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EXCITATION OF 1^+ AND 2^- STATES IN THE NEON ISOTOPES*

A. WILLIS, M. MORLET, N. MARTY, C. DJALALI[1]

Institut de Physique Nucleaire, BP no 1 Orsay, France

G.M. CRAWLEY, A. GALONSKY, V. ROTBERG and B.A. BROWN

National Superconducting Cyclotron Laboratory
and
Department of Physics and Astronomy, Michigan State University, East Lansing MI 48824 USA

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Abstract: High resolution inelastic proton scattering is used to study the excitation of 1^+ states in ^{20}Ne and ^{22}Ne. By comparing these results with those from gamma-ray fluorescence measurements, the strong role of the orbital contribution in the electromagnetic transitions, predicted by the theory, is confirmed. Shell model predictions of the 1^+ strength are compared to the measured strength in ^{20}Ne and ^{22}Ne. The (p, p′) excitation of 2^- states in ^{20}Ne is compared to (π^-, γ) and (e, e′) results.

E | NUCLEAR REACTIONS ^{20,22}Ne(p, p′), $E = 201$ MeV; measured $\sigma(\theta)$ ^{20,22}Ne deduced levels, J, π. DWIA calculations.

1. Introduction

The strength of 1^+ transitions has been studied recently using a variety of different methods including electromagnetic interaction such as (e, e′) [ref. [1]] and (γ, γ') [ref. [2]] and strong interactions such as (p, n) [ref. [3]] and (p, p′) [ref. [4]]. The excitation of 1^+ states by the electromagnetic interaction involves both a spin and an orbital contribution whereas the hadronic interaction has only a spin part.

A common property of M1 excitations is that the measured strength is less than the predicted strength (the strength is said to be "quenched"). For hadronic processes, a fairly uniform quenching is observed for all the nuclei studied except ^{12}C, but in the electromagnetic case the quenching generally decreases with decreasing mass; nearly all the predicted strength is found for the sd-shell nuclei [2]. Different mechanisms have been proposed to explain the quenching: core polarization, configuration mixing and mesonic effects including Δ-hole excitation. This last effect acts mainly on the spin–isospin part of the interaction for $\Delta S = 1$, $\Delta T = 1$ transitions.

Good shell-model calculations are available for the sd-shell nuclei [5]). In order to test these models and to measure the quenching of the spin-flip, $\Delta L = 0$ transitions

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[1] Present address: NSCL, MSU East Lansing, MI 48824, USA.

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in light nuclei, we have measured the excitation of 1^+ states in ^{20}Ne and ^{22}Ne by high resolution proton inelastic scattering. The results are compared with measured B(M1) values and with theoretical predictions of both the (p, p') cross sections and B(M1) values.

Another motivation for the present study is that the shell model calculations predict that orbital and spin contributions to 1^+ excitations are about equal.[6,7]). This prediction has been confirmed at least for the strongly excited state at 11.25 MeV in ^{20}Ne by comparing the electromagnetic excitation of this state with the excitation of its analog in ^{20}F by the (π^-, γ) reaction [8]). For particular transitions a similar comparison between the excitation of the same transition by (p, p') and (e, e') or (γ, γ') allows a determination of the importance of the orbital contribution [9,10]). In ^{20}Ne, previous measurements [8]), have suggested a strong orbital contribution in the electromagnetic excitation of two known 2^- states. These same states are studied in the present experiment. The quenching for the 2^- strength is measured by comparison with shell model predictions.

2. Experimental methods

The experiment was carried out using the 201 MeV proton beam from the Orsay Synchrocyclotron. The experimental arrangement has already been described in an earlier publication [11]), except that in the present measurement gas targets were used. The gaseous targets were enriched to 99.95% for ^{20}Ne and to 99.98% for ^{22}Ne. Each gas cell consisted of a short aluminium cylinder (1 cm long) with the beam entering and leaving through windows which were 2.67 mg $\cdot$ cm^{-2} thick foils of Kapton. The typical pressure used was about 3.5 atmospheres and at this pressure the Kapton windows bowed making a total effective length of the cell of about 1.8 cm. Runs were taken at each angle under the same beam conditions on two identical cells, one filled with neon gas and the other filled with hydrogen gas at the same pressure, so that an accurate subtraction of the effect of the windows could be made. The target thickness was checked regularly by measuring elastic (p, p) scattering on the hydrogen target.

