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Angular distributions of the π^-/π^+ ratio from the $^{12}C(e,e'\pi^{\pm})X$ reaction at $E_e = 200$ MeV

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Angular distributions of the π^-/π^+ ratio for 15.8 and 17.9 MeV pions have been measured from the $^{12}C(e,e'\pi^{\pm})X$ reaction at incident electron energy of 200 MeV. The results show a structure with a minimum at $\theta_\pi \simeq 100°$. Calculations based on the partial conservation of axial-vector current hypothesis and realistic optical potentials fail to reproduce the experimental structure.

[NUCLEAR REACTIONS $^{12}C(e,e'\pi^{\pm})$, $E_e = 200$ MeV; measured $\sigma(E_{\pi^{\pm}},\theta)$, $E_{\pi^{\pm}} = 15.8$, 17.9 MeV; calculated $R = \sigma(\pi^+)$ with (PCAP) derived amplitudes; calculated $[\sigma(\gamma n \to p\pi^-)]/[\sigma(\gamma p \to n\pi^+)]$ with momentum dependent terms.]

I. INTRODUCTION

Pion production from complex nuclei offers the promise of becoming a valuable tool in our understanding of the π-nucleus interaction. In contrast to low-energy π-nucleus elastic scattering where the effective interaction probes the nuclear surface only, pion production, either through hadronic or electromagnetic processes, is affected by the nuclear interior and as such it can provide information more relevant to the problem of pion propagation and absorption in nuclei.

Because of the relatively short decay length of low-energy pions, it is difficult to perform experiments with pions of 25 MeV or less, either incident or produced. One is then forced to interpolate in specifying the low-energy pion-nucleus interaction. In that context experiments where the pions involved have energies less than ~25 MeV are particularly valuable.

In addition to π-nucleus interaction information, pion electroproduction in particular is of interest to nuclear structure studies by means of electron scattering. In order to extract information about purely nuclear processes, such as sum rules or short-range correlations from electron scattering experiments at high momentum transfer, it is necessary to have some knowledge of the meson production cross section. Pion electroproduction experiments for low-energy pions close to threshold are particularly attractive since the production mechanism from a single nucleon is reasonably understood.[1,2] Thus, more information can be extracted from π-nucleus interaction by varying the optical potential parameters, than at higher production energies when the basic production mechanism is not as well established.

The results reported in this paper are an extension to our previously reported measurements of the $^{12}C(e,e'\pi^+)X$ reaction double differential cross sections for 16–13 MeV pions.[3] In the present work measurements of π^-/π^+ ratio angular distributions in the 45°–143° range, for 15.8 and 17.9 MeV pions of both charges, are presented. Incident electron energy was 200 MeV. Both the earlier reported results[3] and the present measurements were part of a research effort to design a low-energy pion detection system to study pion electroproduction from selected light nuclei.[4]

II. EXPERIMENTAL

A detailed description of the experimental apparatus is given elsewhere.[4,5] In summary, a 102 mg/cm^2 natural carbon target, turned 30° to the beam, was bombarded by 1 μs long pulses at 360 Hz. Pions were detected by four telescopes of silicon surface barrier detectors mounted on the focal plane of a 127° double focusing magnetic spectrometer; the telescopes covered the full momentum acceptance of the spectrometer. Each telescope consisted of two 300 μm ΔE detectors and one 2000 μm E detector. Aluminum moderators were remotely placed in front of each telescope. The thickness of the moderator was arranged to be such as to degrade the pion energy by an amount sufficient to stop the pion in the midplane of the E counter. In such an arrangement the muon from the $\pi \rightarrow \mu + \nu_\mu$ decay deposits its full 4.12 MeV of kinetic energy in the E counter having as a result a higher discrimination threshold level and, thus, better background rejection. For the pion energies reported in this paper, however, range straggling in the moderator appropriate to 15 or 17 MeV pions would be large enough to make it uncertain whether the decay muon will lose all or part of its 4.12 MeV of energy in the E counter. This would have effects detrimental to the energy resolution of the spectra.

In this work pions were detected in transmission and the moderator thickness was adjusted for maximum energy loss in the ΔE counters consistent with full transmission. By detecting negative pions in transmission one also avoids the π^- absorption in the nucleus and the resulting emission of two nucleons in the detector material. The transmission spectra are background free to the $\sim 1\%$ level, as shown in Fig. 1.

