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

CELSIUS/WASA Collaboration

K. Schönning [a,*], Chr. Bargholtz [b], M. Bashkanov [c], M. Berłowski [d], D. Bogoslawsky [e], H. Calén [a], H. Clement [c], L. Demirörs [f], C. Ekström [g], K. Fransson [a], L. Gerén [b], L. Gustafsson [a], B. Höistad [a], G. Ivanov [e], M. Jacewicz [a], E. Jiganov [e], T. Johansson [a], S. Keleta [a], O. Khakimova [c], F. Kren [c], S. Kullander [a], A. Kupść [a], A. Kuzmin [h], K. Lindberg [b], P. Marciniewski [a], B. Morosov [e], W. Oelert [i], C. Pauly [f], H. Petrén [a], Y. Petukhov [e], A. Povtorejko [e], W. Scobel [f], R. Shafigullin [j], B. Shwartz [h], T. Skorodko [c], V. Sopov [k], J. Stepaniak [d], P.-E. Tegnér [b], P. Thörngren Engblom [b], V. Tikhomirov [e], A. Turowiecki [l], G.J. Wagner [c], C. Wilkin [m], M. Wolke [i,a], J. Zabierowski [n], I. Zartova [b], J. Złomańczuk [a]

[a] *Department of Physics and Astronomy, Uppsala University, Box 535, S-751 21 Uppsala, Sweden*
[b] *Department of Physics, Stockholm University, S-101 91 Stockholm, Sweden*
[c] *Physikalisches Institut der Universität Tübingen, D-720 76 Tübingen, Germany*
[d] *Sołtan Institute of Nuclear Studies, PL-006 81 Warsaw, Poland*
[e] *Joint Institute for Nuclear Research, Dubna, RU-101 000 Moscow, Russia*
[f] *Institut für Experimentalphysik, Universität Hamburg, D-227 61 Hamburg, Germany*
[g] *The Svedberg Laboratory, S-751 21 Uppsala, Sweden*
[h] *Budker Institute of Nuclear Physics, Novosibirsk, RU-630 090 Russia*
[i] *Institut für Kernphysik, Forschungszentrum Jülich GmbH, D-524 25 Jülich, Germany*
[j] *Moscow Engineering Physics Institute, Moscow, RU-115 409 Russia*
[k] *Institute of Theoretical and Experimental Physics, Moscow, RU-117 218 Russia*
[l] *Institute of Experimental Physics, PL-006 81 Warsaw, Poland*
[m] *Physics and Astronomy Department, UCL, London, WC1E 6BT, UK*
[n] *Soltan Institute of Nuclear Studies, PL-901 37 Lodz, Poland*

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ABSTRACT

The cross section for the $pd \to {}^3\text{He}\,\eta\pi^0$ reaction has been measured at a beam energy of 1450 MeV using the WASA detector at the CELSIUS storage ring. The ${}^3\text{He}$ was detected in coincidence with 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 mass distributions 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 π^0 momentum in the ${}^3\text{He}\,\pi^0$ system.

The $pd \to {}^3\text{He}\,X^0$ 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 $X^0 = \omega$, η', and ϕ [1,2]. Of particular interest are the data on the production of the η 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 η photoproduction from ${}^3\text{He}$, viz. $\gamma\,{}^3\text{He} \to \eta\,{}^3\text{He}$ [8].

However, exclusive measurements of a production process often yield important additional information. The study of $pd \to {}^3\text{He}\,K^+K^-$ showed that the produced ϕ mesons which decayed into K^+K^- were strongly polarised with respect to the incident proton direction [9]. In contrast, the ω mesons detected through the measurement of $pd \to {}^3\text{He}\,\pi^+\pi^-\pi^0$ have very low polarisation [10]. This difference is in marked contrast to the Okubo–

* Corresponding author.
E-mail address: karin.schonning@fysast.uu.se (K. Schönning).
URL: http://www3.tsl.uu.se/~schonnin (K. Schönning).

