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Low energy angular distributions for the $^{12}C(e,\pi^+e')$ reaction

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Angular distributions for near threshold electroproduction of positive pions from ^{12}C are reported and compared to theory. These data provide tests of recently developed second-order optical potentials and of the nuclear response to electroproduction in the giant resonance region.

[NUCLEAR REACTIONS $^{12}C(e,\pi^+e')$; measured $\sigma(E_\pi,\theta)$, $E_e=200$ MeV, $E_\pi=6-13$ MeV; calculated σ, distorted wave Born approximation; giant resonances.]

One of the exciting challenges in medium energy physics is to understand pion propagation and absorption in complex nuclei. One approach to this complicated many-body problem is to approximate the pion-nucleus interaction by an optical potential. As first became apparent in studies of pion-nucleus elastic scattering, low-energy pion-nucleus interactions can provide particularly stringent constraints on the form of such potentials. For instance, careful treatments of the angle transformation, Pauli blocking, and second-order density corrections due to true absorption and short-range correlations were required to remove the discrepancies between first-order optical potential predictions and the 50 MeV elastic scattering data for ^{12}C.[1] And, if recent reports of anomalous shifts and widths for short-lived 3*d* levels in pionic atoms prove correct,[2] our understanding of low-energy π-nucleus reactions may still be far from complete.

Pion electroproduction can be particularly helpful in furthering our understanding of π-nucleus interactions. First, in contrast to elastic scattering, this reaction depends on the pion wave function in the nuclear interior, and not simply on its asymptotic behavior. Second, the freedom to vary the pion angle (and thus the three-momentum transfer to the nucleus) for fixed pion energy provides convolutions of the pion wave function with different Fourier components of the nuclear magnetization density, which is often well understood from electron scattering studies. And third, for the low-energy pions we have investigated, the production operator is on firm theoretical ground, in contrast to the situation in pion inelastic scattering. Thus electroproduction may be viewed as a tool for producing pions at a known rate and known energy within the nucleus in order that subsequent π-nucleus interactions may be studied.

In this paper we report angular distributions for $^{12}C(e,\pi^+e')$ obtained at the University of Saskatchewan electron linear accelerator. Measurements were made for pion energies between 6 and 13 MeV and for six angles from 45° to 143°. These angular distributions are the first obtained for such low-energy pions. In addition, since an electron beam energy of 200 MeV was used, relatively little energy was available for nuclear excitation; thus our cross sections provide the first mapping of the nuclear response to $(e,\pi e')$ in the giant resonance region. This portion of the nuclear response surface has been thoroughly studied by inelastic electron scattering and is amenable to theoretical treatment. Since the relatively large cross sections in this region allowed us to obtain high quality angular distributions, our data can provide meaningful tests of the final-state π-nucleus interaction.

A 102 mg/cm^2 thick natural carbon target, turned 30° to the beam to effectively double its thickness, was bombarded by 1 μs electron pulses at 360 Hz. Pions were detected by four telescopes of silicon surface barrier detectors mounted in the focal plane of a 127°, double-focusing magnetic spectrometer. Each telescope consisted of two 300 μm ΔE detectors and one 2000 μm E detector. Aluminum moderators of various thicknesses were placed in front of each telescope to reduce the pion energy so that the pion would stop near the midplane of the third detector. The $\pi^+ \rightarrow \mu^+ + \nu_\mu$ decay, which deposited an additional 4.1 MeV in the third detector, helped to distinguish pions from background events. A detailed description of the detection system is given elsewhere.[3]

The associated electronics primarily recognized triple coincidences among the three detectors of each telescope and recorded detector pulse heights. A triple coincidence signal enabled two analog to digital converters (ADC) per telescope which digitized the second detector pulse height and the sum of the pulse heights of all three detectors. ADC outputs were histogrammed by an on-line computer. Pulse height spectra showed very well defined pion peaks with typical backgrounds of 1%. No detector sensitivity to muons produced in pion decay or to target positrons was found. Heavier particles were stopped in the moderator or first detector. During the experiment, electronic stability was checked frequently by measuring the yield of 15 MeV protons from ^{12}C(e,pe').

Pion yields, determined by integrating separately peak areas of both the second detector and the sum histograms, typically agreed within 2%. Yields were corrected for pion decay in flight, multiple scattering losses in the telescopes, pion creation by real photons in the target, and a 1% flat background. Pion absorption in the target, moderator, and first two detectors is negligible at these energies.[4] Cross sections were calculated for the pion energy that corresponded to production in the center of the target. Results were averaged and interpolated to round pion energies. Our full set of measurements and statistical uncertainties, ranging from 6% to 14%, are summarized in Table I. When estimated uncertainties for the individual terms in the cross section equation were added in quadrature, an overall systematic uncertainty of 7% was found.