Measurements were made from 3° to 10° in 1° steps. The energy resolution became worse as the angle increased due to geometrical effects. The best resolution obtained at 3° was about 75 keV full width at half maximum.

Spectra taken at 3° on ^{20}Ne and ^{22}Ne are given in fig. 1 and fig. 2, together with the corresponding spectra obtained from the H target. Absolute normalization of the cross sections was obtained by comparison with the known (p, p) scattering cross section using a $(CH_2)_n$ target. The overall efficiency, including transmission of the spectrometer, efficiency of the wire chambers and of the electronics, was (93 ± 2)%.

In the off-line analysis, spectra measured on the H-filled target were subtracted channel by channel from each of the Ne spectra. Examples of these subtracted

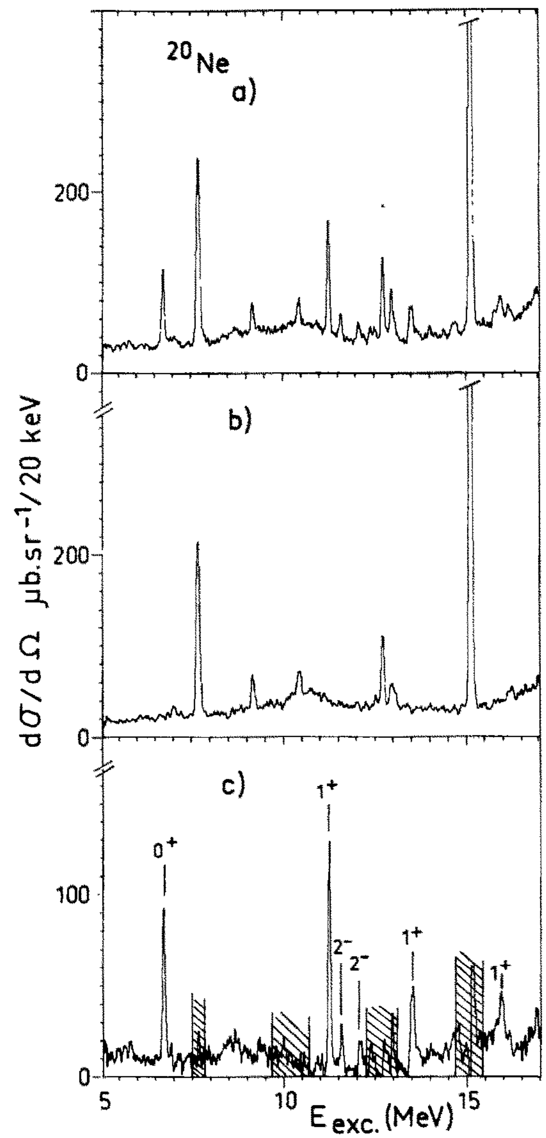

Fig. 1. Spectrum from (p, p′) at $\Theta_{lab} = 3°$ for ^{20}Ne. (a) Measured spectrum, (b) spectrum for H-filled target, (c) subtracted spectrum (see text).

spectra are given in figs. 1c and 2c, where the cross-hatched areas correspond to those portions of the spectra which are obscured by strong peaks from the carbon and oxygen in the windows. The peak due to elastic scattering on H appears only at angles greater than 8°. Spectra were analyzed with a fitting procedure; the strong peaks at 11.25 MeV in ^{20}Ne and 9.18 MeV in ^{22}Ne were taken as a reference peak shape at each angle. The energy calibration was deduced from known levels of ^{12}C

