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F. Balestra[*], L. Busso[*], R. Garfagnini[*], C. Guaraldo, A. Maggiora, G. Piragino[*] and R. Scrimaglio: ELASTIC BACKWARD SCATTERING OF POSITIVE PIONS FROM ^{12}C AT 23, 29 AND 35 MeV.

Pion-nuclear reactions at low energies are expected to yield more information about the nucleus than reactions at energies near the πN(3, 3) resonance. This expectation arises simply from the fact that at resonance energies ($T_\pi \simeq 120 \div 250$ MeV), the nucleus looks black to the incoming pion, more subtile details of the nuclear interaction being masked by the dominance of the resonance. An indication that this expectation may not be totally naive is that a first order optical potential constructed from free πN scattering amplitudes adequately describes elastic scattering data above 100 MeV but such a potential fails badly at 50 MeV(1, 2). At low energies ($0 \div 50$ MeV), where the dominance of the (3, 3) resonance is less pervasive, the nucleus is more transparent to the pion and the elastic scattering data are much more sensitive to nuclear medium effects such as nucleon-nucleon correlations and true absorption of the pion. Because of the above situation, in these last three years significant experimental and theoretical steps have been made in the study of low energy pion elastic scattering. Beside old ($\pi^\pm$, ^{12}C) and (π^+, ^{16}O) data(3) at 30 MeV and ($\pi^\pm$, ^{4}He) data(4) at 51 MeV, data at 30, 40 and 50 MeV $\pi^\pm$ from various targets including ^{12}C, ^{16}O, ^{28}Si, ^{40}Ca, ^{56}Fe, ^{90}Zr and ^{208} Pb are now available (even if mostly preliminary)(1, 5 ÷ 10). Recent developments in the theoretical analysis including better kinematics and nuclear structure effects have shown considerable sensitivity of the elastic data to these phenomena(8, 11÷23).

In the effort to learn more about these questions, we have studied the elastic scattering of π^+ from ^{12}C at 23, 29 and 35 MeV in an angular region ($150^\circ \div 180^\circ$) not covered by the existing data and in which theoretical models exhibit significant discrepancies.

The experimental data were taken at the LEALE pion beam facility of Laboratori Nazionali di Frascati. The pion beam is photoproduced on a graphite target by a Bremmstrahlung beam obtained, in turn, by the electrom beam of Frascati Linac on a tugsten radiator.

The pion channel delivers about 10^5 pions per second at a nominal energy of 41 MeV, corresponding to an energy of 33 MeV at the centre of the target, with a 50 μA at 320 MeV primary current(24). In this experiment we accepted a beam with a $\pm$ 15% momentum distribution around the nominal value, in order to carry out simultaneously measurements for more than one incident energy.

The experimental apparatus, described in detail in ref. (25, 26) consisted of a magnetic spectrometer with a helium filled self-shunted streamer chamber for identifying scattering events by detecting both the incident and scattered pion tracks.

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A hodoscope of thin scintillation counters defined the number of pions deflected by the magnet and impinging on the experimental target. The target was a pressed natural carbon sheet of 99.9% purity and 558 mg/cm^2 thickness. Pions scattered in the backward direction by the target were deflected with opposite curvature and were detected by two large scintillation counters in coincidence with the odoscope.

The coincidence triggered the high voltage pulse on the streamer chamber and the command circuits of two cameras, thus allowing to photograph the scattering events.

A schematic layout of the experimental apparatus is presented in Fig. 1.

