Elastic scattering of 13.9 MeV positive pions from ^{12}C

D. R. Gill, K. L. Erdman, and E. W. Blackmore
TRIUMF, Vancouver, British Columbia, Canada V6T 2A3

W. Gyles, B. M. Barnett, C. Oram, and R. R. Johnson
University of British Columbia, Vancouver, British Columbia, Canada V6T 1W5

T. G. Masterson
Nuclear Physics Laboratory, University of Colorado, Boulder, Colorado 80309

N. Grion
Instituto Nazionale di Fisica Nucleare, Trieste, Italy

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Differential cross sections for elastic scattering of 13.9 MeV π^+ from ^{12}C have been measured for $30° < \theta_{lab} < 150°$. The data agree well with coordinate space optical potential calculations.

[NUCLEAR REACTIONS $^{12}C(\pi^+,\pi^+)^{12}C$. $E_{\pi_{lab}} = 13.9$ MeV $30° < \theta_{lab} < 150°$, comparison with coordinate space optical potential calculations.]

The low-energy (0–100 MeV) region is the testing ground for optical potential theories of pion nucleus scattering because the pion mean free path is large, of the order of the nuclear size. These theories incorporate pion-nucleon scattering parameters into a multiple scattering framework.[1–3] Absorption parameters have been empirically determined both from pionic atom data and from 50 MeV elastic scattering data.[4,5] They differ by about a factor of 2. The lowest energy measurements[6] made to date are at approximately 30 MeV. The present scattering experiment was carried out on ^{12}C at 13.9 MeV to determine differential scattering cross sections in this energy region and to examine what absorption properties are required at this low energy.

The experiment was performed on the TRIUMF M13 channel which had a flux of 10^5 π^+ sec^{-1} at $T_\pi = 14$ MeV when 20 μA of protons were delivered to the production target. The π^+:μ^+:e^+ composition of this beam was, respectively, 55:24:21%. The scattering apparatus, similar to that used previously,[7] is shown schematically in Fig. 1. Each scattering arm consisted of a Si(Li)-sodium iodide (NaI) ΔE-E telescope preceded by a 1 mm thick plastic (NE102) direction defining scintillation counter.

The overall resolution of this detection system, including the contribution from the channel resolution, varied between 1 and 2 MeV full width at half maximum as a function of scattering angle of the experiment. Any pions inelastically scattered to the first excited state of ^{12}C at 4.4 MeV were, therefore, well separated from the elastically scattered pions. Very little evidence of inelastic scattered pions was seen in our spectra. This was due to three circumstances: First, these pions would have had an energy of 9.5 MeV and therefore a substantial fraction were stopped or scattered before reaching the NaI detector; second, a large fraction decayed in the telescope; and third, the inelastic cross section is small at these energies. The target was 0.115 g/cm^2 natural carbon and the mean pion energy at the center of the target was 13.9 MeV. The pion flux was monitored with an ion chamber and with two plastic scintillators, S1 and S2, in the beam downstream from the scattering target (see Fig. 1). The use of the Si(Li)-NaI counter combination gave excellent particle identification, as seen in the two dimensional spectrum shown in Fig. 2 for pions scattered to $\theta_{lab} = 30°$, and allowed separa-

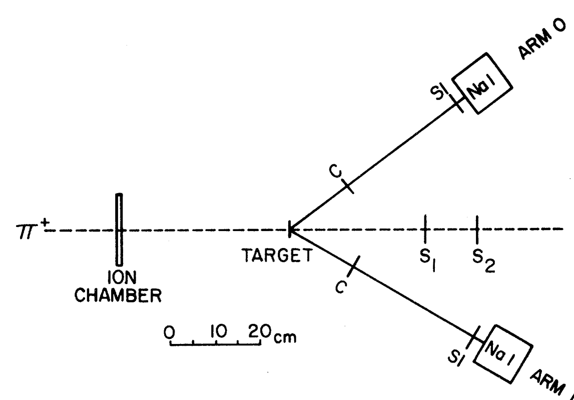

FIG. 1. Experimental apparatus. An ion chamber and two in-beam plastic scintillators monitored the pion beam. Two counter telescope systems measured the scattered pion flux.

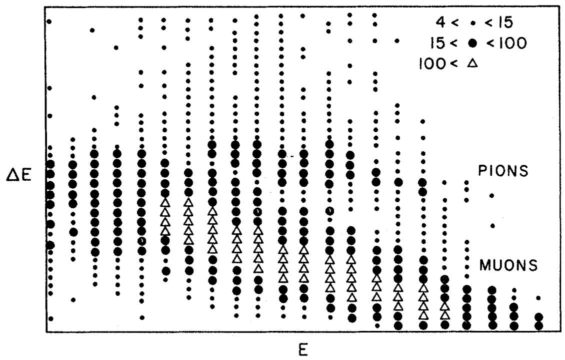

FIG. 2. E vs ΔE spectrum for scattered particles at $\theta_{lab} = 30°$, clearly showing separation between pions and muons.

