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(π^-, ^{12}C) INELASTIC BACKWARD SCATTERING.

1. - INTRODUCTION -

There has been very little study of inelastic scattering of pions, with target nuclei left in specific excited states. The energy resolution required for such experiments has only recently become available.

One exception has been the study of the low-lying states in ^{12}C, which are separated by several MeV(1). The three lowest excited states of ^{12}C have all T = 0 isospin:

$$J = 2^+ \text{ at } 4.43 \text{ MeV}$$

$$J = 0^+ \text{ at } 7.66 \text{ MeV}$$

$$J = 3^- \text{ at } 9.63 \text{ MeV}$$

Six other T = 0 states start at about 10 MeV: they are particularly broad and their relative separations are a few hundreds KeV. A group of levels with T = 1 starts around 15. MeV.

Kane(2) measured elastic and inelastic differential cross sections for incident positive pions of 31.5 MeV. He tried to separate the

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combined contribution of the 4.43 and 7.66 MeV levels, and that of the 9.63 MeV level, but his energy resolution was so poor as to make these separations somewhat doubtful. Baker et al.(3) performed similar measurements with negative pions at 80 MeV. Edelstein et al.(4) extended the investigation to 69.5 and 87.5 MeV, with improved energy resolution.

In these experiments, the angular distribution up to 130° of pions which lost about 5 MeV and 10 MeV (presumably exciting the 4.43 and both 7.66 and 9.63 MeV levels, respectively) and about 15 MeV, were measured separately. All the angular distributions, at these energies, increase at backward angles: at 87.5 MeV, for instance, the 4.43 MeV inelastic cross section is going from 0.5 mb/sr at 65° to 4 mb/sr at 130°.

Binon et al.(5) have measured at CERN, with a double achromatic spectrometer, the elastic and inelastic scattering of negative pions on carbon in the region of the first (3/2, 3/2) pion-nucleus resonance ($120 \lesssim T \lesssim 280$ MeV). Their over-all momentum resolution at the final hodoscope of scintillation counters was $\Delta p/p \simeq 0.5$ to 1%; quite sufficient to separate clearly the 4.43 MeV level, the group of levels around 10 MeV and the group of levels starting at 15 MeV. The analyzer of the energy loss spectrometer could rotate up to an angle of about 140°. The angular distributions of the excitation of the 4.4, 9.6 and 15 MeV levels show considerable structure from 30° to 140°. The 4.4 level shows minima at $\sim 70°$ and 110°, the 9.6 group has one minimum at $\sim 75°$, the 15.1 group, measured only between 200 and 280 MeV, reaches also a further minimum at 110°. The separation of the 7.66 MeV level from the 9.63 MeV level was at the limits of resolution of the apparatus: it could be measured at only very few angles and for the lowest energies. All differential cross sections are dropping by 10^{-1} from 40° to 140° at 150 MeV and by 10^{-2} at 200 MeV.

As a conclusion, from an experimental point of view, in the investigation of inelastic scattering of pions, knowledge has been gained up to now only in the energy region where the probabilities of exciting nuclear levels are strongly dominated by a resonance.

At intermediate energies ($40 \div 120$ MeV) the status of the art is rather poor: the available experimental data are few and with unsatisfactory energy resolution; moreover, large angle and backward scattering data are completely lacking.

