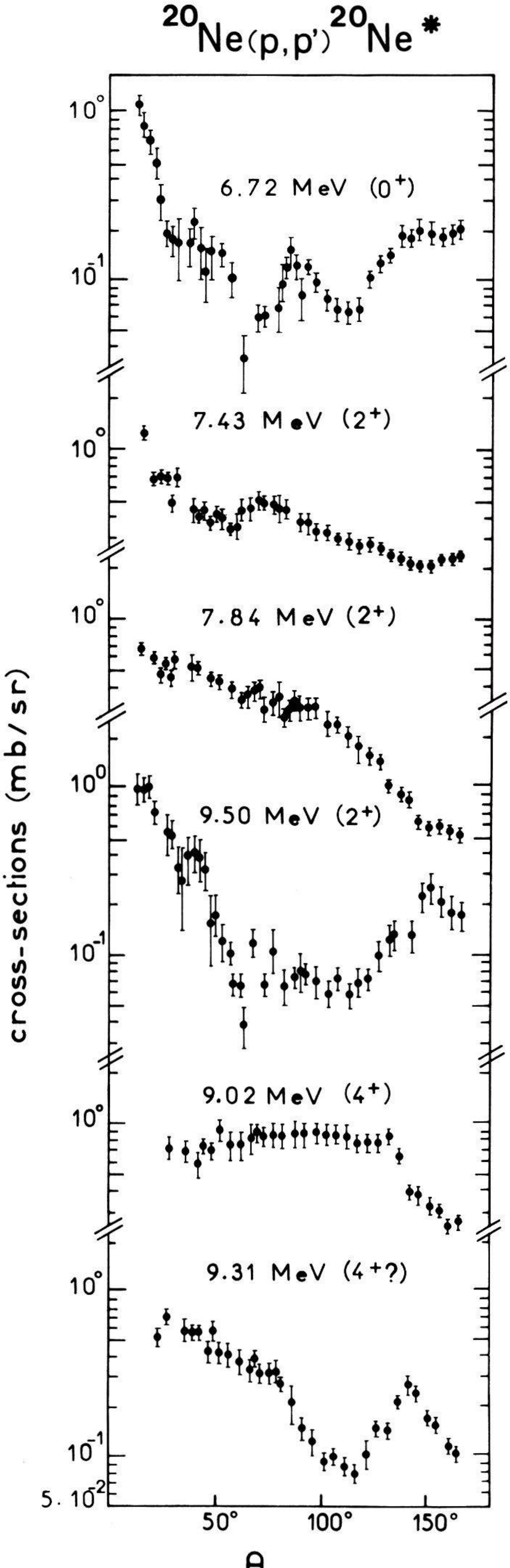

Figure 4
Experimental cross-sections for some positive parity states in ^{20}Ne.

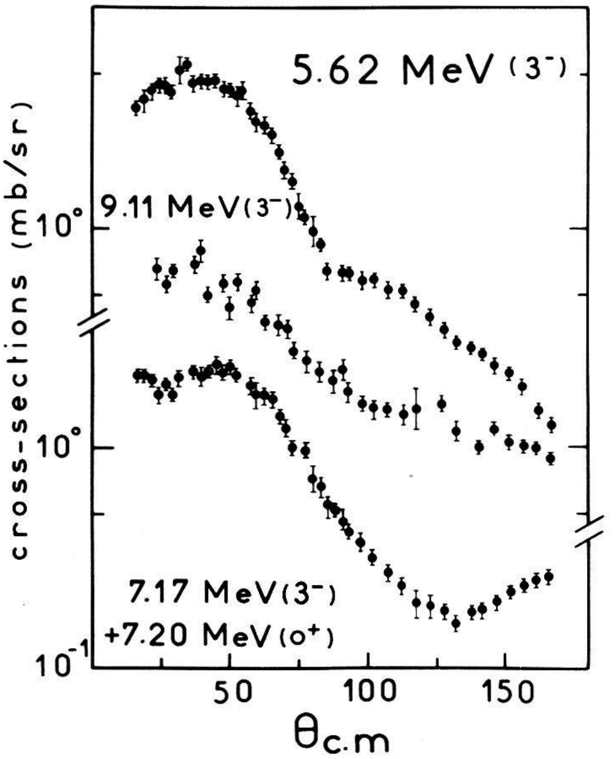

Figure 5
Experimental cross-sections for several 3^- states in ^{20}Ne.

