PHYSICAL REVIEW C VOLUME 22, NUMBER 2 AUGUST 1980

True absorption and scattering of π^+ on carbon in the (3,3) resonance region

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(Received 27 February 1980)

The cross section for true absorption of positive pions in carbon was obtained from experiments at 85, 125, 165, 205, and 245 MeV. The results are compared with theoretical calculations. The total π^+-carbon cross section is decomposed into its major channels: elastic scattering, inclusive inelastic scattering, true absorption, and single charge exchange, as a function of pion energy. The inclusive π^+ angular distribution was also measured and the results suggest that quasifree processes play an important role for backward scattering.

[NUCLEAR REACTIONS $^{12}C(\pi^+, \pi^{+\prime})$, ($\pi^+$, absorption) $E = 85$–245 MeV, measured $\sigma(E, \theta)$, deduced decomposition σ_{react}.]

The pion-nucleus total cross section was studied systematically in recent years over the (3, 3) resonance region.[1] At the same time, the elastic scattering of pions from nuclei was studied and methods to calculate this process were developed which give satisfactory agreement with the data at these energies.[2,3] From these results the pion-nucleus reaction cross section is deduced. There is, however, very little information on the way the reaction cross section is decomposed into its major channels: the inelastic scattering (to bound and unbound final states), single and double charge exchange, and pion absorption (where there are no pions in the final state). This information is important not only for understanding the pion-nucleus reaction cross section but also for interpretation of the elastic scattering. The problem of how to deal with true absorption in the analysis of elastic scattering has not yet been completely solved[4] and experimental information on the true absorption cross section will be an important contribution to the solution of this problem. In order to obtain this decomposition we carried out a systematic study of the pion absorption and scattering processes on several nuclei. Data for π^+ and π^- at 125 MeV for several nuclei have been published elsewhere.[5] Bellotti *et al.* measured the absorption cross section on carbon at 130 MeV (Ref. 6) and a compilation of earlier measurements in emulsions is given by Ginocchio.[7] In the present work we report the results for pion-carbon interaction in the (3, 3) resonance region.

The absorption cross sections were obtained by combining the results of two experiments carried out at the accelerator of the Swiss Institute of Nuclear Research (SIN). The incident pion energies were 85, 125, 165, 205, and 245 MeV, and the carbon target thickness was 1.8 gr/cm^2.

The first experiment was done in a transmission geometry normally used for the measurement of total cross sections. Several disk-shaped plastic scintillators were positioned behind the target and covered solid angles ranging from 0.1 to 0.7 sr. These detectors were used to measure the number of charged pions removed from the incident flux by the target. Three processes can remove charged pions from the incident flux:

(a) pion absorption in the target,

(b) single charge exchange reaction in the target, and

(c) scattering of charged pions (elastic and inelastic) to angles larger than Ω, the solid angle subtended by the disk counter.

Denoting the cross section for these processes by σ_{abs}, σ_{cx}, and $\int_\Omega^{4\pi} (d\sigma_{sc}/d\Omega) d\Omega$ respectively, the result of the transmission experiment is the sum of those cross sections: $\sigma_{abs} + \sigma_{cx} + \int_\Omega^{4\pi} (d\sigma_{sc}/d\Omega) d\Omega$.

In order to obtain the third contribution we measured in a second experiment the angular distribution for scattering (elastic and inelastic) of charged pions. The scattered pions were detected with plastic scintillator telescopes and separated from other charged particles through measurement of the energy loss in the detectors. Pions that were stopped in the telescope were also identified by observing the muon decay after the pion came to rest. The beam was monitored by two plastic scintillator counters positioned upstream from the target. Deadtime was typically 1%. The muon and electron contamination in the beam was measured by time of flight and was in the range of 1–7%. Further experimental details may be found in Ref. 5. The angular distribution was measured in steps of 5°–10° with angular resolution of 5.2°. The differential scattering cross sections $d\sigma_{sc}/d\Omega$ obtained from these experiments were integrated over the angular range from 180° to the angle subtended by the disk counter in the first experiment: $\int_{\Omega}^{4\pi} (d\sigma_{sc}/d\Omega)d\Omega$. By subtracting this result from that of the first experiment we obtained directly the sum of cross sections for absorption and single charge exchange, $\sigma_{abs}+\sigma_{cx}$. These values are listed in Table I and plotted in Fig. 2(c). Pion production was estimated from $H(\pi, 2\pi)$ data[8] multiplied by N_{eff} (see below) and found to be smaller than 1 mb and hence neglected. We will now discuss separately the various results of these experiments.