From a theoretical point of view, since the pion nucleus elastic scattering is reasonably well described by an optical model (for instance, in terms of a Kisslinger type potential(6)), it seems that a multi-channel extension of the model should equally reproduce the inelastic scattering, at least from the lowest excited states. The most serious problem lies in the choice of the pion-nucleus interaction, since it is not uniquely determined by the pion nucleon t-matrix on the energy shell. Wilkin(7) and Fäldt(8) have independently proposed a pion-nucleus optical potential which on the energy-shell becomes identical to the Kisslinger one. Nishiyama and Ohtsubo(9), with a simple reaction mechanism, i.e. the plane wave impulse approximation (PWIA), examined the inelastic scattering of pions from ^{12}C and found a qualitative agreement between the theory and the experiment. Lee and Mc Manus(10) investigated the excitation of the low-lying levels 2^+ and 3^- of ^{12}C in the distorted wave impulse (Born) approximation (DWIA). They adopted the particle-hole model of Gillet and Vinh-Mau(11) for the nuclear form factors with the diffraction approximation approach (sometimes referred to as the WKB-Glauber or eikonal approximation(12)) for the reaction mechanism. Edward and Rost(13) calculated (π^-, ^{12}C) inelastic scattering in the DWBA adopting a macroscopic nuclear model, in which the 2^+ and 3^-levels were treated as pure rotational states; the distorted waves were calculated using the version of Auerbach et al.(14) of the Kisslinger optical potential. Nishiyama and Ohtsubo(15) extended the investigation of the excitation of the lowest levels of ^{12}C up to the group of levels around 15 MeV in the DWIA. The transition nuclear form factors were calculated by adopting the wave functions of Gillet and Vinh Mau under Tam-Dancoff approximation (TD) and the random phase approximation (RPA) in the particle-hole model(11). The distorted pion waves are assumed to be determined by the modified Kisslinger optical potential of Ericson and Ericson(16), which is taken so as to give a good fit to the experimental data on differential cross sections for elastic scattering. All the results of these authors have been compared with the elastic and inelastic data of Binon et al(5), in the pion energy range $120 \div 280$ MeV. The conclusions are that, although the qualitative features of inelastic scattering cross section can be explained by a simple plane wave impulse approximation, as was shown in ref.(9), the absolute values and the angular distributions of the cross sections depend upon the initial and final state interactions of the pion and the DWIA gives a good fit to experimental data for excitation of levels with $T = 0$. The wide angle data, however, (where they exist) sometimes exceed the predicted cross sections by as much as an order of magnitude. As far as the $T = 1$ levels around 15 MeV (1^+, 15.1 MeV; 2^+, 16.1 MeV; 2^-, 16.6 MeV; 1^-, 18.1 MeV) are concerned, the angular distributions of the sum of the single cross sections seem to fit the experimental data, but the absolute values are smaller than those of experimental data by an order of magnitude. Here it should be noticed that the data of Binon et al. involve also excitation of the levels with $T = 0$ lying around $15 \sim 18$ MeV and that the interactions of pion and nucleon without isospin-flip are stronger than those with isospin-flip. By this way, levels such as the 14.1 MeV (4^+, $T = 0$) and the 18.3 MeV (3^-, $T = 0$) may be strongly excited. With the contribution of these two levels, the agreement of the Nishijma and Ohtsubo re sults with the experiment is almost fair except, again, for large angle scattering, where the cross section depends upon the distortion of the pion wave. This quantitative failure of the models at large angles (when experimental data are available), appears in the elastic fit as well, both in (3, 3) energy region (Nishijma and Ohtsubo(15), Lee and McManus(10), Krell and Barmo(17), Sternheim and Auerbach(18), Kisslinger and Tabakin(19)) and at intermediate energies (Auerbach et al.(14), Silbar and Sternheim(20)). More sophisticated optical models such as the "effective radius" and the "matter radius" ones(20) don't either show a better behaviour.

In this point of view, inelastic (and elastic) large angle pion-nucleus scattering can provide essential informations on pion-nucleus reaction mechanism. Moreover, it has been pointed out by Wilkin(21) that for excitation of nuclear levels involving magnetic transitions, such as the excitation of the 15.1 MeV ($T = 1$, $J^P = 1^+$) level in ^{12}C, pion scattering should in principle allow for a separation of the orbital and spin contributions. This is not possible in electron scattering.

In this paper we report backward differential inelastic cross sections corresponding to excitation by negative pions of the individual nuclear levels or groups of levels of ^{12}C at 4.43 MeV, 7.66 MeV, 9.63 MeV, 15 MeV. For energy losses above 15 MeV, we report differential cross sections corresponding to a nuclear excitation, for energy losses between 20 MeV and 35 MeV about, that can be identified in the electric-dipole giant resonance. In the lower tail of this region a contribution to the cross section is kinematically consistent with backward scattering of pions upon quasi-free α-clusters (in the three α-particle model of ^{12}C): the corresponding differential cross sections are reported.

2. - EXPERIMENTAL APPARATUS -

Inelastic cross sections were measured, together with the elastic ones, in the experiment described in ref. (22). The experimental apparatus, reported in detail in ref. (23, 24), consists in a magnetic spectrometer with a streamer chamber for identifying scattering events, by detecting both the incident and scattered pion tracks. A hodoscope of thin scintillation counters defines the number of pions deflected by the magnet and impinging on the experimental target of carbon of measured density. Pions scattered in the backward direction by the target are deflected with an opposite curvature by the magnetic field and are detected by scintillation counters in coincidence with the hodoscope. The coincidence triggers the high voltage pulse on the streamer chamber and the command circuits of the two cameras, whose axes are parallel to the magnetic field.

The nominal π^- beam central energy was 88 MeV, corresponding to 77.5 MeV at the target position. Typical beam intensities were about $5 \cdot 10^4$ pions per second, corresponding to about 10^2 π^-/sec on target, and to about 0.05/sec streamer chamber triggers (events + background). The pion dose has been corrected for the counters efficiences(> 90%) and for contamination of the pion beam due to e^- and to decay μ^-. The e^- contamination has been measured by a CO_2 gas Cerenkov counter and resulted to be about 2%. The μ^- contamination has been measured by means of integral and differential range techniques and was found of the order of 8%.

