The $pd \rightarrow ^3\text{He}\,\eta\pi^0$ reaction at $T_p = 1450$ MeV

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Abstract

The cross section for the \( pd \rightarrow ^3\text{He}\eta\pi^0 \) reaction has been measured at a beam energy of 1450 MeV using the WASA detector at the CELSIUS storage ring and detecting one \(^3\text{He}\) and four photons from the decays of the two mesons. The data indicate that the production mechanism involves the formation of the \( \Delta(1232) \) isobar. Although the beam energy does not allow the full peak of this resonance to be seen, the invariant masses of all three pairs of final particles are well reproduced by a phase space Monte Carlo simulation weighted with the p-wave factor of the square of the \( \pi^0 \) momentum in the \(^3\text{He}\pi^0\) system.

Key words: \( \eta, \pi^0 \) meson production, invariant mass distribution, \( \Delta \) resonance;
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The $pd \rightarrow ^3\text{He}X^0$ reaction has long been used to study the production of neutral mesons or mesonic systems. Missing-mass experiments carried out near the production thresholds have clearly identified peaks corresponding to $X^0 = \omega, \eta'$, and $\phi$ [1, 2]. Of particular interest are the data on the production of the $\eta$ meson [3–6], which show a threshold enhancement that might indicate the formation of a quasi-bound $\eta^3\text{He}$ nuclear state [7]. Evidence in favour of this hypothesis is to be found also in the coherent $\eta$ photoproduction from $^3\text{He}$, $\gamma^3\text{He} \rightarrow \eta^3\text{He}$ [8].

However, exclusive measurements of a production process often yield important additional information. The study of $pd \rightarrow ^3\text{He}K^+K^-$ showed that the $\phi$ mesons produced and decaying into $K^+K^-$ are strongly polarised with respect to the incident proton direction [9]. In contrast, the $\omega$ mesons detected through the measurement of $pd \rightarrow ^3\text{He}\pi^+\pi^-\pi^0$ have very low polarisation [10]. This difference is in marked contrast to the Okubo-Zweig-Iizuka rule [11], which would suggest rather that the polarisations of these two vector mesons should be similar.

The most quoted data on the $pd \rightarrow ^3\text{He}X^0$ reaction are connected with the ABC effect, where a strong and sharp enhancement of the missing mass $X^0$ spectrum is seen a little above the threshold of two pions [12]. The effect might be connected with the production of two $\Delta(1232)$ isobars or with the sequential decay of the Roper $N^*(1440)$ resonance. However, the full rich structure could only be made accessible through exclusive measurements, such as those carried out recently for $pd \rightarrow ^3\text{He}\pi^0\pi^0$ and $pd \rightarrow ^3\text{He}\pi^+\pi^-$ [13].

Many important results have appeared recently on the photoproduction of the $\pi^0\eta$ system. The data from hydrogen [14] have been interpreted in terms of a dominant cascade decay of the $D_{33} \Delta(1700)$ isobar through the $s$-wave $\Delta(1700) \rightarrow \eta\Delta(1232)$ followed by the $p$-wave $\Delta(1232) \rightarrow \pi^0p$ [15]. The evidence for the importance of the $\Delta(1232)$ is clear from the invariant mass distribution, though some signal of the interaction of the $\eta$ with the observed proton through the $N^*(1535)$ is also apparent [14]. The coherent photoproduction of $\pi^0\eta$ pairs in $\gamma d \rightarrow \eta\pi^0d$ has also been observed [16]. The positive signal of the similar reaction on $^3\text{He}$ raises the tantalising possibility of using the $\gamma^3\text{He} \rightarrow \eta\pi^0^3\text{He}$ reaction to study also the final state interaction (fsi) of the $\eta$ with the $^3\text{He}$ [17]. The competition between the $n^3\text{He}$ and $^3\text{He}\pi^0$ interactions would, of course, also be equally relevant if the system were produced in proton-deuteron collisions.

