

## STUDY OF THE $dp \rightarrow ppp\pi^-$ REACTION NEAR THE $\eta$ PRODUCTION THRESHOLD\*

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Excitation function as well as differential distributions for  $dp \rightarrow ppp\pi^-$  reaction have been measured near the  $\eta$  production threshold in a search for a signal from decays of  ${}^3\text{He}-\eta$  bound state. We observe an enhancement in the excitation function above the  $\eta$  threshold. Calculation of the counting rate corresponding to the production of  $\eta$  mesons in the reaction  $dp \rightarrow {}^3\text{He}\eta$  and their subsequent absorption on neutron in the  ${}^3\text{He}$  nucleus underestimates the observed enhancement by one order of magnitude. Also the differential distributions determined for the outgoing particles contradict the  $\eta$  absorption scenario.

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### 1. Introduction

Experiments, which results are presented in this contribution, were motivated by the hope of the observation of signals from the  $\eta$ -mesic nucleus, a new kind of nuclear matter in the form of the strongly bound  $\eta$  meson and nucleus. A comprehensive physics motivation of such investigations is discussed in the accompanied article [1] as well as in contributions of Haider [2] and Krusche [3].

For studies of the  ${}^3\text{He}-\eta$  system the  $d + p$  collisions are very well suited due to the relatively high cross-sections for the  $\eta$  production in the  $dp \rightarrow {}^3\text{He}\eta$  process and due to much better beam momentum definition compared to measurements with photon or pion beams. We expect that  $ppp\pi^-$  is one of favorable decay channels of the  ${}^3\text{He}-\eta$  bound state since it corresponds to

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one step process of absorption of the  $\eta$  meson on the neutron inside the  ${}^3\text{He}$  nucleus leading to creation of the  $p\pi^-$  pair in the reaction  $\eta n \rightarrow N^*(1535) \rightarrow p\pi^-$ . In the  $N^*$  rest frame the pion and the proton are emitted back-to-back with momenta of about 430 MeV/ $c$ . In the center-of-mass system these momenta are smeared due to the Fermi motion of the neutron inside the  ${}^3\text{He}$  nucleus [1]. However, they are significantly larger than momenta of the two remaining protons which are in the order of 100 MeV/ $c$ , and which play a role of “spectators”.

In this paper we present results of experimental study of the  $dp \rightarrow ppp\pi^-$  reaction, motivated by the search for the  $\eta$ - ${}^3\text{He}$  bound state. In our experiment, a signature of existence of the  $\eta$ - ${}^3\text{He}$  bound state would be an observation of a resonance like structure with the center lying below the  $\eta$  production threshold in the excitation curve for the  $ppp\pi^-$  channel.

## 2. Experiment

The measurements were conducted at the Cooler Synchrotron COSY-Jülich with the COSY-11 detection system [4–6]. The internal deuteron beam of COSY was scattered on a proton target of the cluster-jet type. The data were taken during a slow acceleration of the beam from 3.095 GeV/ $c$  to 3.180 GeV/ $c$ , crossing the kinematical threshold for the  $\eta$  production in the  $dp \rightarrow {}^3\text{He}\eta$  reaction at 3.141 GeV/ $c$ . The momenta of protons originating from the  $dp \rightarrow ppp\pi^-$  reaction were analyzed in the COSY-11 dipole magnet and their trajectories were registered with a pair of drift chambers. The experimental trigger required at least three charged tracks in the COSY-11 scintillation hodoscope S1 standing in a distance of about 3 m from the target and at least two tracks in the hodoscope S3 placed 9 m behind S1. The momentum acceptance defined by the S1–S3 pair covered the momenta expected for the spectator protons. The time of flight measured between S1 and S3 combined with the momentum measurement was used for identification of the outgoing protons. For identification of protons registered in the S1 but not reaching the S3 hodoscope, the time of flight between the target and S1 was used. The negatively charged pions accompanying the three outgoing protons were identified using the missing mass method based on a knowledge of the beam momentum and of the momentum vectors of the protons.

Parallel to the discussed  $dp \rightarrow ppp\pi^-$  reaction we registered also  ${}^3\text{He}\eta$ ,  ${}^3\text{He}\pi^0$  channels as well as the elastic  $pd$  channel, the latter was used for luminosity determination. Our data for the total and differential cross-sections for the  $\eta$  production in the  $dp \rightarrow {}^3\text{He}\eta$  reaction [7] and similar results of the ANKE Collaboration [8] indicate a presence of a bound or virtual state in the  $\eta$ - ${}^3\text{He}$  system [9]. In turns, the excitation function for the  $dp \rightarrow {}^3\text{He}\pi^0$  process registered in the present experiment does not show

any structure which could originate from the decay of  $\eta$ - $^3\text{He}$  bound state [10]. This does not exclude existence of such state since its signal can lie below the sensitivity of the measurements due to too low probability of its decay in the  $^3\text{He}\pi^0$  channel [10].