2.1. - Resolution of the apparatus. -

The resolution of the apparatus is a function of a number of parameters: the tracks lenght in the streamer chamber, the number of points measured along the track, the uncertainty in the reconstruction of the measured point, and the applied field, which directly affects the curvature radius. Measuring the two images of every track with a semi-automatic plane digitizer, it turned out that the track points could be reconstructed within about $\pm$ 0.2 mm. Then, for an applied magnetic field of 5 KG, the resolution of the apparatus has been estimated with the help of a Monte-Carlo calculation which proceeds through the following steps. For a given radius of curvature, R, the corresponding circumference has been traced and an arc of prefixed lenght has been chosen on it. Within this arc a number, n_p, of equidistant points has been selected and their coordinates have been slightly and randomly changed within the previously quoted precision of reconstruction of a track. A new circumference has then been fitted to the extracted coordinates. A repeated use of this procedure led us to a distribution of curvature radii around the starting one. The above calculation has been carried out for curvature radii up to 1200 mm (corresponding to a pion kinetic energy of 90 MeV), for a number of measured points n_p up to 20 (a substantial independence of the resolution from n_p turned out for $n_p \gtrsim 15$) and for tracks 20 to 70 cm long. The percent standard deviation, σ/R, corresponding to the calculated distribution of radii, for a track 30 cm long and for $n_p = 15$, together with the calculated over-all momentum and energy resolutions, are reported in Table I, for various incident pions energies.

The Monte-Carlo distribution of radii has been compared with the histogram of the curvature radii of a track (28 cm long, R = 1110 mm) measured 40 times: the percent standard deviation resulted to be around 1%, in very good agreement with the value quoted in Table I.

As a conclusion, since our average track's lenght is about 28 cm, the over-all momentum resolution of our experimental apparatus turns out to be sufficient for clearly separating the 4.43 MeV le-

TABLE I

Resolution of our experimental apparatus.

(B = 5 KGauss, n_p = 15, L = 30 cm)

T (MeV)	R (mm)	σ/R (%)	$\Delta p/p$ (FWHM) (%)	$\Delta E/E$ (FWHM) (%)
30	642	0.46	1.08	1.97
40	753	0.53	1.25	2.22
50	855	0.60	1.41	2.45
60	951	0.67	1.58	2.67
70	1042	0.73	1.72	2.86
80	1130	0.80	1.88	3.07
90	1215	0.87	2.05	3.29

TABLE II

Improved resolution of our new experimental apparatus

(B = 5 KGauss, n_p=15, L = 40 cm)

T (MeV)	R (mm)	σ/R (%)	$\Delta p/p$ (FWHM) (%)	$\Delta E/E$ (FWHM) (%)
30	642	0.25	0.59	1.07
40	753	0.31	0.73	1.29
50	855	0.36	0.85	1.47
60	951	0.40	0.94	1.60
70	1042	0.44	1.03	1.71
80	1130	0.49	1.15	1.89
90	1215	0.52	1.22	1.96

vel, the group of levels around 10 MeV and the group of levels starting at 15 MeV. As far as the 7.66 MeV level is concerned, our apparatus is fully able to separate it from the 9.63 MeV level for incident pion energies less than about 70 MeV, while it is at its resolution's limits near 90 MeV.

A valuable improvement has already been afforded to the resolution of the entire apparatus, for the measurements to be carried out in the near future. A larger streamer chamber has been constructed, which can contain tracks up to 40 cm long. The new values for the over-all resolution of our apparatus are reported in Table II, vs T_π.

2.2. - Assignement of the events to the inelastic channels. -

Inelastic cross section data reported in this paper have been evaluated upon a total of 405 backward scattering events, whose vertices were unambiguously lying in the volume of the target. Due to the relatively low statistics, we took advantage of the redundacy of parameters measured for each event (initial and final energies and angle between the trajectories) for statistically assigning each event to the elastic or to the inelastic channels. Referring to fig. 1, we call T_{in} and T_{out} the incident and outgoing energies of the scattered pion, σ_{in} and σ_{out} the R.M.S. errors. A kinematical relation exists between the two energies

$$T_{out} = T_{out}(T_{in}, \theta, Q) \tag{1}$$

where θ is the scattering angle and Q the value of the ^{12}C nuclear energy levels.

The above relation is plotted in Fig. 1 for an event actually occurred. The experimental point is also plotted in the figure, within a rectangle whose half sides are $3\sigma_{in}$ and $3\sigma_{out}$, respectively.