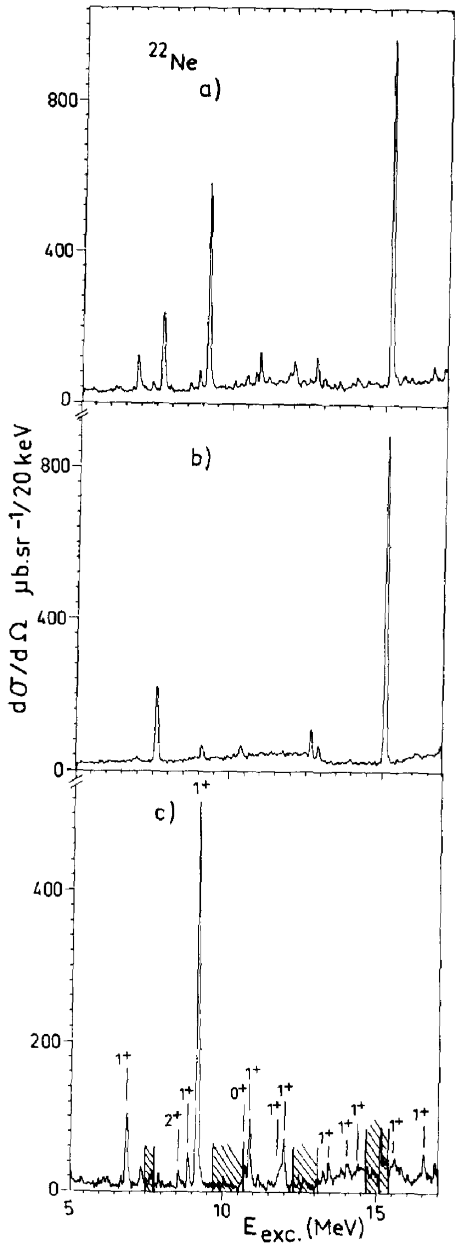

Fig. 2. Spectrum from (p, p′) at $\Theta_{lab} = 3°$ for ^{22}Ne. (a) Measured spectrum, (b) spectrum for H-filled target, (c) subtracted spectrum (see text).

contained in the windows, taking into account the kinematic shift. Due to the strong excitation of the 12.71 and 15.11 MeV states of ^{12}C, small peaks in Ne could have been missed in these energy regions, as well as around 10 MeV due to oyxgen peaks from the windows. Only states located below 17 MeV could be analyzed because above this energy, the continuum background increases so much that only strong individual 1^+ states could be identified.

3. Description of the models

The wave functions for ^{20}Ne and ^{22}Ne were obtained with the new empirical mass-dependent interaction of Wildenthal [5]). This interaction is based on a fit to 440 binding-energy and excitation-energy data over the region $A = 17$–39 with a resulting rms deviation between experiment and theory of 150 keV. The wave functions based on this interaction have been used to calculate the Gamow–Teller beta-decay matrix elements for essentially all beta unstable nuclei in the sd-shell [12]). The ratios of the experimental to theoretical matrix elements are systematically smaller than unity with an average value of 0.58 ± 0.05 for the middle of the sd-shell ($A = 28$). The experimental to theoretical ratio for an individual transition often deviates significantly from this average, especially for a weak transition, but the deviation is much smaller when one sums over all final states observed in the beta decay.

These wave functions have also been used to calculate essentially all M1 transitions and magnetic moments for the sd-shell nuclei [13,14]). The ratio of the experimental $\sigma \cdot \tau$ M1 strength to the theoretical strength is larger (0.7–1.0) than that observed for beta decay, and this is understood as a consequence of exchange currents which are small for GT but provide an enhancement for M1 transitions [13,15]). In first approximation the (p, p′) strength is expected to be quenched by the same amount as Gamow–Teller and therefore a ratio of experimental to theoretical strength of about 0.6 is expected.

The transition densities for the 2^- states were calculated from wave functions for the 0^+ and 2^- states based on the SGII Skyrme-type two-body interaction [16]). The model space for the 2^- state consisted of the complete space of $1\hbar\omega$ excitations of the type $(s)^4\,(p)^{11}\,(sd)^5$ and $(s)^4\,(p)^{12}\,(sd)^3\,(pf)^1$ which had a J–T dimension of 2299. The spurious states were removed by the method of Gloeckner and Lawson [17]).

4. Discussion

The energies and cross-sections measured at 4° for the 1^+ states in ^{20}Ne and ^{22}Ne are given in table 1 together with the energies and $B(M1)$ values extracted from the width reported in ref. [2]). There is good agreement between the energies of the states excited in both experiments. In the γ-fluorescence experiment, the threshold for (γ, particle) reaction limits the measurement to states whose excitation energies are below 13 MeV in ^{20}Ne and 11 MeV in ^{22}Ne.