$R_c = r_c A^{1/3}$ with $r_c = 1.10$ fm. The functions $f(r, r_0, a_0)$, $f(r, r_I, a_I)$ and $f(r, r_{LS}, a_{LS})$ are the Woods–Saxon form factors

$$f(r, r_0, a_0) = \left\{1 + \exp\left[\frac{r - r_0 A^{1/3}}{a_0}\right]\right\}^{-1}$$

The determination of the optical parameters in a deformed nucleus like ^{20}Ne is complicated by the strong coupling between the excited states and the ground state. Starting optical model parameters were obtained by fitting only the elastic cross-section using the search code Mercy (Set A, Table II). Very good fits to the elastic cross-sections were obtained with several distinct sets of optical-model parameters which were obtained generally by searching on all parameters. These parameters were then adjusted to preserve the fits to the elastic scattering in the coupled channels calculations. Usually it was sufficient to adjust only W_D, a_I and V_0. These parameters which were used in the coupled-channels calculations to get the Y_4 deformation in ^{20}Ne have been published in a previous paper [10a].

After these parameters were determined, good polarization data for the lowest 0^+, 2^+ and 4^+ states were obtained with the Berkeley polarized source [29]. New optical parameters were then obtained in a similar way first by fitting the elastic cross-section and polarization data together. (Set B parameters Table II). For these calculations the search code Magali [30] was used. The corresponding fits to the elastic cross section and polarization are shown in Figure 7. Surprisingly the only large change in the optical parameters when the polarization data are included in the search is in the real well depth; the spin-orbit parameters are almost unchanged. These parameters were then used as starting parameters in the coupled-channels calculations including the first 0^+ (g.s.), 2_1^+ (1.63 MeV) and the 4_1^+ states belonging to the $K = 0^+$

