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On the Collective Isobaric Resonances in Pion-Nucleus Scattering at Intermediate Energies.

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Summary. — The excitation functions of differential cross-sections in pion-nucleus scattering at intermediate energies have been obtained by fitting in the c.m.s. with Legendre polynomials all the existing data on ^1H, ^2H, ^3He, ^4He, ^{12}C and ^{16}O. The spectra have been deduced by calculating the maximum-likelihood Lorentz lines through a Monte Carlo method. Among the main features, we find a resonant behaviour of the excitation functions at energies much lower compared to the free Δ-resonance position. The shift is angle dependent and A-dependent. A possible explanation of the downward energy shift is given on the ground of the recent developments of the collective isobaric resonance model.

1. – Introduction.

The most striking feature in pion-nucleon scattering at intermediate energies is the well-known Δ(1232) P_{33} resonance in the total cross-section at pion energy

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$E = 180$ MeV and with a width $\Gamma_N \simeq 110$ MeV (1). Excitation functions of differential cross-sections at all angles exhibit the same behaviour.

A slight downward energy shift of the resonance occurs in the pion-nucleon case (2). Pion-proton scattering below 300 MeV is almost completely dominated by the $l = 1$ partial wave due to the isospin-$\frac{3}{2}$, spin-$\frac{3}{2}$ P-wave resonance. At $E = 195$ MeV, the phase shift for this channel passes very rapidly through 90°. Correspondingly, since this one wave dominates the scattering, the real part of the forward-scattering amplitude $\mathrm{Re}\, f_{\pi N}(0°) = 0$ at $E = 195$ MeV. However, because of the momentum factor $1/k$ in the expression for the imaginary part $\mathrm{Im}\, f_{\pi N}(0°)$, the $\mathrm{Im}\, f_{\pi N}(0°)$ has its maximum shifted downwards slightly to $E \simeq 187$ MeV. Since the expression of the optical theorem for the total cross-section has an additional $1/k$ factor in front, the resonance is shifted down further to the experimental value $E = 180$ MeV.

Measurements of pion-nucleus total cross-sections show a peak clearly related to the 3-3 resonance of the pion-nucleon system (3). However, this experimental peak is broadened and shifted approximately $(40 \div 50)$ MeV downward in energy compared to the peak in $\sigma(\pi, N)$ $(E \simeq (130 \div 140)$ MeV). Theoretical explanations or calculations of this shift appeared in several studies (4-7). The resonance shift seems not to be an exotic effect (6), but it is simply a consequence of the passage of the pion through a dispersive, absorptive medium (2). This multiple scattering tends to diminish the energy variation of the forward π-nucleus scattering amplitude $f_{\pi n}(0°)$ and, thus, leads to a broadening. In addition, including nucleon Fermi motion also broadens and lowers the peak

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(1) G. GIACOMELLI, P. PINI and S. STAGNI: CERN-HERA, 69-1 (1969); F. J. BUSSEY, J. R. CARTER, D. R. DANCE, D. V. BUGG, A. A. CARTER and A. M. SMITH: *Nucl. Phys. B*, **58**, 363 (1973).

(2) R. H. LANDAU, S. C. PHATAK and F. TABAKIN: *Ann. Phys.* (*N. Y.*), **78**, 299 (1973).

(3) N. D. GABITZSCH, G. S. MUTCHLER, C. R. FLETCHER, E. V. HUNGERFORD, L. COULSON, D. MANN, T. WITTEN, M. FURIC, G. C. PHILLIPS, B. MAYES, L. Y. LEE, J. HUDOMALJ, J. C. ALLRED and C. GOODMANN: *Phys. Lett. B*, **47**, 61 (1973); C. WILKIN, C. R. COX, J. J. DOMINGO, K. GABATHULER, E. PEDRONI, J. ROHLIN, P. L. SCHWALLER and N. W. TANNER: *Nucl. Phys. B*, **62**, 61 (1973); A. S. CLOUGH, G. K. TURNER, B. W. ALLARDYCE, C. J. BATTY, L. J. BAUGH, W. J. MCDONALD, R. A. J. RIDDLE, L. M. WATSON, M. E. CAGE, G. J. PYLE and G. T. A. SQUIER: *Nucl. Phys. B*, **76**, 15 (1974); A. S. CARROLL, I. M. CHIANG, C. B. DOVER, T. F. KYCIA, K. K. LI, P. O. MAZUR, D. N. MICHAEL, P. M. MOCKETT, D. C. RAHM and R. RUBINSTEIN: *Phys. Rev. C*, **14**, 635 (1976).

(4) K. BJORNENAK, J. FINJORD, P. OSLAND and A. REITAN: *Nucl. Phys. B*, **22**, 179 (1970); T. KOHMURA: *Nucl. Phys. B*, **36**, 228 (1972); C. SCHMIT: *Lett. Nuovo Cimento*, **4**, 454 (1970); L. A. CHARLTON and J. M. EISENBERG: *Ann. Phys.* (*N. Y.*), **63**, 286 (1971); W. R. GIBBS: *Phys. Rev. C*, **5**, 755 (1972).

(5) C. WILKIN: *Proceedings of Spring School on Pion Interactions at Low and Medium Energies*, (SIN, CERN) Cern 71-14, 4 August 1971; C. WILKIN: *Lett. Nuovo Cimento*, **4**, 491 (1970).

(6) T. E. O. ERICSON and J. HUFNER: *Phys. Lett. B*, **33**, 601 (1970).

(7) M. P. LOCHER, O. STEINMANN and N. STRAUMANN: *Nucl. Phys. B*, **27**, 598 (1971).

slightly. Multiplication of $\operatorname{Im} f_{\pi n}(0°)$ by the energy-dependent $1/k$ term, to form the total pion-nucleus cross-section, therefore, leads to a considerably larger shift in the peak position than was found in the corresponding step for the pion-nucleon cross-section.

