Electroproduction of Charged Pions from ^{12}C Leading to Discrete Final Nuclear States

N. Paras, A. M. Bernstein, K. I. Blomqvist, G. Franklin, M. Pauli, and B. Schoch[(a)]
Physics Department and Laboratory of Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

J. LeRose, K. Min, D. Rowley, P. Stoler, E. J. Winhold, and P. F. Yergin
Physics Department, Rensselaer Polytechnic Institute, Troy, New York 12181

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$\pi^\pm$ electroproduction from ^{12}C has been studied at 90° (laboratory) for $T_\pi \simeq 17$ and 29 MeV. Transitions to discrete final states in ^{12}B and ^{12}N were observed up to 4.5-MeV excitation energy. The results are analyzed using virtual-photon theory. The resulting photoproduction cross sections are in reasonable agreement with recent theoretical calculations.

Photoproduction (or electroproduction) of pions leading to discrete final nuclear states has been theoretically discussed as potentially useful for studying the pion-nucleus interaction as well as $T_z = T_0 \pm 1$ spin-flip analog states.[1] However, a comprehensive experimental study has not yet appeared. Recent measurements bearing on these points include the following: total $(\gamma, \pi^\pm)$ cross sections within 19 MeV of threshold[2,3] in which only the ground-state transition was involved; photon spectrum measurements for the inverse (γ, π^-) reaction[4,5] where the pion energy is zero and only $\Delta T_z = -1$ is accessible; and angular distribution studies of ^{12}C$(\gamma, \pi^\pm)$ leading to the lowest two levels in ^{12}B,[6] but with limited statistics and also limited to $T_z = -1$.

We report here differential cross-section measurements for pion electroproduction on ^{12}C. These are the first such measurements which combine (a) good energy resolution, (b) good statistics, (c) observation of transitions to a series of discrete final states, (d) measurements at two different nonzero pion energies, and (e) observation for the first time of transitions to both the $T_z = T_0 + 1$ and $T_z = T_0 - 1$ spin-flip analog states in $(e, \pi^\pm)$ reactions. ^{12}C is a favorable nucleus for initial study because there are a series of accessible final states of varied character for which the nuclear matrix elements are reasonably well known from electron scattering.[7] The cross-section values are sensitive to pion final-state interactions; data were therefore obtained at pion energies ($T_\pi = 17$ and 29 MeV) which bridge the previously unexplored gap between the lowest-energy pion-scattering data ($T_\pi \simeq 30$ MeV) and pionic atom data. The study of both (e, π^+) and (e, π^-) reactions to mirror states is important because the cross-section differences are sensitive to possible differences in the nuclear matrix elements as well as to the isospin-dependent part of the pion-nucleus interaction.

In the experiment, a 25-μA electron beam from the Bates linac irradiated a 0.2-g/cm^2 graphite target. Pions emitted at 90° to the beam were momentum analyzed and detected using a magnetic spectrometer ($\Omega = 15$ msr) with a multiwire proportional counter in the focal plane, and scintillation and Cherenkov detectors to select pions from background electrons. System resolution was $\simeq 0.6$ MeV.

Pion spectra were obtained for two different spectrometer settings corresponding to $T_\pi = 17$ and 29 MeV. At each of these settings, measurements were made at a series of electron energies and from the combined spectra, the double-differential electroproduction cross section $d^2\sigma / dT_\pi \, d\Omega_\pi$ was obtained as a function of electron energy. The results for $T_\pi = 29$ MeV are given in Fig. 1. The cross sections vary continuously with electron energy because electroproduction involves a three-body final state, so that a given nuclear state may be excited by any electrons with energies above that state's threshold; the total observed cross section is the sum of the cross sections for all energetically accessible final states. Absolute cross sections were obtained by calibrating the apparatus with the known ^{1}H(γ, π^+) cross sections[8]; this calibration agrees well with calculations of solid angle and efficiency after correction for the small muon contamination (< 10%) and for pion decay. About 30% of the pions were due to real photons from bremsstrahlung in the target. These were accounted for in obtaining the electroproduction cross sections of Fig. 1.