Measurements of the $pd \rightarrow ^3\text{He}\eta\pi^0$ reaction were carried out at the CELSIUS
storage ring of the The Svedberg Laboratory in Uppsala, Sweden, using the WASA detector [18]. The circulating proton beam of energy 1450 MeV was incident on a deuterium pellet target [19,20]. The $^3$He ejectiles were measured in the WASA forward detector (FD) [21], which covered laboratory polar angles from $3^\circ$ to $18^\circ$. This corresponds to 92% of the $^3$He phase space for $\eta \pi^0$ production at 1450 MeV. The lost events are those where the $^3$He are emitted at small laboratory angles such that they escape detection down the beam pipe.

The forward detector consists of a sector-like window counter (FWC) for triggering, a proportional chamber for precise angular information (FPC), a hodoscope (FTH) for triggering and off-line particle identification, a range hodoscope (FRH) for energy measurements, particle identification and triggering, and a veto hodoscope (FVH) for triggering.

The $\eta$ and $\pi^0$ mesons were identified via their decay into $\gamma \gamma$ pairs, with these photons being measured in the central detector (CD). Their energies and directions were determined using the information from the Scintillating Electromagnetic Calorimeter (SEC), which covers polar angles from $20^\circ$ to $169^\circ$. The absence of a signal in the Plastic Scintillating Barrel (PSB) indicated that the photons arose from the decay of a neutral particle.

A schematic overview of the WASA detector setup is shown in Fig. 1.

![Fig. 1. (Colour online) Side view of the CELSIUS/WASA detector setup [18,21]. The CELSIUS beam pipe runs horizontally and the target pellets are injected downwards through the vertical pipe.](image)

The hardware $^3$He trigger selected events where there was a hit with a high energy deposit in the FWC and an overlapping hit in either the FTH or the FRH. The $^3$He were identified in the FD using the $\Delta E-E$ method, as described in detail in Refs. [22,23].
In the data analysis we considered only those events where the $\eta$ meson decayed into two photons (BR = 39.3%), and therefore selected events with one $^3$He plus four photons. Furthermore, one $\gamma\gamma$ combination was required to have an invariant mass close to that of the $\pi^0$, $|IM(\gamma\gamma) - m_{\pi^0}| < 45$ MeV/c$^2$. The two remaining photons must have an opening angle $\theta_{\eta\gamma\gamma} > 70^\circ$, motivated by Monte Carlo simulations of the reaction, and an invariant mass larger than 460 MeV/c$^2$. In addition, the overall missing mass should be small, $MM(3^\text{He}4\gamma) < 100$ MeV/c$^2$. Finally, all events with two $\pi^0$ candidates, i.e., where two $\gamma\gamma$ combinations satisfied $|IM(\gamma\gamma) - m_{\pi^0}| < 45$ MeV/c$^2$, were rejected. This reduced the background contribution from $2\pi^0$ production by almost an order of magnitude. These selection criteria, when applied on phase space produced $pd \rightarrow 3^\text{He}\eta\pi^0$, $\eta \rightarrow \gamma\gamma$, lead to an acceptance of 11.1%.

The above cuts reduce the acceptances for $2\pi^0$ and $3\pi^0$ production to $\approx 0.1\%$ and $\approx 0.2\%$, respectively. However, since their cross sections are so much larger than that for the $\eta\pi^0$ channel, and only 39.3% of the $\eta$ mesons decay into $\gamma\gamma$, a significant background from multipion production will remain.

The $pd \rightarrow 3^\text{He}\eta\pi^0$ events are identified by the peak at the $\eta$ position that appears in the $3^\text{He}\pi^0$ missing mass spectrum shown in Fig. 2. The points are experimental data that satisfy the selection criteria. Phase space simulations are shown of $pd \rightarrow 3^\text{He}2\pi^0$ (dash-dotted line), $pd \rightarrow 3^\text{He}3\pi^0$ (dotted line), and $pd \rightarrow 3^\text{He}\eta\pi^0$ (solid red line). The three contributions are normalised such that their sum (solid black line) gives the best fit to the experimental data. The $2\pi^0$ and $3\pi^0$ distributions are then roughly consistent with the cross sections obtained in Ref. [23]. The $\eta\pi^0$ distribution normalised in this way contains $375 \pm 35$ events, where the quoted error is systematic, mainly arising from the ambiguity in the background subtraction.