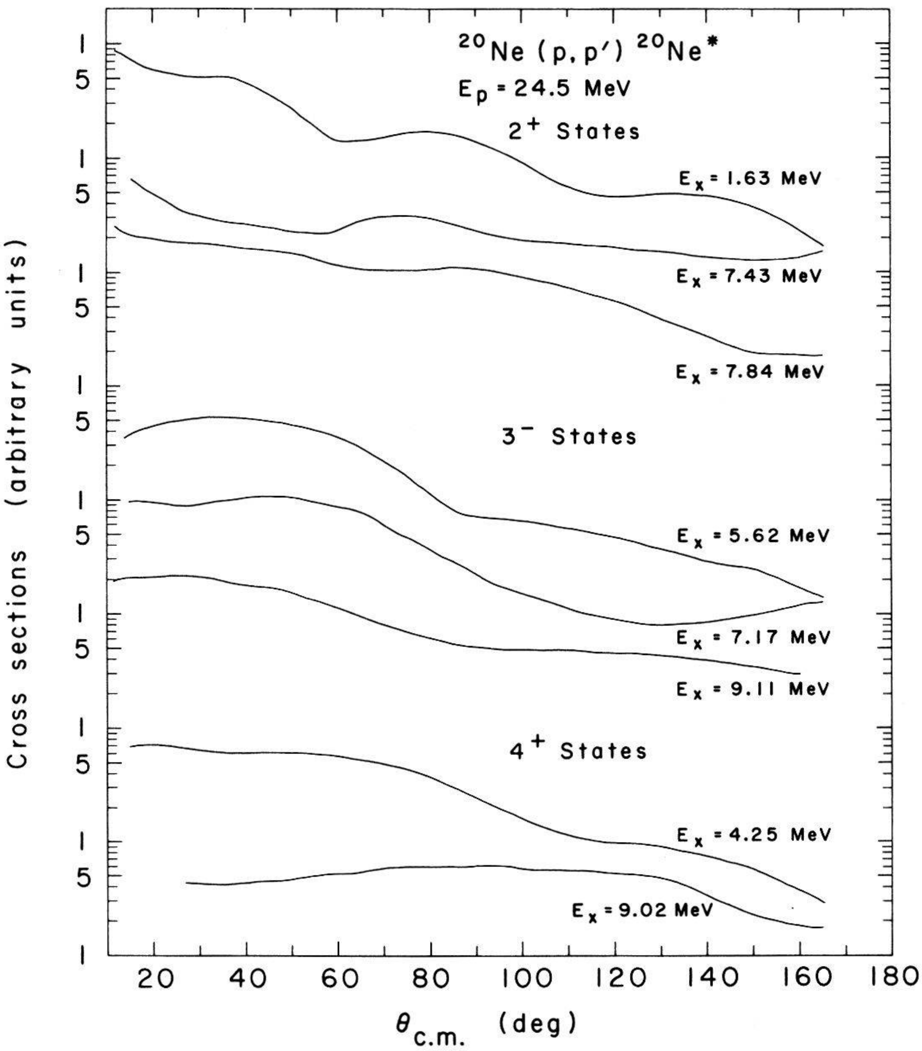

Figure 6
Comparison between different cross-sections in ^{20}Ne having the same spins and parities. A continuous line is drawn through the experimental points as a visual guide.

ground state rotational band; they were adjusted to preserve the fits to the elastic scattering. The coupled channels code ECIS 71 written by J. Raynal was used for all the following calculations. This time cross-sections and analyzing power were used simultaneously in the calculations. As observed previously [10a], the optical model parameters had to be changed only slightly and here also it has been found that it was sufficient to adjust only W_D, a_I, and slightly V_0 and r_{LS}. The parameters used in all the further C.C. calculations are presented in Table II also (C.C. parameters).

4.2. Coupled-channels calculations: ground state rotational band $K = 0^+$

4.2.1. With the new optical model parameters (C.C. parameters, Table II) coupled-channels calculations have been performed for several states in ^{20}Ne and deformation parameters extracted.

Figure 8 presents the C.C. calculations for the 0^+, 2^+, 4^+ and 6^+ cross-sections of the $K = 0^+$ ground state band in ^{20}Ne. The fits are slightly improved from the previously published calculations [10a] mainly at back angles, but the conclusions concerning the β_2(quadrupole) and β_4(hexadecapole) deformations are not changed.

Table II
Optical model parameters (Set A, Set B) and coupled-channels parameters

Search	V_0 (MeV)	r_0 (fm)	a_0 (fm)	W_D (MeV)	r_I (fm)	a_I (fm)	
σ_{only}	55.45	1.05	0.76	7.38	1.26	0.61	Set A
$\sigma + p$	59.10	1.01	0.77	7.54	1.26	0.62	Set B
	59.0	1.01	0.75	6.50	1.26	0.55	C.C.

Search	V_{LS} (MeV)	r_{LS} (fm)	a_{LS} (fm)	χ^2_σ	χ^2_P	$\sigma_R^{th\,a)}$	
σ_{only}	3.57	0.95	0.33	94		713	Set A
$\sigma + p$	3.57	0.86	0.33	217	1290	717	Set B
	3.57	0.90	0.33				C.C.

[a]) σ^{th} is the reaction cross-section (theoretical) obtained from the optical model calculation.

The prediction for the 6^+ cross-section is improved if a β_6 deformation equal to -0.10 is added to the β_2 and β_4 deformations while the corresponding fits to the 2^+ and 4^+ cross-sections are almost unchanged. If β_6 is set positive, the fit to the 6^+ cross-section is less satisfactory. It is nevertheless impossible to claim from this fact the existence of a negative β_6 deformation in ^{20}Ne. As already pointed out in the introduction, the values of the β_2 and β_4 deformations for ^{20}Ne have been recently confirmed at 30 MeV [10c]. The discrepancies between (p, p') and recent (α, α') [11] results have also been removed [15, 17].

