Quasifree π^0 and π^- Electroproduction on ^{4}He in the Δ-Resonance Region

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The reactions $^4\text{He}(e, e'p\,^3\text{He})\pi^-$ and $^4\text{He}(e, e'p\,^3\text{He})\pi^0$ were studied simultaneously, and for the first time, in a large kinematical domain including the Δ-resonance region. This was achieved by detecting the recoiling ^{3}He and ^{3}H nuclei instead of the emitted pions. The dependences of the cross section on the recoil momentum p_{rec}, the invariant mass $W_{\pi\text{N}}$, and the direction $\theta_{\pi,q'}$ and $\phi_{\pi,q'}$ of the produced pion, are globally well described by the results of (quasifree) distorted-wave impulse approximation calculations. However, in the Δ-resonance region there are clear discrepancies, which point to medium modifications of the Δ in ^{4}He.

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A modification of the properties of hadrons in cold or hot nuclei and nuclear matter has been a subject of great interest for many years [1]. Such medium effects are, e.g., reflected in the effective masses and/or decay widths of the created hadrons [2,3]. In this respect, the first excited state of the nucleon, i.e., the Δ resonance, is a prime case to study, since it is easily excited in many reactions.

Several studies have been devoted to a search for medium modifications of the Δ. In particular, pion photoproduction and electroproduction are important, since the electromagnetic probe is well understood, and initial-state interactions are minimized. Indications for a medium modification of the Δ were extracted from coherent π^0 photoproduction in various nuclei [4] and a measurement of the longitudinal, transverse, and longitudinal-transverse interference cross sections in the reaction $^3\text{He}(e, e'\pi^+)^3\text{H}$ [5].

Electroproduction of neutral pions in ^{4}He is an excellent probe to study medium effects on the Δ, since the density of ^{4}He is relatively large, and the π^0 mesons are predominantly created via intermediate Δ excitation.

In this Letter we report on the results of an experiment in which the reactions $^4\text{He}(e, e'p\,^3\text{He})\pi^-$ and $^4\text{He}(e, e'p\,^3\text{H})\pi^0$ were measured simultaneously. Since in π^0 production the nonresonant Born terms are strongly suppressed, the comparison of the results for both reaction channels gives direct information on the relative importance of Born and resonant contributions to the cross section in the Δ region, and hence a much cleaner picture of the role of the Δ resonance in pion production on a nucleus.

The measurements were performed at the internal-target facility of the Amsterdam Pulse Stretcher and storage ring (AmPS) [6] at NIKHEF. The energy of the electrons in the ring was 672 MeV and the average beam current was 100 mA. The ^{4}He gas was contained in a 40 cm cylindrical storage cell [7,8], which gave a target thickness of about 6×10^{14} atoms/cm^2. The integrated luminosity was 0.29 fb^{-1}. In addition, data were taken with an empty cell and a cell filled with hydrogen. The measurements with the empty cell were performed to estimate the contribution of reactions in the cell wall to the triple coincidence events, and the data collected with the hydrogen target were used to check the detector calibrations.

The momenta of the scattered electrons were measured in the magnetic spectrometer BigBite [9]. The large momentum acceptance of this spectrometer (200–900 MeV/c) enabled a simultaneous measurement of electrons from elastic scattering, quasielastic electron scattering and (quasifree) pion production. To optimize the yield, BigBite was positioned at its most forward central angle (30°). In combination with a central momentum of 500 MeV/c, this yields a range in the transferred energy ω and momentum q of 250–450 MeV and 350–500 MeV/c, respectively. The value of $Q^2(= q^2 - \omega^2)$ for the pion production reaction varied between 0.03 and 0.08 GeV$^2/c^2$.

Protons from the $(e, e'p)$ and $(e, e'p\pi)$ reactions were detected with a highly segmented plastic scintillator array (HADRON4) [10]. This detector was positioned close to the direction of the momentum transfer $\mathbf{q}$, and covered the angular range 30°–74°.

Rather than detecting the emitted neutral and charged pions, the recoiling ^{3}He and ^{3}H nuclei were detected with a recoil detector [11], and the momentum of the pion was determined by using kinematical completeness. The recoil detector consists of a low-pressure avalanche chamber, two silicon strip detectors and a plastic scintillator. The active parts of the detector are separated from the vacuum of the target chamber by a mylar foil of 0.9 μm thickness. In this way a detection threshold for ^{3}He particles as low as

1 MeV was achieved. The central angle was 115° with respect to the beam direction, opposite to the direction of the momentum transfer.

