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True absorption and scattering of 50 MeV pions

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The inclusive pion inelastic scattering and true absorption cross sections at 50 MeV were measured for π^+ on natural Li, C, Fe, Nb, and Bi and for π^- on C, Fe, and Bi. The results show that π^- cross sections are much larger than π^+, the difference being significantly larger than expected from a simple Coulomb calculation. In particular, in ^{12}C the absorption of negative pions is about twice that of positive pions.

[NUCLEAR REACTIONS Li, C, Fe, Nb, Bi $(\pi^+,\pi^{+\prime})$ and C, Fe, Bi $(\pi^-,\pi^{-\prime})$, $E_\pi=50$ MeV; measured $\sigma(\theta_{\pi'})$, transmission; deduced $\sigma_{\text{absorption}}$.]

In a previous series of experiments carried out at the Swiss Institute for Nuclear Research, the inclusive cross sections for true absorption and scattering of pions were measured[1-3] on nuclei from Li to Bi at bombarding energies from 85 to 315 MeV. The agreement between the data and theoretical calculations that used pionic atom parameters[4] was not very good, probably due to the difficulty in extrapolation from zero to high energies. We focus now on lower energies to see whether the absorption process exhibits different features away from the (3-3) resonance, and to have more meaningful comparison with the calculations based on zero energy parameters. It is expected that absorption data at low energy might also help to narrow down the ambiguities in the parameters of the reactive part of the optical potential, since they are not uniquely determined by existing data of pionic atoms.[5]

We measured the absorption and inclusive scattering cross section of 50 MeV positive pions on Li, C, Fe, Nb, and Bi and of negative pions on C, Fe, and Bi. The experimental method was the same as used previously,[1-3] and will be reviewed here only briefly.

In order to obtain the true absorption cross sections, two separate experiments had to be performed and their results combined together. Both experiments were carried out at the TRIUMF laboratory, in the M9 and M13 channels. The targets were squares 40×40 mm, and their thicknesses were 0.29, 0.45, 1.27, 1.67, and 1.01 g/cm^2 for Li, C, Fe, Nb, and Bi, respectively.

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. Muon and electron contaminations, measured by time of flight, were 1.6% and 1.3% for π^+, 2.6% and 9.5% for π^-. Two 3 mm thick plastic scintillation counters of disk shape and diameters of 38 and 34 cm were placed on the beam axis behind the target. The counters were placed in four different positions so that they covered eight solid angles in the range 0.46–1.28 sr. A disk counter that subtends a solid angle Ω from the target serves to measure $\sigma_{\text{tr}}(\Omega)$, defined as the cross section for removing pions from the incident flux without rescattering a charged pion into the solid angle Ω. This is done by measuring the small fraction of the incident beam that no longer hits the disk counter when the target is inserted. The transmission cross section $\sigma_{\text{tr}}(\Omega)$ is given by

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

where n_t is the number of target nuclei, and $N(t)$ and $N(0)$

are the number of counts in the detector with and without 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 double charge exchange reactions. The integration of the differential cross section is taken over the angle Ω^c, complementary to the solid angle Ω subtended by the disk detector.

In the second experiment the differential scattering cross section was measured. Beam monitoring and contamination measurement were done as in the transmission experiment. The scattering pions were measured by three plastic scintillator telescopes, separated by 10°. Each consisted of a thin ΔE ($27\times27\times5$ mm) and a thick E ($50\times50\times50$ mm) detector, placed at distances of 30 and 40 cm, respectively, from the center of the target. With these telescopes it was possible to identify pions and resolve them from other charged particles.

From the number of scattered pions detected at each angle the inclusive differential cross section (regardless of the scattered pion energy) was obtained in the angular range 25°–150°. The angular distributions for scattering of positive and negative pions from ^{12}C are given in Fig. 1. The errors in the data points of the distribution vary between 4% and 10% including the statistical and angle-dependent systematic errors. Although the energy spectrum was not directly measured, only a small fraction of the counts were out of the elastic energy domain in an E vs ΔE graph. This implied that the correction due to the low energy cutoff at 12 MeV was very small. The estimated overall normalization uncertainty is 12%.