The probability P_i for the event to belong to a specific level i, has been numerically evaluated by performing the following integral along the line representing the level

$$P_i = K \int_{A_i}^{B_i} P_G(T_{in}) P_G\left[T_{out}(T_{in})\right] ds \tag{2}$$

where K is a normalization constant and

$$P_G(x) = \exp\left[-\frac{1}{2}\left(\frac{x-\bar{x}}{\sigma_x}\right)^2\right] \tag{3}$$

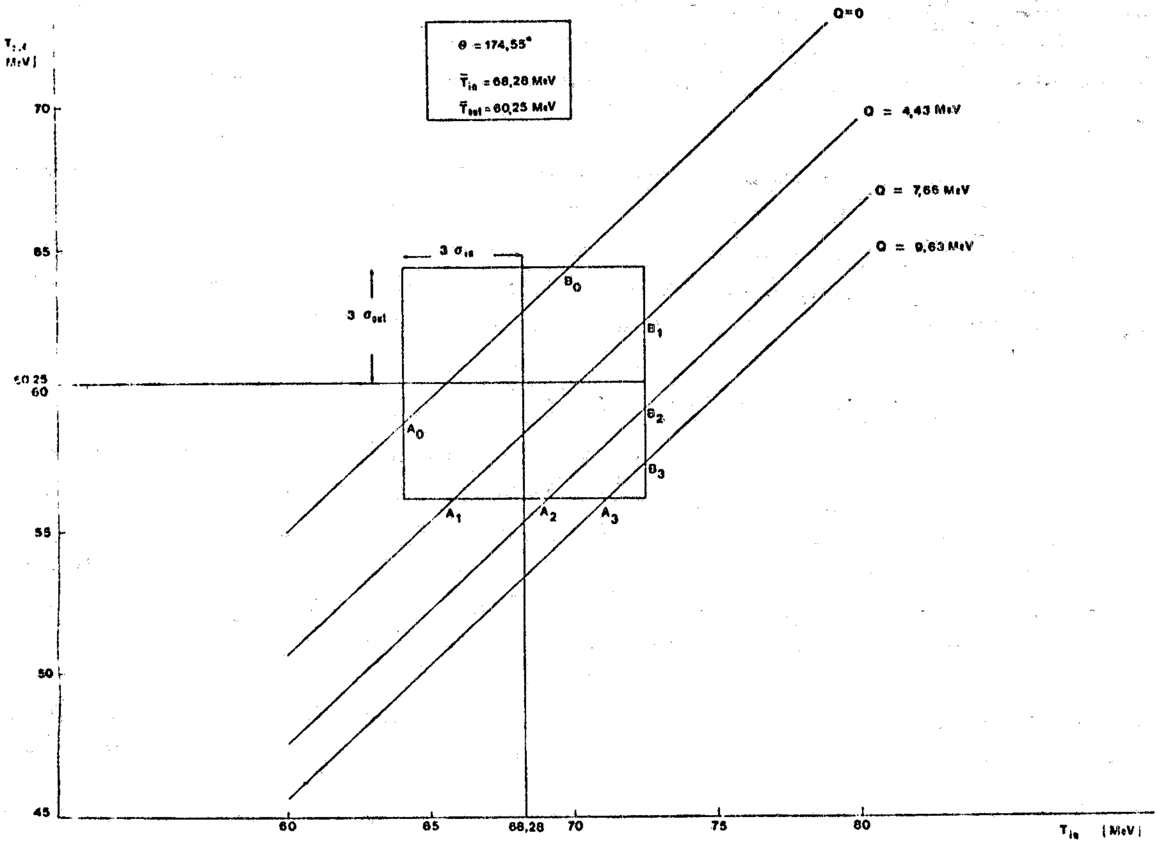


FIG. 1 - The kinematical relation $T_{out} = T_{out}(T_{in}, \theta, Q)$ is plotted for $\theta = 174.55^{\circ}$ and four values of Q-levels (elastic, 4.43 MeV, 7.66 MeV, 9.63 MeV inelastic levels). A rectangle is also plotted around an actually occurred event ($\bar{T}_{in}$ = 68.28 MeV, $\bar{T}_{out}$ = 60.25 MeV). The half sides of the rectangle are 3 σ_{in} and 3 σ_{out} respectively, with σ_{in} = 1.40 MeV and σ_{out} = 1.36 MeV.

The integration has been carried out for all the levels intercepting the rectangle. The probability has then been normalized "within the event" by taking the ratio

$$(4) \qquad p_i = \frac{P_i}{\sum_{\alpha} P_{\alpha}} \qquad \alpha = i, j, \ldots.$$

as a measure of the "level contamination" in the event under consideration. The unscrambling computer routine also corrects data by taking into account the energy lost in the target by ionization by both the incident and the outgoing pions.

3. - RESULTS AND DISCUSSION. -

A typical inelastic spectrum from scattering of 75 MeV π^- on ^{12}C at 165^o laboratory angle is shown in Fig. 2: the corresponding momentum transfer is q = 273 MeV/c. The form of the spectrum is rougly in accord with quasi-free scattering modified by bound and virtual states at small energy loss.

