Forward-Angle ^{3}He$(e, e'\pi^{\pm})$ Coincident Electroproduction and the Search for Δ's in the Ground State of ^{3}He

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Forward-angle coincident electroproduction cross sections of charged pions from ^{3}He have been measured at electron energies $E_0 = 855$, 675, 600, and 555 MeV. The overall features of the data for energy transfers of $\omega = 370$ to 430 MeV with pions detected along the momentum transfer axis are reproduced in terms of a microscopic model, including pole terms, final state rescattering and produced and preformed Δ resonances. Separation of the cross section into its longitudinal and transverse parts was performed at $Q^2 = 0.045\ (\mathrm{GeV}/c)^2$. The longitudinal part of the cross section in the π^+ channel does not contradict with the assumption of a preformed Δ^{++}. [S0031-9007(96)01208-2]

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A fundamental question in nuclear structure physics concerns the role of meson degrees of freedom. The meson-nucleon interaction shows several resonances, and it is only natural to expect that these resonances affect the interaction of the constituents in nuclei. Indeed, the first attempts to explicitly incorporate these effects in nuclear interactions date back some 25 years [1]. However, so far it has been impossible to "see" these resonances in nuclei since the production of a resonance such as the $\Delta(1232)$ is much more probable than the knockout of a preformed Δ. Electroproduction of pions on few nucleon systems in selected kinematics is expected to offer a means to overcome this difficulty. The production of Δ's is dominated by transverse photons by more than 2 orders of magnitude, while the knockout of preformed Δ's is both transverse and longitudinal. Thus, the knockout is enhanced in the longitudinal channel which can be singled out via a Rosenbluth separation. Additionally, simple isospin arguments [2] yield that a preformed Δ in the ^{3}He nucleus has a 50% probability to be a Δ^{++} while no Δ^- occurs. Since the coupling of a photon to a preformed Δ is proportional to the charge, a preformed Δ in the ^{3}He ground state gives an extra contribution only to the π^+, but not to π^- cross section. Therefore, it was suggested by Lipkin and Lee [2] that the study of the $\sigma(e, e'\pi^+)/\sigma(e, e'\pi^-)$ ratio in photoproduction and electroproduction of pions on ^{3}He is suited to examine the presence of Δ's in the ground state of nuclei. Recent experiments [3,4], prompted by this suggestion, set an upper limit of $\approx$2% for this component, in qualitative agreement with current theoretical estimates [5–7]. Unfortunately, the quantitative modeling of the $\sigma(\pi+)/\sigma(\pi^-)$ ratio by Lipkin and Lee cannot be applied since their model is still too crude; e.g., they did not take into account the pion pole term and all sorts of final state interactions [8]. They suggested that this contribution could be somehow subtracted; this, however, is not possible since there is no way to separate it experimentally.

New experiments have been proposed at the continuous wave (cw) electron facilities BATES, NIKHEF, and CEBAF [9–11] which in polarization experiments will make use of the particular sensitivity of the asymmetries in charged pion production to the Δ admixture [12]. It should be noted that, besides the question of Δ's, so far the only existing coincident charged pion electroproduction data on a nucleus are from deuterium for which forward-angle positive and negative pion production cross sections were measured [13].

This Letter reports on results of a first round of measurements with the three-spectrometer setup at the cw electron beam of the Mainz microtron facility (MAMI) to address the question of preformed Δ's. The facility is described elsewhere [14,15]. High intensity ($\leq$30 μA) electron beams of small energy spread (<50 keV) were used. The aim was to exploit coincidence measurement capabilities for electrons and pions with two of the three existing spectrometers of good momentum resolution ($<10^{-4}$), and of large momentum (20%, 15%) and solid angle (28 msr, 5.6 msr) acceptances. Data were taken at three different polarizations of the virtual photon, ϵ. Thus, it was possible for the first time to separate the longitudinal and transverse contributions to the pion electroproduction cross section on a composite nucleus, hence, hopefully, getting a handle on preformed Δ's. The kinematical settings are summarized in Table I.

The ^{3}He target was similar to that of Ref. [16]. The target cell was made of a stainless steel foil of 80 μm

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thickness and had a diameter of 80 mm. It was run at a pressure of 15 bar and a temperature of 20 K, this corresponds to an effective thickness of about 170 mg/cm^2. The luminosity was monitored by the single rate obtained in the electron spectrometer with an accuracy better than 0.5%. Absolute cross sections were determined by normalization to elastic scattering data [16,17]. Momentum tracking and particle identification of electrons and pions were performed by four planes of vertical drift chambers and two planes of scintillators in the focal plane of each spectrometer. Problems associated with large single rates (the pions are detected additionally to 150 kHz protons or electrons) were overcome by fast hardware anticoincidences using scintillators and threshold gas Čerenkov detectors. Also, abundant positrons were identified and suppressed by means of the Čerenkov detector. Events originating from the target cell walls were identified due to good vertex resolution of both spectrometers in the offline analysis. Positive and negative pions were detected along the direction of the virtual photon under identical kinematical settings by just reversing the polarity of the pion spectrometer to minimize systematical errors. Contributions from interference terms in the cross section due to nonparallel pion detection (finite opening angle of the spectromters) are estimated to be smaller than 2%. The detailed data analysis, including radiative corrections, pion decay corrections, etc., is described in Ref. [18].