The number of $\eta\pi^0$ candidates is corrected for acceptance, taking the $\eta \rightarrow \gamma\gamma$ branching ratio into account, and then divided by the integrated luminosity, which was determined as described in Ref. [24], in order to obtain the total cross section. This procedure gave a value of $\sigma_{\text{tot}} = 22.6 \pm 1.5 \pm 2.1 \pm 14\%$. The first error is statistic and the second systematic, coming from uncertainties in the number of $\eta\pi^0$ events and the acceptance estimation. The third reflects the uncertainty in the normalisation, in which effects from both the luminosity (12%) and time-overlapping events (< 8%) are included, being added quadratically.

In the $pd \rightarrow 3^\text{He}\eta\pi^0$ reaction there are potentially three important final state interactions, which have been investigated by constructing the invariant mass distributions for the $\eta\pi^0$, $3^\text{He}\pi^0$, and $3^\text{He}\eta$ systems. For this purpose we take all the events in Fig. 2 that lie within the interval $490$ MeV/c$^2 < MM(3^\text{He}\pi^0) < 580$ MeV/c$^2$. This asymmetric choice is motivated by the fact that the $\eta$ peak is shifted towards lower masses in both the Monte Carlo
Fig. 2. (Colour online) The missing mass of the $^3\text{He}\pi^0$ system for all events fulfilling the selection criteria given in the text. The dash-dotted line represents simulated $pd \rightarrow ^3\text{He}2\pi^0$ events, the dotted line $pd \rightarrow ^3\text{He}3\pi^0$, and the red line $pd \rightarrow ^3\text{He}\eta\pi^0$. The weights of these three contributions have been adjusted so that their sum (solid black line) reproduces well the experimental data (points).

Within this mass interval there are $\approx 335 \eta\pi^0$ candidates, with a signal-to-background ratio of 1.7.

Figure 3 shows the invariant mass of the $^3\text{He}\pi^0$ system, where the background, obtained from simulated $2\pi^0$ and $3\pi^0$ data has been subtracted from each bin. The remaining numbers of events have been corrected for acceptance, also estimated bin by bin. The results are shown as points with error bars that represent the statistical uncertainties. In addition to these there is a systematic uncertainty in each bin of less than 10% due to the background subtraction and acceptance estimation. The solid line shows a phase space simulation of $pd \rightarrow ^3\text{He}\eta\pi^0$ events. The experimental data peak slightly below 3100 MeV/c^2, which is approximately equal to $2m_p + M_{\Delta(1232)}$ and points towards an involvement of the $\Delta(1232)$ isobar in the production process. At this energy, the full $\Delta$ peak is not covered and the data are primarily sensitive to the $p$-wave rise towards the resonance position. To simulate this effect, Monte Carlo events have been weighted with $k^2$, the square of the momentum of the $\pi^0$ in the $^3\text{He}\pi^0$ rest frame. The resulting distribution is shown in Fig. 3 by the dotted histogram, where the normalisation is to the total number of events. This model reproduces well the shape of the data.

Instead of studying the invariant mass of the $^3\text{He}\eta$ system, it is in practice more reliable to construct the missing mass of the $\pi^0$. This is because the electromagnetic calorimeter was calibrated using the neutral pions decaying
Fig. 3. The invariant mass of the $^3\text{He}\pi^0$ system for all events fulfilling the selection criteria given in the text and, in addition, $490 < M_{\text{M}(^3\text{He}\pi^0)} < 580$ MeV/$c^2$. The background has been subtracted and the distribution corrected for acceptance. The error bars represent only the statistical uncertainties. The solid lines show a phase space simulation $^3\text{He}\eta\pi^0$ events. The dotted histogram shows phase space events weighted with the square of the $\pi^0$ momentum in the $^3\text{He}\pi^0$ rest system.

into $\gamma\gamma$ so that it is in this region more precise than for $\eta$ decay. The basic procedure for obtaining the distribution is similar to that for the $^3\text{He}\pi^0$ invariant mass. After subtracting the background, the data were corrected for acceptance and the result is shown in Fig. 4. Compared to the broadly semi-circular form of the phase space distribution, the experimental data show a peaking towards low missing masses. At first sight this might be interpreted as being due to a $^3\text{He}\eta$ final state interaction, which is very strong and attractive near the kinematic threshold. However, the dotted histogram, again showing phase space simulations weighted by the square of the $\pi^0$ momentum in the $^3\text{He}\pi^0$ rest frame, strongly suggests that this also could be an effect of the $p$-wave interaction between the $\pi^0$ and the $^3\text{He}$.

