Longitudinal Electroproduction of Charged Pions from ^{1}H, ^{2}H, and ^{3}He

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Separated longitudinal and transverse cross sections for charged pion electroproduction from ^{1}H, ^{2}H, and ^{3}He were measured at $Q^2 = 0.4\ (\text{GeV}/c)^2$ for two values of the invariant mass, $W = 1.15$ GeV and $W = 1.60$ GeV, in a search for a mass dependence which would signal the effect of nuclear pions. This is the first such study that includes recoil momenta significantly above the Fermi surface. The longitudinal cross section, if dominated by the pion-pole process, should be sensitive to nuclear pion currents. Comparisons of the longitudinal cross section target ratios to a quasifree calculation reveal a significant suppression in ^{3}He at $W = 1.60$ GeV. The $W = 1.15$ GeV results are consistent with simple estimates of the effect of nuclear pion currents, but are also consistent with pure quasifree production.

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Conventional pictures of the nucleon-nucleon force, in which pion-exchange currents play a significant role, predict a mass dependent modification of the pion field in nuclei [1]. Early measurements of the mass dependence of the F_2 structure function in deep inelastic scattering (DIS) appeared to confirm this expectation when a large enhancement was seen at $x < 0.2$ [2]. This was quickly attributed to contributions from excess pions in the nucleus [3]. However, later DIS measurements observed a much smaller enhancement of F_2 at low x [4,5]. Studies of the Drell-Yan reaction, which is sensitive to antiquark distributions in nuclei, revealed no mass dependence at low x [6]. Polarization transfer measurements, first $(\vec{p}, \vec{p}\,')$ [7] and later $(\vec{p}, \vec{n})$ [8], of the ratios of longitudinal to transverse spin-isospin response functions in nuclei saw no evidence for the expected enhancement of the response ratio as predicted by models including nuclear pion effects. While evidence of large effects from pions in nuclei seems to be lacking in the above experiments, the interpretation is ambiguous. Recent calculations of both the mass dependence of DIS [9] and the Drell-Yan reaction [10] that explain the existing data include contributions from excess pions in nuclei. Furthermore, later analysis of the $(\vec{p}, \vec{n})$ results indicates that the enhancement of the response ratio due to pion-exchange contributions to the longitudinal response may have been masked by an unexpected enhancement of the transverse response [11]. Clearly, a more direct probe of the pion field of the nucleus is needed.

To the extent that the pion-pole process (i.e., scattering of virtual pions into the continuum) dominates, longitudinal charged pion electroproduction directly probes the virtual pion field of nuclei. If current models of the nucleon-nucleon force are correct, one expects a suppression of the pion field in nuclei relative to the free nucleon at low values of the virtual pion momentum, $k \approx 0.1-0.2$ GeV/c (in the pole process k, the virtual pion momentum, is equivalent to the 3-momentum transfer to the nucleus) and an enhancement at moderate pion momentum, $k \approx 0.3-0.6$ GeV/c. Furthermore, these models predict the modification of the pion field in ^{3}He to be significant and in ^{4}He to be comparable to that in heavier nuclei. These modifications should manifest themselves in measurable changes to the longitudinal pion electroproduction cross section. An earlier measurement of the unseparated π^+ electroproduction cross section from the deuteron at $k \approx 0.18$ GeV/c measured a ratio of 0.80 ± 0.05 relative to hydrogen [12]. This result motivated further study, in particular the isolation of the longitudinal response to increase sensitivity to the nuclear pion field.

In Jefferson Lab experiment E91003, charged pion electroproduction from ^{1}H, ^{2}H, and ^{3}He was measured. Data were taken for $Q^2 = 0.4$ (GeV/c)^2 at kinematics corresponding to the negative enhancement region ($k = 0.20$ GeV/c and $W = 1.60$ GeV) and the positive enhancement region ($k = 0.47$ GeV/c and $W = 1.15$ GeV) of the pion excess distribution of Ref. [1]. The experiment was carried out in Hall C using electron beam energies that ranged from 0.845 GeV to 3.245 GeV. Electrons were detected in the High Momentum Spectrometer and pions in the Short Orbit Spectrometer.