4.2.2. Coupled-channels analysis of other cross-sections. The analysis of the cross-sections for the states in ^{20}Ne is complicated by the fact that most of the states belong to rotational bands; coupling of these bands with the ground state is difficult to handle and is generally ignored. Moreover the way to handle this coupling or interaction between several rotational bands in the same nucleus is up to now still an open question. Therefore some calculations were done in the DWBA or coupled-channels formalism mainly to determine the deformation parameters β_L and to compare more precisely the cross-sections of states having the same spins and parities.

Figures 9, 10 and 11 show the C.C. calculations for the 3^- states at 5.62 MeV, 7.17 MeV and 9.11 MeV, for the 1^- states at 8.71 MeV and 5.78 MeV and for the 2^+ state at 7.84 MeV and the new level at 9.31 MeV. The excellent fit obtained for the 9.11 MeV (3^-) state can probably be explained by the fact that this state apparently does not belong to a clearly defined rotational band and therefore presents a pure vibrational or collective model character. On the contrary the fair agreement obtained for the 5.62 MeV (3^-) and for the 7.17 MeV (3^-) states can be explained by the fact that these states are clearly members of the $K = 2^-$ and $K = 0^-$ rotational bands, respectively, since the calculations have not taken into account the various intra-band couplings.

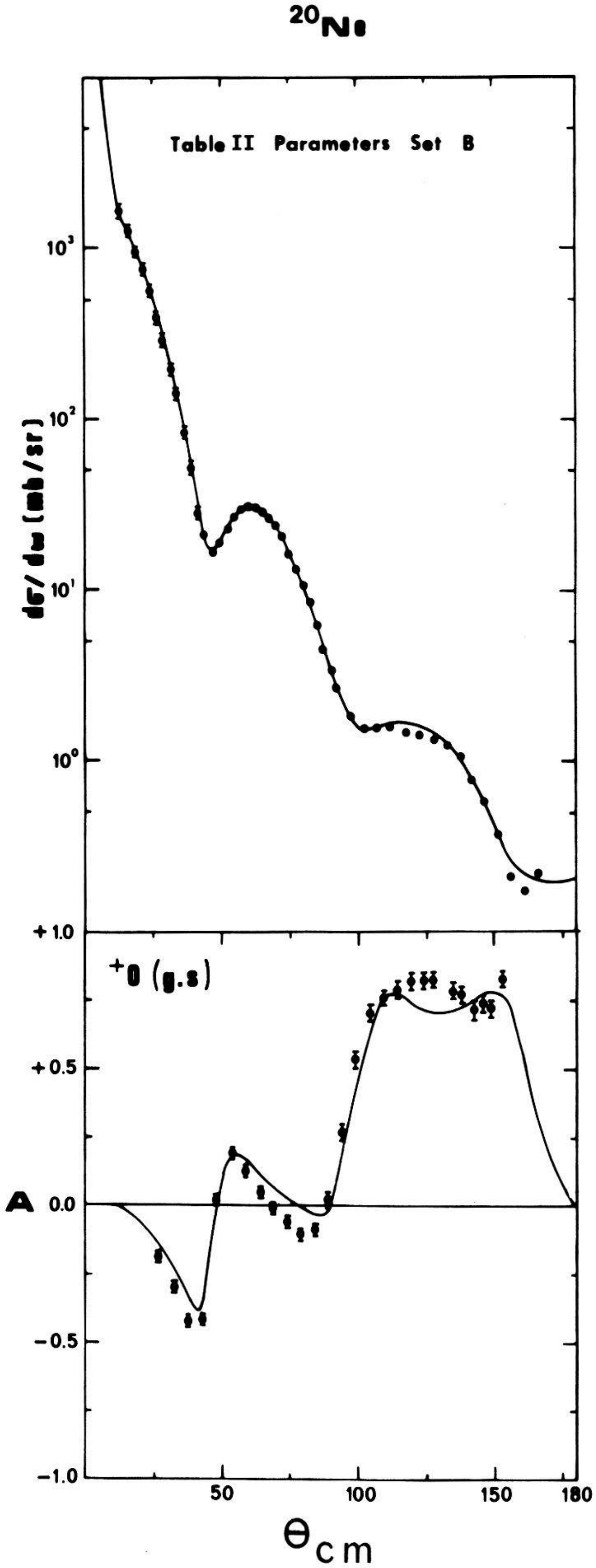

Figure 7
Optical model calculations for the ground-state $J^\pi = 0^+$ cross-section and polarization. The parameters of Table II, set B were used.