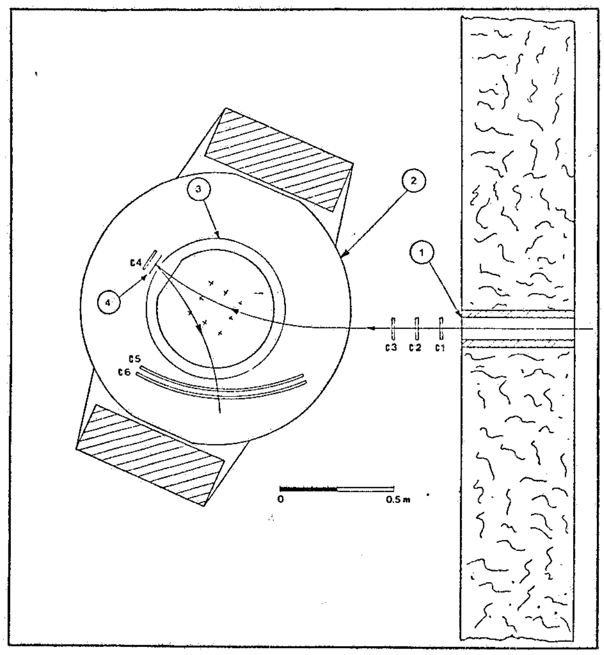

FIG. 1 - Lay-out of the experimental apparatus: 1) collimator, 2) magnet, 3) streamer chamber, 4) target, 5) C_1-C_6 counters.

In order to avoid the pile-up of tracks of incoming pions on the photographs and to reduce the background in the counter telescope, we chose an incident intensity of about 10^2 pions per second at the target position.

The pion dose has been corrected for the counters efficiencies ($>$ 90%) and for contamination of the pion beam due to positrons and decay muons.

The contamination has been measured by a time of flight tecnhique, with a 1.34 meter long basis at 15.8, 20.4, 27.5, 33.1 MeV central target energies. In these measurements the momentum band accepted was $\pm$ 1%.

A typical contamination spectrum is presented in Fig. 2.

The hystogram has been fitted with gaussian curves and the contamination has been evaluated by the relative ratios of muons and positrons gaussian areas on the total area. In the lower part of the figure is reported the resulting energy behaviour of total muons plus positrons contamination.

The probability for the scattered pions to be lost as a consequence of decay in the distance between the target and the final counters C_5C_6 has been evaluated to be negligible.

The detection efficiency of the apparatus has been evaluated as a function of the incident pion energy, the scattered energy and the scattering angle by means of a Monte Carlo calculation which simulates both the incident pion beam and the scattering (elastic and inelastic) events. The Monte Carlo distributions of particles on the target and on the detectors C_5C_6 (see Fig. 1) have been compared with the experimental ones and the agreement turned out to be quite satisfactory.

The technique of track reconstruction in space and data analysis procedure are described in ref. (25, 27). The energy resolution of a track depends on the energy lost in the target and is a