### 3. Excitation function

Fig. 1 shows center-of-mass distribution of the transversal *vs* longitudinal momentum components of the registered protons from the  $dp \rightarrow ppp\pi^-$  reaction. This distribution is dominated by events of quasi-free  $\pi^-$  production in the process  $np \rightarrow pp\pi^-$  where the neutron projectiles originate from the deuteron beam. The corresponding spectator protons from the deuteron beam are visible as a group of counts on the right hand side. In the further analysis we rejected the quasi-free  $\pi^-$  production by setting an upper limit for the longitudinal proton momenta equal to 0.18 GeV/*c* in the center-of-mass system, represented by the dashed line in Fig. 1.

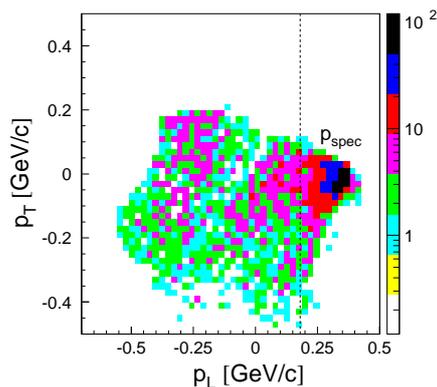


Fig. 1. Transversal *vs* longitudinal momentum distribution of protons in the center-of-mass system. The dashed vertical line represents the cut ( $p_L < 0.18$  GeV/*c*) applied on the longitudinal proton momenta. The counts at  $p_L > 0.18$  GeV/*c* correspond predominately to the spectator protons from the deuteron beam.

The counting rate of all identified  $dp \rightarrow ppp\pi^-$  events including the quasi-free  $\pi^-$  production remains constant in the scanned range of the beam momentum (see Fig. 2 (a)). However, after rejection of the quasi-free events, the number of  $dp \rightarrow ppp\pi^-$  counts in the beam momentum interval above the  $\eta$  threshold is higher than the number of counts in the beam momentum interval of equal width below the threshold (see Fig. 2 (b)). This difference is equal to  $23 - 9 = 14$  and its statistical significance is of  $2.5\sigma$ . Observation of this effect we reported in Ref. [11]. As a possible reaction mechanism explaining the observed enhancement we suggested the production of “on-shell”  $\eta$  mesons in the reaction  $dp \rightarrow ^3\text{He}\eta$  which subsequently convert

to pions in the interaction with one of nucleons in the  ${}^3\text{He}$  nucleus via excitation of the  $N(1535)$  resonance. Further on, we use a term “ $\eta$  absorption” for this process. Absorption of the  $\eta$  meson on the proton leads to creation of  $p\pi^0$  or  $n\pi^+$  pair. In turns, absorption on the neutron leads to  $n\pi^0$  or  $p\pi^-$  pair. In our measurements we detect the final state particles corresponding to the last possibility.

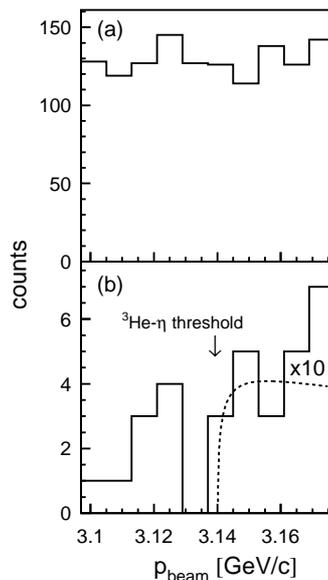


Fig. 2. Number of  $dp \rightarrow ppp\pi^-$  events as a function of the beam momentum without any cuts (a) and after rejection of events corresponding to the quasi-free  $\pi^-$  production (b). The dashed line represents calculations of the  $\eta$  absorption described in the text.