To compare the electroproduction results with theoretical photoproduction calculations, the data were analyzed using the Dalitz-Yennie virtual-photon spectrum.[9] This spectrum was multiplied

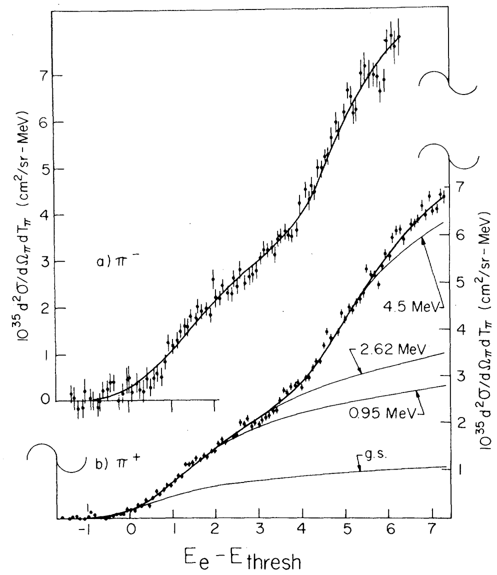

FIG. 1. π^+ and π^- electroproduction cross sections at $T_\pi = 29$ MeV as a function of $E_e - E_{\text{thresh}}$, where E_e is the electron energy and E_{thresh} is the ground-state threshold. Vertical bars on the data points represent statistical errors. The light lines are the contributions of transitions to individual final states (see text). The heavy solid curves through the data points are the sums of all light curves and represent least-square fits to the total observed cross sections.

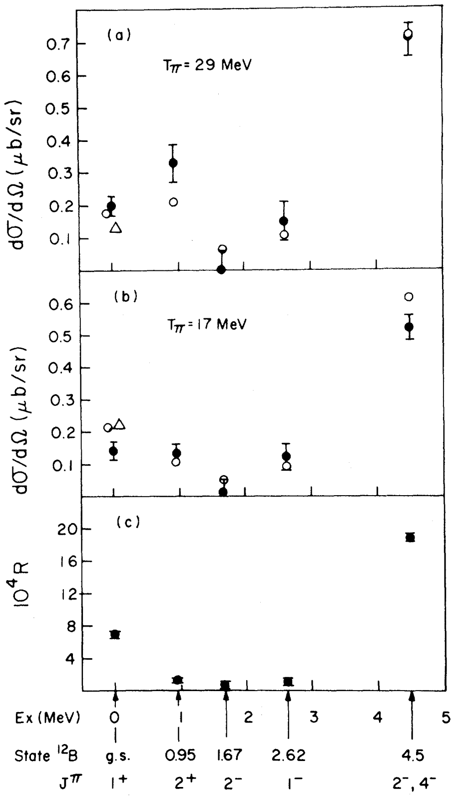

FIG. 2. (a), (b) (γ, π^+) cross sections to ^{12}B states. Experimental points (solid circles), and theoretical results of Nagl and Überall, Ref. 10 (open circles), and Epstein *et al.*, Ref. 11 (triangles), are shown. Experimental error bars include contributions from counting statistics and from uncertainty in absolute electron energy. No corrections have been made for quasifree production (see text). (c) The (π^-, γ) branching ratio R (capture γ's per stopped pion), from Ref. 5.

by 1.26 to reflect the electroproduction-to-photoproduction ratio which we have actually measured for ^{9}Be and ^{16}O within 3 MeV of the endpoint. The result of this analysis is shown in Fig. 1. Each curve (light line) represents transitions to a particular final state and has the shape of the virtual-photon spectrum folded with the experimental resolution. The amplitudes of these curves, determined by a least-squares fit to the data, give values for the differential photoproduction cross sections $(d\sigma/d\Omega_\pi)$ for each state in ^{12}B or ^{12}N. Figure 2 shows the (γ, π^+) cross sections at $T_\pi = 17$ and 29 MeV obtained in this way. The largest cross sections for both π^+ and π^- are for transitions to states at 4.5 MeV in ^{12}B and ^{12}N, which are the analogs of the $T = 1$, $J = 2^-, 4^-$ states in ^{12}C near 19.5 MeV previously reported in (e, e').[7]