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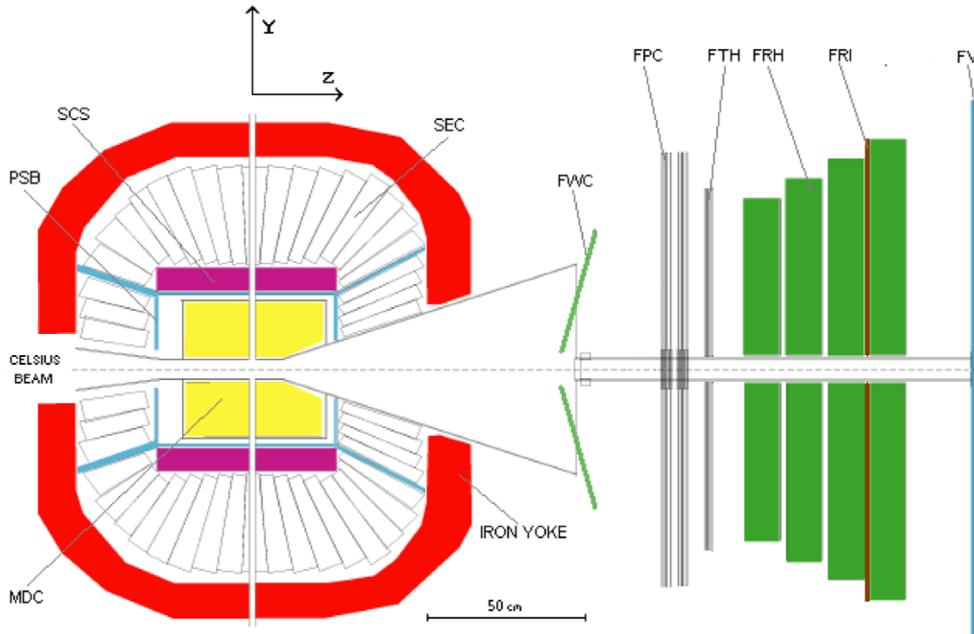

Fig. 1. Side view of the CELSIUS/WASA detector setup [18,21]. The CELSIUS beam pipe runs horizontally and the target pellets are injected downwards through the vertical pipe.

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 $pd \to {}^3\text{He}\,X^0$ 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, both of which involve two p-wave decays. However, the full rich structure could only be made accessible through exclusive measurements, such as those carried out recently for $pd \to {}^3\text{He}\,\pi^0\pi^0$ and $pd \to {}^3\text{He}\,\pi^+\pi^-$ [13]. It is interesting to see if any similar ABC effect is to be found in the production of other pairs of pseudoscalar mesons, such as $\eta\pi^0$. In this case an exclusive measurement would be required in order to identify the reaction against the much larger background arising from multi-pion production.

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

Measurements of the $pd \to {}^3\text{He}\,\eta\pi^0$ 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° to 18°. This corresponds to 92% of the ^{3}He phase space for $\eta\pi^0$ production at this energy. The events lost were those where the ^{3}He was emitted at small laboratory angles such that it escaped 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, a forward range intermediate hodoscope (FRI) for precise position information and a veto hodoscope (FVH) for triggering. However, the FRI and FVH were not used in this work.

The η and π^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° to 169°. The absence of a signal in the plastic scintillating barrel (PSB) indicated that the photons originated from the decay of a neutral particle.

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

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 ΔE–E method, as described in detail in Refs. [22,23].

In the data analysis we considered only those cases where the η meson decayed into two photons (BR = 39.3%) and therefore selected events with a ^{3}He plus four photons. Furthermore, one $\gamma\gamma$ combination was required to have an invariant mass close to that of the π^0, $|IM(\gamma\gamma) - m_{\pi^0}| < 45\ \text{MeV}/c^2$. Motivated by Monte Carlo simulations of the reaction, we demanded that the two remaining photons have an opening angle $\theta^{\eta}_{\gamma\gamma} > 70°$ and an invariant mass above 460 MeV/c^2. In addition, the overall missing mass should be small, $MM({}^3\text{He}\,4\gamma) < 100\ \text{MeV}/c^2$. Finally, all events with two π^0 candidates, i.e., where two $\gamma\gamma$ combinations satisfied $|IM(\gamma\gamma) - m_{\pi^0}| < 45\ \text{MeV}/c^2$, were rejected. This reduced the background contribution from $2\pi^0$ production by almost an