Electrons were selected using a gas Čerenkov counter containing C_4F_{10} at 0.42 atmospheres. Pions were identified using time-of-flight information from two pairs of scintillating hodoscope arrays to reject protons at positive polarity and a gas Čerenkov containing Freon-12 at atmospheric pressure to reject electrons at negative polarity. Backgrounds from random coincidences and the aluminum walls of the cryogenic targets were subtracted in the charge-normalized yields. These yields were also corrected for dead times and efficiencies. Cuts on the reconstructed missing mass excluded the region above the two-pion threshold.

The pion electroproduction cross section can be written as the product of a virtual photon flux (Γ) and a virtual photon cross section (evaluated in the laboratory frame),

$$\frac{d\sigma}{d\Omega_e dE_e d\Omega_\pi dM_x} = \Gamma \frac{d\sigma}{d\Omega_\pi dM_x}, \quad (1)$$

where M_x is the missing mass of the recoiling system, $M_x^2 = (q + P_A - p_\pi)^2$. The virtual photon flux is given by

$$\Gamma = \frac{\alpha}{2\pi^2} \frac{E_e'}{E_e} \frac{1}{Q^2} \frac{1}{1-\epsilon} \frac{W^2 - M^2}{2M}. \quad (2)$$

We take M to be the proton mass so that equal laboratory cross sections result in equal virtual photon cross sections regardless of target mass. The virtual photon cross section can be written

$$\frac{d\sigma}{d\Omega_x dM_x} = \frac{d\sigma_T}{d\Omega_\pi dM_x} + \epsilon \frac{d\sigma_L}{d\Omega_\pi dM_x} + \epsilon \frac{d\sigma_{TT}}{d\Omega_\pi dM_x} \times \cos 2\phi_{pq} + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{LT}}{d\Omega_\pi dM_x} \cos\phi_{pq}, \quad (3)$$

where ϵ describes the longitudinal polarization of the virtual photon. In the parallel kinematics of E91003, the interference terms (σ_{LT} and σ_{TT}) are small, and, for complete ϕ_{pq} coverage, integrate to zero.

To compare the longitudinal cross sections from ^{1}H, ^{2}H, and ^{3}He, it is necessary to integrate the cross sections over the missing mass peak. In this case the cross section can be expressed (after integrating over ϕ_{pq})

$$\int_{\Delta M_x} \frac{d\sigma}{d\Omega_\pi dM_x} = \int_{\Delta M_x} \frac{d\sigma_T}{d\Omega_\pi dM_x} + \epsilon \int_{\Delta M_x} \frac{d\sigma_L}{d\Omega_\pi dM_x}, \quad (4)$$

where ΔM_x is the region of missing mass within the experimental acceptance. In the case of the free proton, the missing mass is just a radiation and resolution broadened δ function at the neutron mass. For ^{2}H and ^{3}He, the Fermi motion of the bound nucleons broadens the distributions, and the missing mass coverage is limited by the acceptance of the spectrometers. At the $k = 0.20$ GeV/c kinematics the coverage is nearly complete, while at $k = 0.47$ GeV/c a significant fraction (10%–30%) of the missing mass distribution is outside the experimental acceptance, as illustrated in Fig. 1.

The (unseparated) missing mass integrated cross sections were measured at two values of ϵ for each k (W)