Moreover, shape and position of the peak in pion-nucleon scattering depend on A, the mass number of the target nucleus. As A is increased, the peak becomes broader and its maximum moves to a lower energy. SEDLAK and FRIEDMAN (8) have shown that this A-dependent behaviour originates in geometric and refractive features, rather than in microscopic nuclear dynamics. This results from the blackness of the nucleus to the pion wave in the 3-3 resonance region.

As far as differential cross-sections in pion-nucleus scattering are concerned, available data on light nuclei give excitation functions with resonant behaviours at energies much lower compared to position of the Δ-resonance, especially at large angles (9). Positions and widths of the peaks depend on the scattering angle and also on the mass number.

In order to study the excitation functions of differential cross-sections, comparing homogeneously data from experiments covering different energy and angular intervals, we have fitted all the existing data on light nuclei such as ^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{12}C, ^{16}O. The main features of the excitation functions have been then deduced and compared to the elementary pion-nucleon scattering. A possible explanation of the downward energy shifts has been given on the ground of the recent collective resonance model of Klingenbeck *et al.* (10) and Händel *et al.* (11).

2. – Excitation functions of differential cross-section for light nuclei.

The backward-angle ($\pi^{\pm}$, ^{12}C) differential elastic cross-section in the energy range (23÷90) MeV has been measured by the authors (12) with a streamer

(8) J. E. SEDLAK and W. A. FRIEDMAN: *Phys. Rev. C*, **16**, 2306 (1977).

(9) F. BALESTRA, E. BOLLINI, L. BUSSO, R. GARFAGNINI, G. PIRAGINO, A. ZANINI, C. GUARALDO, R. SCRIMAGLIO, I. V. FALOMKIN, M. M. KULYUKIN, R. MACH, F. NICHITIU, G. B. PONTECORVO and YU. A. SHCHERBAKOV: *Proceedings of the VII International Conference on Few-Body Problems in Nuclear and Particle Physics* (Delhi, 1976), p. 315; TORINO-DUBNA-FRASCATI COLLABORATION: Frascati Report LNF 76/50 (1976).

(10) K. KLINGENBECK, M. DILLIG and M. G. HUBER: *Phys. Rev. Lett.*, **41**, 387 (1978); E. BOSCHITZ: *Proceedings of the VII International Conference on High-Energy Physics and Nuclear Structure* (Zürich, 1977), p. 133.

(11) R. HÄNDEL, M. DILLIG and M. G. HUBER: *Phys. Lett. B*, **73**, 4 (1978).

(12) F. BALESTRA, L. BUSSO, R. GARFAGNINI, G. PIRAGINO, R. BARBINI, C. GUARALDO and R. SCRIMAGLIO: *Lett. Nuovo Cimento*, **12**, 351 (1975); **13**, 673 (1975); F. BALESTRA, L. BUSSO, R. GARFAGNINI, G. PIRAGINO, C. GUARALDO, A. MAGGIORA, R. SCRIMAGLIO and F. CANNATA: *Phys. Lett. B*, **80**, 203 (1979).

chamber spectrometer ([13]) exposed to the pion beam of the LEALE Laboratory of Frascati. The spectrometer consisted of a self-shunted streamer chamber filled with ^{4}He at 1 atm and placed in an electromagnet. In this way the chamber visualized the incident and the scattered pions for events occurred both in the ^{12}C external target and in the filling gas.

The corresponding excitation function for ^{12}C is reported in fig. 1. The solid line is the maximum-likelihood Lorentz function obtained with a Monte Carlo calculation. Our lower-energy values ($E < 20$ MeV) are presently under analysis, however, the figure seems to show a resonant behaviour. The peak position is shifted to an energy much lower compared to the position of the Δ-resonance in pion-nucleon scattering.

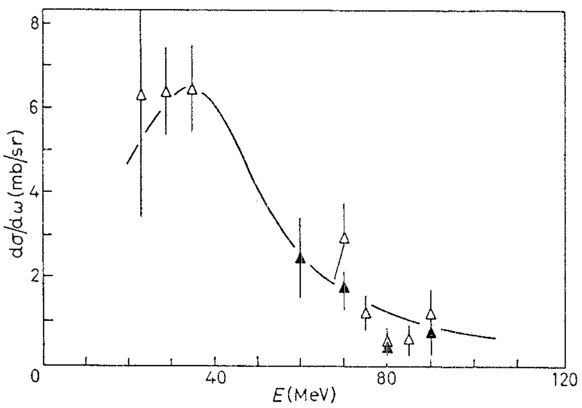

Fig. 1. – Excitation function of ($\pi^\pm$, ^{12}C) differential elastic cross-section at $(175 \pm 5)°$. Experimental data: ref. ([12]). Symbols: ▲ (π^-, ^{12}C). △ (π^+, ^{12}C). The solid line is the maximum-likelihood Lorentz function obtained with a Monte Carlo calculation.

Two large-angle ($\pi^\pm$, ^{4}He) values, $((150 \pm 10)°$ and $(165 \pm 15)°)$ have been measured ([14]) with a streamer chamber with 81 MeV π^- and 33 MeV π^+. In fig. 2, the corresponding excitation functions have been deduced from these data and large-angle elastic data from other experiments ([15]). The Lorentz lines show a maximum at $E = 73.5$ MeV at $\theta = 150°$ and at $E = 72.6$ MeV at $\theta = 165°$.

