Coherent Photoproduction of $\pi^+$ from $^3$He with CLAS at Jefferson Laboratory

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Abstract. We have measured the differential cross section for the $\gamma^3\text{He} \to t\pi^+$ reaction. This reaction was studied using the CEBAF Large Acceptance Spectrometer (CLAS) at Jefferson Lab. Real photons produced with the Hall-B bremsstrahlung tagging system in the energy range from 0.5 to 1.55 GeV were incident on a cryogenic liquid $^3$He target. The differential cross sections for the $\gamma^3\text{He} \to t\pi^+$ reaction were measured as a function of photon-beam energy and pion-scattering angle. Theoretical predictions to date cannot explain the large cross sections except at backward angles, showing that additional components must be added to the model.

1. Introduction
Comparing an elementary meson production process on a free nucleon with the same process inside a nucleus has become an interesting problem in nuclear physics. Reactions such as $\gamma^3\text{He} \to \pi^+ + t$, $\gamma^3\text{He} \to \pi^0 + ^3\text{He}$, $\gamma + t \to \pi^- + ^3\text{He}$, and $\gamma + t \to \pi^0 + t$ have been studied by both experimental and theoretical groups over the last four decades. Studying these processes is useful in developing our understanding of nuclear structure and the long-range part of the nucleon-nucleon interaction described by the one-pion exchange model. However, all the previous measurements and calculations were done near threshold and in the $\Delta$ resonance region $[1] - [9]$. The goal of the present analysis is to measure the differential cross section for the $\gamma^3\text{He} \to \pi^+ + t$ reaction for energies above the $\Delta$ resonance region. The $^3$He target is the lightest nucleus on which one can observe coherent $\pi^+$ photoproduction with charge exchange and which also leads to a well-defined final state that can be easily identified. This channel is one of the most important pion-production channels because it is an isoscalar nuclear transition within the isodoublet $(^4\text{H}, ^3\text{He})$ with the same quantum numbers as the elementary reaction on the nucleon. The same nuclear wave functions can be used for the initial and final states (except for Coulomb effects). Studying this production process is ideal for understanding the interaction of pions with nuclei and to search for possible effects mediated by nucleon resonances in nuclear matter.

A model was developed by Tiator et al. [7] based on realistic three-body Faddeev functions in plane-wave impulse approximation (PWIA). Good agreement was found with low-momentum-transfer data (up to 3.1 fm$^{-2}$) from Ref. [3], however, the PWIA could not explain the data at higher momentum transfer.

In a later calculation performed by Kamalov et al. [8], the intermediate pion scattering between two nucleons also has been taken into account. In this model, the coherent $\pi^0$ and $\pi^+$ photoproduction and elastic and charge-exchange pion scattering on $^3$He have been calculated in...
In a consistent way. In this model, realistic three-body Faddeev wave functions have been used and full nonlocal distorted-wave impulse-approximation (DWIA) results for pion photoproduction were obtained. Comparison with experimental data shows good agreement over a wide range of momentum transfer for the photon energy range between 230 and 450 MeV.

In 1995, the two-body mechanisms were explicitly included in the Model [10] where the photon is absorbed by one nucleon and the pion is emitted from the other nucleon. The inclusion of these processes resulted in a better agreement between the calculations and the previous data at higher momentum transfers. However, after all of the considered effects and pion distortions, the model could not account for the large enhancement seen in the experimental data at large $Q^2$ ($Q^2 > 6$ fm$^{-2}$)[3].

2. Experiment and Data Analysis

The $^3\text{He} \rightarrow t\pi^+$ reaction was measured during the g3a experiment in December 1999 with the CEBAF Large-Acceptance Spectrometer (CLAS) at Jefferson Lab [11]). CLAS is a large acceptance multi-layer spectrometer used to detect multiparticle final states. Six superconducting coils generate a toroidal magnetic field around the target with azimuthal symmetry about the beam axis. The coils divide CLAS into six sectors, each instrumented with three regions of drift chambers, time-of-flight detectors, and, in the forward region, Cherenkov counters, and electromagnetic calorimeters. Real photons produced with the Jefferson Lab Hall-B bremsstrahlung-tagging system [12] in the energy range from 0.35 to 1.55 GeV were incident on an 18-cm-thick liquid $^3\text{He}$ target. The primary electron beam operating at 1.645 GeV was incident on the thin radiator of the Hall-B Photon Tagger [12]. Tagged photons were produced with 20-95% of the energy of the primary electron beam. About $10^9$ triggers were collected at the production current of 10 nA.