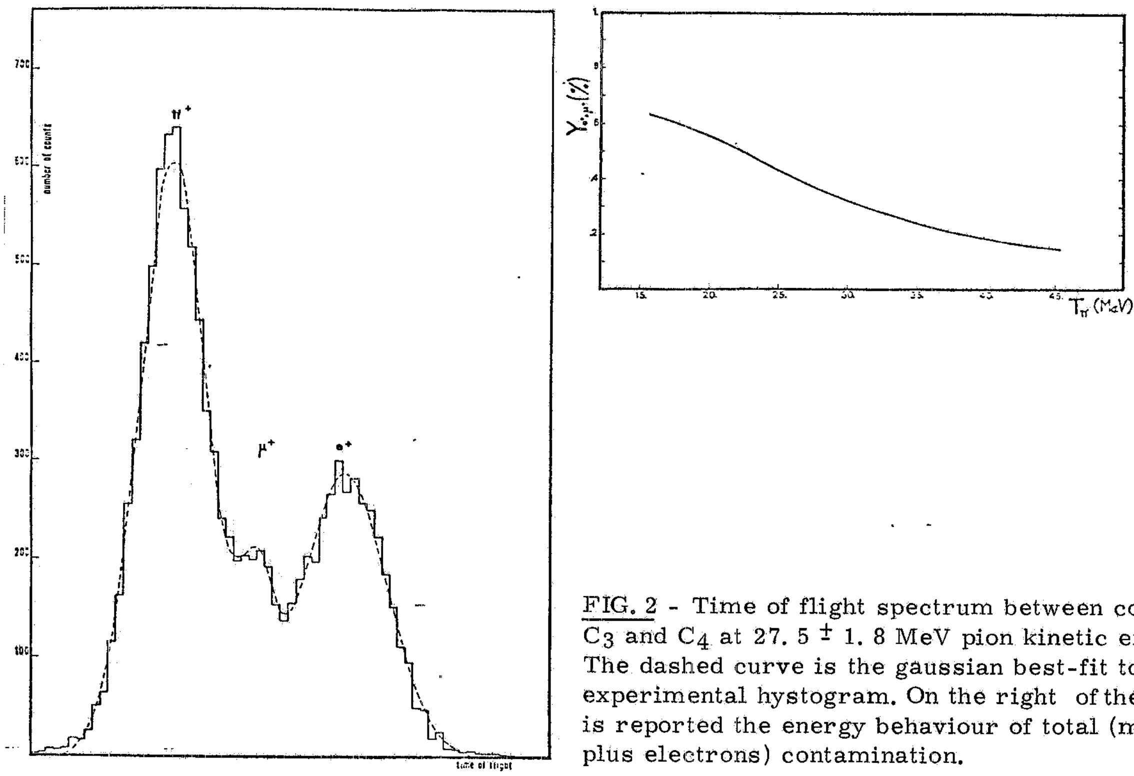

FIG. 2 - Time of flight spectrum between counters C_3 and C_4 at 27. 5 ± 1. 8 MeV pion kinetic energy. The dashed curve is the gaussian best-fit to the experimental hystogram. On the right of the figure is reported the energy behaviour of total (muons plus electrons) contamination.

function of a number of parameters: track lenght in the streamer-chamber, number of measured points along the track, uncertainty in measuring points, value of curvature radius. An overall energy resolution (FWHM) $\Delta T/T \simeq 6\%$ (- sufficient for clearly selecting the elastic scattering -) was obtained for a 30 cm average track lengh, 15 measured points, ± 0. 2 mm uncertainty in locating points, curvature radius 1200 mm (corresponding to 33 MeV pion kinetic energy). The reconstructed scattering angle is negligibly affected by reconstruction errors (± 0. 5°) and by multiple scattering in target.

A computer routine (LEVEL) which takes advantage of the angular and energy informations (with their errors) statistically assigns the events to the elastic or to the inelastic channels by evaluating the normalized probability for the event to belong to each of the above processes. 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 pion.

After correcting for the effective solid angle, a total of 457 backward scattering events was used for evaluating the elastic cross sections reported in this paper. The data was grouped in three energy intervals: 23±3 MeV, 29±3 MeV, 35±3 MeV and in three angular bins 161°±3°, 168°±4°, 176°±4°. The corresponding elastic differential cross sections are listed in Table I.

TABLE I - (π^+, ^{12}C) elastic differential cross section.

	T_π = 23 ± 3 MeV	T_π = 29 ± MeV	T_π = 35 ± 3 MeV
θ_{lab} (degrees)	$\frac{d\sigma}{d\Omega}\Big\vert_{lab}$ (mb/sr)	$\frac{d\sigma}{d\Omega}\Big\vert_{lab}$ (mb/sr)	$\frac{d\sigma}{d\Omega}\Big\vert_{lab}$ (mb/sr)
161° ± 3°	5. 55 ± 3. 41	5. 07 ± 1. 74	3. 23 ± 1. 16
168° ± 4°	7. 37 ± 2. 63	5. 69 ± 1. 04	3. 37 ± 1. 08
176° ± 4°	5. 61 ± 3. 13	5. 64 ± 1. 12	5. 82 ± 1. 22

The errors quoted on the cross sections were deduced from propagation of statistical errors on incoming dose and backward events. The large errors at lower energy reflect the poor statistics in that energy region of the incident spectrum.

The large and backward angle data for positively charged pions elastically scattered from ^{12}C is presented in Fig. 3. In the Figure is also reported the 28.4 MeV ^{12}C elastic angular distribution of UBC-TRIUMF Collaboration(8).