([13]) F. Balestra, L. Busso, R. Garfagnini, G. Piragino, R. Barbini, C. Guaraldo, R. Scrimaglio, I. V. Falomkin, M. M. Kulyukin and Yu. A. Shcherbakov: *Nucl. Instrum. Methods*, **119**, 347 (1974); **125**, 157 (1975).
([14]) F. Balestra, M. P. Bussa, L. Busso, R. Garfagnini, G. Piragino, C. Guaraldo, A. Maggiora and R. Scrimaglio: in press.
([15]) Yu. A. Budagov, P. F. Ermolov, E. A. Kushnirenko and V. I. Moskalev: *Sov. Phys. JETP*, **15**, 824 (1962); M. E. Nordberg and K. F. Kinsey: *Phys. Lett.*,

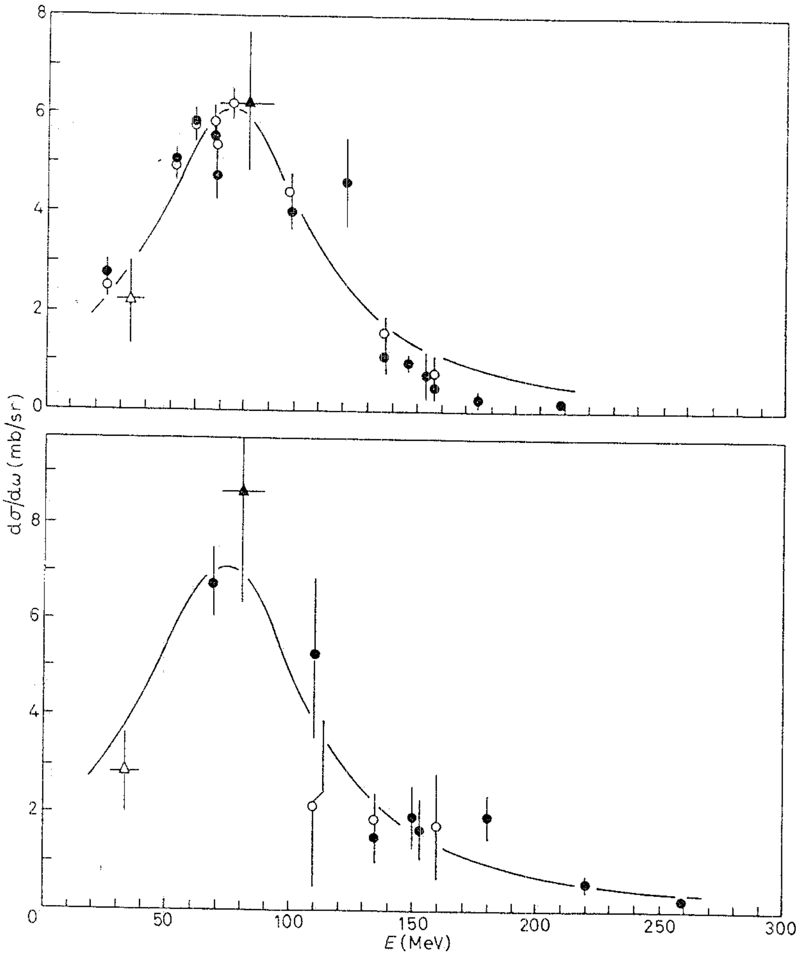

Fig. 2. – Excitation functions of ($\pi^\pm$, ^{4}He) differential elastic-cross sections at $(150 \pm 10)°$ and $(165 \pm 15)°$, upper and lower part, respectively. Experimental data: triangles ref. [14]; circle ref. [15]. Symbols ▲ and ● (π^-, ^{4}He), △ and ○ (π^+, ^{4}He). The solid curves are Lorentz lines.

20, 692 (1966); K. M. CROWE, A. FAINBERG, J. MILLER and A. S. M. PARSON: *Phys. Rev.*, **180**, 1349 (1969); R. BARBINI, L. BUSSO, S. COSTA, R. GARFAGNINI, C. GUARALDO, G. PIRAGINO and R. SCRIMAGLIO: preprint LNF 72/62 (1972); YU. A. SHCHERBAKOV, T. ANGELESCU, I. V. FALOMKIN, M. M. KULYUKIN, V. I. LYASHENKO, R. MACH, A. MIHUL, N. M. KAO, F. NICHITIU, G. B. PONTECORVO, V. K. SARYCHEVA, M. G. SAPOZHNIKOV, M. SEMERDJEVA, T. M. TROSHEV, N. I. TROSHEVA, F. BALESTRA, L. BUSSO, R. GARFAGNINI and G. PIRAGINO: *Nuovo Cimento A*, **31**, 249 (1976); F. BINON, P. DUTEIL, M. GOUARNÈRE, L. HUGON, J. JANSEN, J. P. LAGNAUX, M. PALEVSKY, J. P. PEIGNEUX, M. SPIGHEL and J. P. STROOT: *Phys. Rev. Lett.*, **35**, 145 (1975); *Nucl. Phys. A*, **298**, 499 (1978); I. V. FALOMKIN, V. I. LYASHENKO, G. B. PONTECORVO, YU. A. SHCHERBAKOV, F. BALESTRA, R. GARFAGNINI, G. PIRAGINO, T. ANGELESCU, A. MIHUL and F. NICHITIU: *Nuovo Cimento A*, **43**, 219 (1978).

A similar behaviour can be found for the large-angle excitation function in ($\pi^{\mp}$, ^{2}H) scattering. In fig. 3 is reported the excitation function of the differential cross-section at $(155 \pm 5)°$ from the experimental data available in the literature on pion-deuteron scattering [16]. The figure shows a peak again at a much lower energy ($E = 98.7$ MeV), compared to the free Δ-resonance.

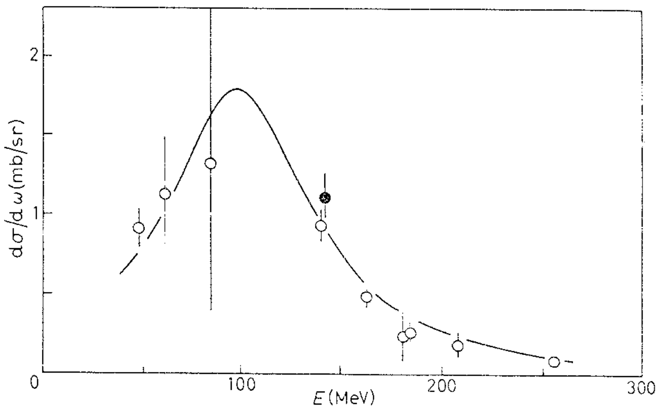

Fig. 3. – Excitation function of ($\pi^{\mp}$, ^{2}H) differential elastic cross-section at $(155 \pm 5)°$. Experimental data: ref. [16]. Symbols: • (π^{-}, ^{2}H), ○ (π^{-}, ^{2}H). The solid curve is a Lorentz line.