In order to associate the reaction of interest with the triggering tagged photon, the coincidence time between the Tagger and CLAS was required to be within 1 ns. The systematic effect of this cut on the final cross sections was studied and found to be less than 0.1%. The particles were identified by determining their charge, momentum, and velocity. Charge and momentum were obtained from the drift-chamber tracking information and the velocity from the time of flight and path length to the time-of-flight detectors. The upper panel of Fig. 1 shows the reconstructed mass distribution of all positively charged particles that are detected in CLAS. The events of interest were those with two and only two positively charged particles detected in coincidence as shown in the lower panel of Fig. 1. A triton candidate was required to have a positive charge and a reconstructed mass squared between 6.5 and 10.0 (GeV/c$^2$)$^2$. A pion candidate was required to have a positive charge and a reconstructed mass squared between 0.05 and 0.3 (GeV/c$^2$)$^2$. In order to assure that the events of interest are produced within the $^3\text{He}$ target volume, a cut was applied to the $z$-component of the interaction vertex along the beam line.

Energy-loss corrections were applied to the selected particles because they lose a non-negligible part of their energy in the target material and start counter before they reach the drift chambers. The importance of these corrections can be demonstrated by comparing the missing-mass squared of either the detected pion or the detected triton before and after applying these corrections. As expected, the amount of the energy loss for a particle depends on the mass of that particle and, therefore, these corrections have a larger effect on the measurement of the triton than of the pion. Table 1 summarizes the result of fitting Gaussians to the pion and triton missing-mass-squared distributions before and after the energy-loss corrections.

Also, fiducial-volume cuts were applied to ensure that the particles are detected within those parts of the volume of CLAS where the detection efficiency is high and uniform. These cuts select regions of the CLAS where simulations reproduce the detector response reasonably well.

In order to select cleanly the $^3\text{He} \rightarrow t\pi^+$ channel, two-body kinematics were used. The two-
Figure 1. Hadron mass calculated from the time-of-flight information. The histogram in the top panel shows the mass distribution for all the positively charged hadrons. The solid histogram in the lower panel is the selected sample of pions and tritons that are detected in coincidence. The shaded histogram shows the same distribution after applying all the kinematical cuts to remove the background (see text).

Figure 2. The calculated values for the missing mass squared for the detected pion (top) and the detected triton (bottom), before (solid histogram) and after (shaded histogram) applying the kinematical cuts. The background is completely removed by the kinematical cuts.

Table 1. Summary of the mean values and widths of the pion and triton missing-mass-squared distributions before and after the energy-loss corrections. The accepted values for the pion and triton mass squared are 0.0195 and 7.890 (GeV/c^2)^2, respectively.

|                      | without corrections | with corrections |
|----------------------|---------------------|------------------|
| \(MM^2_\pi\) (GeV/c^2)^2 | 7.898               | 7.880            |
| Width (GeV/c^2)^2    | 0.08009             | 0.06860          |
| \(MM^2_t\) (GeV/c^2)^2 | 0.09580             | 0.02154          |
| Width (GeV/c^2)^2    | 0.02809             | 0.02333          |

body final-state kinematics for real events requires that the missing energy, missing momentum, and missing-mass squared for \(tn\pi^+\) events be zero \((\pm 3\sigma \text{ cuts were used})\). Also, the opening angle between the three-vectors of the detected pion and triton \(\theta_{tn^+}\) should be close to 180° in the center-of-mass frame. The sample of events used after these kinematical cuts is therefore essentially background-free. This also can be confirmed by calculating the missing-mass squared of either the detected pion or the detected triton. These distributions are shown before and after the above cuts in Fig. 2, and show that the background has been removed completely.
The clean sample of pions and tritons that are detected in coincidence is also shown within the shaded areas of Fig. 1. The raw $t\pi^+$ yields are obtained as a function of the photon beam energy $E_\gamma$ and the pion polar angle in the center-of-mass frame $\theta_\pi^{cm}$. The yields are corrected for the detector acceptance using a Monte-Carlo simulation of phase-space-distributed $t\pi^+$ events within the entire $4\pi$ solid angle. The photon energy was generated randomly with a uniform distribution from 0.35 to 1.55 GeV. The standard GEANT-based CLAS simulation package was used to simulate the detector response. The simulated events were processed with the same event-reconstruction software that was used to reconstruct the real data. Owing to the geometry and the structure of CLAS, there are regions of solid angle that are not covered by the detector. Furthermore, the inefficiencies in the various components of the detector affect its acceptance and, consequently, the event reconstruction in CLAS. The acceptance correction factors are obtained as functions of pion angle $\theta_\pi^{cm}$ and photon energy $E_\gamma$ for each kinematic bin. The differential cross section is obtained from

$$d\sigma \over d\Omega = \eta_o N_T$$

where $N$ is the number of measured events in a given energy and angular bin of solid angle $\Delta\Omega = 2\pi\Delta\cos\theta_{cm}$. The CLAS acceptance is given by $\eta_o$; $N_\gamma$ is the number of photons within the given energy range incident on the target; and $N_T$ is the number of target nuclei per unit area.