The detection system was frequently checked by measuring the yield of 15 MeV protons from the ^{12}C$(e,e'p)X$ reaction.[6] The non-pion-generated background was found to be $\sim 1\%$ for the π^+ and $\sim 2\%$ for π^- for angles larger than $\sim 55°$. For 45° the background from scattered electrons was severe in the π^- spectra; however, it was possible to extract the π^- spectrum by fitting the π^+ spectra shape to the π^- spectra for the same angle. For angles smaller than 40°, the π^- spectra were obscured by electron background and the π^+ peak-to-background ratio was deteriorating. Thus, the angular range reported in this work is restricted to 45°–143°.

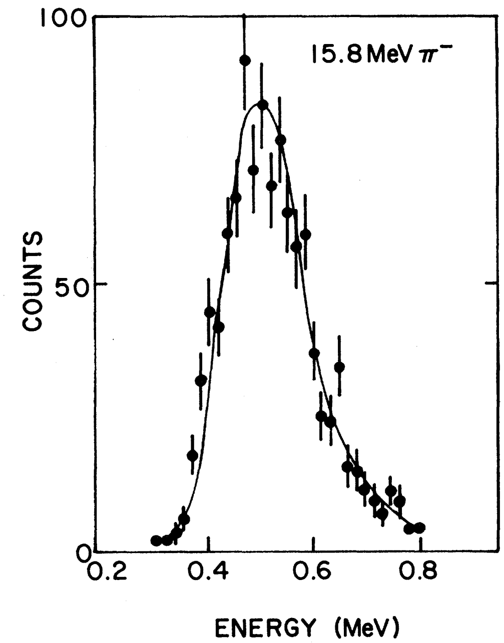

FIG. 1. Pulse height spectrum for the second ΔE counter and for 15.8 MeV π^-. No background contribution was subtracted.

III. RESULTS

For a relative ratio type of experiment such as the present one, most of the corrections such as muon contamination, pion decay, and real bremsstrahlung pion production cancel out. Although pion absorption depends on the pion charge sign, the differences in π^-,π^+ absorption cross sections are very small, as one would epxect from charge independence considerations.

The pion yields were determined by integrating the peak areas for both the second ΔE detector and the sum histogram of all three detectors in each telescope. The yields generated by the two peaks agreed to better than 2%. In Fig. 2 the angular distribution for the π^-/π^+ ratio is shown for pions of 15.8 MeV. The calculated angular distribution for the π^-/π^+ ratio from the ^{12}C$(e,e'\pi^\pm)X$ reaction is also shown in the same figure.

The calculated distribution shown in Fig. 2 was generated using a nonrelativistic amplitude for threshold pion electroproduction of the form

$$H_{\pi^\pm}^{\text{nuclear}} = ie\sqrt{8\pi}\frac{f}{m_\pi}\left[1 \pm \frac{m_\pi}{2M_N}\right]\int d\vec{r}\phi^*_{\pi^\pm}(\vec{r})e^{i\vec{k}\cdot\vec{r}}\sum_{j=1}^{A}\left[\vec{\epsilon}\cdot\vec{\sigma}_j - \epsilon_0\frac{\vec{\sigma}_j\cdot\vec{k}}{\omega_k}\right]\tau_\pm\delta(\vec{r}-\vec{r}_j)\ , \qquad (1)$$

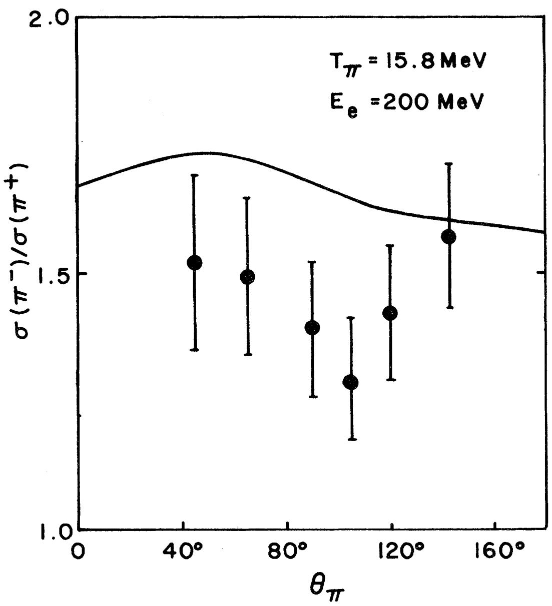

FIG. 2. Angular distribution of the π^-/π^+ ratio for 15.8 MeV pions. The solid line is the calculated distribution for $\xi_{LL}=1.2$ in the optical potential. Statistical errors only.

