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INTERPLAY BETWEEN PION ABSORPTION AND INCLUSIVE-INELASTIC
SCATTERING ON HYDROGEN AND HELIUM ISOTOPES FOR 96.5-MEV
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Measurements of double-differential cross sections for inclusive-inelastic scattering of 96.5-MeV pions from hydrogen and helium isotopes are presented. Differential and angle-integrated cross sections are obtained. Distorted wave impulse approximation calculations are reported. The interplay between inclusive-inelastic scattering and pion absorption is discussed.

Inclusive-inelastic scattering of pions with energies on the low side of the delta resonance, from nuclei of masses 12 or higher, exhibits several general features. 1) Pion true absorption is the main competing channel, and single charge exchange is the only other reaction channel of significant magnitude. 2) Inelastic scattering to the continuum is dominated by quasi-free scattering from one nucleon. 3) The angular distributions are backward peaked. Because, on the low side of the resonance, π^+ are scattered backward by protons while they are scattered forward by neutrons, the inclusive-inelastic scattering of π^+ (π^-) results primarily from protons (neutrons). 4) The A dependence of the inclusive-inelastic cross section of π^+ (π^-) can be explained in terms of the A dependence of the nuclear size, times a factor depending on N/Z (Z/N), times a Coulomb factor, times an energy dependent ratio for branching between single scattering and absorption.

Because the mean free path for 100-MeV pions in nuclear matter is short, nuclei of masses 12 or higher are essentially black, and the pions mainly scatter in the surface region before they reach the nuclear matter with the central density. Thus the only

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basic properties of the nuclear matter seen by inelastically scattered pions that can be varied with A for masses of 12 or higher is the ratio of protons to neutrons, which only changes by about 50% between carbon and lead.

For the lightest nuclei, ^2H , ^3H , ^3He , and ^4He , however, 100-MeV pions penetrate the nucleus fairly well. Thus studies of inelastic scattering from these targets probes a wide range in nuclear density and in Z/N at the scattering site. Inclusive inelastic scattering measurements in this energy range for ^4He have been reported[1]. However, our goal was to compare the scattering from the above nuclei with reasonable precision. Thus we undertook a measurement of the inclusive-inelastic scattering differential cross sections with these ideas in mind.

The experiment was done at TRIUMF in the M-11 channel using the QGD spectrometer. Three or four spectrometer settings were used in order to cover most of the spectrum of inelastically scattered pions. A high pressure gas cell was used for the target. By monitoring the temperature and pressure of the gas we were able to determine the density to an accuracy of $< 1\%$. The integrated beam was determined by in-beam scintillators, and the cross sections were determined by normalizing to measurements of π -proton scattering, using hydrogen gas. Cross sections with precisions of 5% or better relative to the π -proton cross section were obtained for π^+ . For π^- the relative precisions were somewhat lower, because of the lower beam intensity. This relative precision is the relevant one for discussions of and modifications of the elementary π -nucleon cross section inside nuclei. The π -proton cross sections were obtained from phase shifts[2], with an accuracy of 5.5%. This systematic uncertainty therefore is applied to the absolute cross sections in the present experiment.

Measurements were made at five angles, 40, 60, 75, 100, and 125° with π^+ on ^2H , ^3He , and ^4He , while measurements were made on the two helium isotopes with π^- at three angles, 60, 100, and 125°. Spectra obtained at 100° for all cases are shown in Fig. 1, and spectra obtained at all angles for π^+ scattering from ^3He are shown in Fig. 2. Differential cross sections for inclusive-inelastic scattering were obtained by integrating over outgoing pion energy. Differential cross sections for elastic scattering were also obtained. The angle integrated inclusive-inelastic cross sections were obtained by extrapolating the differential cross sections, which vary smoothly as a function of $\cos(\theta)$, to 0 and 180°. Optical model calculations were fitted to the elastic scattering and the total reaction cross section, and from these fits total (nuclear) elastic scattering cross sections were obtained. For the $\pi^- - ^3\text{He}$ case, elastic scattering data of Källne *et al.*[3] was used.