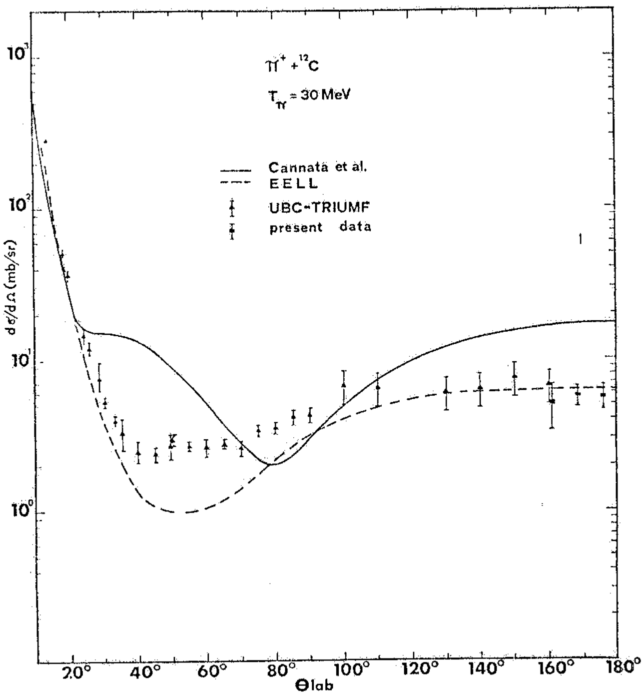

FIG. 3 - The elastic backward scattering data measured in the experiment (Torino-Frascati Collaboration) together with the angular distribution of TRIUMF(8) are compared to theories. The solid line is the improved Kisslinger potential of Cannata et al(28). The dotted line is the result of a calculation by F. Cannata with the only EELL effect in the original gradient potential.

The back angle data are in agreement with the large angle general shape of the UBC-TRIUMF elastic distribution. In particular, the 160° value agrees, within the error, with the TRIUMF result. It must be noticed, however, that the agreement is much better with the values originally published (see ref. (7)) by the same group.

The figure also shows the theoretical predictions made using two potentials of current interest: the modified Kisslinger potential of Cannata et al(28) and the pionic atom potential of Ericson and Ericson(29). The first one differs from the originally proposed gradient potential(30) by containing an additional term proportional to the Laplacian of the nuclear density. This term, because of its surface-peaked nature, affects mainly the large angle scattering. In particular, the agreement is fairly good with our previous backward scattering results at 60, 70 and 80 MeV(31÷33). However, the most striking feature of the actual comparison, is that also this improved optical potential fails badly in reproducing lower energy pion elastic scattering.

As we observed in the introduction, we are presented with a situation in which none of the "simple" theories can describe the data, even with moderate excursions of the parameters from the values-predicted by the free π-N phase shifts. Though good fits can be obtained, the resulting potentials are not physically reasonable(1, 2). Second order corrections to the first order optical potential, which take into account effects such as nucleon-nucleon correlations, true absorption of pions, nucleons binding, Pauli blocking of some intermediate states, must be made.

It was first pointed out by Ericson and Ericson(29) that short range correlations between nucleons play an important rôle in determining the way in which a low energy pion propagates through a nucleus of low density. The essential effect is that the local p-wave pion field is a modification of the external field due to the presence of dipole emitters (nucleons) in the same way that a free electromagnetic field would be modified by the presence of dielectric material. The local fields thus obviously depend on the correlated position of the nucleons or atoms. In the electromagnetic case, the dipole scattering of electromagnetic waves through a dense homogeneous medium of polarizable atoms was calculated by Lorentz and Lorenz. This gives rise to an observable non linear dependence of the refractive index on the density (the Lorentz-Lorenz effect). Ericson and Ericson were led to a pion optical potential in which the gradient term of the original Kisslinger potential is replaced by the same non-linear density renormalization of the Lorentz-Lorenz effect:

$$\nabla \varrho \nabla \longrightarrow \nabla (\varrho / 1 + \frac{4\pi}{3} \xi \varrho) \nabla \qquad (1)$$

where the parameter ξ is related to the nucleon correlation function. In Fig. 3 is reported the result obtained solving[34] the relativistic Schrödinger equation with the optical potential including the only Ericson-Ericson - Lorentz-Lorenz effect described by equation (1). Large angle and backward data are well reproduced by the model, stressing the important role of nucleon-nucleon correlations in low energy pion nucleus scattering. However, the potential misses the Coulomb-nuclear interference region making clear the necessity of taking into account a further nuclear effect.