In order to estimate the counting rate of the  $dp \rightarrow ppp\pi^-$  events originating from the  $\eta$  absorption we assumed that the absorption cross-section  $\sigma_{\text{abs}}$  is equal to the cross-section for the  $dp \rightarrow {}^3\text{He}\eta$  reaction. This assumption we justify by the observation that the real and imaginary part of the  ${}^3\text{He}\text{-}\eta$  scattering length [7] have comparable values. The number  $\Delta N$  of the  $dp \rightarrow ppp\pi^-$  events corresponding to the momentum interval  $\Delta p$  of the ramped beam was calculated using the following formula:

$$\Delta N = \frac{\delta L}{\delta p} A \frac{1}{3} \frac{2}{3} \sigma_{\text{abs}} \Delta p, \quad (1)$$

where  $\delta L/\delta p$  is the integrated luminosity per beam momentum unit which was equal to about  $1.0 \text{ nb}^{-1}/\text{MeV}/c$ .  $A$  is the acceptance of the COSY-11 detection system for the  $dp \rightarrow ppp\pi^-$  channel equal to 0.0005. It was calcu-

lated in computer simulations assuming that the two spectator protons have c.m. momenta described by the Fermi momentum distribution of protons in the  ${}^3\text{He}$  nucleus taken from Ref. [12]. For the proton-pion pair associated with the two spectator protons, an isotropic angular distribution in the c.m. system of this pair was assumed. The factor  $1/3$  in the above formula represents probability of absorption on the neutron being one of three nucleons in the  ${}^3\text{He}$  nucleus and the factor  $2/3$  is the Clebsch-Gordan coefficient associated with the isospin coupling in the process  $\eta n \rightarrow \pi^- p$ .

The result of our estimation multiplied by a factor of 10 is shown with dashed line in Fig. 2 (b). It underestimates the experimental counts roughly by an order of magnitude and thus it does not corroborate the  $\eta$  absorption hypothesis.

#### 4. Momentum and angular distributions

For testing the  $\eta$  absorption hypothesis we analyzed also momentum and angular distributions of the final state particles in the  $dp \rightarrow ppp\pi^-$  reaction. For this, we compared them with results of simulations of the  $\eta$  absorption and of a process leading to the uniform distribution over phase space available for the reaction products. Further on, we use a term “direct production” to refer to these later simulations. The experimental distribution of the pion momentum in the center-of-mass system (see Fig. 3 (top)) is centered at about  $430 \text{ MeV}/c$  as expected for pions originating from the decay of the  $N^*(1535)$ . It agrees with results of simulations of the direct production (see Fig. 3 (middle)) as well as with simulations of the  $\eta$  absorption (see Fig. 3 (bottom)). Therefore, it cannot be used to distinguish between the two considered reaction scenarios. Fig. 4 shows momentum distributions for the proton from the  $dp \rightarrow ppp\pi^-$  reaction, with the highest momentum which we call the leading proton. The experimental distribution is very close to the result of simulations of the direct production. The distribution corresponding to the  $\eta$  absorption has a mean value slightly larger.

The most pronounced difference appears however in the momentum distribution for the spectator protons (see Fig. 5). The experiment and the simulations of the direct production give much higher momenta than the momentum obtained under the assumption of the  $\eta$  meson absorption. This indicates, that the dominant process in the observed  $dp \rightarrow ppp\pi^-$  reaction is not associated with the  $\eta$  meson absorption. This is also confirmed by the distribution of the center-of-mass angles between the pion momentum vector and the momentum vector of the leading proton (see Fig. 6) which, in the case of simulations of the  $\eta$  absorption, are close to  $180^\circ$  and for the experiment lie around  $160^\circ$ . Contrary to the discussed momentum spectra, the experimental angular distribution does not agree with results of simulations for the direct production.

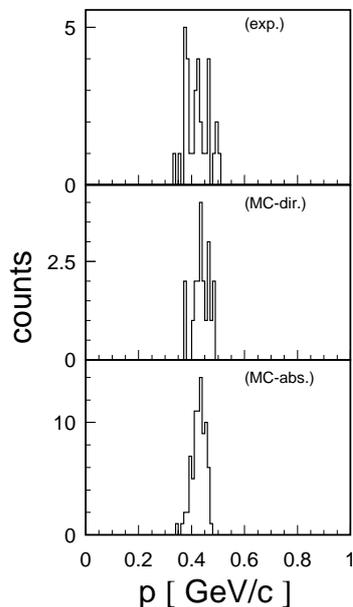


Fig. 3. Distribution of pion momentum in the center-of-mass system for experimental events (top) and for Monte Carlo events corresponding to direct production (middle) and to the  $\eta$  meson absorption (bottom).

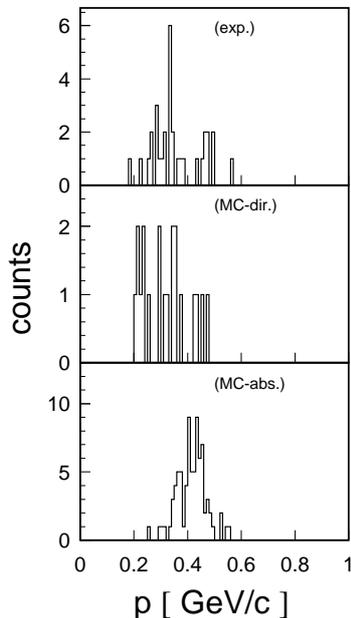


Fig. 4. Distribution of leading proton momentum in the center-of-mass system for experimental events (top) and for MC events corresponding to direct production (middle) and to the  $\eta$  meson absorption (bottom).