The measured angular distributions were integrated over the solid angles defined in Eq. (1) and the results of the integrations were subtracted from $\sigma_{tr}(\Omega)$. The differences should equal to $\sigma_{abs}+\sigma_{cx}$ [see Eq. (1)], but in reality they

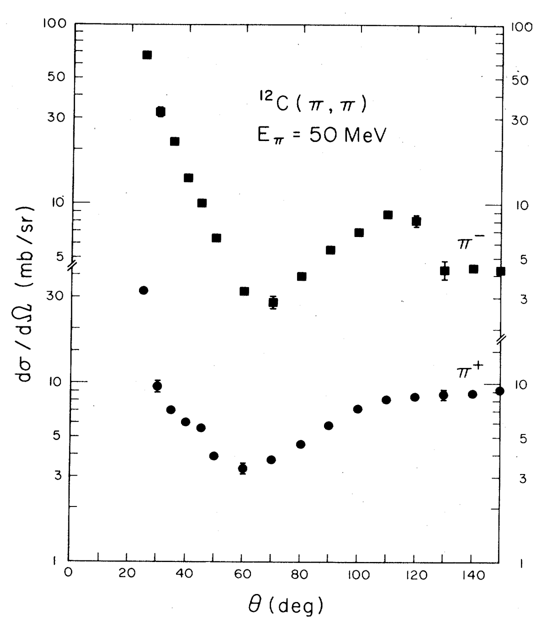

FIG. 1. Angular distributions for scattering of π^+ and π^- from ^{12}C at 50 MeV. Only the statistical errors are shown.

TABLE I. Cross sections for π^+ and π^- (mb).

	Target	$\sigma_{abs}+\sigma_{cx}$	σ_{cx}[a]	σ_{abs}
π^+				
	Li	40 ±17	12	28 ±21
	C	106 ±21	18	88 ±27
	Fe	478 ±48	35	443 ±58
	Nb	782 ±95	40	742 ±107
	Bi	1737 ±188	49	1688 ±203
π^-				
	C	238 ±24	18	220 ±30
	Fe	1232 ±92	35	1197 ±102
	Bi	5137 ±328	49	5088 ±343

[a]Estimated, see text.

also have Ω dependence because of charged particles that are knocked out of the target. Extrapolation to $\Omega=0$ eliminates this effect and gives the value of $\sigma_{abs}+\sigma_{cx}$ that are listed in Table I. The errors include contribution from statistics, systematic errors, and errors introduced by this subtraction procedure. Figure 2 shows the details of this

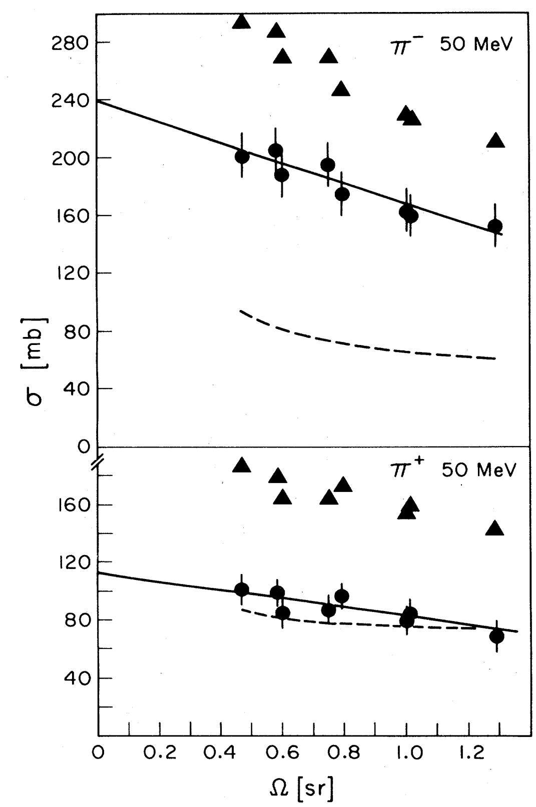

FIG. 2. Details of the subtraction procedure in ^{12}C, for π^- (top) and π^+ (bottom). The triangles are the results of the transmission measurement. The dashed line is the result of integrating the scattering cross section from Ω to 4π. The circles are the difference between the transmission and the integrated scattering. The solid line is a linear least squares fit, and its value at $\Omega=0$ is equal to $\sigma_{abs}+\sigma_{cx}$.

subtraction for ^{12}C, and the line that was fitted to get $\sigma_{abs}+\sigma_{cx}$ at $\Omega=0$. More detailed discussion of this subtraction procedure is given in Ref. 3. In order to obtain the true absorption cross section the contribution of the single charge exchange reaction σ_{cx} has to be subtracted. In the absence of complete experimental data, we used the results of Bowles *et al.* for ^{16}O(π^+,π^0) at 50 MeV,[6] and extrapolated them to other targets using the A dependence deduced from the (π^-,π^0) measurement at 70 MeV.[7] In this crude approximation we used the same charge exchange cross sections for π^+ and π^-, and the errors were set arbitrarily to 30%. Since these cross sections are relatively small, as can be seen in Table I, the error that they introduce to the absorption cross sections is small.