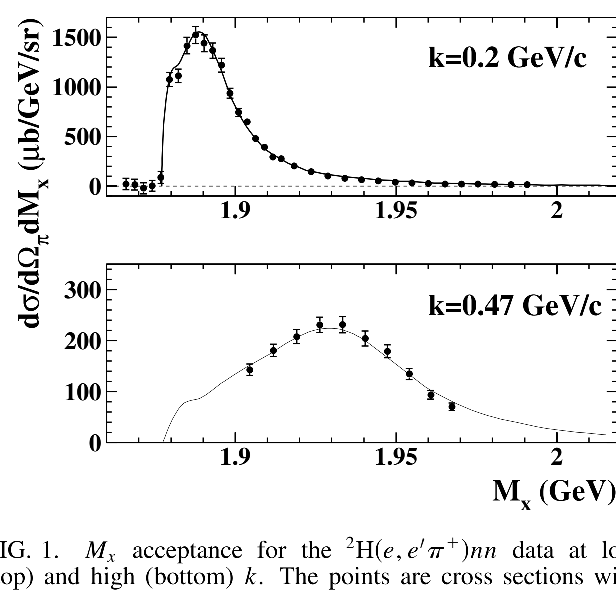

FIG. 1. M_x acceptance for the ^{2}H$(e, e'\pi^+)nn$ data at low (top) and high (bottom) k. The points are cross sections with statistical errors only and the curves are quasifree calculations (normalized to the data) that include NN final state interaction effects.

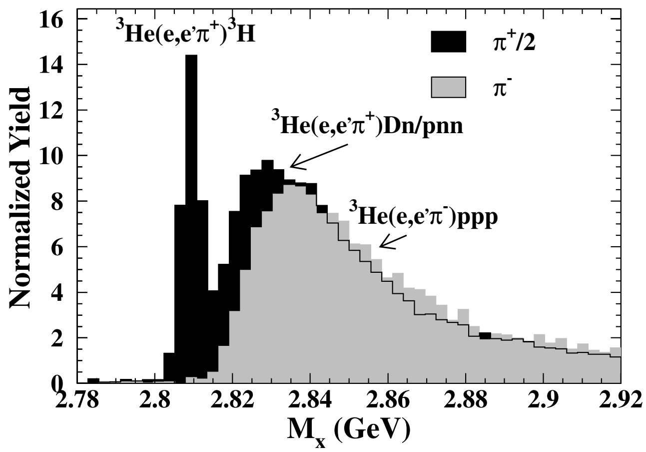

FIG. 2. Missing mass distributions for π^+ and π^- production from ^{3}He at $k = 0.20$ GeV/c. The π^+ data have been divided by 2 for comparison with the π^- data. The coherent ^{3}H final state is clearly distinguishable from the Dn/pnn continuum states.

setting, and the missing mass integrated longitudinal and transverse cross sections were extracted via a Rosenbluth separation [Eq. (4)]. The experimental cross sections were extracted using a Monte Carlo simulation of the experiment that included detailed descriptions of the spectrometers, decay of the pions in flight, multiple scattering, ionization energy loss, and radiative effects. The simulation used the MAID [13] model of charged pion electroproduction from nucleons to account for variations of the cross section across the acceptance. For electroproduction from ^{2}H and ^{3}He, the MAID model was implemented in a quasifree approximation in combination with realistic nucleon momentum distributions [14,15]. The ^{3}He calculation also included a missing energy distribution [fit from $(e, e'p)$ data [16]] which was used to model the Dn strength relative to the pnn strength in the ^{3}He$(e, e'\pi^+)$ reaction. Effects from nucleon-nucleon final state interactions were also included via a simple Jost function prescription [17]. An iterative procedure was used to optimize the pion electroproduction model and match the resulting Monte Carlo distributions to the data. Details of the analysis and iteration procedure can be found in Ref. [18].

In π^+ and π^- electroproduction from ^{2}H, it is appropriate to describe the process as quasifree since there are no bound nn or pp states. This is also the case for π^- production from ^{3}He where the final state is ppp. However, for π^+ production from ^{3}He, one has the ^{3}H (triton) bound state in addition to the Dn and pnn continuum states available. At the high-k kinematics, this state is not in the experimental acceptance and should be greatly suppressed by the ^{3}He form factor. At low k, the ^{3}H peak is clearly visible in the data (see Fig. 2) and the cross sections for the coherent and continuum processes can be independently extracted. In this Letter, we focus on the continuum final states and present results only for the combined Dn/pnn cross section in the ^{3}He$(e, e'\pi^+)$ reaction.