To obtain the total reaction cross sections, we need single charge exchange and true absorption cross sections. The former were estimated from the inclusive-inelastic scattering cross section using the N and Z values and the ratio of the cross sections for scattering (with and without charge exchange) from free nucleons. The latter were ob-

Figure 1: Inclusive spectra of 96.5-MeV pions scattered from all targets at 100° . The histograms are the measurements and the solid curves are the results of the DWIA calculations described in the text.

Figure 2: Inclusive spectra of 96.5-MeV π^+ scattered from ^3He at all five angles. The histograms and solid curves are as described in Fig 1.

tained from cross sections or cross section ratios available in the literature[4,5,6,7]. These total cross sections are presented in Table 1.

Using the program THREEDEE[10] we carried out distorted wave impulse approximation (DWIA) calculations, modeling the inclusive-inelastic pion scattering as a quasi-free knockout. Standard optical parameters were used for the knocked out nucleon, but, since this particle was not detected, the imaginary part of the potential was set to zero. Kisslinger potential parameters for the incoming and outgoing pions were obtained by fitting the elastic scattering and total reaction cross sections for 96.5 MeV pions. Since we did not have a reliable prescription for adjusting the parameters for the various energies of the outgoing pions, we simply used the same parameters for the outgoing pions as for the incoming ones. The double differential cross sections obtained from the DWIA are shown in Fig. 1 and Fig. 2. The differential cross sections are shown in Fig. 3. These results were not sensitive to variations in the pion optical model parameters. Except at the most forward angles, they agree reasonably well both in shape and magnitude with our experimental results, as seen in Fig 3. The success of the DWIA calculations lends support to the idea that the inclusive-inelastic pion scattering can be characterized as a quasi-free process, involving a single interaction with a single nucleon.

Table 1: Measured and inferred integrated cross sections (mb) for 96.5-MeV pion interactions in hydrogen and helium isotopes. Estimated cross sections are enclosed in parentheses. For each target either the absorption or the total reaction cross section is obtained algebraically from the others. The value so obtained is enclosed in square brackets. The absorption width and normalized absorption width (fm^3), described in the text, are also listed.

	π^+-p	π^+-n	$\pi^+-^2\text{H}$	$\pi^+-^3\text{He}$	$\pi^+-^3\text{He}$	$\pi^+-^4\text{He}$
elastic	55.5 ^a	5.8 ^a	31.3 ± 3.2	66.6 ± 6.7	40.0 ± 6.0^b	72.8 ± 7.3
inelastic			34.1 ± 1.7	67.3 ± 3.2	32.0 ± 4.3	42.1 ± 1.5
absorption			9.6 ± 0.2^c	$(20. \pm 4)^d$	—	$[63. \pm 10]$
SCX		16.4 ^a	(9.1 ± 1.4)	(9.5 ± 1.4)	(15.5 ± 3.1)	(11.3 ± 1.7)
Total Reaction			$[53. \pm 3]$	$[97. \pm 6]$	—	$116. \pm 9^e$
γ^{++}			0.149 ± 0.004	0.19 ± 0.04	0.33 ± 0.14	1.1 ± 0.3
γ_r			1.06 ± 0.03	1.20 ± 0.20	1.04 ± 0.45	2.1 ± 0.6

^a See Ref. 2.

^b See Ref. 3.

^c See Ref. 4.

^d Estimated using ratios of three body to two body absorption from Refs. 5 and 6. ratio of cross sections for two body absorption on ^3He to that on ^2H from Refs. 6 and 7. and value for absorption cross section on ^2H from Ref. 3.

^e Average of results of Ref. 1 and Ref. 9.

Although the DWIA is moderately successful, one is not able to gain much insight into the pion-nucleus interaction from it. The main channel competing with scattering is pion absorption, but the pion optical parameters describe the absorption process only implicitly, and these parameters were obtained by fitting the elastic differential cross section and the total reaction cross sections. The parameters are found to be quite different for the different nuclei, but it is not clear what this difference means.