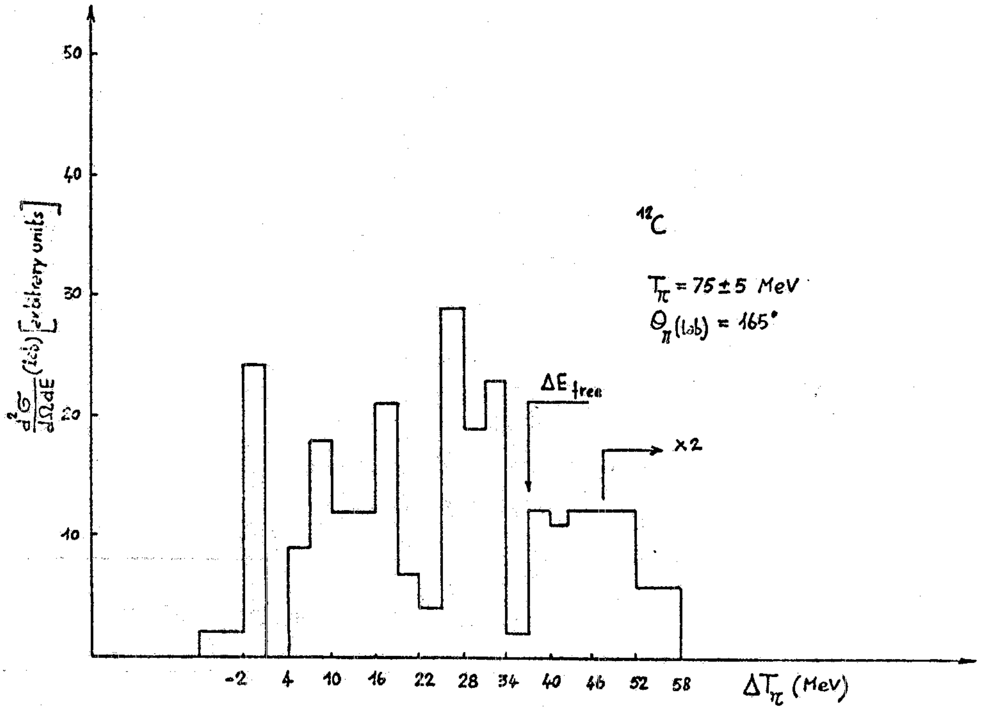


FIG. 2 - Energy loss spectrum at 165^o laboratory angle of 75 MeV π^- scattering by ^{12}C. The arrow ΔE_{free} indicates the energy of pions scatterd by free nucleons.

At low energy loss there are binding effects: the ground state and the individual levels or groups of levels of ^{12}C. At intermediate energy losses, the structure between 20 MeV and 35 MeV about may be positively identified in the excitation of the electric-dipole giant resonance. The high energy loss region of the spectrum is a broad peak, which resembles the form expected for quasi-elastic πN scattering, i.e. direct collisions with the individual nucleons in the nucleus.

A similar wide inelastic spectrum of pion scattering was previously observed only by Rohlin et al. (for ^{16}O)(25) with 270 MeV π^+ at 45^o laboratory, i.e. at about the same momentum transfer of our experiment (q_{Rohlin} = 277 MeV/c). It is interesting to note that both (π, π') spectra show a close similarity with the, respectively, $^{12}C(p, p')$ and $^{16}O(p, p')$ inelastic spectra obtained by Tyren and Maris(26), by Hasselgren et al.(27) and by Sundberg and Tibell(28) at about the same momentum transfer (185 MeV protons scattered 25°: q = 260 MeV/c), if the proton spectra are spread according to the pions energy resolution. This similarity between inelastic scattering of protons and pions had already been emphasized by Koltun(29) comparing the (π^-, ^{12}C) inelastic scattering angular distributions of Binon et al.(5) for 300 MeV/c pions with the corresponding measurements of Peterson et al.(30), obtained with 300 MeV/c (45 MeV kinetic energy) protons. Pion and protons have much the same form of angular distributions, both for excitation of the 2^+ state and the 3^- state of ^{12}C, with the proton cross sections a factor of ten larger.

3.1. - Low excited states. -

The backward inelastic differential cross sections corresponding to excitation by negative pions of the individual nuclear levels or groups of levels of ^{12}C at 4.43, 7.66, 9.63 and 15 MeV are reported in Table III.

TABLE III

(π^-, ^{12}C) Inelastic differential cross sections $d\sigma/d\Omega$ (mb/sr).