In order to obtain the excitation functions of differential cross-section from light nuclei and to compare in a homogeneous way data from different experiments, we have fitted in the c.m.s. with Legendre polynomials all the existing data on ^{1}H: ref. [1], ^{2}H: ref. [16], ^{3}He: ref. [17], ^{4}He: ref. [14,15], ^{12}C: ref. [12,18], ^{16}O: ref. [19]. The excitation functions have then been deduced

(16) K. ROGER and L. M. LEDERMAN: *Phys. Rev.*, **105**, 259 (1957); A. M. SACHS, H. WINICK and B. A. WOOTEN: *Phys. Rev.*, **109**, 1733 (1958); E. G. PEWITT, T. H. FIELDS, G. B. YODH, J. G. FETKOVICH and M. DERRICK: *Phys. Rev.*, **131**, 1826 (1963); J. H. NOREM: *Nucl. Phys. B*, **33**, 512 (1971); K. GABATHULER, C. T. COX, J. J. DOMING, J. ROHLIN, N. W. TANNER and C. WILKIN: *Nucl. Phys. B*, **55**, 397 (1973); R. H. COLE, J. S. MC CART, R. C. MINEHART and E. A. WADLINGER: *Phys. Rev. C*, **17**, 681 (1978).

(17) YU. A. SHCHERBAKOV, T. ANGELESCU, I. V. FALOMKIN, M. M. KULYUKIN, V. I. LYASHENKO, R. MACH, A. MIHUL, N. M. KAO, F. NICHITIU, G. B. PONTECORVO, V. K. SARYCHEVA, M. G. SAPOZHNIKOV, M. SEMERDJEVA, T. M. TROSHEV, N. I. TROSHEVA, F. BALESTRA, L. BUSSO, R. GARFAGNINI and G. PIRAGINO: *Nuovo Cimento A*, **31**, 262 (1976), and ref. (15).

(18) H. BYFIELD, J. KESSLER and L. M. LEDERMAN: *Phys. Rev.*, **86**, 17 (1952); W. F. BAKER, M. BYFIELD and J. RAINWATER: *Phys. Rev.*, **112**, 1773 (1958); R. M. EDELSTEIN, W. F. BAKER and J. RAINWATER: *Phys. Rev.*, **122**, 252 (1961); F. BINON, P. DUTEIL, J. P. GARRON, J. GORRES, L. HUGON, J. P. PEIGNEUX, C. SCHMIT, M. SPIGHEL and J. P. STROOT: *Nucl. Phys. B*, **17**, 168 (1970); H. DOLLARD, K. L. ERDMAN, R. R. JOHNSTON, T. MASTERSON and P. WALDEN: *Phys. Lett. B*, **63**, 416 (1976); J. PIFFARETTI, R. CORFÙ, J. P. EGGER, P. GRETILLAT, C. LUNKE, C. FERRIN and E. SCHWARZ:

calculating the maximum-likelihood Lorentz lines through a Monte Carlo method.

In fig. 4 the excitation functions of differential cross-sections at 30°, 90° and 120° for light nuclei such as ^{2}H, ^{3}He, ^{4}He, ^{12}C and ^{16}O are reported, together with the curves relative to elementary $\pi^{\pm}$ scattering.