Identification of the recoiling ^{3}H and ^{3}He particles that stopped in the second layer of the Si detector or in the scintillator was performed using the energies deposited in two subsequent layers. Similarly, the charge of the particles stopped in the first Si layer was deduced from the energy deposited in this layer and the wire chamber; the mass of these particles was obtained from their time of flight, measured with the avalanche chamber.

Missing-mass spectra were used to select pions and to discriminate against events in which a photon is emitted, e.g., the ^{4}He$(e, e'p^3$H$)\gamma$ reaction. After correcting the data for inefficiencies and for events from the cell wall, the cross sections for π^0 and π^- production were obtained by normalizing the yields to the phase space and the luminosity. The former was extracted from a Monte Carlo simulation, taking into account the extended target density profile along the beam direction.

As a check on the analysis and cross section determination using recoil detection, the reduced cross section ("distorted" proton momentum density) [12] extracted from simultaneously measured ^{4}He$(e, e'p^3$H$)$ data was compared to the results of previous measurements [13,14]. Since the latter were measured at different kinematic conditions, a direct comparison is not possible. Instead, the comparison was done via the results of distorted-wave impulse approximation (DWIA) calculations. The parameters of the Woods-Saxon potential for the bound-state wave function were taken so as to reproduce the $\langle ^3\mathrm{H}|^4\mathrm{He}\rangle$ overlap function used in Refs. [13,14]. Furthermore, an energy dependent Woods-Saxon type optical potential was used for the distorted wave of the outgoing proton. With this potential a good description was obtained for the cross sections reported in Refs. [13,14]. At the kinematics of this experiment, the measured cross sections agreed within 5% with the calculated ones, which is within the systematic uncertainties.

The cross section for pion production on an unpolarized nucleus with an unpolarized electron can be expressed [15] as a flux factor Γ_v times the cross section for absorption of a virtual photon:

$$\frac{d^8\sigma}{dE' d\Omega_{e'} dE_\pi d\Omega_\pi d\Omega_p} = \Gamma_v \frac{d^5\sigma_v}{dE_\pi d\Omega_\pi d\Omega_p} \equiv \Gamma_v(\epsilon\sigma_L + \sigma_T + \sqrt{\epsilon(1+\epsilon)}\sigma_{LT} + \epsilon\sigma_{TT}), \tag{1}$$

where the short-hand notation $\sigma_X = \frac{d^5\sigma_X}{dE_\pi d\Omega_\pi d\Omega_p}$ $(X = L, T, LT, TT)$ has been introduced; the indices refer to the longitudinal (L) and transverse (T) components of the virtual photon and their interferences.

The cross sections σ_X depend on seven independent variables. A convenient choice for the first five variables is q, ω (or alternatively Q^2 and T_π, the kinetic energy of the pion), p_{rec} (the momentum of the recoiling nucleus), $W_{\pi\mathrm{N}}$ (the invariant mass of the final pion-nucleon system), and $\theta_{\pi,\mathrm{q}}$ (the angle between the outgoing pion and $\mathbf{q}$). The remaining two variables account for azimuthal dependences of σ_X, which are contained only in the interference terms σ_{LT} and σ_{TT}. It is convenient to express these dependences through the variables $\Phi = (\phi_{\pi,\mathrm{q}} + \phi_{\mathrm{p,q}})/2$ and $\Delta\Phi = (\phi_{\pi,\mathrm{q}} - \phi_{\mathrm{p,q}})/2$, rather than $\phi_{\pi,\mathrm{q}}$ and $\phi_{\mathrm{p,q}}$ [16]. In this way the dependence of σ_{LT} and σ_{TT} on Φ is factored out. The most relevant variables are, in view of a study of the reaction mechanism and the role of the Δ-excitation, p_{rec}, $W_{\pi\mathrm{N}}$, $\theta_{\pi,\mathrm{q}}$, and $\Delta\Phi$.

The data are compared to DWIA calculations and, in order to investigate the influence of distortions, also to plane-wave impulse approximation (PWIA) calculations, performed with the code of Lee [15], which uses the Blomqvist-Laget pion production operator [17]. In these calculations the reaction mechanism is assumed to be quasifree production. The calculations were performed with the same potential parameters as in the calculations performed for the reaction ^{4}He$(e, e'p^3$H$)$. The parameters in the potential that accounts for the pion-nucleus interaction were taken from Ref. [15].

