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True Absorption and Scattering of 125-MeV Pions on Nuclei

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The cross section for absorption of 125-MeV positive and negative pions in Li, C, Al, Fe, Nb, and Bi was measured. The results were obtained by combining a transmission experiment, a measurement of the angular distribution for pion scattering, and an estimate of the charge-exchange cross section. Information about inelastic scattering and decomposition of the total pion-nucleus cross section into its contributions from the major channels is also obtained.

Pion-nucleus reactions have been widely investigated in recent years. Yet very little is known about the process of true pion absorption in flight, one of the special features of the pion as a nuclear probe, where there are no pions in the final state. Also, since pion absorption is a large part of the reaction cross section, it affects strongly all other reaction channels and the elastic-scattering process. The available experimental information from direct measurements of the cross section for pion absorption in flight is limited to positive-pion absorption in the deuteron[1] and in carbon at 130 MeV.[2] Some early measurements in emulsions and cloud chambers were also done.[3] There is no information about the dependence of the absorption cross section on the energy and charge of the incident pion and the atomic number of the target.

In this work we present the results of experiments in which the cross sections for positive- and negative-pion absorption in nuclei were measured. These cross sections were obtained by combining the results of two separate experiments. Both experiments were carried out at the $\pi M3$ channel of the Schweizerisches Institut für Nuklearforschung accelerator at a bombarding energy of 125 MeV. The targets studied were Li, C, Al, Fe, Nb, Bi, and CH_2.

The first experiment was done using a standard transmission technique of the kind used for measurements of total cross sections. The pion beam hit the target after passing through two plastic scintillators used to monitor the beam flux. Protons present in the beam were eliminated by degraders positioned inside the beam transport channel. Muon and electron contaminations in the beam were measured by time of flight. Five plastic scintillation counters of disk shape were positioned on the beam axis behind the target position. The counters covered the solid-angle range of 0.1–0.7 sr and by changing the distance from the target, the measurements were taken at nine different solid angles for Li, C, Al, and Fe and thirteen for Nb and Bi. The disk counter which is seen from the target by a solid angle Ω served to measure the cross section $\sigma_{tr}(\Omega)$ for removing pions from the incident flux without rescattering a charged pion into the solid angle Ω. $\sigma_{tr}(\Omega)$ is therefore given by

$$\sigma_{tr}(\Omega) = \frac{1}{n_t} \ln\left(\frac{N(0)}{N(t)}\right) = \sigma_{abs} + \sigma_{cx} + \int_{\Omega^c} \frac{d\sigma_{sc}}{d\Omega} d\Omega, \quad (1)$$

where n_t is the number of target nuclei, $N(t)$ and $N(0)$ are the number of counts in the detector with and without a target in the beam, respectively. σ_{abs} is the absorption cross section, σ_{cx} is the single-charge-exchange cross section, and σ_{sc} is the charged-pion scattering cross section which includes elastic scattering, inelastic scattering to all final states, and the double-charge-exchange reaction. The integration of the differential scattering cross section is taken over the solid angle Ω^c complementary to the solid angle Ω subtended by the disk detector.

When comparison was possible, the present results for $\sigma_{tr}(\Omega)$ were found to be in good agreement with the data of total-cross-section experiments.[4]

In the second experiment the differential scattering cross section was measured. Beam monitoring, proton elimination, and contamination measurement were done as in the transmission experiment. The outgoing pions were measured by three telescopes, each consisting of two cubes $5\times5\times5$ cm^3, of plastic scintillators which were placed at a distance of 55 cm from the center of the target. Positive pions were discriminated against protons and heavier particles using two, partially overlapping, methods:

(a) Fast pions that passed through the first detector of the telescope were identified by the combination of their energy losses in the detectors $(\Delta E_1 - \Delta E_2)$.

(b) Slow positive pions which stopped in the telescope were identified and separated from protons by detecting the signal produced by muon decay that follows the pion decay.

The overlap group consisted of the pions that stopped in the second detector. It is important to note that the second method, which can be used only for positive pions, was needed only for those pions that stopped in the first detector ($E_\pi < 22$ MeV). These amounted to only a small fraction, typically 6%, of the whole spectrum. Negative pions that stopped in the first detector were not identified. This was corrected for by assuming that approximately the same fraction of negative and positive pions were stopped in the first detector. The results are not sensitive to this assumption because the correction is small. The telescopes were therefore sensitive to the whole range of pion energies present in this experiment. From the number of outgoing pions dectected at each angle the differential scattering cross section was obtained over the angular range of 13°–150°. A more detailed description of the experimental setups for both experiments will be published later.

The general features of the measured angular distribution are very similar for all the targets and two typical ones are shown in Fig. 1. The error in each point of the distribution varies between 2 and 8%, including the statistical and angle-dependent systematic errors. Our estimate of the error in the overall normalization is 7%. As an independent check, the results of $\pi^+ + C$ were subtracted from those of $\pi^+ + CH_2$. The difference is in agreement with twice the $\pi^+ + p$ results[5] within an error of less than 10%.