### 3. Results and Comparison with Model Calculations

Our results are compared with the model calculations by Tiator and Kamalov and with previous measurements. The calculations were originally suited only for the energies from threshold to the $\Delta$ resonance region. Recently this model has been extended (with the MAID) to higher energies [13] (see Figs. 3-6). There is good agreement between the calculations and experimental data for small momentum transfers. For larger momentum transfers the calculations can describe the data only at backward angles. The old measurement of Bachelier et al. at 137 degrees [3] can be nicely extended with our data up to $Q^2 = 34$ fm$^{-2}$ or $1.4$ GeV$^2$ (Fig. 3). In fact with the new elementary production operator from MAID the agreement with data from Ref. [3] is much improved compared to the previous calculations in 1995. For other angles a huge discrepancy is found, e.g., at 90 or 60 degrees (Fig 4 and 5).

![Figure 3](image-url)  
**Figure 3.** Momentum-transfer dependence of the differential cross section for a fixed pion angle of 137 degrees in the c.m. frame. The curves show the calculations by Tiator and Kamalov for three different assumptions: plane-wave impulse approximation PWIA (dotted lines); distorted-wave impulse approximation DWIA (dashed lines); and DWIA + 2-body mechanism [10](solid lines). Our data are from CLAS as shown as open circles and from Ref. [3] as filled circles.

These are interesting results, which were not observed before where only high-$Q^2$ data were available at one angle, namely 137 degrees. Our new data suggest that there are other mechanisms that produce much larger contributions than the 1-body (impulse approximation) and the 2-body mechanisms that were proposed in Ref.[10]. It is possible that two- or even three-body effects are driving those large cross sections, but it is not precisely known to what
Figure 4. Momentum-transfer dependence of the differential cross section for a fixed pion angle of 90 degrees in the c.m. frame. The curves are described in Fig. 3. Our data from CLAS are shown as open circles and from Ref. [9] as a filled circle.

Figure 5. Momentum-transfer dependence of the differential cross section for a fixed pion angle of 60 degrees in the c.m. frame. The curves are described in Fig. 3. Our data from CLAS are shown as open circles. Note that in the forward direction, the DWIA and the DWI+2body calculations coincide as expected, so the 2-body mechanism included in the model does not contribute.

Figure 6. Comparison of the model calculations from Tiator and Kamalov with the differential cross section as a function of pion scattering angle in the c.m. frame for various photon-energy bins. The model includes DWIA + 2-body mechanism.

extent. In fact, strong evidence from analyzing CLAS data in other channels, for example, $\gamma^{3}\text{He}$
\(-ppn\) [14], \(\gamma^3\text{He} \rightarrow pd\) [15], and \(\gamma^4\text{He} \rightarrow pt\) [16], suggests that 3-body contributions become more important, especially at \(E_\gamma=0.6-0.8\) GeV.

Figure 6 show the comparison of angular dependence of our cross sections with the full model calculations for four bins of photon energy from 0.5 to 0.8 GeV. In general, the calculations fail to describe our data at higher photon energies and forward angles.

One way to improve the models would be to include 2-body and 3-body meson-exchange currents (MEC). These processes become more important especially at high momentum transfers because the momentum is shared between two or three nucleons. The very first attempt to include a two-body MEC in the pion-photoproduction model, where a pion is exchanged between the two nucleons, was considered by Raskin et al. [17]. In that model, a formalism for the pion-photoproduction amplitude with binding-induced contributions was given. However, no numerical calculation was ever performed. The two- and three-body MEC were also considered in the calculations for the \(^3\text{He}\) and \(^3\text{H}\) form factors [18].

Another possible process to include in the model would be the photo-induced reaction \((\gamma; N \rightarrow N + \pi N)\) on a free \(\Delta\) that is created from \(N+N \rightarrow \Delta + N\) reaction. The existence of these preformed deltas were investigated by studying reactions such as \(A(\gamma, \pi^+ p)B\) [20]. Preformed deltas were also introduced in the calculations of \(^3\text{He}\) and \(^3\text{H}\) form factors [19].

4. Summary
In summary, we have measured the differential cross section for the \(\gamma^3\text{He} \rightarrow t\pi^+\) reaction in the energy range from 0.5 to 1.55 GeV, for pion center-of-mass angles between 40 and 140 degrees. It is important to emphasize that the interpretation of these data is model dependent. We have compared them with the results of the only available theoretical calculation for these energies [8, 10, 13]. The comparison shows that the calculations cannot describe our data at large momentum transfer and forward angles. This strongly suggests that there are additional production mechanisms that are not included in the current formulation of the model.

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