In $^3\mathrm{He}(e,e'\pi^\pm)$, the π^- channel consists of a pure 4-body final state ($ppp\pi^-$) while the π^+ channel contains 2-, 3-, and 4-body final states ($t\pi^+$, $nd\pi^+$, and $pnn\pi^+$). Figure 1 shows the $\pi^\pm$ cross sections measured for an incident electron energy of $E_0 = 855$ MeV over a wide range of missing mass M up to about 140 MeV/c^2 (note that the narrow peak of the $t\pi^+$ channel has been put at zero missing mass). An overall missing mass resolution of better than 800 keV was achieved, allowing for the first time the separation of the 2-body final state from the 3- and 4-body continuum in the π^+ channel. A discussion of the 2-body final state will be published elsewhere. It is seen in Fig. 1 that the continuum in both π^+ and π^- channels is rather structureless.

Missing mass spectra in the continuum are shown in Fig. 2 for all kinematical settings. Both π^+ and π^- cover the same range of missing mass. The π^- production cross sections are less than half of the π^+ channel at all energies, and the production rate of pions detected at 855 and 675 MeV, i.e., at forward electron angles, was larger than at the two lower energies, leading to spectra of higher quality than at the two lower energies. Figure 2 shows also calculations of a multiple scattering model of electroreactions and photoreactions [19–21], developed originally for pion production off the proton, which has already been quite successful in describing the photoproduction of pions off ^{3}He [22]. The calculations include diagrams depicting elementary processes (Born terms and Δ excitation), and they account for pion-nucleon and nucleon-nucleon rescattering, i.e., for final state interaction (FSI). Furthermore, contributions from preformed Δ's are explicitly included. A more detailed account is given in Refs. [21,22]. The location of the maxima and the overall trend of the measured cross sections are well reproduced in this model. In the π^- channel, the integrated cross sections are in quantitative agreement. For the π^+ channel, however, the model overestimates the cross section by about 30%. Therefore, the theoretical curve was normalized by a factor of 0.7. The inclusion of a knocked out Δ component (about 2%) has no effect at small missing mass M, but enhances the cross section in the tail region. The difference between the shapes of the π^+ and the π^- spectra at low missing mass is due to the strong contribution of $nd\pi^+$, which has no counterpart in the π^- channel. The strong nd-FSI shifts strength towards lower missing mass. In view of the strong reduction of the ^{3}He cross sections, as compared to the free nucleon case (a factor of about 2 for positive pions and of 6 for negative ones [21]), it is remarkable that the model reproduces, besides the shape of the spectra, the magnitude of the cross sections so well.

One of the main aims of the present experiment was the separation of the longitudinal and transverse parts of the pion electroproduction cross section. The cross section

TABLE I. Kinematical settings of the $^3\mathrm{He}(e,e'\pi^\pm)$ experiment. The four-momentum transfer squared Q^2 was 0.045 (GeV/c)^2 for all settings. The notation is E_0 the incident electron energy, ω the energy transfer, θ_e the electron scattering angle, ϵ the virtual photon polarization, θ_π the pion detection angle, and p_π the pion momentum.

E_0 (MeV)	ω (MeV)	θ_e	ϵ	θ_π	p_π (MeV/c)
855	368–430	19.5°	0.79	19.6°	226–414
675	368–425	28.4°	0.63	16.8°	260–404
600	395–432	36.4°	0.48	13.8°	266–413
555	363–398	40.8°	0.47	14.8°	242–376

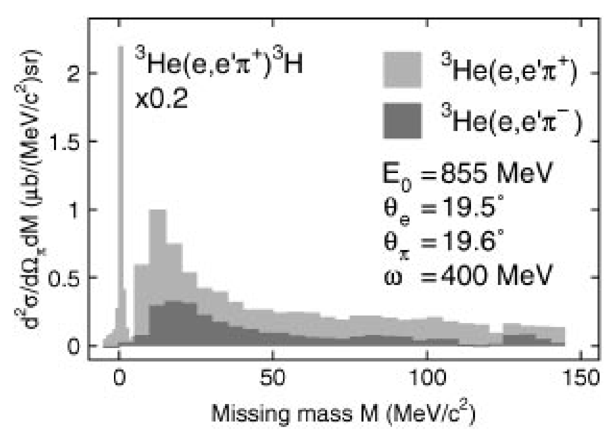

FIG. 1. $^3\mathrm{He}(e,e'\pi^\pm)$ cross sections for an incident electron energy of $E_0 = 855$ MeV. The narrow peak at the origin is due to the 2-body $t\pi^+$ channel and is scaled by a factor of 0.2. It is clearly separated from the 3- and 4-body continuum.

