Proton Inelastic Scattering to Dipole States of ^{12}C and Isovector Collective Models

M. Buenerd, P. de Saintignon, P. Martin, and J. M. Loiseaux
Institut des Sciences Nucléaires, 38044 Grenoble-Cedex, Grenoble, France
(Received 8 August 1974)

The dipole strength has been measured in ^{12}C between 22- and 27-MeV excitation energy by inelastic scattering of 45- and 155-MeV protons. The dipole cross section is compared to the results of isovector-collective-model, distorted-wave Born-approximation calculations and to photonuclear experimental results.

Multipole giant resonances in the nuclear continuum, excited via inelastic scattering of electrons and hadrons, are now eliciting more and more interest among both experimentalists and theoreticians. A survey of this topic has recently been made.[1] Isovector collective models describing the excitation of the giant dipole resonance (GDR) have been derived by Satchler,[2] but the lack of reliable data has restrained a useful check of their reliability. The aim of this paper is to present new experimental data and comparison with calculations performed in the framework of those models. The fine structure of the GDR in ^{12}C has been investigated by inelastic scattering of 45- and 155-MeV protons. This study also provided an evaluation of the isovector strength of the optical potential for 155-MeV protons.

The 155-MeV experiment was performed at the Orsay Institut de Physique Nucléaire. The experimental setup has been described elsewhere.[3] The target consisted of a 35-mg/cm^2 sheet of graphite. Spectra were recorded up to about 35-MeV excitation energy from 9° to 70°. The resolution was 150 to 200 keV, depending on the angle (Fig. 1). The 45-MeV proton beam of the Grenoble Institut des Sciences Nucléaires was used in the second experiment. The target was a 3-mg/cm^2-thick sheet of natural graphite. Outgoing particles were detected in a ΔE-E silicon-counter telescope (600 μm, 10 mm). Protons were selected with a Goulding-type particle identifier. Spectra were obtained up to about 30-MeV excitation energy at angles from 7.5° to 170°. Overall resolution was about 150 keV (essentially due to kinematical effects and target thickness).

In both experiments, kinematical shifts versus angle were carefully checked. Contaminant peaks originating from ^{16}O, ^1H, and ^{13}C were easily identified and separated out. No contaminant bump was observed in the upper part of the spectra, but around 29–30 MeV at forward angles in the 45-MeV experiment. The calibration of each 45-MeV spectrum provided fairly precise excitation energies up to 27 MeV, whereas, beyond 18-MeV excitation energy, the same accuracy could not be achieved in the 155-MeV experiment for experimental conditions. However, unambiguous correspondence could be made between a few peaks of that region in both experiments, located at 18.35 ± 0.05, 23.50 ± 0.05, and 23.92 ± 0.08 MeV, which were used to calibrate the 155-MeV spec-