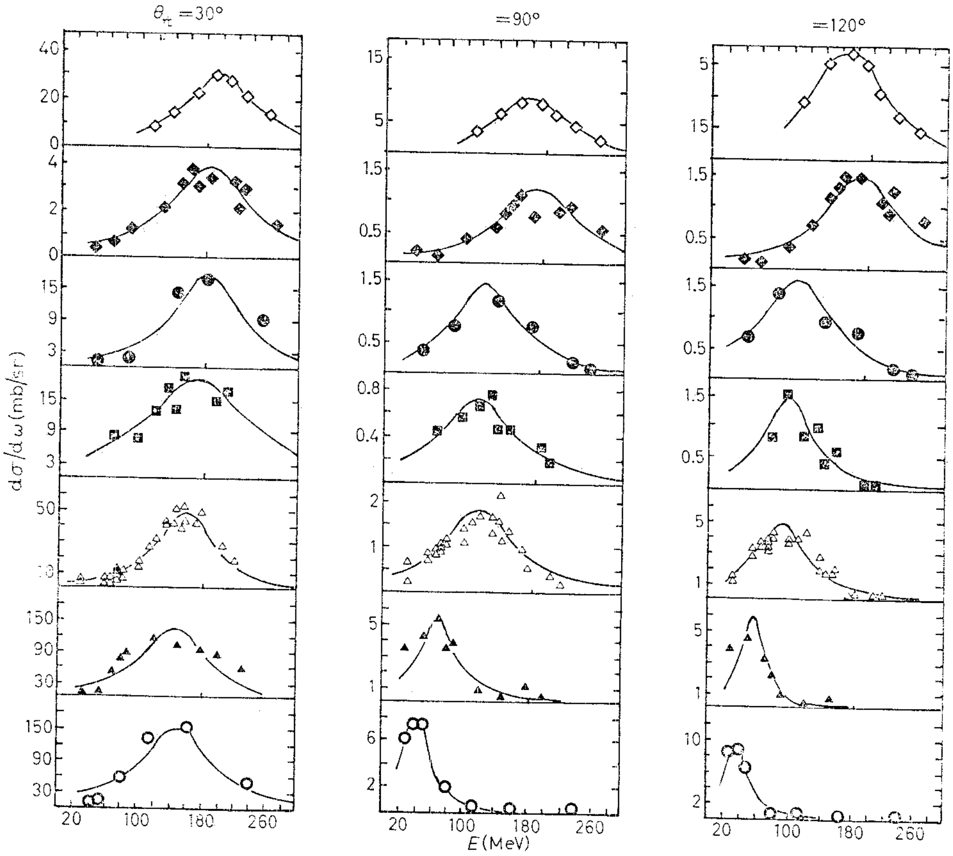

Fig. 4. – Excitation functions of differential elastic cross-sections of $\pi^{\pm}$ on proton and light nuclei at 30°, 90° and 120°. Symbols: ◇ (π^+, p), ◆ (π^-, p), ● ($\pi^{\pm}$, ^{2}H), ■ (π^-, ^{3}He), △ ($\pi^{\pm}$, ^{4}He), ▲ ($\pi^{\pm}$, ^{12}C), ○ (π^+, ^{16}O). They represent the best-fit values obtained at the energies where differential cross-section data are available. The solid curves are Lorentz lines.

Phys. Lett. B, **67**, 289 (1977); S. A. Dytman, J. F. Amann, P. D. Barnes, J. N. Craig, K. G. R. Doss, R. A. Eisenstein, J. D. Sherman, W. R. Whatson, R. J. Peterson, G. R. Burlerson, S. L. Werbeck and H. A. Thiessen: *Phys. Rev.*, **38**, 1059 (1977).
(19) D. J. Malbrough, C. W. Darden, R. D. Edge, T. Marks, B. M. Preedeom, R. L. Burman, M. A. Moinester, R. P. Redwine, F. E. Bertrand, J. P. Cleary, E. E. Gross, C. A. Ludemann and K. Gotow: *Phys. Rev. C*, **17**, 1395 (1978); J. P. Albanese, J. Arvieux, E. Boschitz, C. H. O. Ingram, L. Pflug, C. Wiender and J. Zichy: *Phys. Lett. B*, **73**, 119 (1978).

3. – Analysis of the excitation functions.

The following main features can be drawn from the analysis of the excitation functions.

a) The excitation functions of $(\pi^{\pm}, p)$ differential cross-sections show a resonant behaviour peaked at the same energy of the free resonance Δ over the whole angular interval.

b) The excitation functions of π-nucleus differential cross-sections show a resonant behaviour peaked at energies much lower compared to the Δ position. The shift is angle dependent and A-dependent: it is as much pronounced as the angle increases and the nucleus is heavier. All this is stressed in fig. 5, in which are reported the angular dependences of the peak positions for the considered nuclei, compared with the behaviours of the elementary processes. Δ-resonances do not exhibit nearly any angular dependence, as is known and appears also in the figure. On the contrary, the positions of the peaks of the excitations functions of differential cross-sections seem to decrease with the scattering angle, the angular behaviour becoming flat only at backward angles. Moreover, the angular behaviours of the peak position show an A-dependence: steeper slopes and lower-energy values for heavier nuclei.

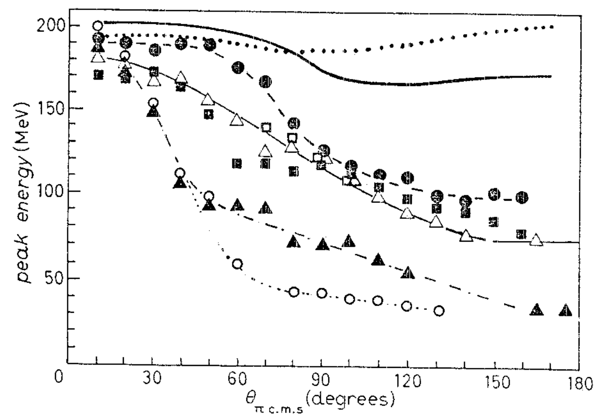

Fig. 5. – Angular behaviours of peak positions of the excitations functions. Solid line: (π^+, p); dotted line: (π^-, p). Symbols: ● $(\pi^{\pm}, {}^2H)$, □ $(\pi^+, {}^3He)$, ■ $(\pi^-, {}^3He)$, △ $(\pi^{\pm}, {}^4He)$, ▲ $(\pi^{\pm}, {}^{12}C)$, ○ $(\pi^+, {}^{16}O)$. They represent peak positions at 10° intervals, except for the lack of experimental data. Lines are drawn as a guide to the eye.

What is significant to stress is that, at forward angles, angular behaviours and peaks positions are close to those of the elementary resonances.

c) The angular behaviours of the momentum transfer q_p, corresponding to the energy value E_p of the peaks, show (see fig. 6) the significant feature of the existence, for each nucleus, of some characteristic maximum angle θ_m such that for $\theta_\pi < \theta_m$ the q_p values are close to those of (π^+, p), while for $\theta_\pi \neq \theta_m$ the behaviours become nearly flat. Again, the θ_m values are A-dependent: higher for lighter nuclei. Moreover, the θ_m values seem to be close to the first diffraction minima in the differential elastic cross-section.

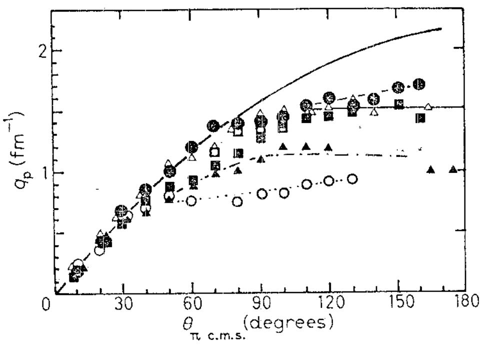

Fig. 6. – Angular behaviours of the momentum transfer q_p corresponding to the peak positions of the excitation functions. The symbols are those of fig. 5. Lines are drawn as a guide to the eye.

d) Excitation functions widths at forward angles seem to be almost equal to the Δ width value, while at large angle the peaks are as much narrow as heavier is the nucleus.