TABLE 1

Energies in MeV and cross sections in μb/sr measured at 4° in the present experiment compared to energies and $B(M1)$ values in μ_N^2 from ref. [2])

	(p, p′)		(γ, γ′)	
	E_{exp} (MeV)	$(d\sigma/d\Omega)_{exp}$ (μb/sr)	E_{exp} (MeV)	$B(M1)$ exp (μ_N^2)
^{20}Ne	11.25±0.01	445±31 A	11.262±0.002	2.02±0.36
	13.51±0.03	226±23 A		
	15.72±0.05	129±20 B		
^{22}Ne			5.326±0.001	0.43±0.17
	6.86±0.01	381±32 A	6.853±0.002	1.36±0.56
	8.89±0.01	197±20 B		
	9.18±0.01	1863±117 A	9.178±0.003	1.80±0.07
	10.89±0.01	266±26 A		
	11.87±0.05	101±19 A		
	12.00±0.01	224±27 A		
	13.46±0.01	90±23 B		
	13.89±0.02	77±20 B		
	14.06±0.02	95±18 B		
	(14.45±0.03	90±25)		
	15.58±0.04	185±36 B		
	16.51±0.01	132±25 B		

The letter A indicates that the state is almost certainly a 1^+ state. The states labelled B are not firmly established as 1^+ states.

Experimental angular distributions for some representative states in both ^{20}Ne and ^{22}Ne are shown in fig. 3. Cross sections were calculated for all 1^+ states with the DWIA code RESEDA [18]) using the wave functions described in sect. 3. The optical potential used was taken from the elastic scattering data on ^{27}Al at 156 MeV [ref. [19])]. The calculated angular distributions are compared with the experimental 1^+ angular distributions in fig. 3. The agreement in shape is very good. The absolute values of the experimental (p, p′) cross sections measured at 4° are compared with the theoretical predictions for all 1^+ states in fig. 4a. A similar comparison of measured $B(M1)$ values with those predicted by the same model is also shown in the same figure.

In ^{20}Ne a strong state is predicted at 11.19 MeV in excellent agreement with experiment; the predicted $B(M1)$ value (1.96 μ_N^2) is mainly due to orbital excitation. Using the method described in an earlier publication [9]), the value of the spin contribution to the electromagnetic transition probability ($B(\sigma)$) was extracted from the (p, p′) measurements. This value of 0.49±0.06 μ_N^2 agrees well with the value for $B(\sigma)$ of 0.37 μ_N^2 predicted by the model and is much smaller than the $B(M1)$ value. For this state, the theoretical $B(\sigma)$ is plotted in fig. 4a. Weak states predicted at 12.23 MeV and 15.03 MeV were not observed but could have been obscured in the present experiment by strong peaks from ^{12}C. For the two remaining states predicted

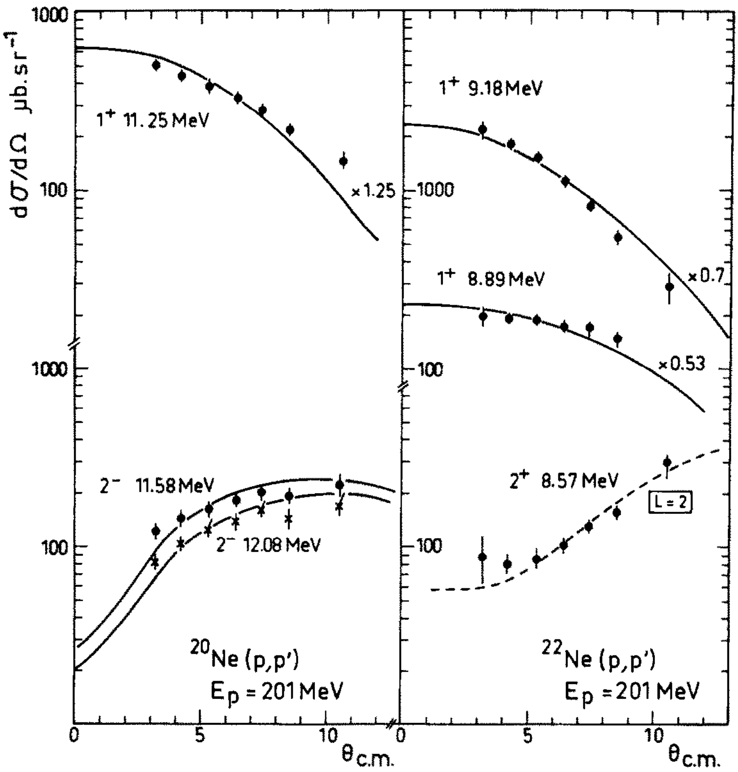

Fig. 3. Angular distributions for some characteristic states in ^{20}Ne and ^{22}Ne.