The measured angular distribution was then integrated over the solid angle Ω^c, defined in Eq.

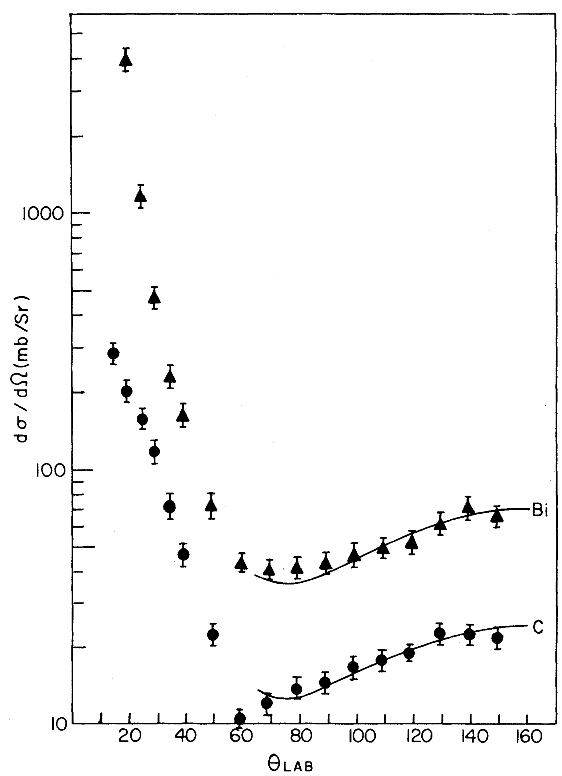

FIG. 1. Differential scattering cross section for 125-MeV π^+ on C (circles) and Bi (triangles). The solid line is the free $(\pi^+ + p) + (\pi^- + n)$ cross section normalized to the data.

(1). Although the differential cross section had to be extrapolated to the region 150°–180°, the result of the integration is insensitive to this extrapolation because the cross section at backward angles is slowly varying and is multiplied by $\sin\theta$ in the integration.

The results of the integrations are subtracted from the corresponding values of $\sigma_{tr}(\Omega)$ [Eq. (1)]. Ideally this difference should be Ω independent and equal to $\sigma_{abs}+\sigma_{cx}$. In practice, the results of transmission measurements include not only pions scattered into the disk counters but also protons and other charged particles which result from various reactions. This contribution vanishes in the limit $\Omega=0$. Therefore, in order to obtain $\sigma_{abs}+\sigma_{cx}$, the value of $\sigma_{tr}(\Omega)-\int_{\Omega^c}(d\sigma_{sc}/d\Omega)d\Omega$ is taken as a function of Ω and extrapolated to $\Omega=0$. The Ω dependence of this difference is small for the π^+ measurements and negligible for the π^- measurements. As a consequence the extrapolation procedure was simple and did not introduce a large error. The results of the extrapolations, which are now equal to $\sigma_{abs}+\sigma_{cx}$, are listed in Table I. The errors include contributions from statistics, systematic errors, and errors due to the extrapolation procedure.

Before we turn to estimate σ_{cx}, some interesting features of the measured scattering cross section should be noted. At forward angles the differential scattering cross section is dominated by the elastic-scattering process, as can be seen from comparison of Fig. 1 with available elastic-scattering data.[8] At larger angles the elastic-scattering contribution is small and the scattering is dominated by inelastic processes. The shape of the angular distribution at backward angles is very similar to that of the free-pion-nucleon cross section. The solid line in Fig. 1 is the sum of the measured cross sections for the π^++p and π^-+p (equal to π^++n) scattering,[5] normalized to the data for $\theta_{lab}>70°$. This similarity may support the assumption that at backward angles the scattering is dominated by quasifree processes. The values of the normalizing factor between the data and the free-pion–nucleon scattering cross section, denoted by N_{eff}, are given in Table I. These values are plotted in Fig. 2 against the proton number (Z) of the target for π^+ scattering and against the neutron number ($A-Z$) for π^- scattering. The fact that both results lie on the same line is a further support for the quasifree assumption.

The differential cross section for the (π^+,π^0) reaction was measured by Bowles *et al.*[9] at two angles for several nuclei at 100 MeV. The conclusion drawn by the authors was that this process followed a quasifree pattern. When these data are normalized to the pion-nucleon charge-exchange cross section a corresponding normalization factor N_{eff} can be obtained for each nucleus. Taking into account the different bombarding energies the results are consistent with those of the

TABLE I. Values of N_{eff}, $\sigma_{abs}+\sigma_{cx}$ obtained from these experiments, our estimated charge-exchange cross section σ_{cx}, the resulting absorption cross section σ_{abs} (given in mb), and results of previous work.