e) The ratio between the $(\pi^\pm, p)$ differential cross-section values corresponding to the excitation function maximum is, on the average, 9.05 ± 0.1 over the whole angular interval. This is, as is known, the Δ^{++}/Δ^0 ratio value and it means that, at the resonance, there is almost no contribution from the $T = \frac{1}{2}$ state in (π^-, p) interaction. Moreover, it is a good check of our analysis method.

f) Peak intensities of the excitation functions of light nuclei at forward angles seem to be Z multiple of the (π^+, p) value. In table I the light-nuclei peak intensities and their ratio R_p to the (π^+, p) values at 20° are reported. In fig. 7 the angular distributions of the normalized ratios $R_p^n = R_p/Z$ are shown. The

TABLE I. – *Peak intensities of the excitation functions of light nuclei at 20° and relative ratios R_p to the (π^+, p) values.*

	(π^+, p)	(π^-, p)	$(\pi^\pm, {}^2H)$	$(\pi^-, {}^3He)$	$(\pi^\pm, {}^4He)$	$(\pi^\pm, {}^{12}C)$	$(\pi^\pm, {}^{16}O)$
$d\omega)_{peak}$ $(\theta = 20°)$	33.87	4.17	33.65	26.30	76.87	275.16	318.87
	1	1/8.12	0.99	0.78 (^{a})	2.27	8.12	9.41
$= R_p/Z$	1	1/8.12	0.99	0.78 (^{b})	1.13	1.35	1.18

a) In this case R_p is defined as the ratio with $(\pi^-, n) \simeq (\pi^+, p)$ cross-section.
b) In this case $R_p^n = R_p/(A - Z)$.

$R^n_p(\theta_\pi)$ values range from about unity at forward angles, to about 0.1 ± 0.05 for all the examined nuclei.

g) The normalized ratios R^n_p, plotted as a function of $q^2_p a^2$, where q_p is the momentum transfer corresponding to the peak energy and a is the equivalent spherical radius of the nucleus, show (see fig. 8) form-factor-like behaviours. It is interesting to note that deuteron behaves differently from all the other light nuclei.

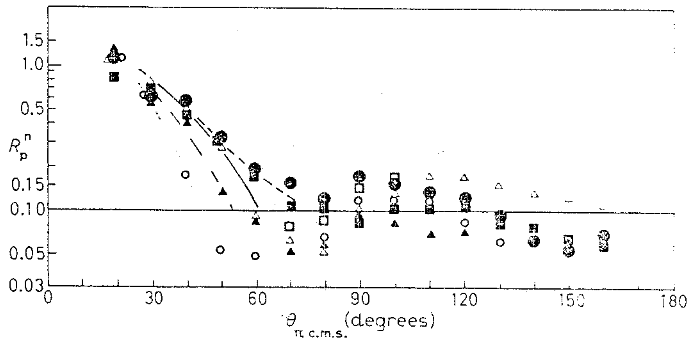

Fig. 7. – Angular behaviours of the Z-normalized ratio R_p between peak intensities of light-nuclei excitation functions and (π^-, p) values. The symbols are those of fig. 5. Lines are drawn as a guide to the eye.

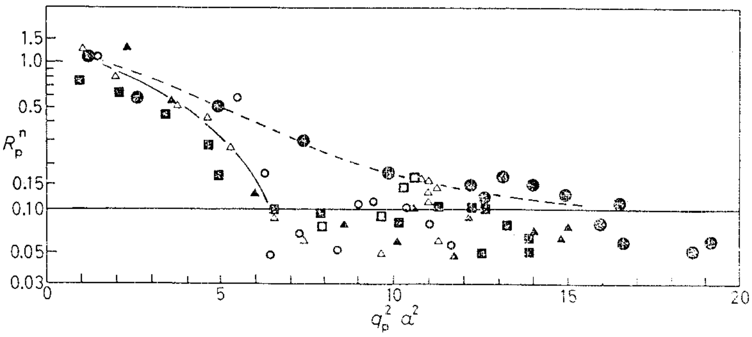

Fig. 8. – Normalized ratios R^n_p between peak intensities of light-nuclei excitation functions and (π^+, p) values, *vs.* $q^2_p a^2$, where q_p is the momentum transfer corresponding to the peak energy and a is the equivalent spherical radius of the nucleus. The symbols are those of fig. 5. Lines are drawn as a guide to the eye.

4. – Discussion.

The diffractive nature of pion scattering on light nuclei explains immediately many of the gross features of the excitation functions. On the basis of the impulse approximation the main features of the analysis can be qualitatively understood. Qualitatively (if on neglects Fermi motion and off-shell effects), the impulse approximation cross-section is

$$\left(\frac{d\sigma}{d\omega}\right)_{\text{nucleus}} = \left(\frac{d\sigma}{d\omega}\right)_{N} |F(q)|^2 ,$$

$$F(q) = \int \exp[i\boldsymbol{q}\cdot\boldsymbol{r}]\varrho(\boldsymbol{r})\, dr^3 = \int \frac{\sin(2kr\sin(\theta/2))}{2kr\sin(\theta/2)}\varrho(r)r^2\, dr ,$$

$$k = \sqrt{E^2 - m^2} .$$

For a given angle, the energy dependence of the π-nucleus cross-section is determined by the π-nucleon cross-section, on the one hand, and by the nuclear form factor, on the other hand.

For very small angles the energy dependence of $(d\sigma/d\omega)_N$ is dominant, for large angles that of the nuclear form factor. Furthermore, for large q the momentum transfer dependence of $F(q)$ is steeper, the larger the nucleus. This qualitatively explains the A-dependence of the peak positions in the excitation functions as well as the narrowing of the peak with increasing A at large angles.

As far as the peak intensities at forward angles are concerned, one expects in a single black-disc optical model for forward scattering

$$\frac{d\sigma}{d\omega} \sim Z^{\frac{4}{3}} .$$

For a finite small angle the nuclear form factor will lead to a weaker Z-dependence, thus explaining the experimental result. In this way, the points *a*), *b*) (partially), *d*), *f*) and *g*) of sect. **3** can be qualitatively explained.