Level ^{12}C	Angular bin (lab. syst.)	Pion kinetic energy (MeV)		
		65±5	75±5	85±5
4.43 MeV	160°÷170°	1.28±0.75	0.47±0.22	0.64±0.50
	170°÷180°	0.37±0.25	0.61±0.24	0.44±0.31
7.66 MeV	160°÷170°	0.40±0.34	0.26±0.16	0.50±0.42
	170°÷180°	0.34±0.24	0.77±0.27	0.43±0.28
9.63 MeV	160°÷170°	0.37±0.33	0.36±0.17	0.47±0.37
	170°÷180°	0.60±0.32	0.86±0.27	0.55±0.30
15 MeV	160°÷170°	1.45±0.69	1.22±0.41	0.68±0.36
	170°÷180°	2.21±0.89	1.45±0.36	1.63±0.51

The data have been divided in two 10° angular bins: 160°÷170°, 170°÷180° and are given for three incident pion energies: 65±5, 75±5, 85±5 MeV. The errors quoted are only statistical.

Excitation of the 7.66 MeV level is of the same order of magnitude of the others. The experimental apparatus is able to separate clearly this level from the 9.63 MeV level at 65 MeV and 75 MeV: a contamination from the 9.63 MeV level may be present in the data at 85 MeV.

Contributions, if any, from the levels at 10.3 MeV and 10.84 MeV could not be subtracted from the 9.63 MeV distribution.

The differential cross sections for the over-all excitation of the group of levels around 15 MeV are larger, within the errors, than the others, according to the first data of Baker et al.(3) in this energy region.

3.2. - Excitation of the giant dipole states of ^{12}C.

Shell model calculations on the structure of the giant resonance in ^{12}C ascribe the main effect to four $J^P = 1^-$, $T = 1$ levels, of which the second contributes most of the E_1 strenght. The computed levels energies are: 19.6, 23.3, 25.0, 35.8 MeV. The most probable identification are $E^* = 19.2$, 22.6, 25.4 and 33.4 MeV (for all the references see: Ajzenberg-Selove and Lauritsen(1)).

Observations of $\sigma(\gamma, n)$ show a giant resonance centered at about 22.5 MeV, with a tail sloping off to about 40 MeV. The giant resonance appears to have a fine structure: at least two major components are identified at $E^* = 22$ and 23.5 MeV. The photoproton cross section $\sigma(\gamma, p)$ exhibits a single broad giant resonance peak centering at $E^* = 22.5$ MeV and with significant difference from $\sigma(\gamma, n)$ both in shape and in peak cross sections. Inelastic excitation of the giant resonance with $^{12}C(e, e')$ scattering has shown evidence for structure at 18.1, 19.5, $\sim$24 and $\sim$34 MeV. In forward inelastic scattering of protons a large and broad resonance peak is clearly visible, several MeV wide, for a proton energy corresponding to the excitation of about 20 MeV in the residual nucleus.

Koltun and Nalcioǧlu(31) have proposed the inelastic scattering of pions by nuclei, with excitation of electric dipole states, as a sensitive test of the non-locality of the π-N t matrix. They calculated differential cross sections for exciting the strongest of the giant dipole states of ^{12}C ($E^* \simeq 23$ MeV), assuming the reaction to be one-step, so that PWIA or DWIA could be valid, and obtaining nuclear transition densities from the particle-hole model of Gillet and Vinh-Mau(11). The pion kinetic energies were 75 and 120 MeV and the angular distributions were limited to forward direction, where the momentum dependence of non-local t matrix leads to strong excitation of the electric dipole states.

The bump centered around 28 MeV in our inelastic $^{12}C(\pi, \pi')$ spectra extends, as shown in the example of fig. 2, from about 20 MeV up to about 35 MeV. We have calculated the differential cross sections assuming an excitation of the strongest of the giant dipole states ($Q = 23$ MeV). The data have been divided in two 10° angular bins: 160° ÷ 170°, 170°÷180° and for three incident pion energies: 65 ± 5, 75 ± 5, 85 ± 5 MeV, and are reported in Table IV. The errors quoted are only statistical.

TABLE IV

Giant resonance excitation by (π^-, ^{12}C) scattering.
Inelastic differential cross sections $d\sigma/d\Omega$(mb/sr).

Angular bin (lab. syst.)	Pion kinetic energy (MeV)		
	65 ± 5	75 ± 5	85 ± 5
160° ÷ 170°	1.26 ± 0.63	2.83 ± 0.70	1.14 ± 0.43
170° ÷ 180°	3.45 ± 1.17	1.56 ± 0.37	1.30 ± 0.44

3.3. - (π - α) Scattering in the α-particle model of ^{12}C. -

A particularly simple version of the α-particle model of the nucleus, where the α-clusters are taken to be at the vertices of an equilateral triangle, gives a good description of the electromagnetic form factor of ^{12}C, out to the first subsidiary maximum(32). The same model has been used to calculate the cross section for the scattering of 1 GeV protons from ^{12}C in the framework of Glauber theory(33÷35). Germond and Wilkin(36) have calculated elastic (π^-, ^{12}C) scattering in the region of (3, 3) resonance, within Glauber theory on the basis of the naive α-particle model. They took as input the empirical α-particle amplitudes, as obtained from the new unpublished (π, α) scattering measurements of the IISN (Brussels) - IPN (Orsay) collaboration. A good agreement with the data of Binon et al.(5), which seems to improve with increasing energy, was obtained.