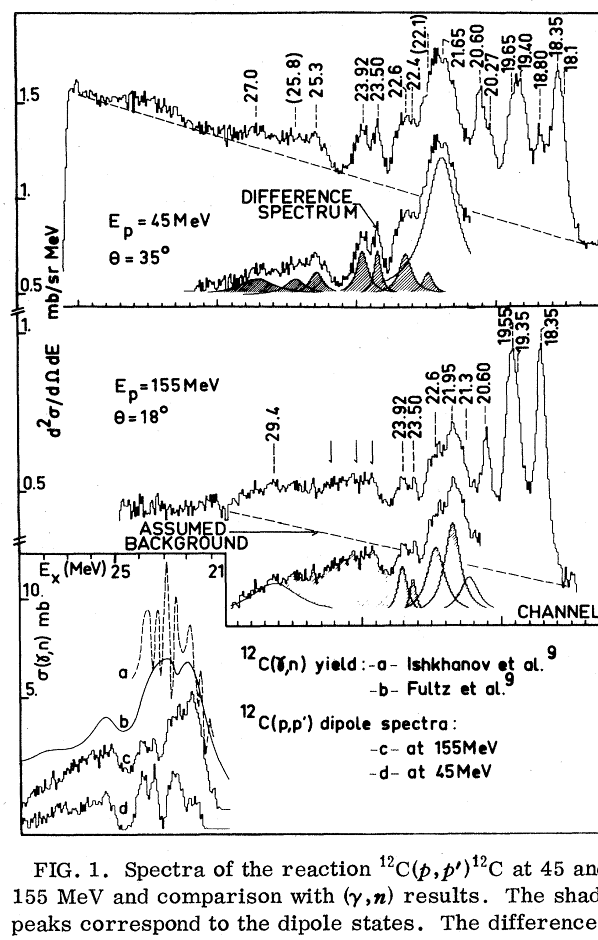

FIG. 1. Spectra of the reaction $^{12}C(p,p')^{12}C$ at 45 and 155 MeV and comparison with (γ,n) results. The shaded peaks correspond to the dipole states. The difference spectra have been shifted slightly upwards. Since the 155-MeV spectra are linear versus momentum, the vertical scale is only approximate. It is exact at 23-MeV excitation energy.

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The region of interest is limited to 20–30-MeV excitation energy, corresponding to photonuclear dipole cross-section measurements.[4] This paper is therefore concerned only with this region and the derivation of the total dipole strength. For that purpose, the L value of each state has to be determined. The many possible sources of background $[(p,pn),\ (p,2p),\ (p,p\alpha),\ \ldots]$, for which quantitative information is not available, make the extraction of the data points rather difficult.[5] Therefore the simplest assumption has been made using points below and above the region of interest in the spectra where no peaks were ever observed at any angle (about 17- and 30-MeV excitation energy). The shape of the background was chosen to be linear and its slope and magnitude smoothly varying with the angle. At 155 MeV this procedure may lead to overestimated cross sections. The difference spectra were decomposed into single peaks assuming Breit-Wigner shapes (Fig. 1). Error bars on the data points are mostly due to the uncertainties in the background and the width of the peaks. Estimating the shape and magnitude of the background on a different basis could change the magnitude of the total dipole angular distribution by a factor as large as 1.5–2. The dipole character of the states was established after comparing the shapes of experimental and calculated angular distributions (Fig. 2). Such a comparison is actually relevant since the main features of angular distributions are determined by the L transfer involved in the reaction. Despite the little difference between the calculated curves for $L=1$ and $L=2$, the 45-MeV data were definitely best reproduced with $L=1$. The latter is, in fact, corroborated by the unambiguous $L=1$ assignment at 155 MeV. Identified dipole states and widths are listed in Table I. The total dipole cross section was derived by integrating the dipole region as a whole in each spectrum, after subtraction of the contribution of the levels not identified as $L=1$. The resulting angular distributions are shown in Fig. 2.

The deduced dipole spectra in both experiments are very similar beyond 23-MeV excitation energy (Fig. 1). Whereas levels are rather well determined in the 45-MeV experiment at 25.3, (25.8), and 27.0 MeV, they are not so clearly seen in the 155-MeV experiment. However, angular distributions of 1-MeV bins centered around these energies are compatible with an $E1$ assignment. The angular distribution of the broad bump