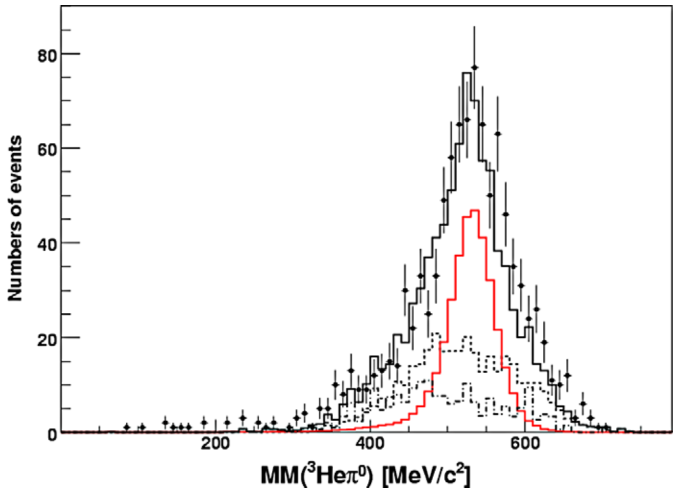

Fig. 2. The missing mass of the $^3\mathrm{He}\,\pi^0$ system for all events fulfilling the selection criteria given in the text. The dash-dotted line represents simulated $pd \to {}^3\mathrm{He}\,2\pi^0$ events, the dotted line $pd \to {}^3\mathrm{He}\,3\pi^0$, and the red line $pd \to {}^3\mathrm{He}\,\eta\pi^0$. The weights of these three contributions have been adjusted so that their sum (solid black line) reproduces well the experimental data (points). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

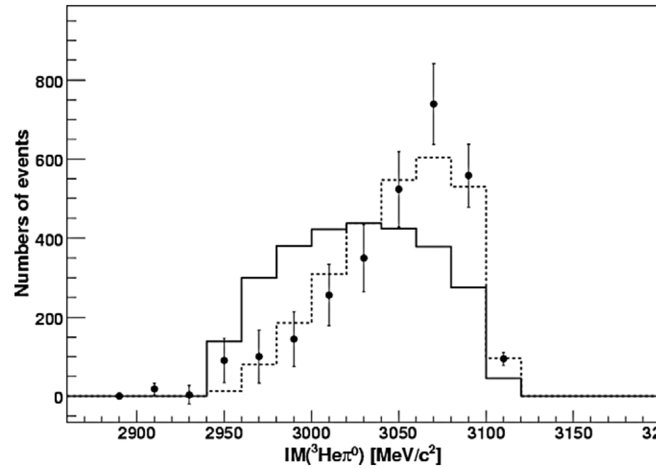

Fig. 3. The invariant mass of the $^3\mathrm{He}\,\pi^0$ system for all events fulfilling the selection criteria given in the text and, in addition, $490 < MM(^3\mathrm{He}\,\pi^0) < 580$ MeV/c^2. The background has been subtracted and the distribution corrected for acceptance. The error bars represent only the statistical uncertainties. The solid line shows a phase space simulation $^3\mathrm{He}\,\eta\pi^0$ events, whereas for the dotted histogram this has been weighted with the square of the π^0 momentum in the $^3\mathrm{He}\,\pi^0$ rest system.

order of magnitude. The application of these selection criteria to a phase-space simulation of $pd \to {}^3\mathrm{He}\,\eta\pi^0$, $\eta \to \gamma\gamma$, resulted in an acceptance of 11.1%.

The main background reactions are $pd \to {}^3\mathrm{He}\,\pi^0\pi^0$ and $pd \to {}^3\mathrm{He}\,\pi^0\pi^0\pi^0$. The cuts described above 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 [23], and only a fraction of the η mesons decay into $\gamma\gamma$, a significant background from multi-pion production remains. Simulations show that other reactions with a ^{3}He in the final state, e.g. $pd \to {}^3\mathrm{He}\,\pi^+\pi^-\pi^0\pi^0$, have negligible acceptance. Since their cross sections are not expected to be significantly larger than that of $pd \to {}^3\mathrm{He}\,\eta\pi^0$, their contribution to the background can be safely neglected. The same is also true for reactions such as quasi-free $pp \to pp\pi^0\pi^0$ and $pp \to pp\pi^0\pi^0\pi^0$ [23]. Other possible background sources are time-overlapping events and reactions taking place outside the target region (see e.g. [25]) but these effects should also be small [23].