The separated cross sections are given in Table I. The ^{2}H and ^{3}He cross sections also include the experimental missing mass range over which they have been integrated. These separated cross sections are given in the laboratory frame at $Q^2 = 0.4$ (GeV/c)^2 and $\theta_{pq} = 1.72°$.

The longitudinal cross section ratios, R_L, are presented in Table II. These ratios do not directly relate to the pion field modification due to the limited M_x acceptance. Rather than attempt to extrapolate the measured spectra to full M_x acceptance, we compare the measured ratios to a calculation over the same region of M_x in which the process is treated as quasifree, i.e., in the absence of pion excess or other nuclear effects beyond binding. In this way, we take into account the limited M_x acceptance as well

TABLE I. Longitudinal and transverse separated cross sections for $A(e, e'\pi^{\pm})$. $\sigma_{L(T)}$ denotes $\int_{\Delta M_x} \frac{d\sigma_{L(T)}}{d\Omega_\pi dM_x}$ (in the laboratory). Uncertainties on the cross sections are statistical (systematic). ^{3}He$(e, e'\pi^+)$ cross sections have been divided by two (the number of protons) for comparison with the other targets.

Target	ΔM_x (GeV)	σ_L (μb/sr)	σ_T (μb/sr)
$k = 0.20$ GeV/c, $W = 1.60$ GeV, $\epsilon = 0.49, 0.89$			
^{1}H	...	34.6 ± 1.4(4.4)	27.3 ± 1.0(2.9)
D (π^+)	$M_x < 2.01$	29.7 ± 1.1(3.8)	25.3 ± 0.9(2.5)
D (π^-)	$M_x < 2.01$	46.8 ± 1.2(4.2)	11.3 ± 0.8(2.0)
^{3}He (π^+)	$M_x < 2.94$	19.3 ± 1.4(2.6)	18.1 ± 1.0(1.8)
^{3}He (π^-)	$M_x < 2.94$	25.9 ± 1.2(2.7)	13.3 ± 0.8(1.6)
$k = 0.47$ GeV/c, $W = 1.15$ GeV, $\epsilon = 0.44, 0.86$			
^{1}H	...	18.4 ± 1.0(2.0)	9.2 ± 0.6(1.1)
D (π^+)	$1.90 < M_x < 1.97$	13.4 ± 1.1(1.4)	6.2 ± 0.7(0.7)
D (π^-)	$1.90 < M_x < 1.97$	16.9 ± 1.0(1.5)	1.8 ± 0.6(0.5)
^{3}He (π^+)	$2.85 < M_x < 2.93$	9.6 ± 0.9(1.1)	5.5 ± 0.7(0.6)
^{3}He (π^-)	$2.85 < M_x < 2.93$	11.6 ± 0.9(1.1)	2.2 ± 0.6(0.4)

TABLE II. Experimental and quasifree calculations of longitudinal cross section ratios. Uncertainties on the experimental ratios are statistical (systematic). The experimental ratios are not corrected for pion-nucleon final state interactions, although these effects are expected to be small in all cases but the ^{3}He, π^+ data at high k.

Ratio	R_L^{exp}	$R_L^{\text{q.f.}}$	$R_L^{\text{exp}}/R_L^{\text{q.f.}}$
$k = 0.20$ GeV/c, $W = 1.60$ GeV			
D/^{1}H (π^+)	0.86 ± 0.05(0.11)	0.95 ± 0.03	0.90 ± 0.12
^{3}He/D (π^-)	0.55 ± 0.03(0.06)	0.95 ± 0.02	0.58 ± 0.07
^{3}He/H (π^+)	0.56 ± 0.05(0.09)	0.92 ± 0.05	0.61 ± 0.12
$k = 0.47$ GeV/c, $W = 1.15$ GeV			
D/^{1}H (π^+)	0.73 ± 0.07(0.07)	0.67 ± 0.04	1.09 ± 0.16
^{3}He/D (π^-)	0.69 ± 0.07(0.06)	0.70 ± 0.04	0.99 ± 0.14
^{3}He/H (π^+)	0.52 ± 0.06(0.07)	0.49 ± 0.05	1.07 ± 0.21

as the kinematic variation of the fundamental γ^*-N cross section due to the Fermi motion of the bound nucleon.