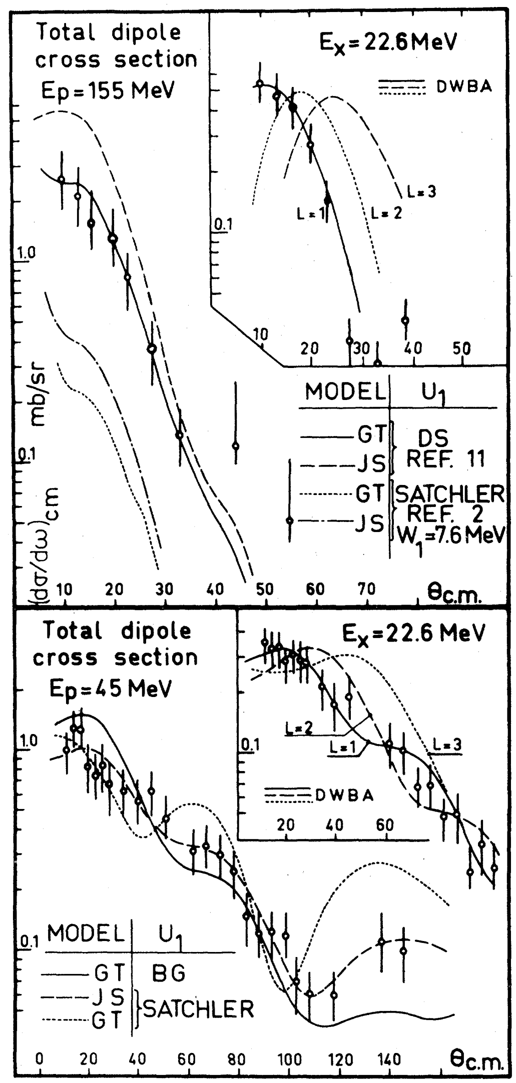

FIG. 2. Experimental angular distributions and results of the distorted-wave Born-approximation (DWBA) predictions with isovector models. Radius and diffuseness parameters in the form factor are the same as in the incoming channel. As illustrated on the right-hand side of the figure, the $L=1$ character of the single levels is determined by comparison of the data with DWBA calculations. At 155 MeV the curves represent 100% of the sum rule. The 45-MeV curves were fitted to the data points. Percentages of the sum rule are given in Table II. Symbols are defined in the text.

($\Gamma \sim 2$ MeV) observed at 29.4 ± 0.3 MeV is poorly reproduced with $L=1$ calculations. Around 22 MeV, the identification of $L=1$ states and the derivation of their cross sections is made rather difficult because of the presence of higher multipolarity states. At 155 MeV, two levels only could be identified at 21.3 MeV ($L \geq 3$) and 21.95 MeV for which the $L=1$ assignment is unambigu-

TABLE I. Dipole states observed in ^{12}C nucleus in the present experiments and comparison with (γ,n) results.

45 MeV Excitation energy E_x (MeV)	Width (keV)	155 MeV Excitation energy E_x (MeV)	Width (keV)	E_x from (γ,n) experiments[a] Firk *et al.*	Fultz *et al.*	Ishkhanov *et al.*
(22.1)	(600 ± 300)	21.95 ± 0.15	800 ± 100	22.0	22.1	21.95
22.6 ± 0.1	650 ± 200	22.6 ± 0.15	900 ± 100	22.8		22.5
					23.0	23.0
23.50 ± 0.05	230 ± 80	23.50	230	23.5		23.3
23.92 ± 0.08	400 ± 100	23.92	400		24.0	23.7
				24.8		
25.3 ± 0.15	510 ± 100			25.4	25.5	
(25.8 ± 0.3)	(750 ± 150)			25.8		
27.0 ± 0.2	1400 ± 200			27.5		

[a]Ref. 9.

ous. At 45 MeV, the 22.4-MeV peak is seen only at backward angles ($\theta \geq 80°$) and does not show an $L=1$ character. The 21.65-MeV peak, also observed in (e,e') experiments,[6] shows an $L=3$ angular distribution with a high cross section.[7] It was checked that a small difference on the parameters of this peak could increase the cross section of the (22.1)-MeV peak by a factor of 2, with the overall fit being still satisfactory. This lack of accuracy could explain the large discrepancy between the two dipole spectra. Although this discrepancy seems to be genuine, assuming the same relative strength in that part of the dipole spectra at 45 and 155 MeV would increase the total dipole cross section at 45 MeV by less than 25%. As will be seen further below, this increase would not affect the results of the comparison with the model.