(a) Pion scattering. In Fig. 1 we show the angular distribution for the pion scattering process. The statistical error of each point was less than 3%. Systematic errors due to beam integration, thick-target effects, pion decay, detector solid angle, and efficiency were estimated to be 7%, and corroborated by using a CH_2 target as described in Ref. 5. At forward angles the cross section is dominated by elastic scattering (the line at forward angles represents the elastic scattering results of Ref. 9). At backward angles the cross section is almost totally inelastic and the shape of the angular distribution there follows the shape of the free pion-nucleon scattering. This similarity suggests that the scattering to backward angles can be described as a quasifree process. This hypothesis is supported by the shape of the inelastic pion energy spectrum.[3] The solid line in the figure is the sum of the cross sections for π^+p and π^-p (the latter being equal to π^+n) scattering, normalized to the data for $\theta > 90°$. The normalization factor N_{eff} is a measure of the effective number of nucleons which participate in

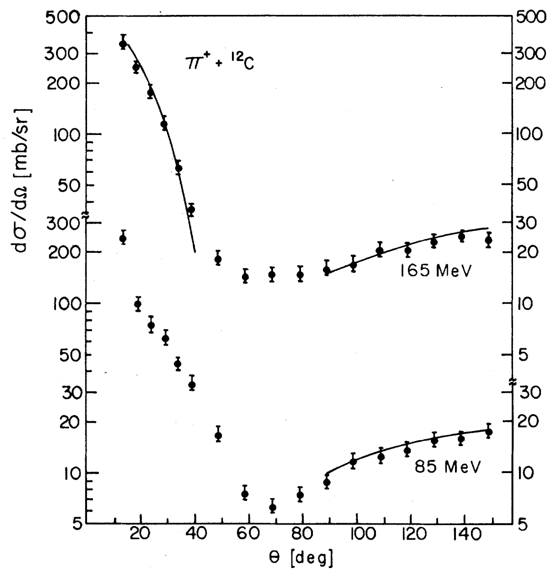

FIG. 1. Angular distributions of π^+ scattering at two energies. The line at forward angles represents elastic scattering data of Ref. 9. The line at backward angles represents the free $[\sigma(\pi^+p)+\sigma(\pi^-p)]$ cross sections normalized to the data by a factor N_{eff}.

the process. Since in this energy region the π^+p cross section is much larger than the π^+n cross section, N_{eff} will be related to the protons in the target nucleus for π^+ scattering. For π^- scattering the same argument will relate N_{eff} to the neutrons. This affinity of N_{eff} to Z for π^+ scattering and to $(A-Z)$ for π^- scattering has, in fact, been shown to exist.[5] The energy dependence of N_{eff} for π^+ backward scattering on carbon is shown in Fig. 2(a). These results can be interpreted as reflecting the behavior of the mean free path of the pion in the nucleus for the scattering process.

(b) Pion absorption. As was previously mentioned, the combination of the two experiments yields directly the sum of absorption and single charge exchange cross sections, $\sigma_{abs}+\sigma_{cx}$, with errors of about 10% [Fig. 2(c)]. The errors include those

TABLE I. N_{eff} and partial cross sections for $\pi^+ + {}^{12}C$.

E_π (MeV)	N_{eff}	$\sigma_{abs}+\sigma_{cx}$ (mb)	σ_{cx} (mb)	σ_{abs} (mb)	σ_{tot}[a] (mb)	σ_{el} (mb)	σ_{inel} (mb)
85	3.67	144 ± 16	35 ± 12[b]	109 ± 17	460 ± 12	178 ± 27	138 ± 34
125	1.97	204 ± 19	38 ± 12[b]	166 ± 22	638 ± 10	220 ± 20	214 ± 30
165	1.41	240 ± 24	46 ± 23[c]	194 ± 33	670 ± 8	222 ± 22	208 ± 34
205	1.85	202 ± 26	45 ± 23[c]	157 ± 34	626 ± 6	213 ± 21	211 ± 34
245	2.78	142 ± 18	47 ± 23[c]	95 ± 29	552 ± 7	185 ± 19	225 ± 27

[a] σ_{tot} are interpolated from the data of Ref. 1.
[b] Interpolated from measurements Refs 10, 11, and 12.
[c] Estimated—see text.