at 13.48 MeV and 15.72 MeV, the agreement between measured and calculated (p, p′) cross sections is also excellent. The 13.48 MeV state is predicted to have a small $B(M1)$ value and has not been detected in a recent (e, e′) experiment [20].

The ratio of the experimental cross sections summed over the three 1^+ states listed in table 1, to the calculated cross sections summed over the theoretical states predicted at 11.20, 13.50 and 15.86 MeV is 1.0 ± 0.1. Thus over the energy range considered, no quenching is observed in ^{20}Ne. However there is substantial 1^+ strength predicted at 17.27 MeV with an expected (p, p′) cross section of 353 μb/sr at 4° but with a small $B(M1)$ value (0.0037 μ_N^2). No 1^+ state is known from the (e, e′) experiment in this energy region [20]. In the present experiment a state is seen near 17 MeV, with an upper limit of 70 μb/sr at 4°, but its angular distribution is not compatible with a 1^+ assignment. If the state predicted at 17.27 MeV is included in the theoretical sum, the ratio of experiment to theory is reduced to 0.7.

For ^{22}Ne, as seen in fig. 4b, the agreement between measured and predicted strengths for both (p, p′) and (γ, γ') is quite good. For example the state at 9.178 MeV with a measured $B(M1)$ of 1.80 μ_N^2, is also strongly excited in (p, p′) scattering (see table 1), implying that this transition is dominated by a spin excitation as predicted