From the experimental point of view, the disintegration of ^{12}C into three α-particles in the inelastic scattering of pions has been first investigated by Della Corte et al.(37) and extensively studied by Bogatin et al.(38). It was established that a significant contribution to the total cross section for this reaction is provided by the process of excitation of the carbon nucleus to the 9.63 MeV level, which then decays with formation of a "first" α particle and a ^8Be nucleus in the ground state (about 20%) and by the mechanism of simultaneous breakup of the ^{12}C nucleus into three α particles, with a resonance interaction of these particles in the final state (45%). The strong interactions between particles in the final state, conceals the possible direct knocking out of a single α particle by the meson, analogous of that observed in reactions with high energy protons$^{(39)}$. Moreover, when all α particles from ^{12}C were considered, forward peaking was observed (the forward-to--backward ratio was 1.37 ± 0.20), which could indicate the existence of direct knock-on processes. Banin et al.$^{(40)}$ made an analysis of the reaction

$$\pi^+ + {}^{12}C \longrightarrow \pi^+ + 3\alpha$$

by means of the Treiman-Yang criterion, utilizing both the data of Bogatin et al.$^{(38)}$ and data at higher meson energies, in order to increase the contribution of the pole approximation. They found a distribution in the Treiman-Yang angle close to isotropic for those events in which ^8Be nuclei were observed in the first excited state. Moreover, the angular distribution of the "first" α particle was anisotropic (front/back ratio in c.m.s. = 1.7 ± 0.3) confirming the existence of direct processes. A correlation was observed between the π-meson energy loss and meson scattering angle, corresponding, at backward angle (as in the case of the present experiment), to the kinematics of elastic scattering of π meson by an α particle.

In this point of view, we have assumed, in the intermediate region of energy loss of the $^{12}C(\pi,\pi')$ inelastic spectra, a contribution due to the kinematics of free (π,α) elastic scattering. It must be noticed, at this regard, that owing to the emphasized anisotropy of the angular distribution, the α particles from the breakup of ^{12}C could not be revealed in our experimental arrangement. In Table V the corresponding differential cross sections are reported. The errors quoted are only statistical.

TABLE V

(π,α) Scattering in the α-particle model of ^{12}C.
Elastic differential cross sections $d\sigma/d\Omega$ (mb/sr).

Angular bin (lab. syst.)	Pion kinetic energy (MeV)		
	65 ± 5	75 ± 5	85 ± 5
160° ÷ 170°	0.47 ± 0.37	0.27 ± 0.15	0.42 ± 0.34
170° ÷ 180°	0.35 ± 0.24	0.68 ± 0.24	0.42 ± 0.24

3.4. - Quasi-free (π, N) scattering. -

The knock-out reactions of the type A($\pi^{\pm}$, πN)B constitute a major component of the pion-nucleus reaction cross section(29, 41). These reactions have been studied over the energy range of 30 to 1900 MeV(42÷49). The excitation function of the reaction ^{12}C($\pi^{\pm}$, πN)^{11}C has a peak near the energy of the (3, 3) resonance in the (π, N) cross section. This feature led to impulse approximation interpretations(29, 42, 46, 50÷52) of the knockout reaction based on the idea of quasi-free scattering of pions from individual nucleons within the nucleus. In a two-step mechanism(42), the incident pion undergoes a fast collision with a single nucleon and escapes the nucleus without further interactions. The collision partner shares its recoil energy with the other nucleons and the resultant nuclear excitation eventually leads to evaporation of one nucleon. In ^{12}C(π^-, π^-n)^{11}C the initial collision may be with either a proton or a neutron. The one-step mechanism or pure knock-out mechanism(42) is similar to the two-step mechanism except that both collision partners escape the nucleus immediately after the collision and without any other interactions. For a (π^-, π^-n) reaction the Initial collision can be only with a neutron. Comparison of experimental and calculated ^{12}C(π^-, π^-n)^{11}C excitation functions around (3, 3) resonance up to 1600 MeV made by Reeder and Markowitz(42), indicates that the two-step mechanism is distinctly different from the experimental excitation function. As it is well known, however, there are some clear discrepancies between the experimental results and the single impulse approximation predictions for the $\sigma(\pi^-, {}^{12}C)/\sigma(\pi^+, {}^{12}C)$ ratio; not only near the (3, 3) resonance but also in the low energy region(49). Several explanations have been proposed. In particular, Wilkinson(53), Chivers et al.(46), and Cannata and Ros(54) suggested, for the ^{12}C(π^-, π^-n)^{11}C reaction, that knock-out reactions can proceed via an inelastic scattering followed by evaporation of a neutron.