The GDR region has been studied in great detail through photonuclear reactions.[8] Three representative sets of data[9] have been picked out to be compared with the present work. The energies of the levels identified in this experiment are in good agreement with the fine structure observed in (γ,n) reactions (Table I). The general pattern of the 155-MeV (p,p') spectra is quite similar to those observed in photonuclear reactions (Fig. 1). The comparison is not so satisfactory at 45 MeV, although the results of Ishkhanov *et al.* are not all that different.[9]

An α-particle scattering experiment was undertaken at 60 MeV in order to investigate this excitation energy region.[7] No peaks were observed except for a weak bump at about 25–26 MeV. This supports the $T=1$ assumption for the dipole states observed in the (p,p') reaction.

The total GDR cross section has been compared to isovector-collective-model calculations. The two models derived by Satchler[2] are constructed by folding in the isovector nucleon-nucleon interaction and a nuclear vibrating density, assuming either a harmonic Goldhaber-Teller (GT) or a hydrodynamic Jensen-Steinwedel (JS) vibration. The $\Delta T=1$, $\Delta L=1$ transition operators derived in these models are related to the isovector strength $U_1(r)$ of the optical potential. As usual U_1 includes a real volume part V_1, and imaginary volume W_1 and surface W_{D1} parts. In this formalism, the coupling strength is proportional to $\partial U_1(r)/\partial r$ (GT vibration) or to $rU_1(r)$ (JS vibration).

The calculations were carried out using the code DWUCK as modified by Rost[10] to include more sophisticated form factors. Coulomb contributions were included. They interfere constructively with nuclear amplitudes.[11]

In the 45-MeV analysis, the optical-model parameters of incoming and outgoing protons are taken from the works of Kolata and Galonsky[12] and Lowe and Watson,[13] respectively. Two types of isovector strength have been tried in the form factor. The first one is taken from the global potential of Becchetti and Greenlees (BG).[14] The second one is that derived by Satchler,[2] from (p,n) data. As seen in Table II, the results of the GT calculations are in fairly good agreement with those of the photonulcear reactions.[4] Although the JS model reproduces very nicely the shape of the experimental angular distribution (Fig. 2), the calculated cross section is too large by a factor of about 3.

Several sets of parameters have been tried in the 155-MeV analysis. The best overall agreement was obtained with those of Comparat *et al.*[16]

TABLE II. Percentage of the sum rule as the ratio of experimental cross sections to the results of DWBA calculations, assuming a single vibration lying at 24-MeV excitation energy and a mean square radius $\langle r^2 \rangle = 5.76\ \mathrm{fm}^2$ (Ref. 15).

References	V_1 (MeV)	W_{D1} (MeV)	% sum rule GT	JS
BG[a]	24	12	50	15
Satchler[b]	10	15.5	80	15
$(\gamma,n)+(\gamma,p)$ [c]			51	
γ absorption[c]			63 to 78	

[a]Ref. 14. [b]Ref. 2. [c]Ref. 4.

The same parameters were used in the incoming and outgoing channels. As for the form factor there is no available value of the U_1 strength derived from experimental data. Applying the estimate use by Satchler[2] ($V_1 = 0$, $W_1 = 0.3W_0$) gives a cross section too small by a factor of 4 to 10, depending on the model, whereas the value of U_1 taken from the work of Dabrowski and Sobiczewski[17] ($V_1 = 5$ MeV, $W_1 = 25$ MeV) turned out to give a reasonable agreement with the data (Fig. 2).

It was shown that the largest uncertainty on the data comes from the assumptions on the underlying background. Within those limits the analysis of these data leads to the two conclusions that the GT model for isovector dipole excitations can provide a fair estimate of the GDR cross section when the isovector strength is known and that the U_1 strength of Dabrowski and Sobiczewski is satisfactory for medium energies.

It is a pleasure to thank A. Garin and C. Chianelli from Saclay for providing us with a 10-mm silicon detector. We are also indebted to V. Comparat, R. Frascaria, N. Marty, M. Morlet, and A. Willis for assistance during the experiment in Orsay.

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