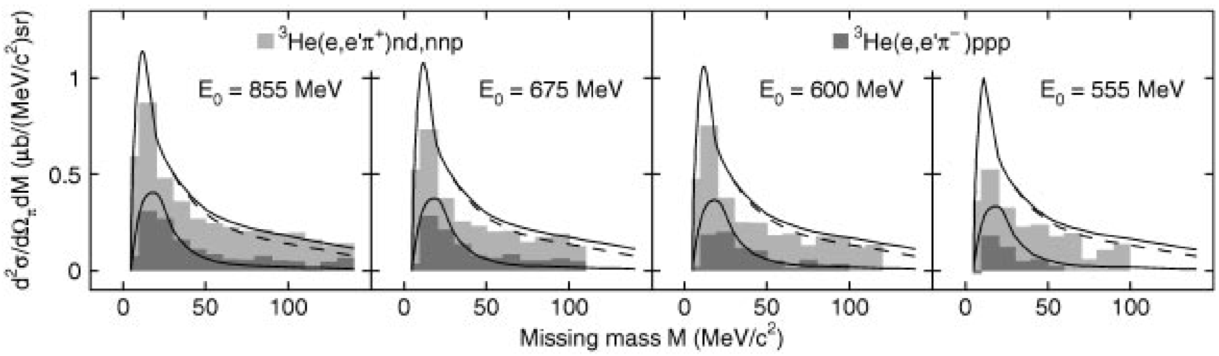

FIG. 2. ^{3}He$(e, e'\pi^\pm)$ cross sections for the kinematical settings shown in Table I. The 2-body channel $t\pi^+$ is not shown. The solid lines are results of microscopic calculations. For the π^+ channel, the model includes a Δ admixture of about 2% and is compared with a calculation without Δ's (dashed lines). The calculations are normalized by 0.7 (see text) for the π^+ channel.

for pion production parallel to the momentum transfer is given by

$$\frac{d^4\sigma}{d\omega d\Omega_e dM d\Omega_\pi} = \Gamma_\nu \frac{d^2\sigma}{dM d\Omega_\pi} = \Gamma_\nu \left[\frac{d^2\sigma_T}{dM d\Omega_\pi} + \epsilon \frac{d^2\sigma_L}{dM d\Omega_\pi} \right].$$

The photon flux Γ_ν and the polarization ϵ are defined, e.g., in Ref. [19]. For the Rosenbluth separations, the cross sections were integrated first over the lower missing mass range in the continuum extending from 3 to 50 MeV$/c^2$ and second over the upper one from 50 to 100 MeV$/c^2$. These two ranges were chosen because, according to the model calculation, they are distinguished by a different sensitivity to a preformed Δ. The peak at about 15 MeV$/c^2$ missing mass is due to the strong nd scattering, at low energy, which—as already remarked above—shifts the strength of the quasifree peak toward low missing masses. The broader structure in the upper mass range contains the contributions from pion rescattering, either on the deuteron in the $nd\pi^+$ channel or on one of the nucleons in the $NNN\pi$ channels: they shift part of the strength of the quasifree peak toward higher masses. Since a preformed Δ^{++} can only come from a p-p interaction in the ^{3}He ground state, it is always knocked out together with a neutron, which takes away kinetic energy of the Δ^{++} and shifts the contribution of this amplitude to higher missing mass. The interference of this small amplitude with the large ones described before finally results in the visible effect depicted in Fig. 2 in the upper missing mass range.

Figure 3 shows the cross section integrated over the missing mass range from 3 to 50 MeV$/c^2$, as a function of ϵ. From these, the transverse and longitudinal parts are extracted via the fit of a straight line, the results are given in the upper part of Table II. Here, as well as in Fig. 3, are also shown the results obtained from the calculations. While, on the weighted average, the calculation overestimates the transverse part by about a factor of 4, it underestimates the longitudinal by a factor of 1.6. Figure 4 shows the cross section integrated over the missing mass from 50 to 100 MeV$/c^2$, the resulting transverse and longitudinal contributions are compiled in the lower part of Table II.