We have made a theoretical estimate of the contributions to the data from ^{12}C$(e, \pi^+ n)$ and ^{12}C$(e, \pi^- p)$, neglected in the above analysis. The calculation assumes quasifree production, uses the amplitudes of Berends, Donnachie, and Weaver[12] and nucleon momentum distributions from harmonic-oscillator wave functions, and treats pion absorption by a mean-free path approximation.[13] According to this calculation, the cross sections to the states below 4.5 MeV are unaffected, but the cross sections to the 4.5-MeV states in ^{12}B and ^{12}N are reduced by roughly one-third. While this calculation accounts reasonably well for electroproduction at higher energies, it is subject to large uncertainties in the present threshold region, especially for π^- emission for which the Coulomb distortion of the proton is treated only approximately. We have therefore not attempted to correct the data for this effect.

The cross sections for transitions to the lowest two ^{12}B levels are in reasonable agreement with the angular-distribution data previously obtained of Shoda, Ohashi, and Nakahara[6]; however, the present results have considerably greater precision due to better statistics and somewhat better energy resolution. The relative populations of the ^{12}B levels in π^+ production also appear to be quite consistent with π^- capture results[5] [Fig. 2(c)] when the differences in momentum transfer q are taken into account. The yield of the transition to the ^{12}B ground state in comparison to the other states is smaller in the present experiment ($q \simeq 1.0$ fm^{-1}) than in π^- capture ($q = 0.6$ fm^{-1}). This reflects the q dependence of the form factor for this transition as mapped in electron scattering to the 15.11-MeV analog state in ^{12}C.[7]

Figure 2 also shows the results of two recent theoretical calculations.[10,11] Nagl and Überall[10] use nuclear form factors from a Helm-model fit to electron scattering data assuming spin-flip contributions only. The pion optical potential they use is an improved version over that used in Ref. 1, and includes absorptive and Lorentz-Lorenz terms, with parameters from πN scattering data. The ground-state calculations of Epstein, Singham, and Tabakin[11] employ shell-model wave functions and a pion optical potential[14] with parameters from pionic atom and π-nucleus elastic-scattering data. This is an extension of their previous calculation (Ref. 1) to our experimental conditions. Overall agreement between these calculations and experiment is satisfactory. A third calculation, similar to that of Epstein, Singham, and Tabakin,[11] has also been performed very recently by Haxton.[15] For π^- capture, there are several calculations[5] which, except for the ground-state transition, agree poorly with experiment. The shell-model wave functions used were not tested with electron-scattering data and may therefore be inaccurate.

The π^+ [Fig. 1(a)] and π^- [Fig. 1(b)] cross sections are closely similar in shape, indicating that the π^-/π^+ cross-section ratios are similar for the various pairs of analog states. This is also true for 17-MeV pions. These ratios depend on several factors including the $(\gamma n \to p\pi^-)/(\gamma p \to n\pi^+)$ elementary amplitude ratio ($\simeq 1.3$ at these energies) and the interference between Coulomb and nuclear final-state interactions. Calculations[10,11] indicate that in the present pion-energy range the strong-interaction part of the pion-nucleus interaction should have a significant effect on the cross-section values. Table I compares experimental and theoretical π^+ and π^- cross-section results. We note that agreement between experiment and theory is as good for π^- as for π^+. Moreover, the π^-/π^+ ratios are reasonably well predicted by theory. This suggests that the theoretical treatments of pion final-state interactions in the calculations are indeed yielding reasonable results, within the present level of experimental error. For the ground state, the two calculations, with quite different inputs, agree about equally well with experiment. However, the spin-flip form factor for the ground-state transitions is near its minimum in the kinematic region of this experiment, and the calculated ground-state cross sections are quite sensitive to small uncertainties in the parameters describing the nuclear transition density.