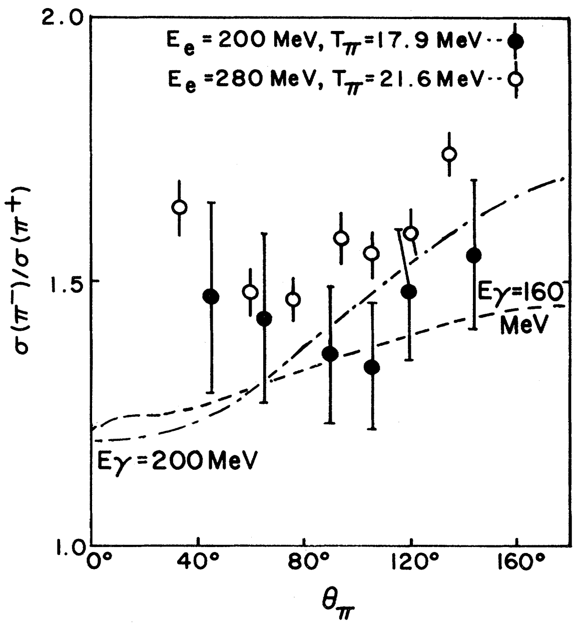

FIG. 3. Comparison of our 17.9 MeV results (solid circles) with the results of Ref. 10 for 21.6 MeV pions and 280 MeV electron energy (open circles). The dashed and dashed-dotted lines are for the π^-/π^+ ratio for 160 and 200 MeV incident photon energy, respectively, for $\gamma p \to n\pi^+$ and $\gamma n \to p\pi^-$ reactions from Refs. 13–15.

where $\epsilon^\mu = -ie\bar{U}(k_2)\gamma^\mu U(k_1)$ is the electron matrix element and $k^\mu = k_1^\mu - k_2^\mu = (\vec{k}, \omega_k)$ is the four-momentum transfer to the nucleus. The pion wave function is derived from the solution of

$$(\vec{\nabla}^2 + \vec{q}_\pi^{\,2})\phi_\pi^* = [2\omega_\pi(V_C + V_\pi) - V_C^2]\phi_\pi^* , \quad (2)$$

where V_C is the Coulomb potential and V_π a pion-nucleus optical potential. The method of evaluation of the electroproduction π^-/π^+ ratio was based on the formulation in Ref. 7. The choice of optical potential is also taken from Ref. 7 and it was based on the Thies-Colorado group potential.[8,9]

As can be seen in Figs. 2 and 3 the experimental data show a structure with a minimum at $\sim 105°$ for the 15.8 MeV and at $\sim 100°$ for the 17.9 MeV data. The calculated distributions fail to reflect this structure. The same poor agreement with the experimental π^-/π^+ ratio had been seen earlier for higher incident electron and pion energies.[10] In the present case the failure of the calculated distributions is more surprising, than in the case of Ref. 10, since the double differential cross sections generated by the nuclear amplitude in Eq. (1) and the method of evaluation in Ref. 7 are in good agreement with our earlier reported results in Ref. 3.

Angular distributions of the π^-/π^+ ratio have been measured from the $^{12}C(e,e'\pi^\pm)X$ reaction earlier by the Mainz group[10] for 21.6 and 30.2 MeV pions at 280 MeV incident electron energy. The discrepancies between experiment and theory[7] were thought to be attributed to the difficulties in predicting the nuclear response to the higher-energy electrons as well as, perhaps, the higher pion energy. The results in Ref. 10, however, show a behavior similar to the one observed in this work obtained at substantially lower incident electron energy, as can be seen in Fig. 3.

Experimental results for the π^-/π^+ ratio from the $^{12}C(e,e'\pi^\pm)X$ reaction have also been measured at Tohoku[11] for $\theta_\pi = 90°$ and $E_e = 250$ MeV. At similar pion energies, however, their reported values for the π^-/π^+ ratio are considerably lower than our results.

IV. DISCUSSION

At this point it is not clear why a theory that yields good agreement with the $^{12}C(e,e'\pi^+)X$ reaction cross sections fails to explain the observed structure in the π^-/π^+ ratio measurements for the same reaction. Since nuclear structure uncertainties involved in cross-section calculations tend to cancel out, one might suggest that studies of the π^-/π^+ ratio could prove promising in investigations concerning the nature of the pion-nucleus final interactions. In this respect the observed discrepancies between theory and the π^-/π^+ ratio may indicate the inadequacies of the optical potential and, as such, measuring π^-/π^+ ratio distributions, in addition to cross sections, could prove to be a more critical experimental approach to pion electroproduction from nuclei. Changes in the optical potential used in the present work, such as varying the Lorentz-Lorenz effect ($\xi_{LL}=0$ or $\xi_{LL}=1.2$), did not produce any noticeable improvements.