Since the experimental cross section is always integrated over parts of the kinematic acceptance, the same has to be done for the theoretical cross section in order to be able to compare the two. For this the Monte Carlo integration method was used. The precision of this method is limited by the number of generated Monte Carlo events. In the presented results of the PWIA and DWIA calculations this shows up as statistical fluctuations.

First, the dependence of the cross section on p_{rec} was investigated. The data for both reactions are shown in Fig. 1, together with the results of the PWIA and DWIA calculations. Clearly the dependence on p_{rec} is very well described by the DWIA calculations, and close to the PWIA curves, which are given by the momentum distributions $\rho(p_{\mathrm{rec}})$ of the proton and neutron in ^{4}He. This in-

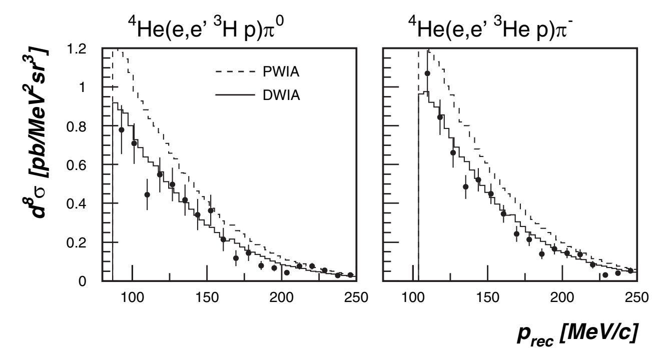

FIG. 1. The cross section $d^8\sigma$ for the reactions ^{4}He$(e, e'p^3$H$)\pi^0$ and ^{4}He$(e, e'p^3$He$)\pi^-$ as a function of p_{rec}.

dicates that the reaction can globally be described as quasifree pion production.

Figure 2 shows the measured cross sections as a function of $W_{\pi N}$. The lack of strength in the $^4\mathrm{He}(e, e'p^3\mathrm{H})\pi^0$ reaction at low $W_{\pi N}$ clearly indicates that the π^0 is dominantly produced via the Δ resonance, whereas π^- production has a sizeable Born-term contribution in that region. Generally, the data are well reproduced by the calculations. In the data as well as the calculations only events for which $p_{\mathrm{rec}} \leq 180$ MeV/c are included. This choice is based on a detailed comparison of the measured and calculated invariant mass spectra for the reaction $^4\mathrm{He}(e, e'p^3\mathrm{H})\pi^0$ in three domains in p_{rec}, which showed significant differences between the data and the calculations at $p_{\mathrm{rec}} \geq 180$ MeV/c. Obviously, at these high recoil momenta, where the cross section for quasifree pion production becomes small, other reaction mechanisms start to play an important role.

The measured ratio between the cross sections for neutral and charged pion production in the Δ-resonance region $1180 \leq W_{\pi N} \leq 1250$ MeV is about 1.5. This is consistent with a large contribution of Δ excitation to the cross section, which would give a factor of 2 for the cross section ratio [17,18]. The difference with the value extracted from the data can easily be explained by the contribution of the Born terms to the cross section, which is sizeable for π^- production and relatively small for π^0 production.

In a quasifree reaction mechanism the initial momentum of the struck nucleon is approximately $-\mathbf{p}_{\mathrm{rec}}$ and, therefore, the momentum $\mathbf{q}'$ of the γN system is equal to $\mathbf{q} - \mathbf{p}_{\mathrm{rec}}$. In an analogy to pion production on a free nucleon, the z axis of the reference coordinate system is defined in the direction of this vector. Hence, the cross sections are shown as functions of $\theta_{\pi,\mathrm{q}'}$ (Fig. 3) and $\phi_{\pi,\mathrm{q}'}$ (Fig. 4) instead of $\theta_{\pi,\mathrm{q}}$ and $\phi_{\pi,\mathrm{q}}$.