As is frequently the case the L-T separated cross sections reveal difficulties of models more clearly. Table II shows that there are marked differences between theory and experiment. Most remarkable in the context of this paper is the very small calculated longitudinal contribution in the π^- channel at the higher masses, differing from that in the lower mass region by a factor of 9. Contrarily, this ratio is about 3 times smaller in the π^+ channel. Such difference is also—at least qualitatively—observed in the experiment. In the π^- channel the ratio is 3.9 ± 0.4 and in the π^+ channel 1.8 ± 0.1. The difference between the $\pi^\pm$ channels, for which we have no explanation at present, might be taken as a possible hint for the existence of a preformed Δ. The large L/T ratio provides thus a handle on this long standing problem. Of course, considering the still unsatisfactory overall agreement between the model and the data, a quantitative statement is premature. But it is clear that the data are now precise enough to challenge a theoretical explanation.

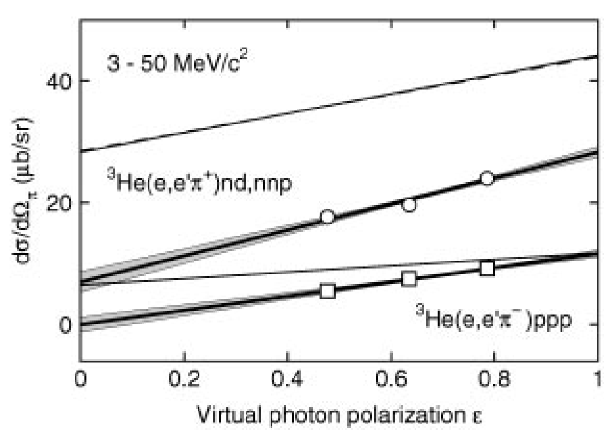

FIG. 3. The ^{3}He$(e, e'\pi^\pm)$ cross sections, integrated over the missing mass from 3 to 50 MeV$/c^2$, as a function of the virtual photon's polarization ϵ. The thin solid and dashed lines have the same meaning as in Fig. 2, but no normalization factor is applied. The bold solid lines are the result of a fit to the data. The shaded area indicates the error band associated with the fit.

TABLE II. Separated cross section integrated over the missing mass from 3 to 50 and from 50 to 100 MeV/c^2, respectively, at $Q^2 = 0.045$ (GeV/c)^2. The letters L and T stand for $d\sigma_L/d\Omega_\pi$ and $d\sigma_T/d\Omega_\pi$, respectively. The columns under "exp" and "th" contain the experimental results and the values calculated with the multiple scattering model, respectively. The cross section errors given in brackets are the correlated ones, the others are the uncorrelated errors.

	Cross section (μb/sr)				
	$\pi+$		π^-		M range (MeV/c)
	exp	th	exp	th	
L	21.3 ± 0.5(±2.5)	15.8	11.6 ± 0.3(±1.8)	5.3	3–50
T	7.0 ± 0.3(±1.7)	28.3	0.0 ± 0.2(±1.2)	6.5	
L/T	3.0 ± 0.2	0.56	>8	0.82	
L	11.7 ± 0.4(±2.5)	5.3	3.0 ± 0.3(±2.7)	0.6	50–100
T	2.0 ± 0.3(±1.8)	12.5	0.8 ± 0.2(±2.0)	1.1	
L/T	5.9 ± 1.1	0.42	3.8 ± 1.3	0.55	

In conclusion, we performed a high resolution charged pion electroproduction measurement on ^{3}He, using a cryogenic gas target. For the first time, a separation of the longitudinal and transverse cross sections on a composite nucleus was performed, for both the π^+ and π^- channels. To a large extent, the data can be described by a multiple scattering model. This agreement indicates that the nuclear effects on the pion production are roughly understood. The quantitative agreement between the multiple scattering model and the data, however, is not good enough to render a quantitative comparison reasonable, and it seems difficult to trace the deficiencies of the model. This issue can be better addressed in triple coincidence experiments in appropriate kinematics. Such experiments are now underway. The present experiment contributes to the search for Δ's in nuclei by having prepared the ground for the next generation of corresponding experiments.

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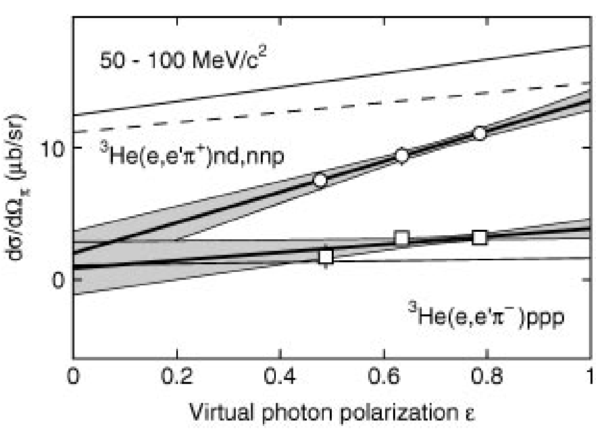

FIG. 4. Same as Fig. 3, but integrated over the missing mass from 50 to 100 MeV/c^2. The lines have the same meaning as in Figs. 2 and 3.

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