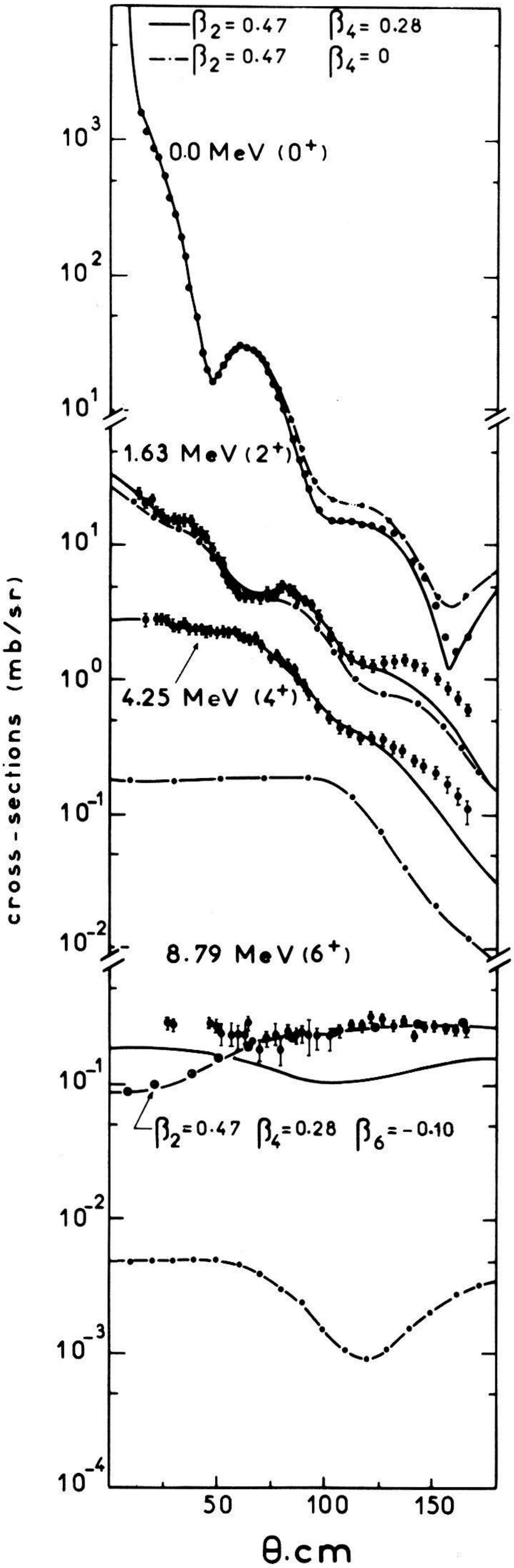

Figure 8
Coupled-channels (rotational model) calculations for the states belonging to the $K = 0^+$ ground state band, namely, the 0^+ (g.s.), the 2^+ (1.631 MeV), the 4^+ (4.25 MeV) and the 6^+ (8.79 MeV) with and without a hexadecapole deformation ($\beta_4 = +0.28$). The prediction for the 6^+ state is slightly improved when a β_6 equal to -0.10 is included in the calculations. The optical model parameters (C.C. parameters) of Table II were used.