The dependences of the data on $\theta_{\pi,\mathrm{q}'}$ differ significantly from the calculated ones. At small values of $\theta_{\pi,\mathrm{q}'}$ the DWIA calculations underestimate the data, whereas they overestimate the data at larger values of $\theta_{\pi,\mathrm{q}'}$. This effect appears to be strongest for values of $W_{\pi N}$ above 1160 MeV, which suggests that the discrepancy is related to medium effects in the excitation and decay of the intermediate Δ. In this respect it is interesting to mention that similar discrepancies have been observed in the reaction $^3\mathrm{He}(e, e'\pi^+)^3\mathrm{H}$ in the Δ-resonance region [5]. The latter could be traced to a discrepancy in the σ_{LT} interference part of the cross section, and could be removed by including a complex self-energy term for the Δ. This interference term has the largest weight in the cross section for the reaction $^4\mathrm{He}(e, e'p^3\mathrm{H})\pi^0$ at large $\theta_{\pi,\mathrm{q}'}$, where the discrepancies are largest (c.f. Fig. 3). Note that for Δ excitation σ_{LT} is responsible for the shift in the maximum value of the cross section from 90° in the $\gamma^* N$ c.m. frame, where all other partial cross sections reach their maximum value, to 120°. Thus we tentatively ascribe the discrepancies shown in Fig. 3 to a medium modification of the Δ.

In Fig. 4 the dependences of the cross sections on the azimuthal angles $\phi_{\pi,\mathrm{q}'}$, Φ, and $\Delta\Phi$ are presented. The peaking of the cross section around $\phi_{\pi,\mathrm{q}'} = 0°$ and $\Delta\Phi = 180°$, which is especially strong in the case of π^0, is due to the fact that within the detection volume the variables $\phi_{\pi,\mathrm{q}'}$ and $\Delta\Phi$, and to a lesser extent Φ, are strongly correlated with $W_{\pi N}$. Around $\phi_{\pi,\mathrm{q}'} = 0°$ and $\Delta\Phi = 180°$ the data mainly stem from the region $W_{\pi N} > 1170$ MeV, in which the cross section is largest, while at $\phi_{\pi,\mathrm{q}'} = \pm 100°$ and $\Delta\Phi < 100°$ or $\Delta\Phi > 260°$ the maximum value of $W_{\pi N}$ is only 1100 MeV. In this domain the cross section is much smaller, especially for π^0 production.

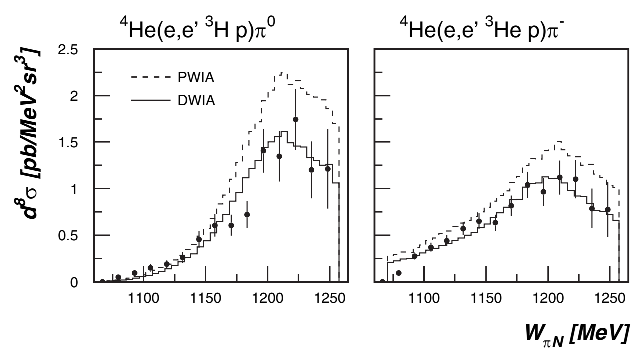

FIG. 2. The cross sections for π^0 and π^- production as a function of $W_{\pi N}$. Only events with $p_{\mathrm{rec}} \leq 180$ MeV/c are included.

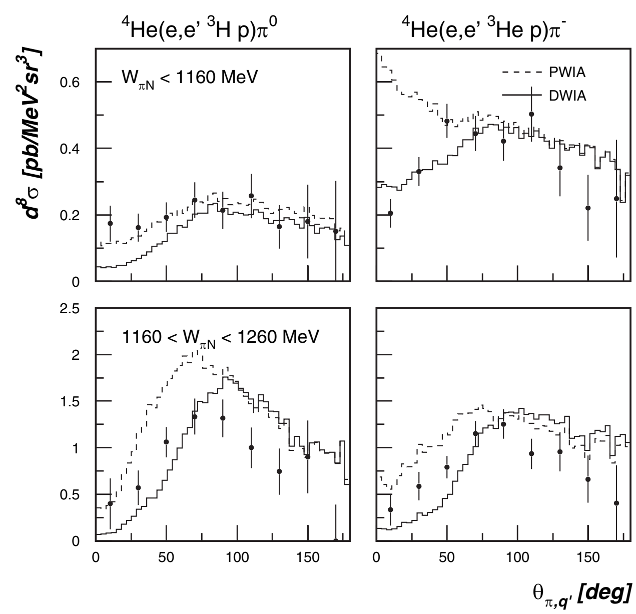

FIG. 3. Dependence of $d^8\sigma$ on $\theta_{\pi,\mathrm{q}'}$ for the reactions $^4\mathrm{He}(e, e'p^3\mathrm{H})\pi^0$ and $^4\mathrm{He}(e, e'p^3\mathrm{He})\pi^-$. The cross sections are shown for two $W_{\pi N}$ bins: $W_{\pi N} < 1160$ MeV (top) and $1160 < W_{\pi N} < 1260$ MeV. Only events with $p_{\mathrm{rec}} \leq 180$ MeV/c are included.