These theoretical calculations do not take into account differences in analog matrix elements. Calculations[16] predict the size of this effect as $\simeq 7\%$ at zero momentum, increasing to $\simeq 10\%$ at the momentum transfers of this experiment; this is below the present experimental accuracy.

Improved experimental and theoretical results are both needed. On the theoretical side, excited-

TABLE I. Experimental and theoretical (γ,π^-) and (γ,π^+) cross sections. $\Sigma(\pi^-)$ and $\Sigma(\pi^+)$ denote the sum of $d\sigma/d\Omega$ values over the final states up to 4.5 MeV excitation, for (γ,π^-) and (γ,π^+), respectively. Experimental values are from the data analysis described in the text with no correction for quasifree production. Systematic errors (estimated at ±10%) are not included.

		$T_\pi = 17$ MeV			$T_\pi = 29$ MeV		
		This work	Ref. 14	Ref. 15	This work	Ref. 14	Ref. 15
$\Sigma(\pi^-)$	(μb/sr)	1.37±0.05	1.76		1.88±0.09	1.91	
$\Sigma(\pi^+)$	(μb/sr)	0.92±0.02	1.07		1.37±0.02	1.22	
$\Sigma(\pi^-)/\Sigma(\pi^+)$		1.50±0.07	1.64		1.36±0.08	1.57	
$(d\sigma/d\Omega)_{\text{g.s.},\pi^-}$	(μb/sr)	0.24±0.05	0.36	0.32	0.34±0.14	0.27	0.17
$(d\sigma/d\Omega)_{\text{g.s.},\pi^+}$	(μb/sr)	0.14±0.03	0.21	0.22	0.20±0.03	0.17	0.13

state cross sections should be calculated using better wave functions. Further studies are needed on the importance of the approximations being made and on cross-section sensitivity to pion wave functions. Experimentally it would be useful to improve pion resolution and to obtain angular distributions. To this end, a new pion spectrometer is being built for use in the new experimental hall under construction at Bates.

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(a) Permanent address: University of Mainz, Mainz, Germany.

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Structure in the ^{24}Mg(^{18}O,^{14}C)^{28}Si Ground-State Excitation Function

J. C. Peng, D. L. Hanson, J. D. Moses, O. W. B. Schult,[a] Nelson Stein,
J. W. Sunier, and N. Cindro[b]
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545

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The excitation function of the reaction ^{24}Mg(^{18}O,^{14}C)^{28}Si(g.s.) has been measured at the second maximum of the angular distributions ($\theta_{\rm lab} \simeq 5°$) from 39- to 65-MeV incident energies. Oscillatory structure in the excitation function is observed with peak-to-valley ratios equal to ~1.5. The angular distributions measured near the maxima of the excitation function decrease more rapidly toward large angles than squares of Legendre polynomials, suggesting a direct reaction process to be important. Standard distorted-wave Born-approximation calculations do fit the angular distributions quite well, but fail to reproduce the structure in the excitation function.

Much recent experimental effort has focused on the resonancelike phenomena observed in the interaction of ^{12}C and ^{16}O with ^{24}Mg, ^{28}Si, and ^{40}Ca nuclei.[1-5] Elastic- and inelastic-scattering excitation functions measured at back angles contain resonances with angular distributions characterized by the squares of single Legendre polynomials. The scattering cross sections at back angles are found to be anomalously large with values several orders of magnitude greater than the predictions of optical models which fit forward-angle scattering data. In the α-particle transfer reactions, where both the entrance and exit channels exhibit resonance behavior, structure is observed at both forward and back angles.[6-10] The structure is quite strong in the case of ^{24}Mg(^{16}O, ^{12}C)^{28}Si excitation functions, but less pronounced for ^{28}Si(^{16}O, ^{12}C)^{32}S. In both cases the back-angle excitation functions show resonance structure which is correlated only weakly, if at all, with the resonances observed by scattering in the entrance and exit channels. Thus far there are too few data to