In Fig. 1 double differential cross sections $d^2\sigma/d\Omega_\pi dE_\pi$ and statistical uncertainties are shown as a function of laboratory angle for 6, 9, and 13 MeV pions. Also shown are the results of a distorted wave impulse approximation calculation, with the contributions expected for transitions to 1-p shell ($0\hbar\omega$) and negative parity $1\hbar\omega$ final states in ^{12}B given separately. The latter states, which include those isovector strengths associated with the $L=1$ 15-dimensional supermultiplet of giant resonances,[5] account for nearly 60% of the cross section.

The single-nucleon operator used in these calculations is taken from a low-energy theorem based on current algebra and the partial conservation of axial-vector current (PCAC) hypothesis.[6] The resulting nonrelativistic amplitude appropriate for threshold $(e,\pi e')$ calculations in nuclei can be written

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

TABLE I. Double differential cross sections for ^{12}C(e,π^+e') (nb/MeV sr).

E_π (MeV) \ θ_π	45°	65°	90°	105°	120°	143°
6.0	0.304 ± 0.023	0.324 ± 0.035	0.300 ± 0.024		0.278 ± 0.035	0.278 ± 0.023
7.0	0.324 ± 0.021	0.345 ± 0.032	0.329 ± 0.033	0.268 ± 0.032	0.310 ± 0.021	0.297 ± 0.021
8.0	0.336 ± 0.020	0.361 ± 0.040	0.340 ± 0.021	0.334 ± 0.020	0.295 ± 0.020	0.304 ± 0.020
9.0	0.347 ± 0.020	0.376 ± 0.030	0.353 ± 0.030	0.339 ± 0.020	0.284 ± 0.020	0.305 ± 0.020
10.0	0.353 ± 0.020	0.382 ± 0.029	0.357 ± 0.030	0.328 ± 0.020	0.278 ± 0.020	0.295 ± 0.020
11.0	0.356 ± 0.029	0.384 ± 0.029	0.351 ± 0.029	0.313 ± 0.019	0.273 ± 0.024	0.283 ± 0.019
12.0	0.358 ± 0.029	0.384 ± 0.029	0.343 ± 0.029	0.297 ± 0.019	0.269 ± 0.029	0.275 ± 0.019
13.0	0.359 ± 0.028	0.381 ± 0.028	0.331 ± 0.029	0.281 ± 0.028	0.265 ± 0.038	0.266 ± 0.019

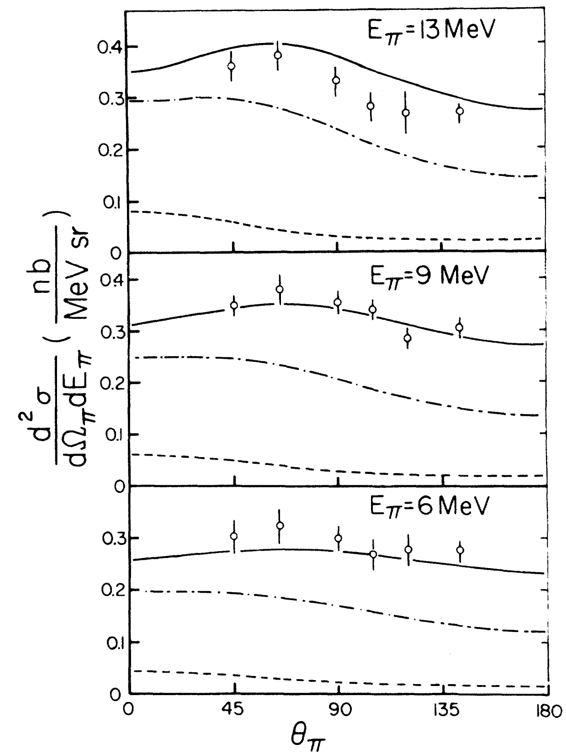

FIG. 1. Double differential cross sections for $^{12}C(e,\pi^+e')$ as a function of θ_π for 6, 9, and 13 MeV pions. Theoretical results are given for transitions to $0\hbar\omega$ final states in ^{12}B (dashed line), to $0\hbar\omega$ and $1\hbar\omega$ states (dash-dotted line), and to all states kinematically allowed (solid line).