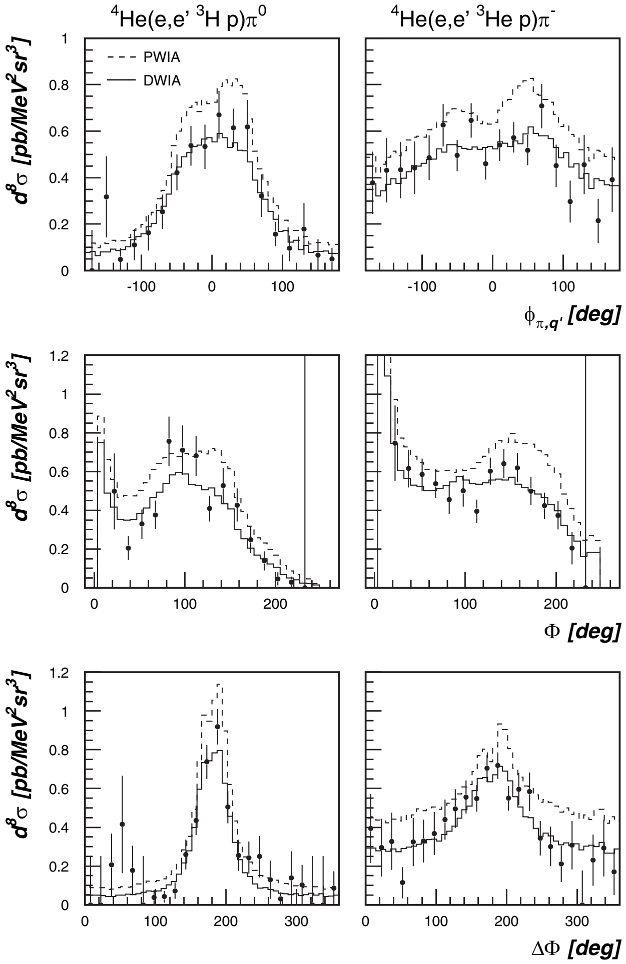

FIG. 4. The cross sections $d^8\sigma$ for the ^{4}He$(e, e'p^3$H$)\pi^0$ and ^{4}He$(e, e'p^3$He$)\pi^-$ reactions as a function of $\phi_{\pi,\mathrm{q}'}$ (top), Φ (middle), and $\Delta\Phi$ (bottom). Only events with $p_{\mathrm{rec}} \leq$ 180 MeV$/c$ are included.

On top of this "kinematic" effect there is a genuine azimuthal dependence, which, e.g., for the case of Φ contains $\cos(\Phi)$, $\cos(2\Phi)$, $\sin(\Phi)$, and $\sin(2\Phi)$ terms [15]. For both channels the data are reproduced well by the DWIA calculations.

In conclusion, the exclusive reactions ^{4}He$(e, e'p^3$H$)\pi^0$ and ^{4}He$(e, e'p^3$H$)\pi^-$ have been studied simultaneously and for the first time in a large kinematical domain, including the Δ-resonance region. For values of the recoil momentum p_{rec} below 180 MeV$/c$ the dependence of the measured cross sections on p_{rec}, the invariant mass of the πN system $W_{\pi\mathrm{N}}$, and the azimuthal angles of the emitted pion and nucleon are reproduced fairly well by the results of standard DWIA calculations, which indicates that quasifree pion production is the main reaction mechanism. However, for values of $W_{\pi\mathrm{N}}$ corresponding to the Δ-resonance region, systematic differences between the data and the DWIA calculations are observed in the angular distribution of the pion. Similar discrepancies observed in the reaction ^{3}He$(e, e'\pi^+)^3$H could be explained by including a complex self-energy term for the Δ. This indicates that medium modifications of the Δ-production operator and/or Δ propagator are needed to describe the data presented here.

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