The experimental points in Fig. 2 show the $^3\mathrm{He}\,\pi^0$ missing-mass spectrum for data that satisfy the given selection criteria. The $pd \to {}^3\mathrm{He}\,\eta\pi^0$ events are identified from this presentation through the peak at the η position. Phase-space simulations, using the same selection criteria, are shown for the $pd \to {}^3\mathrm{He}\,2\pi^0$, $pd \to {}^3\mathrm{He}\,3\pi^0$, and $pd \to {}^3\mathrm{He}\,\eta\pi^0$ reactions. The broad shapes of the $2\pi^0$ and the $3\pi^0$ distributions show that the cuts applied do not generate an artificial peak at the η mass. The three simulated distributions are normalised such that their sum gives the best fit to the experimental data. Within the uncertainties, the number of events in the $2\pi^0$ and $3\pi^0$ distributions are consistent with the cross sections obtained in Ref. [23]. However, due to the strong model dependence of the $2\pi^0$ acceptance, the uncertainty in the $pd \to {}^3\mathrm{He}\,\pi^0\pi^0$ case is of the same order as the cross section itself.

The $\eta\pi^0$ distribution obtained in this way contains 375 events. If instead the $2\pi^0$ and $3\pi^0$ distributions are fixed by the values given in Ref. [23], the number of $\eta\pi^0$ candidates increases to 410. However, the agreement between experimental and simulated data then becomes worse at high $MM(^3\mathrm{He}\,\pi^0)$. Taking the difference between the two values as a measure of the uncertainty in the background subtraction, the number of $\eta\pi^0$ candidates is left at 375 with a systematic error of ± 35.

The number of $\eta\pi^0$ candidates was corrected for acceptance, taking the $\eta \to \gamma\gamma$ branching ratio into account. Using the value of the integrated luminosity determined as described in Ref. [24], this led to a total cross section of $\sigma_{\mathrm{tot}} = 22.6 \pm 1.5 \pm 2.1$ nb. The first error is statistical and the second systematic, coming mainly from the ambiguities in the background subtraction. In addition, there is an uncertainty in the normalisation of 14%, in which effects from both the luminosity (12%, see Ref. [24]) and time-overlapping events (<8%, see Ref. [23]) are included, being added quadratically. In Fig. 2, there is a small excess of events with respect to the simulation at high and low $MM(^3\mathrm{He}\,\pi^0)$. This is probably due to random coincidences and reactions taking place outside the target region. The contribution from these two sources is small and evenly distributed over $MM(^3\mathrm{He}\,\pi^0)$. Their effects on the total cross section are accounted for in the normalisation uncertainty.

In the $pd \to {}^3\mathrm{He}\,\eta\pi^0$ reaction there are potentially three important final state interactions, which have been investigated by constructing the invariant mass distributions for the $\eta\pi^0$, $^3\mathrm{He}\,\pi^0$, and $^3\mathrm{He}\,\eta$ systems. For this purpose we took all the events in Fig. 2 that lie in the range 490 MeV/c^2 $< MM(^3\mathrm{He}\,\pi^0) <$ 580 MeV/c^2. This asymmetric choice around the nominal η mass is motivated by the fact that the η peak is shifted towards lower masses in both the Monte Carlo simulation and the experimental data. This effect comes about because the correction factor that accounts for the energy leakage of photons in the SEC was not optimally tuned for this particular reaction. Within this mass interval there are $\approx 335\eta\pi^0$ candidates, with a signal-to-background ratio of 1.7.

Fig. 3 shows the distribution in the $^3\mathrm{He}\,\pi^0$ invariant mass, where the background, estimated 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 evaluated bin by bin. In addition to the statistical error bars that are shown, there is a systematic uncertainty in each bin of less than 10% associated with the background subtraction and acceptance estimation. It should be noted that different background normalisations give the same general shape for the invariant mass distribution, with differences that are well within the error bars. The solid line shows a phase space simulation of $pd \to {}^3\mathrm{He}\,\eta\pi^0$ events. The experimental data peak slightly below 3100 MeV/c^2, which is approximately

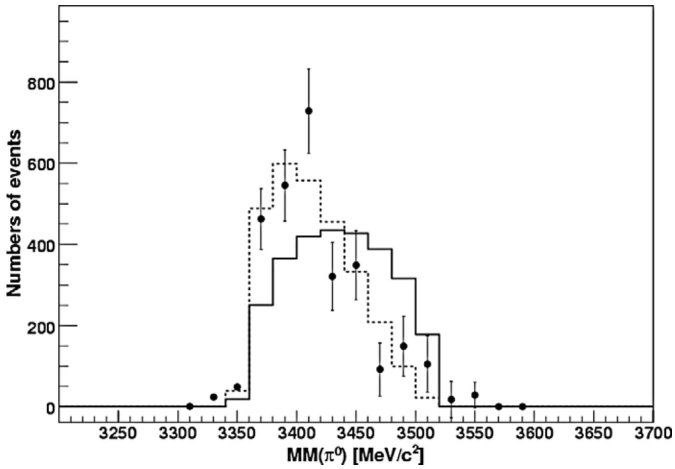

Fig. 4. The missing mass of the π^0 for all events fulfilling the selection criteria given in the text and, in addition, $490 < MM(^3\text{He}\,\pi^0) < 580$ MeV/c^2. This distribution is equivalent to that of the invariant mass of the $^3\text{He}\,\eta$ system. The solid line represents phase space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