However, the large energy differences between peaks positions and $\Delta(3,3)$ free at large angles remain unexplained.

On the other way, as far as the diffractive nature of π-nucleus angular distribution is concerned, the angular position of the first minimum is independent of the pion incident energy in pion-^{4}He scattering, whereas the first minimum takes place at approximately costant t in the pion-^{12}C case. This probably means, according to BINON *et al.* [15], that in the ^{4}He case this minimum is connected with the zero of the spin-nonflip π-N amplitude, rather than being of diffractive nature.

Moreover, it is well known that also the various improved optical potentials do not fit equally well large-angle data [20].

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[20] R. H. LANDAU: *Phys. Rev. C*, **15**, 2127 (1977); J. P. MAILLET, J. P. DEDONDER and C. SCHMITT: *Nucl. Phys. A*, **316**, 267 (1979); B. M. K. NEFKENS: preprint UCLA-10-P25-45 (1978); M. WAKAMATSU: *Nucl. Phys. A*, **312**, 427 (1978).

In this context, explaining all the features of the above-obtained excitation functions of differential cross-sections seems to ask for a more refined description of the π-nucleus scattering which gives more insight into the dynamics of the elementary processes.

A natural way of introducing many-body effects is the explicit inclusion of the isobar degrees of freedom of bound nucleons. For such a description of pion-nucleus scattering various more or less closely related models have been developed during the last few years: the isobar doorway model of Kisslinger and Wang ([21]), the collective model of Dilling and Huber ([22]) and the multiple-scattering approach of Lenz *et al.* ([23]); related aspects have been discussed by BROWN and WEISE ([24]).

Following the collective-model approach, KLINGENBECK *et al.* ([10]) and HÄNDEL *et al.* ([11]) have recently given a new description of pion-nucleus scattering, which treats the isobar on the same footing of the nucleon. The model has been applied to elastic and inelastic pion-carbon scattering and to elastic pion-deuteron scattering. The starting points is the assumption that the incoming pion excites a bound nucleon into the Δ-resonance, thereby creating an isobaric particle-hole ($\Delta\bar{\text{N}}$) configuration. Since the Δ interacts strongly with the surrounding nucleons, the various ($\Delta\bar{\text{N}}$) configurations of the same quantum numbers are coupled, thus leading to new eigenstates $|A_n^*\rangle$ of the whole nucleus. Those nuclear excitations can decay by emitting a pion, thereby leaving the target nucleus in its ground or one of its excited states, respectively.

The propagator of this system

$$G(\omega) = \{H_{\Delta\text{N}}(\omega) - \omega\}^{-1} \tag{1}$$

contains an (energy dependent) ΔN interaction, $V_{\Delta\text{N}}$, and can be expressed the eigenstates $|A_n^*\rangle$ of the ΔN Hamiltonian as

$$G(\omega) = \sum_n \frac{|A_n^*\rangle\langle A_n^*|}{\varepsilon_n^{J^\pi}(\omega) - \omega}, \tag{2}$$

where $\varepsilon_n^{J^\pi}(\omega)$ denotes the complex eingenvalues of the A^* excitation.

([21]) L. S. KISSLINGER and W. L. WANG: *Phys. Rev. Lett.*, **30**, 1071 (1973); *Ann. Phys.* (*N. Y.*), **99**, 374 (1976).
([22]) M. DILLIG and M. G. HUBER: *Phys. Lett. B*, **48**, 417 (1974); in *Mesonic Effects in Nuclear Structure*, edited by K. BLEULER (Mannheim, 1975), p. 80; *Interaction Studies in Nuclei*, edited by H. JOCHIM and B. ZIEGLER (Amsterdam, 1975), p. 781.
([23]) F. LENZ: *Ann. Phys.* (*N. Y.*), **95**, 348 (1976); F. LENZ and E. J. MONIZ: *Phys. Rev. C*, **12**, 909 (1975); F. LENZ: in *Proceedings of the International Conference on Meson-Nucleon Physics*, edited by P. D. BARNES, R. A. EISENSTEIN and L. S. KISSLINGER (Carnegie-Mellon, 1976), p. 403; M. HIRATA, F. LENZ and K. YAZAKI: SIN preprint (1976); M. HIRATA, J. H. KOCH, F. LENZ and E. J. MONIZ: SIN preprint (1977).
([24]) G. E. BROWN and W. WEISE: *Phys. Rep.*, **22**, 909 (1975); W. WEISE: *Nucl. Phys. A*, **278**, 402 (1977).

The sum of these A^* resonances, which differ in their position and width, as well as in their multipolarity and parity, builds up the scattering cross-section.

The relevant role of $V_{\Delta N}$ becomes obvious if one considers the limiting case of no ΔN interaction; then the quasi-free scattering amplitude is recovered from eq. (1):

$$\lim_{v_{\Delta N}\to 0} G(\omega) \to G_{qf}(\omega) = \{\varepsilon_{free} - \omega\}^{-1} . \tag{3}$$

Thus the deviation from quasi-free scattering amplitudes reflects the effects of the ΔN interaction. In particular, the detailed structure of the A^* resonances is expected to manifest itself in a sensitive manner at backward angles, where the deviations from the quasi-elastic picture are expected to be more pronounced.