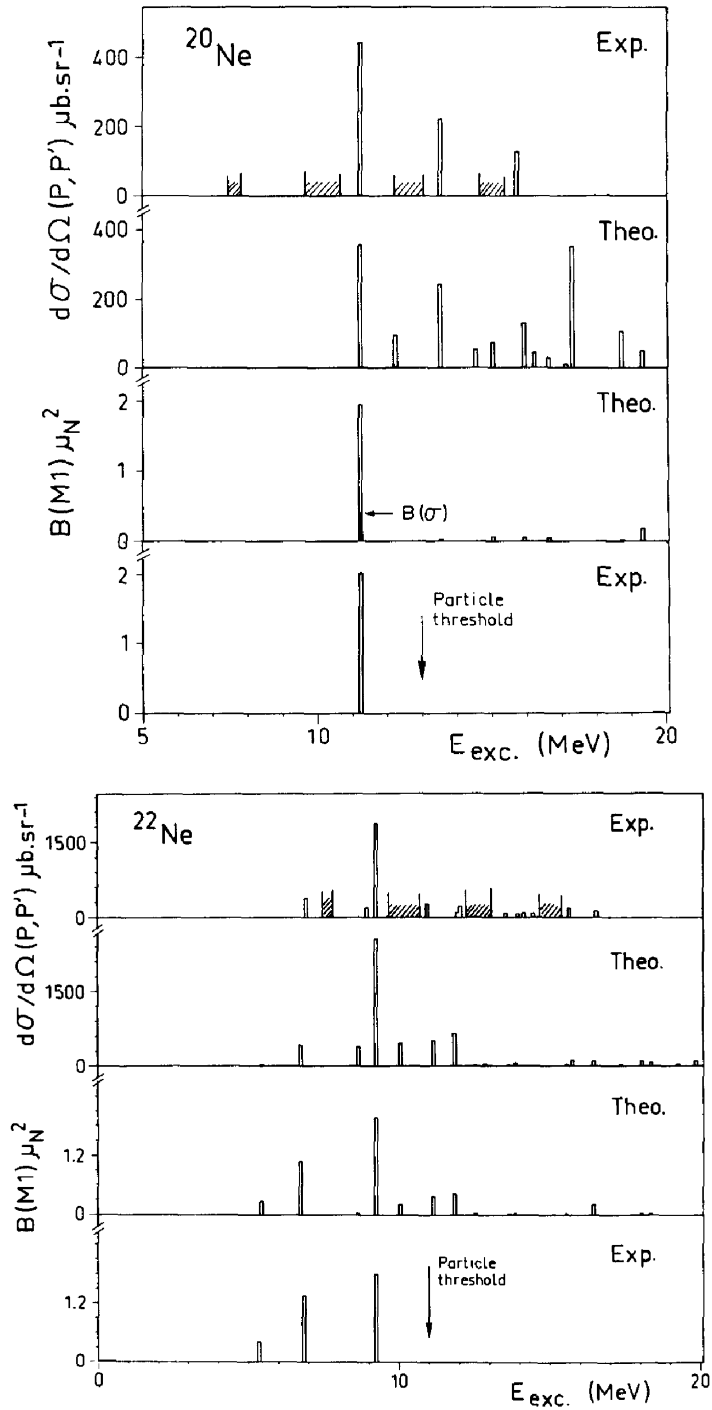

Fig. 4. Comparison between experimental and theoretical values for $B(M1)$ and (p, p′) cross sections at 4°. (a) For ^{20}Ne, (b) for ^{22}Ne.

by the model. The state reported [2] at 8.56 MeV in ^{22}Ne as 1^+ or 2^+, has a (p, p′) angular distribution compatible with a 2^+ assignment (see fig. 3). The two 1^+ states predicted at 5.436 and 6.662 MeV are mainly excited by an orbital interaction with constructive interference between orbital and spin terms; they are strongly excited in (γ, γ') with an experimental B(M1) exceeding the theoretical prediction. In the present experiment the level predicted at 5.436 MeV is too close to the edge of the detectors to be analyzed with confidence; the state seen at 6.86 MeV is more weakly excited relative to the strong state at 9.18 MeV in (p, p′) than in (γ, γ') as predicted by the model. The experimental angular distribution of the isovector 1^+ state at 9.178 MeV decreases more rapidly than predicted; the same effect was observed in ^{28}Si [ref. [21]] indicating that these states are not perfectly described by the model. Another state is observed at 8.89 MeV, with an angular distribution characteristic of an isoscalar M1 transition (see fig. 3). It can be associated with the mainly isoscalar 1^+ state predicted at 8.856 MeV by the model. However the theoretical cross section is too large by a factor of two. In ^{28}Si it has also been observed that the same kind of model overpredicts the strength of the isoscalar 1^+ transitions. A systematic study of the quenching of the 1^+ strength for the sd-shell nuclei ($^{20\text{-}22}$Ne, $^{24\text{-}26}$Mg, ^{28}Si, ^{32}S) will be given elsewhere.

For the states at energies above 10 MeV the interference between orbital and spin interactions is generally destructive; some of them are excited in (p, p′) scattering but with a smaller intensity than predicted. On the other hand many possible 1^+ states, not all given by the model, have been detected between 13.5 and 16.6 MeV. The ratio of the experimental to predicted cross sections summed over all the states between 6 and 17 MeV is 0.73 ± 0.07. The state predicted at 10.015 MeV has been excluded from the theoretical sum since it falls in a zone in the detectors which is obscured by oxygen peaks from the windows of the gas cell. For ^{22}Ne no substantial 1^+ strength is predicted above 17 MeV.

In addition to the 1^+ states discussed above, there are also a few cases where other spin-flip excitations are observed. For example two known 2^- states are excited by the (e, e′) reaction in ^{20}Ne at 11.62 MeV and 12.10 MeV. A large orbital contribution has been suggested [20] for these states since the ratio of the excitation of the states in (e, e′) is quite different from the ratio of the cross sections for exciting their analogues in ^{20}F at 1.30 MeV and 1.84 MeV by radiative capture of π^- particles. Specifically the ratio of cross sections in the (π^-, γ) reaction for the 1.30 MeV compared to the 1.84 MeV state is 0.64 ± 0.24. In the (e, e′) reaction the ratio of the (e, e′) form factors, measured in a range of momentum transfer (0.5–2.5 fm^{-1}) close to where the (π^-, γ) reaction was measured, is 1.84 ± 0.34. This ratio is very different from the ratio observed in (π^-, γ) and therefore suggests that the orbital contribution is significant [20].