One can expect, that due to very similar kinematical conditions, absorption of the  $\eta$  mesons bound in the  ${}^3\text{He}$  nucleus is characterized by differential distributions which are very close to ones predicted in our simulations for the absorption of “on-shell”  $\eta$  mesons. In particular one can expect that the  $\pi^-p$  pairs originating from decay of the  $\eta$ -mesic  ${}^3\text{He}$  are emitted at c.m. angles concentrated predominately in the range  $150^\circ$ – $180^\circ$  as it is the case for the  $\eta$  meson absorption (see Fig. 6 (bottom)). In this angular range, there are only two experimental counts (see Fig. 6 (top)). Assuming, that these two counts originate from decay of the  ${}^3\text{He}\text{-}\eta$  bound state, we estimated the cross-section for the production of such state in the  $d\text{-}p$  collisions close to the  $\eta$  production threshold. The calculation was done using  $\sigma_{\text{abs}}$  derived from the formula 1. The resulting cross-section of  $0.27 \pm 0.19 \mu\text{b}$  should be considered as an upper limit for the production cross-section of the  ${}^3\text{He}\text{-}\eta$  bound state since the observed two events might originate from other processes than the bound state decay. It is worthwhile to note that this limit is comparable with the near-threshold cross-section for the  $dp \rightarrow {}^3\text{He}\eta$  reaction equal to about  $0.4 \mu\text{b}$ .

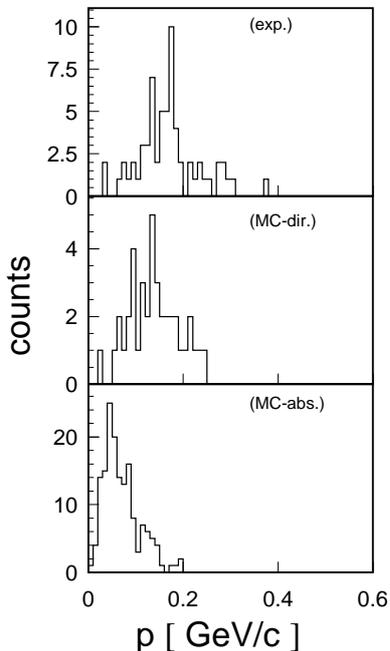


Fig. 5. Distribution of spectator proton momenta in the center-of-mass system for experimental events (top) and for Monte Carlo events corresponding to direct production (middle) and to the  $\eta$  meson absorption (bottom).

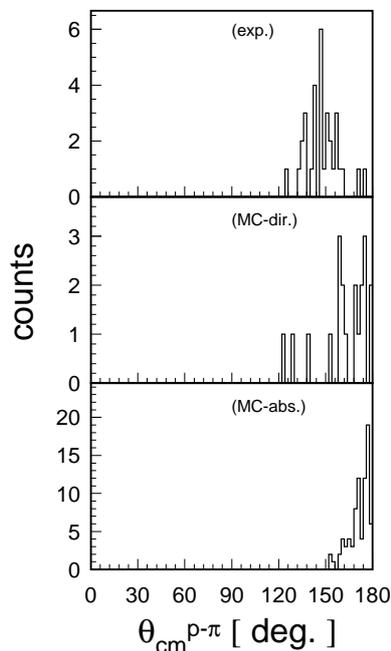


Fig. 6. Angle between the pion momentum vector and momentum vector of the leading proton in center-of-mass system for experimental events (top) and for Monte Carlo events corresponding to direct production (middle) and to  $\eta$  absorption (bottom).

## 5. Conclusions

We performed a measurement of the excitation function for the  $dp \rightarrow ppp\pi^-$  reaction in the vicinity of the  $\eta$  meson production threshold. We observe an enhancement in the counting rate above the threshold with statistical significance of  $2.5\sigma$ . Simple model assuming absorption of on-shell  $\eta$  mesons produced in the reaction  $dp \rightarrow {}^3\text{He}\eta$  underestimates the observed counting rate roughly by an order of the magnitude. Also momentum distributions of the spectator protons as well as the angular distributions of the  $\pi^-p$  pairs do not confirm the proposed scenario. Further measurements with higher statistics and higher acceptance would be very useful for verification of the observed enhancement in the excitation function and for a search of a signal from decay of the  $\eta$ -mesic  ${}^3\text{He}$ .

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