Here $\epsilon^\mu = -ie\overline{U}(k_2)\gamma^\mu U(k_1)$ is the electron matrix element, and $k^\mu = k_1^\mu - k_2^\mu = (\vec{k}, \omega_k)$ is the four-momentum transferred to the nucleus. The outgoing pion wave function ϕ_π^* is generated from a second-order optical potential developed by the Stony Brook and Colorado groups.[1,7] The energy dependence of the parameters in this potential, including the Pauli blocking term and the π-nucleon phase shifts, has been treated properly. Phase shifts were taken from Salomon's parametrization of available data.[8]

A description of the method used to evaluate the electroproduction cross section, including the peaking approximation integration over the final unobserved electron, can be found in Ref. 9. Nuclear transition amplitudes to the $0\hbar\omega$ and $1\hbar\omega$ states in ^{12}B were calculated in the Tamm-Dancoff approximation[10] and then reduced in order to reproduce experimental electron scattering form factors.[11] Such reductions would be unnecessary in more sophisticated shell model calculations which treat ground state correlations in a realistic manner. Higher-lying $2\hbar\omega$ and $3\hbar\omega$ configurations are handled in simple j-j coupling with amplitude reductions corresponding to an effective mass of $M^* = 0.71$ M.[12] Harmonic oscillator single-particle wave functions have been used throughout. Our results differ little from those that would have been obtained had we used continuum wave functions, where appropriate.[9]

In Fig. 2 double differential cross sections are shown as a function of pion energy for angles of 45° 90°, and 143°. Also plotted are the 50° and 90° results of Shoda.[13] We believe the accuracy of the theory to be on the order of 20% based on our predictions of electron scattering form factors and on estimates of the effects of momentum dependent corrections[14] to the threshold operator. The sensitivity of photopion reactions to details of the optical potential is discussed by Haxton.[15]

From the good agreement between experiment and theory shown in Fig. 2 we conclude that calculations employing recently developed optical potentials[1,7] successfully reproduce the observed $(e,\pi e')$ cross

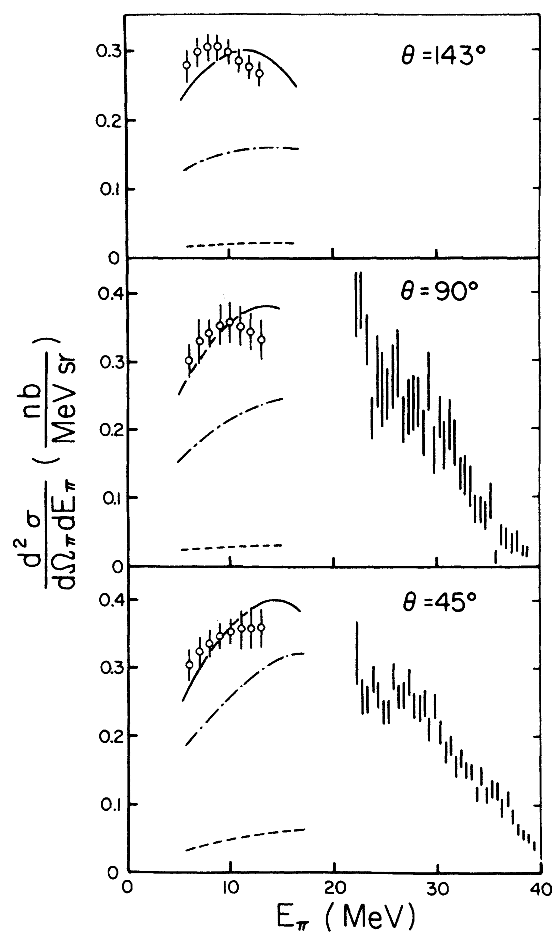

FIG. 2. Double differential cross sections for $^{12}C(e,\pi^+e')$ at $\theta_\pi = 45°$, 90°, and 143° as a function of pion energy. The 50° and 90° data of Shoda (Ref. 13) are shown for comparison. The theoretical curves are as in Fig. 1.

sections. This is a stringent test of such potentials since the pion scattering angle determines the three-momentum transfer to the nucleus. Thus, for a given pion energy, our angular distributions sample convolutions of the pion wave function with varying components of the nuclear magnetization density. Our results complement previous tests of such potentials in pion elastic scattering,[7] which measures the asymptotic behavior of the pion wave function at energies somewhat higher than those we have investigated.

In view of our results we believe that the discrepancies between experiment and theory detected earlier in the $(e, \pi e')$ measurements of Borkowski *et al.*[16] and Haxton[9] are likely due to the theoretical difficulty of predicting the nuclear response to higher energy (280 MeV) electrons,[17] and not to difficulties with the optical potential. On the other hand, it is possible that the pion field behaves anomalously for some critical momentum above those probed in the present experiment.[18] We believe an extension of the present experiment to the pion energies of Ref. 16 (22 and 30 MeV) would distinguish between these two possibilities.

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