The best measurement of the $\eta\pi^0$ invariant mass is obtained through the study of the $^3\text{He}$ missing mass because the nucleus is detected in the Forward Detector, which has a much better resolution than the electromagnetic calorimeter. The background subtracted and acceptance corrected results are shown in Fig. 5. The deviations from phase space are not so marked as in the cases that involved the $^3\text{He}$ but even here the small effects are fairly well reproduced by weighting the Monte Carlo simulation with the $k^2$ factor. It is, of course, not surprising that one sees no significant influence of the $a_0(980)$ scalar resonance since at $T_p = 1450$ MeV the maximum $\eta\pi^0$ invariant mass that is accessible is only about 850 MeV/$c^2$. 

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Fig. 4. The missing mass of the $\pi^0$ for all events fulfilling the selection criteria given in the text and, in addition, $490 < MM(3\text{He} \pi^0) < 580$ MeV/$c^2$. This distribution is equivalent to that of the invariant mass of the $3\text{He}\eta$ system. The solid lines represent phase space $\eta$ Monte Carlo data and the dotted ones the same but weighted by the square of the $\pi^0$ momentum in the $3\text{He} \pi^0$ rest system.

Fig. 5. The missing mass of the $3\text{He}$ for all events fulfilling the selection criteria given in the text and when $490$ MeV $< MM(3\text{He} \pi^0) < 580$ MeV. This distribution is equivalent to that of the invariant mass of the $\eta \pi^0$ system. The solid curve is a Monte Carlo simulation of phase space production, while the dotted curve represents these events weighted by the square of the $\pi^0$ momentum in the $3\text{He} \pi^0$ rest system.

Although the $p$-wave ansatz reproduces all three final invariant mass distributions very economically through the introduction of the $k^2$ factor, there is
no sign of any $p$-wave nature in the angular distributions where, within the limited statistics, the data are fairly isotropic in the angle between the proton and the $\pi^0$ in the overall c.m. frame. The same is true for the angle of the $\pi^0$ in the $^3\text{He}\pi^0$ frame with respect to either the incident proton or recoiling $\eta$. However, in view of the large number of spin degrees of freedom it is hard to draw conclusions from such isotropy.

Since WASA has a very large acceptance, the introduction of the $k^2$ factor into the Monte Carlo has only a limited effect, changing the total acceptance from 11.1% to 10.6% which changes the value of the total cross section for the reaction to $\sigma_{\text{tot}} = 23.6 \pm 1.6 \pm 2.2 \pm 14\%$.

In summary, we have carried out measurements of the $pd \to ^3\text{He}\eta\pi^0$ reaction at a beam energy of 1450 MeV. Although the statistics are not sufficient to make a useful Dalitz plot, the invariant mass distributions of all three final pairs of particles are consistent with the $p$-wave influence that might arise from the formation of the $\Delta(1232)$ in the $^3\text{He}\pi^0$ system. This is very much in line with the photoproduction data on hydrogen and deuterium obtained at higher excess energies [14, 16]. There is no sign of any enhancement of the ABC type in the $\eta\pi^0$ mass distribution and the angular distributions, which within large error bars are consistent with isotropy, are in marked contrast to the very rich structure observed for $pd \to ^3\text{He}\pi\pi$ [13].

It would be highly desirable to have a microscopic model for the $pd \to ^3\text{He}\eta\pi^0$ reaction. In particular it is important to identify the dynamical origin of the $\eta$. Does it come from a sequential decay of the $D_{33} \Delta(1700)$ isobar, as suggested for the photoproduction data [14, 15], or does it arise from a two-step process such as $pn \to d\eta$ followed by $dp \to ^3\text{He}\pi^0$, where the $N^*(1535)$ plays a role? Regarding the final state interactions, it seems already clear from our results that data would have to be obtained at higher energy in order to separate the different final state interactions and to have a chance of investigating the formation of any $\eta^3\text{He}$ quasi-bound state. The data would then extend over the peak of the $\Delta(1232)$ and thus allow firmer conclusions to be drawn. Experiments of this type could be carried out by the WASA-at-COSY collaboration [25].

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