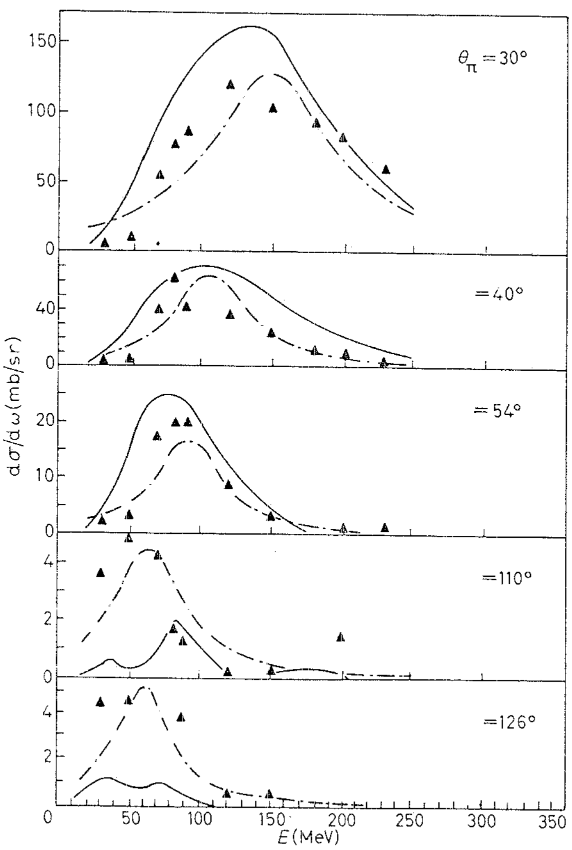

Fig. 9. – Excitations functions of (π, ^{12}C) differential elastic cross-sections. Triangles have the same meaning as in fig. 4. The solid lines represent the prediction of the collective resonance model ([10]). The dot-dashed curves are Lorentz lines.

As far as the $\Delta\bar{N}$ interaction is concerned, since very little is known about it it, is has been constructed in a frame of a one-boson exchange (OBE) model, taking into account explicitly additional contributions resulting from ρ and ω exchange.

The coupling between the various $(\Delta\bar{N})$ configurations is dominantly due to their individual coupling to the pion-nucleus continuum channels. In the OBE description, this manifests itself by the fact that the exchanged pion can be a real pion, propagating on its mass shell and, therefore, leading to a complex and energy-dependent ΔN interaction.

Summarizing the features of this approach, the excitation spectrum of a complex nucleus in the region of the Δ-resonance is characterized by a number of broad resonances of different multipolarity. Because of the similarity in the description, the occurrence of these A^* collective resonances can be considered as giant (3-3) or giant isobaric resonances (GIR).

The significant point, which allows for a connection with the main feature of the experimental excitation spectra of differential cross-sections, is that an A^* resonance, whose energy is pushed down below the free $\Delta(3,3)$ position, may be the dominant one, as stressed by HÄNDEL *et al.* in ref. ([11]).

On the other hand, drastic variations in the excitation functions of differential cross-sections at some large angles, due to the interference of collective resonances of different multipolarities, are clearly observable, as pointed out by KLINGENBECK *et al.* (quoted in BOSCHITZ, ref. ([10])).

In fig. 9 we have reported the excitation functions at some angles for pion-carbon scattering, as resulting from our analysis of the experimental data, together with the predictions of the collective resonance model. The qualitative

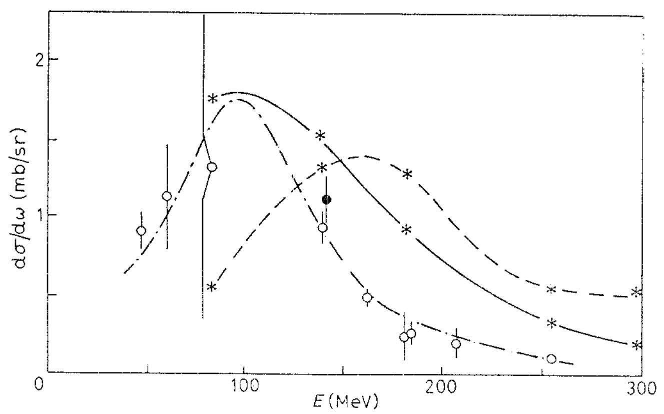

Fig. 10. – Excitation functions of $(\pi, {}^2H)$ differential elastic cross-sections at $\theta = (155 \pm 5)°$. Experimental data: ref. ([16]). Symbols: • $(\pi^-, {}^2H)$, ○ $(\pi^+, {}^2H)$. The crosses and the solid and the dashed lines represent the predictions of the collective resonance model obtained for different ΔN interaction parameters ([11]). The dot-dashed curve is a Lorentz line.

agreement among shapes, widths and positions seems to indicate that the basic ideas about the excitation of isobaric nuclear resonances are realistic.

A similar qualitative agreement can be found for the excitation function in pion-deuteron scattering. In fig. 10 our analysis of the large-angle experimental data is reported, together with the collective resonance model prediction, obtained from the angular distributions at various energies calculated by HÄNDEL *et al.* in ref. (11). The peak position, far from the free Δ-resonance, is reproduced. In the figure another excitation curve is also reported peaked at an energy higher than in the experimental result. It corresponds to a different choice of the coupling constants $f^2_{\rho NN}/4\pi$, $f^2_{\rho\Delta N}/4\pi$, $f_{\rho\Delta\Delta}/4\pi$ used in the construction of the one-boson exchange ΔN potential and thereby it corresponds to different angular distributions (11).

This indicates, as stressed before, that the collective resonance model results to be strongly dependent on the model assumptions: for example, on the coupling constants, or on oscillator parameters, or on the size of the configuration space.

Despite the qualitative agreement found in the two cases now considered, in order to explain all the physical features of the excitation functions of differential cross-sections, the influence of those uncertainties must be thoroughly investigated.

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● RIASSUNTO

Sono state dedotte le funzioni di eccitazione delle sezioni d'urto differenziali di diffusione elastica di mesoni π da ^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{12}C e ^{16}O, analizzando nel s.c.m. tutti i dati sperimentali esistenti con polinomi di Legendre. Gli andamenti energetici sono stati dedotti calcolando le curve di Lorentz di massima verosimiglianza con il metodo di Montecarlo. Tra le caratteristiche generali si nota che le funzioni di eccitazione hanno andamento risonante con il massimo ad energie assai più basse della posizione della risonanza libera Δ. Lo spostamento è dipendente sia dall'angolo sia da A. Una possibile spiegazione dello spostamento a basse energie è dato nell'ambito dei recenti sviluppi del modello delle risonanze isobariche collettive.