Target	Projectile	N_{eff}	$\sigma_{abs}+\sigma_{cx}$	σ_{cx}	σ_{abs}	Previous σ_{abs}
d	π^+					9.7±1.0[a]
He	π^-					82±12[b]
Li	π^+	1.49	158±15	43±21	115±26	
	π^-	1.85	154±15	35±17	119±23	
C	π^+	1.97	204±19	43±21	161±28	189±19[c]
	π^-	1.86	253±19	46±23	207±30	
Al	π^+	2.58	398±32	58±29	340±43	
	π^-	2.48	464±30	60±30	404±42	
Fe	π^+	3.52	610±49	83±41	527±64	
	π^-	3.56	728±46	82±41	646±62	
Nb	π^+	4.21	1030±122	105±52	925±130	
	π^-	4.51	1035±64	98±82	937±80	
Bi	π^+	5.73	1403±200	165±82	1238±220	
	π^-	7.11	1450±230	133±67	1317±240	

[a]See Ref. 6, at 114 MeV.
[b]See Ref. 7, at 105 MeV, includes σ_{cx}.
[c]See Ref. 2, at 130 MeV.

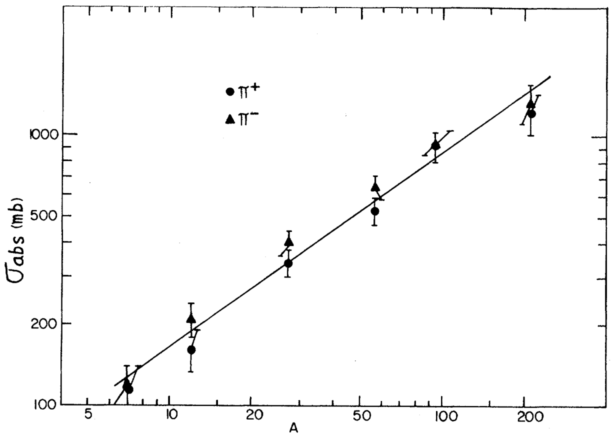

FIG. 2. N_{eff} obtained from π^+ scattering plotted against the proton number (Z) (circles), and from π^- scattering plotted against the neutron number ($A-Z$) (triangles). The straight line is obtained by least-squares fit to the data, and has slope $Z^{0.4}$ and $(A-Z)^{0.4}$ accordingly.

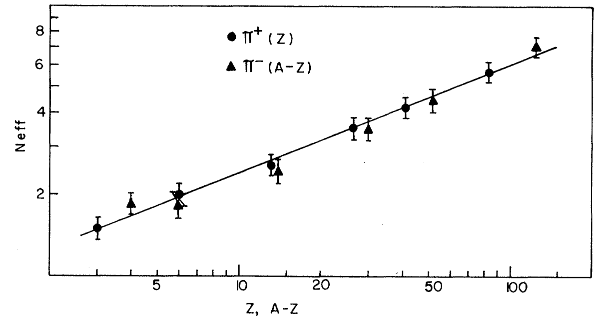

FIG. 3. Cross section for the absorption of 125-MeV pions plotted against the target mass number A. The straight line, obtained by least-squares fit, has a slope of $A^{0.72}$.

present work. Therefore, we used the values of N_{eff} found in the present work to estimate the value of σ_{cx}. Since at forward angles the quasifree process is reduced by Pauli blocking,[10] we estimate σ_{cx} to be $0.8N_{eff}\,\sigma(\pi^- p \rightarrow \pi^0 n)$. This procedure was necessary because of the lack of data on this cross section. To test the validity of this approximation we note that the same blocking exists for the quasifree inelastic scattering. When we take $0.8N_{eff}\,\sigma(\pi N)$, where $\sigma(\pi N)$ is the pion-nucleon scattering cross section, and subtract this value from the measured scattering cross section, the difference is in good agreement with measured elastic-scattering cross sections.[11] In Table I the values of σ_{cx} obtained by this procedure are listed. Since these are relatively small values, their estimate need not be very precise and they were arbitrarily assigned a 50% error. With this estimate and the values of $\sigma_{abs} + \sigma_{cx}$ obtained from the two experiments described in this paper, we obtain the values of σ_{abs}, according to Eq. (1). The values of σ_{abs} are listed in Table I and presented in Fig. 3.

By combining the results of the present work with previous measurements of elastic[5] and total[12] cross sections, it is possible to decompose the pion-nucleus total cross section into its contributions from the major channels. Near the resonance, the elastic contribution can be estimated reliably from simple optical-model calculations,[4] after subtraction of Coulomb and Coulomb-nuclear interference effects. Lenz[7] obtains a dependence of about $A^{0.7}$ for elastic scattering at 150 MeV. In the present work, the absorption cross section is found to vary approximately as $A^{0.7}$. After subtracting the elastic, absorption, and charge-exchange cross sections from the total cross section, the remaining inelastic cross section is found to vary approximately as $A^{0.5}$. Since for carbon, the inelastic and absorption cross sections are approximately equal, it can be concluded that at this bombarding energy, the absorption cross section dominates the reaction cross section in heavy nuclei.

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