The most striking feature of the first π-nucleus inelastic scattering angular distributions of Byfield et al.(55), Kessler and Lederman(56), and Valkx et al.(57) was the strong peaking in backward direction. In these experiments, the different excited states of the nucleus could not be separated, owing to the poor energy resolution, and the angular distributions were obtained for large energy loss scatterings. The backward increasing, similar to that observed in (π^+, p) elastic scattering, had to be explained as resulting from quasi-free pion-nucleon scattering.

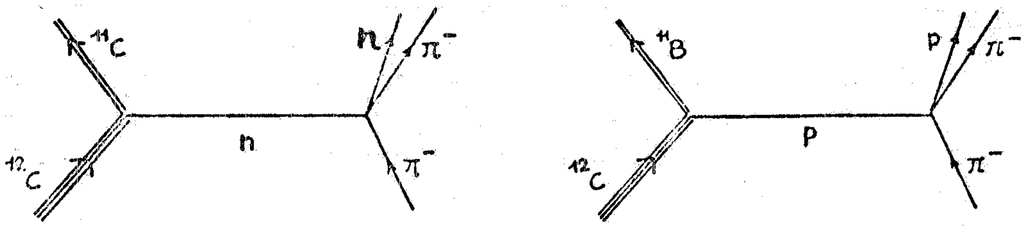
The high energy loss region of the inelastic spectrum from ^{12}C(π, π') scattering in this experiment gives much the same form expected for quasi-free (π, N) scattering. If the nucleons in the nucleus were unbound and at rest, one would expect to see a peak at an energy loss corresponding to free kinematics

$$\Delta E_{free} = q^2/2M_N$$

where q is the momentum transfer and M_N the nucleon mass. Since the nucleons actually are in motion, the peak is displaced and is given a width which depends upon the Fermi momentum in a non interacting Fermi-gas model of the nucleus$^{(58)}$. In Fig. 2 the quasi-free peak is shifted respect to the kinematics elastic limit, according to the Fermi motion of the nucleons. The peak has a roughly gaussian form consistent with scattering by single nucleons in a harmonic oscillator potential of conventional radius. We must note that in this case a detailed analysis of the involved knock-out reactions is not possible, owing to the experimental limitations, by which only a ± 20° angular window in backward direction was covered. Since in the simple knock-on-model the forward to backward ratio should be greater than 1, no kinematical measurements on the reaction products could be made. As a consequence, the quasi-elastic peak of the $(\pi,\pi X)$ backward reaction in ^{12}C of our measurements is dominated by both the Feynman graphs of Fig. 3, corresponding to the processes

$$\pi^- + {}^{12}C \rightarrow \pi^- + n + {}^{11}C$$
$$\pi^- + {}^{12}C \rightarrow \pi^- + p + {}^{11}B$$

The high value of the upper tail of the spectrum (~ 60 MeV) can indicate emission of nucleous also from s shell (separation energy ~ 50 MeV).



(a) (b)

FIG. 3 - a) Feyman diagram for the reaction $\pi^- + {}^{12}C \rightarrow \pi^- + p + {}^{11}B$
b) Feyman diagram for the reaction $\pi^- + {}^{12}C \rightarrow \pi^- + n + {}^{11}C$

The contribution of other possible nuclear reactions, such as

$$\pi^- + {}^{12}C \longrightarrow \pi^- + {}^{12}C^*,$$

where the ^{12}C nucleus is left in a highly excited state, or

$$\pi^- + {}^{12}C \rightarrow \pi^- + mN + X,$$

where more than one nucleon are extracted, has been evaluated small in comparison of the other processes(48).

In Table VI are reported the differential cross sections corresponding to the high energy loss region of the inelastic spectra from $^{12}C(\pi, \pi')$ scattering. The data have been divided in three angular bins 150° ÷ 160°, 160° ÷ 170° and 170° ÷ 180° and for two incident pions energies: 75 ± 5 and 85 ± 5 MeV. The errors quoted are only statistical.

The backward increasing, in agreement with the π-nucleus inelastic angular distributions of Byfield et al.(55), Kessler and Lederman(56) and Valkx et al.(57), further suggests the use of the single-scattering picture.

TABLE VI

Quasi-fre (π, N) scattering. Differential cross sections $d\sigma/d\Omega$ (mb/sr).

Angular bin (lab. syst.)	Pion kinetic energy (MeV)	
	75 ± 5	85 ± 5
150° ÷ 160°	1.26 ± 0.19	3.84 ± 0.45
160° ÷ 170°	2.48 ± 0.35	6.71 ± 0.77
170° ÷ 180°	2.03 ± 0.54	4.75 ± 1.11

In the near future, we will extend, by using the experimental apparatus with improved resolution as quoted above, the angular range (down to 140°), the incident pion energy (down to 30 MeV and up to 150 MeV) and the statistics.

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