Within the statistical uncertainties, the cross sections for π^- and π^+ scattering from ^4He are identical, as expected. We consider that the π^- scattering from ^3He is the same as π^+ scattering from ^3H , and we present the following discussion in terms of π^+ scattering from four targets.

Figure 3: Differential cross sections for inclusive-inelastic scattering of pions, comparing the data of the present experiment with the DWIA calculation described in the text.

In order to gain more insight into the pion-nucleus interaction, we have undertaken a simple classical calculation to examine the relationship between scattering and absorption of pions in the nuclear material. We assume that the incident π^+ interacts initially with a single nucleon, with a cross section the same as that for interaction with a free nucleon. We calculate the average fraction of the incident flux of π^+ present at a given type of nucleon considering the removal of flux by the other nucleons. This fraction varies from 0.97 for the proton in ^2H to 0.74 for the neutron in ^4He . After this initial interaction the pi-nucleon complex either decays (leading to pion emission, possibly with charge exchange) or the pion is absorbed. The fraction of pions being absorbed is given by the ratio of the absorption width, Γ_a , to the total width, which is the sum of the decay width, Γ_d , and Γ_a . Then we can determine the ratio $\gamma = \Gamma_a/\Gamma_d$ from the value of the absorption cross section. Different values of γ may be expected depending on whether the π^+ initially interact with protons or with neutrons, because different numbers of the other type of nucleon are available to participate in the absorption. In general $N\gamma^+ = Z\gamma^{++}$ where the superscripts $-$ ($++$) indicate a π^+ initially interacting with a neutron (proton). Thus for a given target, there is one independent parameter which characterizes the absorption rate. It is taken to be γ^{++} and is listed in Table 1.

We do not have estimates of the absorption cross section for π^- on ^3He (or for π^+ on ^3H). We are able, however, to obtain values for γ^{++} in this case using the values of the differential cross section for inclusive inelastic scattering to backward angles. This technique has been described elsewhere[11], and provides good agreement for π^+ on ^3He .

Can we relate the relative values of γ^{++} to properties of the nuclei? We note that these values change by a factor of seven between ^2H and ^4He . Since pion absorption is known to take place on $T = 0$ pairs in these s-shell nuclei, we expect that Γ_a^{++} might be proportional to the density of partner neutrons – those which could have formed a $T = 0$ pair with the proton involved in the initial pion-nucleon interaction. The average density of such neutrons is proportional to the number of pairs divided by the number of protons and divided by the nuclear volume. We take the volume to be proportional to r_{rms}^3 , and note that the number of $T = 0$ pairs is 1, 1.5, or 3 for the nuclei with $A = 2$, 3, or 4 respectively. If we take Γ_d to be independent of the nucleus, then γ^{++} and Γ_a^{++} should exhibit a common dependence on nuclear properties. Values of γ_r , which is γ^{++} divided by the relative density of partner neutrons, are listed in Table 1. The value of γ_r is remarkably uniform for the mass 2 and 3 cases, but is approximately doubled for mass 4.

This large value of γ_r for ^4He may result from a reduction of Γ_d , possibly resulting from the 20-MeV threshold for excitation of the ^4He nucleus. Alternatively, the large γ_r may indicate additional absorption mechanisms which are not present in the lighter nuclei and which are not considered in our simple picture. However, recent coincidence studies of pion absorption by ^4He at the resonance[12] show that the majority of absorption takes

place on two nucleons, although at the same energy there appears to be substantial three body absorption on ^3He [13].

We conclude that the inclusive inelastic scattering of pions from the lightest nuclei results mainly from single pion nucleon collisions. The magnitude of the cross section may be determined by summing the the free pion nucleon cross section over the available nucleons, if the competition of pion absorption is considered in a simple model. Furthermore, the magnitude of the pion absorption cross section appears to depend in a straightforward way on the density of nucleons which can be partners in a two nucleon absorption process, although for ^4He the absorption cross section is 1.5 to 2 times larger than one would project using the values for the mass 2 and 3 nuclei in the simple model we have presented.

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