On the other hand, the same levels have been observed at 11.58 and 12.08 MeV in our (p, p′) measurements which are also sensitive only to the spin component. Their angular distributions measured in the momentum range 0.19 to 0.46 fm^{-1}, are very similar (fig. 3). The ratio of the cross sections for the 11.58 MeV to 12.08 MeV states is 1.4 ± 0.3 which is reasonably consistent with the values obtained in (e, e′) and much larger than the ratio obtained in the (π^-, γ) experiment. This implies that there is no need to assume large and different orbital contributions for the two M2 transitions. The energy resolution in the present experiment allows a perfect separation of the two 2^- states; this was not the case in the (π^-, γ) experiment.

The model for ^{20}Ne predicts three significant 2^- states at 15.53, 15.83 and 17.89 MeV with B(M2) values of 128.5, 63.6 and 48.7 $\mu_N^2\,\mathrm{fm}^2$ respectively. The calculated (p, p′) angular distributions agree in shape with the experimental ones (see fig. 3). In table 2 are given the predicted and experimental data for these 2^- states. The ratio of the measured (p, p′) cross sections agrees with the theoretical one if the 11.58 and 12.08 MeV states are compared with the predicted levels at 15.53 and 15.83 MeV. However the total strength is overpredicted by a factor of two and the ratio of the measured B(M2) values for these two states does not agree with that predicted.

TABLE 2

Comparison between theory and experiments for the M2 states in ^{20}Ne

Theory				Exp.			
E_{exc} (MeV)	B(M2) ($\mu_N^2\,\mathrm{fm}^2$)	$B(\sigma)$ ($\mu_N^2\,\mathrm{fm}^2$)	$d\sigma/d\Omega$ (μb/sr)	E_{exc}(e, e′) (MeV)[a]	E_{exc}(p, p′) (MeV)[b]	B(M2) ($\mu_N^2\,\mathrm{fm}^2$)	$d\sigma/d\Omega$ (μb/sr)
15.53	128.5	125.4	308	11.62	11.58	64 ± 13	146 ± 15
15.83	63.6	96.27	239	12.10	12.08	56 ± 13	104 ± 12
17.89	48.7	27.62	64.3				

[a]) Ref. [20]).
[b]) This work. Cross sections in μb/sr measured at 4°.

In the case of M2 transitions a $B(\sigma)$ value cannot be extracted from the (p, p′) results by the same method as the one used for M1 transitions. In this latter case only the $\Delta L = 0$ component contributes at small momentum transfers where the matrix element can then be factorized.

In ^{22}Ne, consistent with the (e, e′) results [20]), no measurable 2^- strength is observed in (p, p′) up to an excitation energy of 17 MeV.

5. Conclusions

In conclusion, the comparison between (p, p′) and (γ, γ') excitation of 1^+ states in ^{20}Ne and ^{22}Ne confirms the important role of the orbital interaction which interferes constructively or destructively with the spin interaction in electromagnetic excitations. This comparison gives a good test of the model for these nuclei.

The description is excellent for ^{20}Ne for excitation energies below 17 MeV. All observed 1^+ levels correspond to isovector transitions. If one compares the experimental cross sections with the theoretical calculations for only the three levels whose energies agree with those predicted, then no quenching is observed for the 1^+ strength. This is consistent with the ^{20}Ne(γ, γ') experiment where no quenching is observed for the excitation of the strong 1^+ state at 11.26 MeV. However, substantial 1^+ strength is predicted by the model at 17.27 MeV, which is not observed in the present experiment. If this strength is included in the theoretical prediction then the ratio of experiment to theory is reduced to 0.7.

In ^{22}Ne the measured 1^+ strength is more fragmented than is predicted. In contrast to the ^{20}Ne case, isoscalar contributions are predicted to be significant and the experimental angular distribution matches the predictions for the isoscalar case.

Two known 2^- states are clearly excited in ^{20}Ne. By comparison with (e, e′) results, one finds no need to invoke an important orbital contribution for the electromagnetic excitation of these 2^- states.

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