The most pronounced feature of the absorption cross sections is the large values obtained for π^-: In ^{209}Bi it is more than 5 b and is the dominant part in the total cross section.[8] This is not a surprise though; a smooth extrapolation to 50 MeV of previous π^+ absorption results at higher energies[3] gives about 1700 mb for Bi, and theoretical calculations[4] predicted a ratio of 3 between the absorption of π^- and π^+ in Pb at 50 MeV. One also has to bear in mind that the Coulomb interaction creates a difference between the effective incident energy of π^+ and π^-, and this effect is significant at low energy. Still, there is a striking difference between absorption of positive and negative pions in ^{12}C. Simple calculations of the Coulomb contribution to the ratio, using $(1+E_b/T)/(1-E_b/T)$, where E_b is the Coulomb barrier energy and T is the pion kinetic energy, yield a difference of only about 20%, not a factor of 2.

The unexpected large ratio led us to a careful comparison of our raw data with other existing experimental results. The transmission data for ^{12}C was compared with the Clinton P. Anderson Meson Physics Facility (LAMPF) data of Cooper *et al.*[9] and was found to be in excellent agreement (within 4%). The inclusive scattering differential cross section (Fig. 1) was compared with elastic scattering data of π^+, (Refs. 10–12) and π^-.[13,14] Unfortunately, these measurements of elastic scattering cross sections disagree with one another. The inclusive scattering cross sections measured in the present experiment are, as they should be, larger than the corresponding elastic cross sections, with the exception of Ref. 13. This reference also disagrees with Ref. 14, and a recent measurement performed at TRIUMF[15] indicates that it might have been incorrect. It should be noted, however, that even if the results of Ref. 13 are correct, our conclusions about the absorption cross sections will not change by more than 15%. Summing up all our checks, we are confident that the big ratio is a genuine effect.

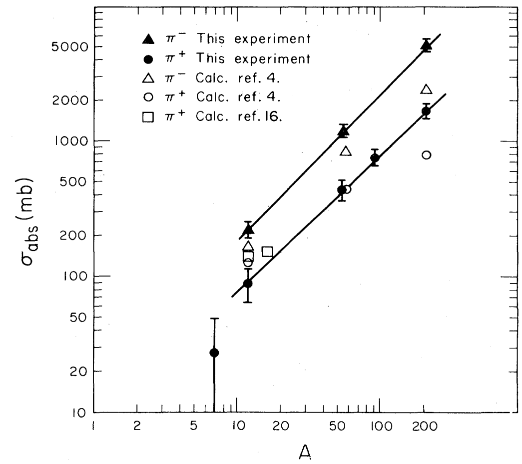

FIG. 3. Calculations (Refs. 4 and 16) and experimental results of this work for absorption of π^+ and π^- at 50 MeV. The lines were drawn through the experimental results to guide the eye.

In Fig. 3 we plot the experimental results together with theoretical predictions.[4,16] As can be seen the data exhibit a smooth dependence on the atomic number. The agreement between the calculations and the data is only fair. A calculation of absorption cross sections[17] on ^{12}C and Cu from an optical potential where successive quasifree processes are subtracted also agrees fairly with the data. The absorption cross section at low energies was also deduced by Nakai *et al.*[18] from measurements of γ multiplicities. The indirect character of that measurement makes the comparison less conclusive, but their ratios between π^- and π^+ seem to be significantly smaller. It is interesting to note that fits to the elastic data,[19] using a model-independent well potential, gave a reactive cross section similar to that observed in this experiment with the same large ratio between π^+ and π^-. (The reactive cross section in this energy is dominated by true absorption because the integrated inelastic scattering is relatively small.) No simple explanation was found for the big ratio seen in ^{12}C. Perhaps the relatively complex nature of the absorption process in which more than one nucleon is usually involved makes the simple Coulomb approximation invalid.

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