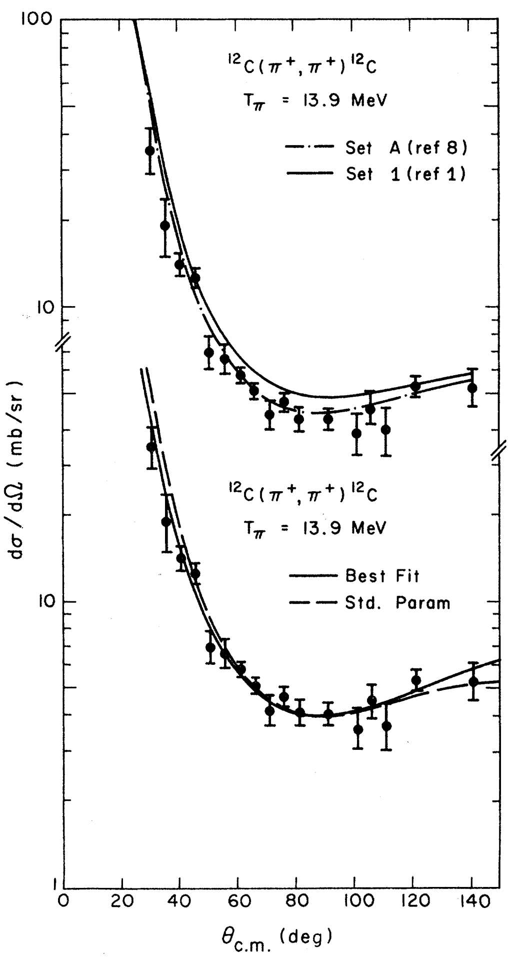

FIG. 3. Top: 13.9 MeV π^+ ^{12}C differential cross sections compared with calculations with MSU potential. Solid curve—set 1 from Ref. 1; dash-dot curve—set A from Ref. 8. Bottom: 13.9 MeV π^+ ^{12}C differential cross sections compared with calculations with Colorado potential. Solid curve—best fit; dashed curve—standard parameters. Errors shown are statistical only. Absolute normalization errors are discussed in text.

tion of the scattered pions from the in-flight decay muons at forward angles.

The 13.9 MeV π^+ ^{12}C elastic differential cross section is displayed in Fig. 3 and the data tabulated in Table I. The error bars that are shown are statistical only. The normalization is absolute, based on pion flux as determined from both the ion chamber and the in-beam scintillators. The pion fraction of the beam was monitored by time-of-flight samples of the beam at random times during each run. The estimated systematic error, i.e., the absolute normalization error, is $\pm 15\%$. In addition the in-flight decay muons cause further uncertainty for the small angle data where the background increased as illustrated in Fig. 2. In the worst case the pion peak to valley separation in the ΔE-E spectrum was 4:1. This background raised the systematic (absolute normalization) error estimate for the 30°, 35°, and 40° data points to $\pm 25\%$.

The solid curve in Fig. 3 (top) is the result of a calculation with the Michigan State (MSU) potential using their set 1 parameters.[1] Agreement with the data is not good ($\chi^2/N = 5.7$). A similar result is achieved using the modified MSU potential[8] (p-wave absorption included in the Ericson-Ericson effect[9]) and their "extrapolated (to 50 MeV) set A" parameters[8] ($\chi^2/N = 5.0$). An improved agreement with the data ($\chi^2/N = 1.6$) is obtained by using parameters derived from pionic atom data (set A).[8] This latter calculation appears as the dot-dash curve in Fig. 3 (top). In the calculations listed in Table II, the differences between the single nucleon parameters used are small. It is seen from this table though that

TABLE I. Differential elastic scattering cross sections for 13.9 MeV π^+ on ^{12}C in the center of mass.