Although the optical potentials derived from π-nucleus elastic scattering and pionic atom data may describe the π-nucleus interaction and pion absorption in a satisfactory manner for the nuclear surface, pion production probes the nuclear interior where the optical potentials in their present form may not work as well. Whether the discrepancies between the π^-/π^+ ratio observed structure and the theory are indicative of the failure of the optical potentials or there are other factors involved as well remains to be seen. The single-nucleon pion-production operator derived from the PCAC hypothesis and the soft pion theorem is of the form

$$H_{\gamma,\pi^\pm}=\left[1\mp\frac{m_\pi}{2M_N}\right][\vec{\sigma}-\vec{k}(\vec{\sigma}\cdot\vec{k})/\omega_k{}^2]\,, \quad (3)$$

where $H_{\gamma,\pi^\pm}$ is the photoproduction operator describing the two processes

$$\begin{aligned}&\gamma+p\to\pi^++n\,,\\&\gamma+n\to\pi^-+p\,.\end{aligned} \quad (4)$$

Since the differential cross section is proportional to the square of the operator in Eq. (3), i.e.,

$$\left[\frac{d\sigma}{d\Omega}\right]_{\gamma,\pi^\pm}\propto|H_{\gamma,\pi^\pm}|^2\,, \quad (5)$$

the photoproduction π^-/π^+ ratio calculated using Eqs. (3) and (5) will give a constant value $R=1.35$ for the ratio. This value for the ratio is both angle and incident photon energy independent. Earlier experiments, however, involving the π^-/π^+ ratio of the two processes in Eq. (4), have shown the π^-/π^+ ratio to be both angle and photon energy dependent.[12] Also, calculations in the threshold to $\sim$240 MeV region for pion photoproduction, which include nucleon, pion, and Δ-pole terms as well as a ρ-exchange term, yield π^-/π^+ ratio distributions dependent on incident photon energy and pion emission angle.[13] The results of these calculations are shown in Fig. 3 for $E_\gamma=160$ MeV (dashed line) and $E_\gamma=200$ MeV (dashed-dotted line). Both curves are for the single nucleon processes in Eq. (4) and have not been incorporated into the more extensive pion electroproduction calculations for the $^{12}C(e,e'\pi^\pm)X$ reaction. The amplitudes leading to these values for the π^-/π^+ ratio have been shown to be in very good agreement with $\gamma p\to n\pi^+$ experimental results[14] and $\gamma n\to p\pi^-$ results derived from the $\pi^-p\to n\gamma$ reaction.[15]

V. CONCLUSIONS

It would be of interest to extend the π^-/π^+ ratio-type experiments to lower pion energies, as well as lower incident electron energies, for a more systematic study on pion energy and momentum transfer dependency of the production operator chosen. It would also be of interest to incorporate the production amplitudes of Ref. 14 into the electroproduction calculations of Ref. 7 for ^{12}C. The calculated π^-/π^+ ratio angular distributions for the elementary amplitudes in Fig. 3 reproduce the large angle increase observed in the data well, in magnitude as well as in shape. When coupled to calculations involving a nuclear target one would expect to observe an enhancement in the π^-/π^+ ratio in the forward angles due to the Coulomb attraction in the same way as the calculated distribution in Fig. 2 reflects the same effect. At the present level, then, the data in Fig. 3 are in qualitative agreement with the distributions calculated using momentum-dependent terms in the elementary amplitudes. The inclusion of the above-mentioned momentum-dependent terms as well as a more realistic account of the Coulomb effect on the energy levels in the mirror daughter nuclei excited in a $(\gamma,\pi^\pm)$ reaction off a self-conjugate nucleus may indeed bring the theory closer to the experimental results. The exclusion of these two terms probably accounts for the failure of the theory in Ref. 7 to a much larger extent than a possible failure of the optical potential used.[16]

It is hoped that the explicit inclusion of the momentum-dependent terms in the elementary amplitudes, when applied to nuclear targets, will provide the theory with a successful enough model as to make it more sensitive to the quality of the optical potentials employed, something that present-day calculations are singularly lacking.

VI. ACKNOWLEDGMENTS

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