The quasifree ratios are calculated using the pion electroproduction model and momentum space wave functions used in the Monte Carlo simulation and are shown with the measured ratios in Table II. The model dependence of the calculated ratio is estimated by comparing the result with the value obtained by using a flat cross section in place of the electroproduction model. The uncertainty in the quasifree calculation of the ratio varies from 2% to 10%—generally largest in the ^{3}He/^{1}H ratio. Figure 3 shows the experimentally determined ratios compared to the quasifree calculated ratios, i.e., $R_L^{\text{exp}}/R_L^{\text{q.f.}}$ as a function of k for the free nucleon. Error bars include the uncertainty in the quasifree calculation as well as the experimental statistical and systematic uncertainties.

At $k = 0.20$ GeV/c, a suppression of the longitudinal cross section in ^{3}He relative to ^{1}H and ^{2}H is clearly evident

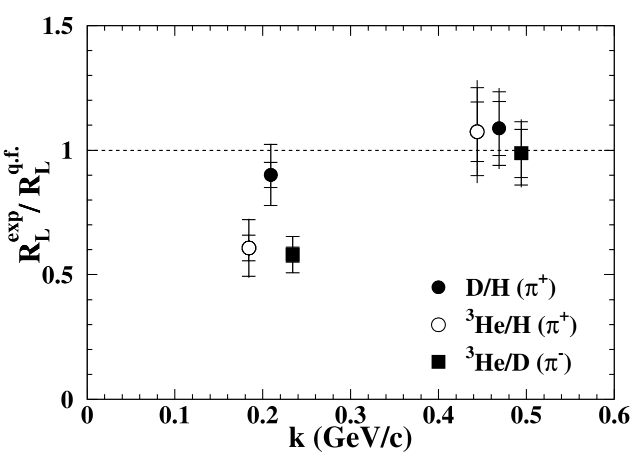

FIG. 3. Longitudinal cross section ratios compared to a quasifree calculation. Note that the calculation is integrated over the same region of the quasifree peak as is sampled experimentally. The experimental ratios are not corrected for pion-nucleon final state interactions (these effects should be less than 5%, except for the ^{3}He, π^+ data at high k). The ^{3}He ratios have been shifted in k for viewing purposes.

while the ^{2}H to ^{1}H ratio is consistent with unity within the uncertainties. At $k = 0.47$ GeV/c, all of the super-ratios are consistent with unity, indicating that the longitudinal strength in ^{2}H and ^{3}He is not significantly enhanced relative to the free nucleon. In all cases, the measured ratios are somewhat suppressed due to final state interactions between the outgoing pion and the spectator nucleons. This suppression is expected to be less than 5%, except for the ^{3}He$(e, e'\pi^+)$ data at high k. In this case, the final pion momentum is 0.29 GeV/c and the pion rescattering effects on the spectator pn pair can be large. In a simple factorization approximation, the suppression due to rescattering is 0.75 [19]. Applying this calculation to kinematics where other estimates are available [20–22], we estimate the uncertainty in the rescattering suppression to be about 20%. Hence, the ^{3}He/^{1}H(π^+) super-ratio of 1.07 might be more accurately interpreted as 1.43, albeit with large experimental uncertainties (±0.28) in addition to the uncertainty in the rescattering calculation.

While the pole term is believed to be the single largest piece of the longitudinal cross section at E91003 kinematics, it is unclear to what extent other processes may contribute. One can check for pole-term dominance by comparing the longitudinal π^-/π^+ ratios in ^{2}H. A deviation from unity indicates the presence of isoscalar terms which, since the pole term is pure isovector, must come from other Born terms. At $k = 0.47$ GeV/c ($k = 0.20$ GeV/c), the longitudinal π^-/π^+ ratio is 1.27 ± 0.16 (1.58 ± 0.19). These ratios clearly deviate from unity, but do not give enough information to determine how the isoscalar backgrounds affect the measured ratios.