$\theta_{c.m.}$	$\frac{d\sigma}{d\Omega}$ $\left(\frac{mb}{sr}\right)$	$\Delta\sigma$ (statistical)	$\Delta\sigma$ (total)
30.39	35.20	±6.46	±10.91
35.45	18.95	4.23	6.36
40.51	13.94	1.29	3.72
45.56	12.62	0.95	2.12
50.60	6.89	0.89	1.37
55.64	6.55	0.74	1.23
60.68	5.72	0.33	0.92
65.72	5.05	0.31	0.82
70.74	4.20	0.48	0.78
75.76	4.65	0.32	0.76
80.77	4.07	0.38	0.72
90.79	4.05	0.34	0.70
100.77	3.63	0.58	0.79
105.76	4.49	0.61	0.92
110.74	3.72	0.70	0.89
120.68	5.24	0.45	0.90
140.50	5.23	0.74	1.07

TABLE II. Absorption parameters for π^+ scattering from ^{12}C at 13.9 MeV obtained with the MSU potentials (Refs. 1 and 8). Statistical errors only.

Parameters	χ^2/N χ^2/degree of freedom	$\mathrm{Re}B_0$ (fm^4)	$\mathrm{Im}B_0$ (fm^4)	$\frac{\mathrm{Re}B_0}{\mathrm{Im}B_0}$	$\mathrm{Re}C_0$ (fm^6)	$\mathrm{Im}C_0$ (fm^6)	$\frac{\mathrm{Re}C_0}{\mathrm{Im}C_0}$
Set 1	5.7	−0.17	0.17	−1	−0.79	0.79	−1
Set 1 "fit"	1.7	−0.07	0.07	−1	−0.48	0.48	−1
Set A	1.6	0.007	0.08	0.088	0.287	0.93	+0.31
Set C	1.7	0.007	0.19	0.037	0.287	0.34	0.84
Extrapolated	5.0	−0.02	0.25	0.08	0.36	1.2	0.3

better agreement with the data is achieved when the absorption parameters are of reduced magnitude.

The bottom half of Fig. 3 shows a comparison of the same data with calculations made with the Colorado potential of Rost *et al.*[2] The dashed curve uses their standard parameters (see Table III) and it agrees with the data very well ($\chi^2/N=1.9$). The solid curve was obtained by varying the volume (B_0) and surface (C_0) absorption and the Thies Lorentz-Lorenz (ξ) terms until a best fit was obtained. The χ^2 per degree of freedom improved to 1.3 but there is little qualitative difference in the calculated differential cross section. The best fit parameters do suggest a smaller ratio (-0.16 ± 0.05) for the real and imaginary parts of the volume absorption than the standard parameter ratio or the pionic atom studies,[9] which set $\mathrm{Re}B_0/\mathrm{Im}B_0=-1$. Our best fit value is almost compatible statistically with no volume absorption and indeed setting $\mathrm{Re}B_0=0$ makes no significant change in either the quality of the fit to the differential cross section or the computed χ^2. The fitting procedure also found that the preferred value for the Thies Lorentz-Lorenz parameter was zero within statistics at this energy.

The analysis with the Colorado potential was repeated including systematic errors. The larger error bars resulted in a factor of 3 decrease in χ^2/N values but negligible change in the best fit differential cross section curve. The ratio of real to imaginary volume absorption terms was more poorly defined ($\mathrm{Re}B_0/\mathrm{Im}B_0=-0.1\pm0.2$) and still compatible with no volume absorption. Again here the best fit for the Thies Lorentz-Lorenz parameter was zero within errors.

In conclusion, the 13.9 MeV π^+ ^{12}C elastic differential cross section data are well represented by standard optical potentials. Fitting procedures suggest that the absorption parameters are different from those required for 30–50 MeV elastic scattering data. Additional low energy scattering and absorption experiments will be required to determine the effects of pion absorption in the 0–20 MeV energy region.

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TABLE III. Absorption parameters for π^+ scattering from ^{12}C at 13.9 MeV obtained with the Colorado potential of Rost *et al.* (Ref. 2).

Parameters	χ^2/N	$\mathrm{Re}B_0$ (fm^4)	$\mathrm{Im}B_0$ (fm^4)	$\frac{\mathrm{Re}B_0}{\mathrm{Im}B_0}$	$\mathrm{Re}C_0$ (fm^6)	$\mathrm{Im}C_0$ (fm^6)	ξ	Errors
Standard	1.9	−1.65	1.65	−1	0	0	0	Statistical
Best fit	1.3	-0.9 ± 0.3	5.6 ± 0.3	-0.16 ± 0.05	2.2 ± 0.1	0.5 ± 0.1	0.0 ± 0.1	Statistical
Standard	0.6	−1.65	1.65	−1	0	0	0	Statistical +systematic
Best fit	0.4	-0.7 ± 1.0	5.9 ± 1.9	-0.1 ± 0.2	2.2 ± 0.4	0.3 ± 0.4	0.0 ± 0.6	Statistical +systematic

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