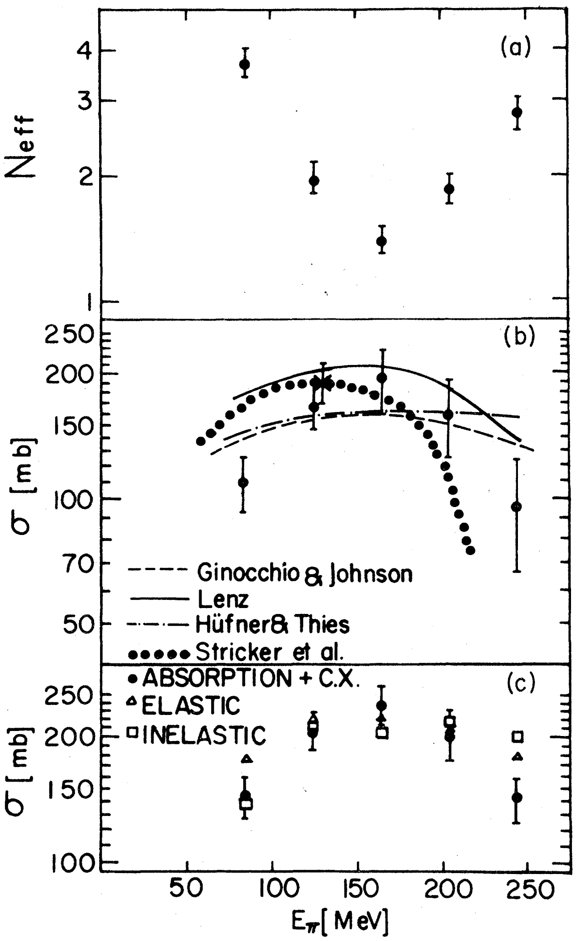

FIG. 2. Energy dependence of (a) N_{eff}, (b) σ_{abs} and (c) partial cross sections for $\pi^+ + {}^{12}C$. The lines are theoretical predictions of Refs. 13–16. The σ_{abs} datum of Bellotti *et al.* (Ref. 6) at 130 MeV is represented by a cross in (b).

due to integration of the angular distribution and the extrapolation procedure described in Ref. 5. The inclusive single charge exchange cross section on carbon was previously measured at 70,[10] 100 (two angles),[11] and (see Ref. 12) 130 MeV. From these measurements we obtain by interpolation the values of σ_{cx} for 85 and 125 MeV. At higher energies, where measured values are not available, an extrapolation is necessary. As suggested by Lenz[13] the ratio $\sigma_{inel}/\sigma_{cx}$, where σ_{inel} is the inclusive inelastic scattering cross section, is equal to the ratio of the corresponding free pion-nucleon cross sections. Since in the present work we are able to obtain σ_{inel} (see below), we can deduce the values of σ_{cx} for the higher energies. At the low energies the measured ratio $\sigma_{inel}/\sigma_{cx}$ is indeed found to be equal to the corresponding pion-nucleon ratio. We assigned an error of 30% to the estimated charge exchange cross section for 85 and 125 MeV, where measurements exist, and 50% at higher energies. Finally, we subtract the values of σ_{cx} from the measured sum $\sigma_{abs} + \sigma_{cx}$ to obtain the absorption cross section. Since for carbon σ_{cx} is not much smaller than σ_{abs}, experimental determination of the charge exchange cross section will allow us to deduce more precise values for the absorption cross section. The results are listed in Table I and shown in Fig. 2(b), together with the result of Ref. 6. Several theoretical calculations of the pion absorption cross section exist and are reproduced in Fig. 2(b).[13–16]

(c) Decomposition of the reaction cross section. The pion-carbon reaction cross section is obtained relatively easily since there exist systematic studies of both elastic scattering and total cross sections. Nevertheless, in order to obtain the angular integrated elastic scattering cross section, one must use some theoretical calculation in order to account for the unmeasured contribution from forward angles and the Coulomb corrections.

In the present work, the optical model code PIRK[17] was used to obtain the integrated π-carbon elastic cross section. A Kisslinger potential was chosen, with parameters obtained from free π-N phase shifts. The results of the calculations were tested against experimental data at various energies around the (3, 3) resonance and for several targets. These comparisons suggest that the error in the integrated elastic cross sections is about 10%, except for low energies where the agreement was poorer. Therefore, for 85 MeV, we used the optical potential of Stricker *et al.*,[16] which is better adapted for low energy scattering, with proper interpolation of their parameters. At 125 MeV, the results of the two methods of calculations were in agreement. The results of these calculations are listed in Table I together with total cross sections taken from Ref. 1. When the experimental results of the present work ($\sigma_{abs} + \sigma_{cx}$) and the elastic scattering cross sections are subtracted from the corresponding total cross section, the inclusive inelastic scattering cross section is obtained, if we neglect the small double charge exchange contribution. These results are listed in Table I and the major channels of the pion-carbon interaction are plotted in Fig. 2(c). As can be seen the elastic scattering, inclusive inelastic scattering, and the sum of absorption and single charge exchange cross sections make comparable contributions to the total cross section. The absorption cross section alone is somewhat smaller than the elastic and inelastic cross sections and has a stronger energy dependence. It is interesting to note that by dividing the inelastic cross section by $N_{eff}[\sigma(\pi^+ p) + \sigma(\pi^- p)]$ a number of ~0.7 is obtained. This number can be interpreted as representing the effect of Pauli blocking on the inelastic forward scattering in nuclei compared to the free pion-nucleon scattering. Indeed the integration of the differential cross section shown by Lenz[13] would yield factors around 0.8.

This work was supported in part by the Israeli Commission for Basic Research and by the Swiss Institute for Nuclear Research.

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