One can use the pion-excess calculations of Ref. [1] together with the formalism of Ref. [23] [Eq. (18)] to estimate the modifications to the nuclear response (and hence the super-ratios of Fig. 3) which might be expected in the best-case scenario of pole dominance. Such a calculation indicates that, at low k, the suppression should be ≈1% (14%) in ^{2}H (^{3}He) relative to the free nucleon. At high k, the expected enhancement is 6% (13%) in ^{2}H (^{3}He) (note that this implies a 7% enhancement in the ^{3}He/D super-ratio). The measured super-ratios are largely consistent with these simple estimates, though contributions from non-pole terms could dilute or enhance the experimental signal. The suppression seen in the ^{3}He data at low k is larger than the naive expectation, but this may come about from the exclusion of the ^{3}H final state which would give additional longitudinal strength to the π^+ data. It should be noted that while the high k results are consistent with the estimated pion-excess effects, they are also consistent with pure quasifree production.

Longitudinal pion electroproduction holds great promise as a probe of the pion field of nuclei. The results reported here show a clear suppression of the longitudinal strength at low k, and at high k are consistent with estimates derived from pion-excess calculations. Further measurements at kinematics where the longitudinal π^-/π^+ ratio is consistent with pole dominance (as is the case in Ref. [24]) and extending the measurement to higher missing mass, where it has been suggested that nucleon-nucleon correlations are important [23], would greatly simplify the interpretation of this type of experiment. Furthermore, extending the measurements to ^{4}He would provide the opportunity to probe a nucleus with potentially twice the enhancement, but where detailed microscopic calculations are still feasible.

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[1] B. L. Friman, V. R. Pandharipande, and R. B. Wiringa, Phys. Rev. Lett. **51**, 763 (1983).
[2] J. J. Aubert *et al.,* Phys. Lett. **123B**, 275 (1983).
[3] M. Ericson and A. W. Thomas, Phys. Lett. **128B**, 112 (1983).
[4] J. Ashman *et al.,* Z. Phys. C **57**, 211 (1993).
[5] J. Gomez *et al.,* Phys. Rev. D **49**, 4348 (1994).
[6] D. M. Alde *et al.,* Phys. Rev. Lett. **64**, 2479 (1990).
[7] L. B. Rees *et al.,* Phys. Rev. C **34**, 627 (1986).
[8] J. B. McClelland *et al.,* Phys. Rev. Lett. **69**, 582 (1992).
[9] O. Benhar, V. R. Pandharipande, and I. Sick, Phys. Lett. B **410**, 79 (1997).
[10] G. A. Miller, Phys. Rev. C **64**, 022201 (2001).
[11] T. N. Taddeucci *et al.,* Phys. Rev. Lett. **73**, 3516 (1994).
[12] R. Gilman *et al.,* Phys. Rev. Lett. **64**, 622 (1990).
[13] D. Drechsel, O. Hanstein, S. S. Kamalov, and L. Tiator, Nucl. Phys. **A645**, 145 (1999).
[14] T.-S. H. Lee (private communication).
[15] R. B. Wiringa (private communication).
[16] E. Jans *et al.,* Nucl. Phys. **A475**, 687 (1987).
[17] J. Gillespie, *Final State Interactions* (Holden-Day, San Francisco, 1964).
[18] D. Gaskell, Ph.D. thesis, Oregon State University, 2001.
[19] T.-S. H. Lee (private communication).
[20] K. I. Blomqvist *et al.,* Nucl. Phys. **A626**, 871 (1997).
[21] S. S. Kamalov, L. Tiator, and C. Benhold, Few-Body Syst. **10**, 143 (1991).
[22] R. J. Loucks and V. R. Pandharipande, Phys. Rev. C **54**, 32 (1996).
[23] D. S. Koltun, Phys. Rev. C **57**, 1210 (1998).
[24] J. Volmer *et al.,* Phys. Rev. Lett. **86**, 1713 (2001).