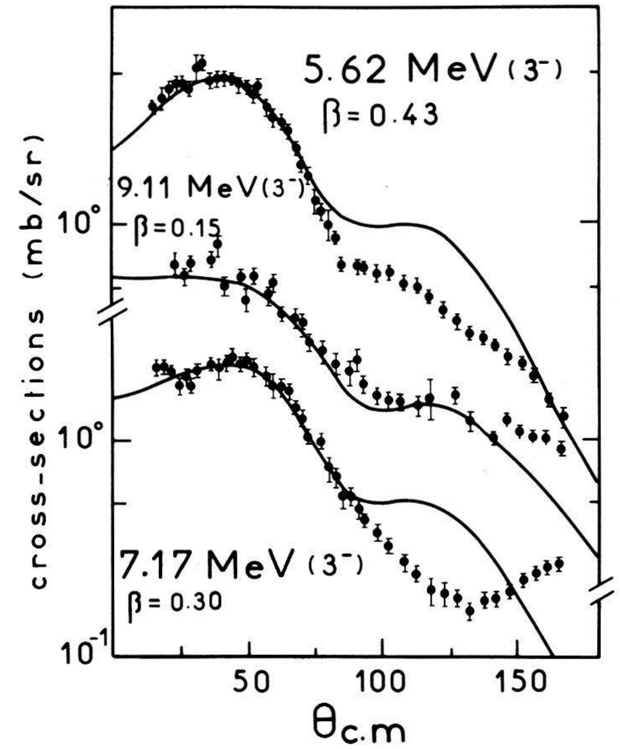

Figure 9
Coupled-channels calculations (vibrational model) for the several 3^- states in ^{20}Ne, namely the 5.62 MeV, the 9.11 MeV and the 7.17 MeV states.

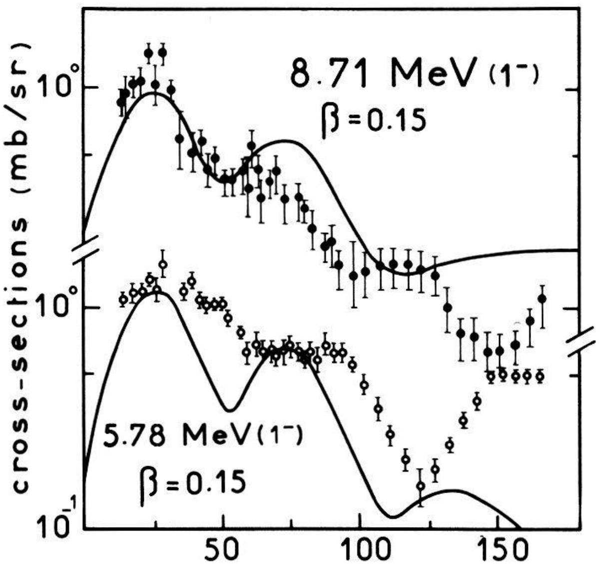

Figure 10
C.C. calculations for some 1^- states in ^{20}Ne.

In Figure 10 one can see the poor agreement obtained for the different 1^- states even if the general shape is more or less reproduced. The reason for this poor agreement between the 1^- data and the C.C. calculation (which assumes always direct excitation from the 0^+ (g.s.) to the state involved) is not known. Figure 11 presents the C.C. calculation for the 2^+ state at 7.84 MeV and for the new state at 9.31 MeV.