An outstanding feature at essentially zero energy is that the energy levels of pionic atoms have finite widths, because pion can be absorbed by nuclei, thereby dissipating a considerable amount of energy. The high momentum transfers involved (~525 MeV/c) could be account for if two (or more) nucleons took place in the absorption process. These considerations led Ericson and Ericson to include a semi-phenomenological term in their optical potential (1) due to coherent scattering on nucleon pairs. This is supposed to present not double scattering of the π by the pair, but, following ad idea of Brueckenr[35], absorption and reemission of the π. In other words, Brueckner remarked that nuclei absorb atomic pions: this account for the level widths. But if a nucleus absorbs and then reemits a slow pion, this contributes to elastic scattering amplitude. In view of this dramatic effect a generalization of the absorptive term in the optical potential to positive energies slightly above threshold has recently been given by Landau and Thomas[16,8].

Fig. 4 shows our back angle data, together with the UBC-TRIUMF distribution, and the theoretical prevision of Landau and Thomas, made using a model with true pion absorption included but

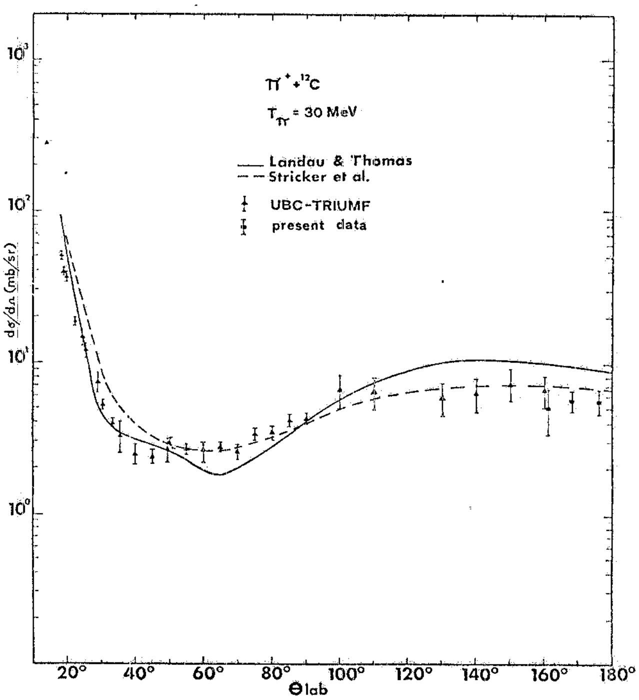

FIG. 4 - The elastic backward scattering data measured in the experiment together with the angular distribution of TRIUMF[8] are compared to theories. The solid line is the calculation by Landau and Thomas[8] using a model with true pion absorption included but without the EELL effect. The dotted line is the preliminary calculation by Stricker[22] taking into account both nucleon-nucleon correlations and true pion absorption.

without the EELL effect. The inclusion of absorption enhances the cross sections in the Coulomb-nuclear interference region respect to the values obtained according to NN correlations effect, thus fitting the TRIUMF experimental data, but misses our large angle results.

In addition, Fig. 4 shows also the result of a preliminary calculation of Stricker et al[22], in which have been taken into account both nucleon-nucleon correlations and true pion absorption. The model describes qualitatively the angular distribution and in particular reproduces the backward angle data, with a less agreement for the forward results and the minimum position.

In conclusion, this backward angle low energy experiment compares favourably with an optical model in which second order corrections are needed, the most challenging effect looking to be the nucleon-nucleon correlations described by the Ericson-Ericson-Lorentz-Lorenz expression.

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