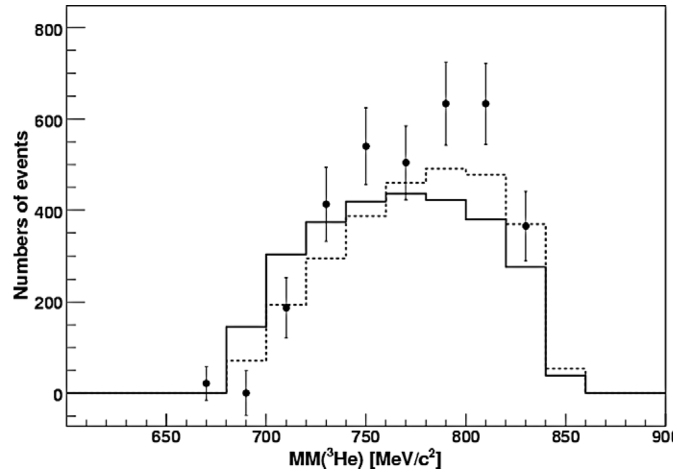

Fig. 5. The missing mass of the ^{3}He for all events fulfilling the selection criteria given in the text together with $490 < MM(^3\text{He}\,\pi^0) < 580$ MeV/c^2. This distribution is equivalent to that of the invariant mass of the $\eta\pi^0$ system. The solid curve is a Monte Carlo simulation of phase space production, while the dotted one represents these events weighted by the square of the π^0 momentum in the $^3\text{He}\,\pi^0$ rest system.

equal to $2m_p + M_{\Delta(1232)}$ and points towards the involvement of the $\Delta(1232)$ isobar in the production process. At this energy, the full Δ 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 π^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 π^0. This is because the electromagnetic calorimeter was calibrated using neutral pions decaying into $\gamma\gamma$, so that it is more precise here than in the η region. 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 results are 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 known to be very strong and attractive near the kinematic threshold [5,6]. However, the dotted histogram, again showing phase space simulations weighted by the square of the π^0 momentum in the $^3\text{He}\,\pi^0$ rest frame, strongly suggests that this could also be an effect of the p-wave interaction between the π^0 and the ^{3}He.

The best measurement of the $\eta\pi^0$ invariant mass is obtained through the study of the ^{3}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 as marked as in the cases that involved the ^{3}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 there is 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. There is also no sign at all of any enhancement at low $\eta\pi^0$ masses that is comparable to the ABC effect seen in two-pion production [12].

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 the 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 π^0 in the overall c.m. frame. The same is true for the angle of the π^0 in the $^3\text{He}\,\pi^0$ frame with respect to either the incident proton or recoiling η. 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, reducing the total acceptance estimate from 11.1% to 10.6%. This increases the value of the total cross section for the reaction to $\sigma_{\text{tot}} = 23.6 \pm 1.6 \pm 2.2$ nb, with a normalisation uncertainty of 14%. Although the change is small compared to the error bars, this value should be more reliable than that obtained on the basis of the unweighted phase-space simulation.

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 construct 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. Furthermore, 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]. This striking difference is possibly due to the $s + p$ nature envisaged for $\eta\pi^0$ production [15] rather than the $p + p$ that is normally invoked for $\pi^0\pi^0$ production [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 η. 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?

It is already clear from our results that data are needed at somewhat higher energy in order to separate the different final state interactions and to have a chance of investigating the formation of any η^3He quasi-bound state. The data would then extend over the peak of the $\Delta(1232)$ and thus allow firmer conclusions to be drawn. Studies of this type could be carried out by the WASA-at-COSY Collaboration [26] through the measurement of the $pd \to {}^3\mathrm{He}\,\eta\pi^0$ reaction and these would then complement the data expected on coherent $\eta\pi^0$ photoproduction on ^{3}He [16].

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