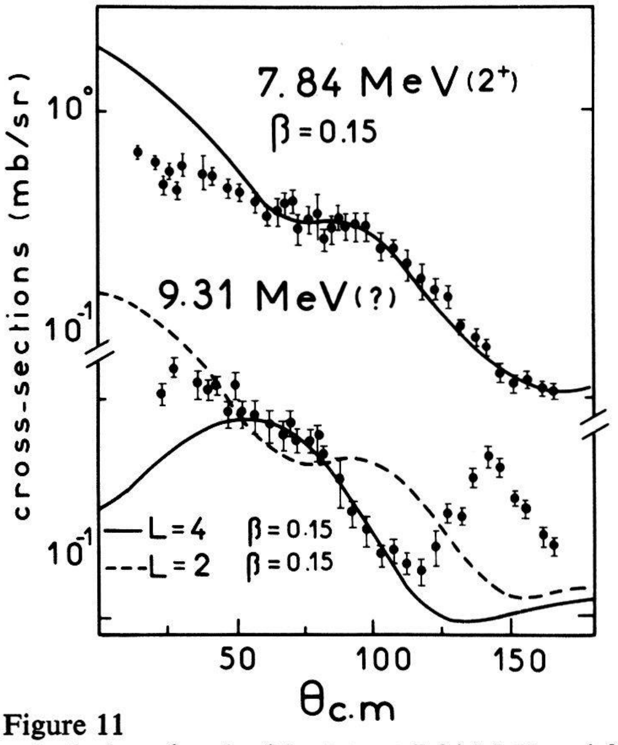

Figure 11
C.C. calculations for the 2^+ state at 7.84 MeV and for the 9.31 MeV state.

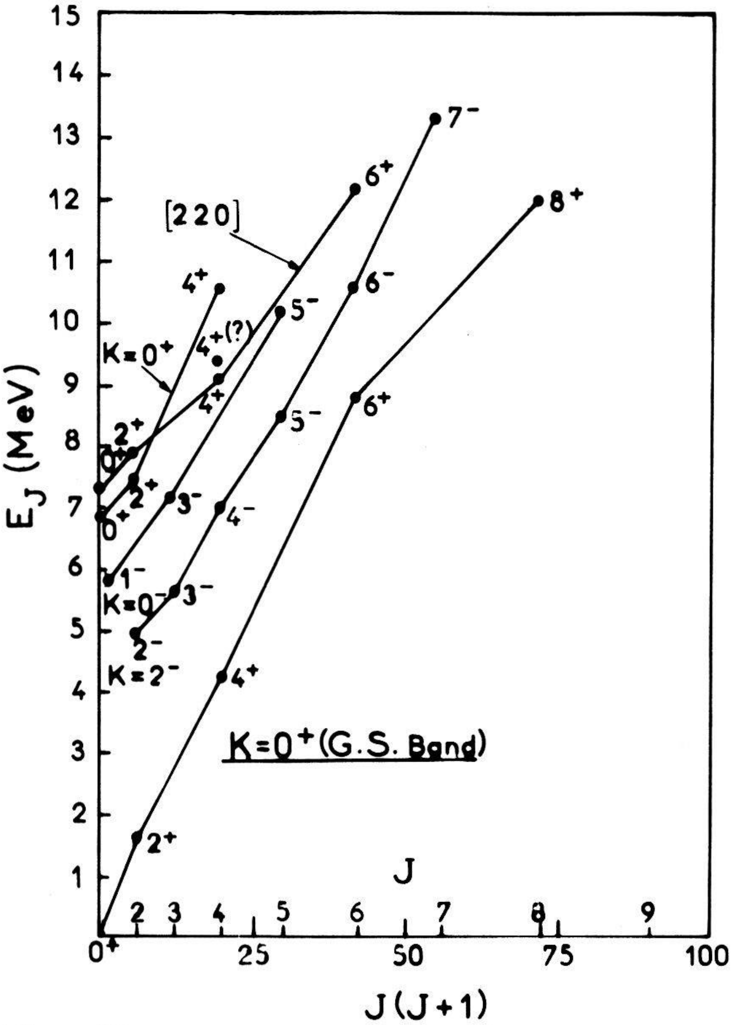

Figure 12
Rotational bands in ^{20}Ne. The excitation energy is drawn versus $J(J + 1)$ (after Refs. [5, 6]).

Table III
Deformation parameters in ^{20}Ne

J^{π}	E_x	β_L
0^+	0.0	—
2^+	1.63	0.47
4^+	4.25	0.28
3^-	5.62	0.43
1^-	5.78	0.15
3^-	7.17	0.30
2^+	7.84	0.15
1^-	8.71	0.15
3^-	9.11	0.15
4^+(?)	9.31	0.15

Relatively good fits were obtained for the 7.84 MeV (2^+) state while the new 9.31 MeV state is best reproduced with an $L = 4$ curve and a deformation parameter of $\beta_2 = 0.15$. From our calculations we suggest a tentative assignment of 4^+ to this state which therefore could well be the missing member of the $K = 0^+$ band based on the 6.72 MeV (0^+) and the 7.43 MeV (2^+) states.

There is indeed now strong evidence that the 7.20 MeV (0^+), the 7.84 MeV (2^+), the 9.04 MeV (4^+) and the 12.16 MeV (6^+) states are members of the same rotational band [31], namely the $8p$–$4h$ or [220] quartet configuration. Indeed these states are strongly excited in the ^{12}C(^{12}C, α)^{20}Ne reactions [5] while the 6.72 MeV (0^+) and the 7.43 MeV (2^+) states are not seen in this reaction. It is puzzling, nevertheless, to point out that the 9.31 MeV state has been seen in an earlier ^{12}C(^{12}C, α)^{20}Ne experiment [26] while in all recent 2α transfer reactions no mention of this state is made. It has been suggested [5] that the third member of the $K = 0^+$ band based on the 6.72 MeV (0^+) and the 7.43 MeV (2^+) state could be the 4^+ state at 10.54 MeV. While the 6.72 MeV (0^+) and the 7.43 MeV (2^+) states are both fairly well excited in the ^{16}0(^{7}Li, t)^{20}Ne reaction, the excitation of the 10.54 MeV (4^+) state has not yet been reported [6] in this one α particle transfer reaction. The different rotational bands in ^{20}Ne are presented in Figure 12 where the excitation energy is shown versus $J(J + 1)$. While the situation seems clear for the $K = 0^+$ (g.s.) band as well as for the low-lying $K = 2^-$ and 0^- bands, this is not the case for the upper $K = 0^+$ bands. Therefore considerably more data and experiments are required to clarify the complicated band structure in ^{20}Ne. Finally the deformation parameters extracted for various states in ^{20}Ne are presented in Table III.

5. Summary and Conclusion

We have measured by inelastic scattering of 24.5 MeV protons the differential cross-sections for about twenty states in ^{20}Ne up to the 9.5 MeV (2^+) level. Considerable variation in the shapes of the cross-sections for states having the same spins and parities have been observed; this may be a reflection of the complicated band structure existing in the ^{20}Ne nucleus. Besides the states belonging to the $K = 0^+$ ground state band, the members of the $K = 2^-$ band based on the 4.97 MeV (2^-) state as well as the members of the $K = 0^-$ band based on the 5.78 MeV (1^-) state are very strongly excited. This appears quite surprising especially for the $K = 2^-$ band composed of several unnatural parity states.

The elastic scattering cross-section has been analyzed by the optical model and several sets of optical model parameters have been obtained which give good fit to the elastic cross-section.

The excited states were analyzed in the coupled-channels or DWBA formalism. The C.C. calculations give very good agreement with the cross-sections for members of the $K = 0^+$ ground state rotational band, using simultaneously quadrupole ($\beta_2 = 0.47$) and hexadecapole deformations ($\beta_4 = +0.28$). An improved fit to the 8.79 MeV (6^+) state has been observed when a negative β_6 deformation equal to -0.10 was added to the β_2 and β_4 deformations. The C.C. calculations give reasonably good fits to the cross-sections of states like the 9.11 MeV (3^-) which don't belong to a clearly defined rotational band. However, generally poor agreement between the C.C. calculations and the experimental cross-sections for the various 1^- states has been observed. The reason for this has still to be explained.

There is definite evidence for a new level in ^{20}Ne around 9.31 MeV (± 20 keV) which is best reproduced with an $L = 4$ transition curve. We therefore tentatively propose for this state the spin 4 and positive parity ($J^\pi = 4^+$). It is obvious, however, that more elaborate calculations as well as other types of experiments, like transfer reactions, will be required to confirm definitively the assignment made for this new state. Therefore the 9.31 MeV (4^+) could well be a member of the $K = 0^+$ band based on the 6.72 MeV (0^+) state, since the situation for this band is not yet clear. Besides, a very weak state is seen at some angles around 8.6 MeV which could be the 0^+ state postulated by Arima although no cross-section could be extracted for this state.

We would like to thank Dr. J. Raynal for using his coupled-channels code ECIS 71.

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