Incoherent photoproduction of η mesons from the deuteron near threshold

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Incoherent photoproduction of the η meson on the deuteron is studied for photon energies from threshold to 800 MeV. The dominant contribution, the γN-ηN amplitude, is described within an isobar model. The final state interaction derived from the CD-Bonn potential is included and found to be important for the description of the production cross section close to threshold. Possible effects from the ηN final state interaction are discussed.

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I. INTRODUCTION

Recent measurements by the TAPS collaboration [1–3] at the MAMI accelerator of the η-meson photoproduction on deuterium and helium indicate an enhancement of the total inclusive cross section at photon energies close to the reaction threshold. The data were specifically collected with high statistical accuracy in order to clarify the first observation [1] of the rather large total cross section in that energy regime. It was suggested [2] that such a threshold enhancement could result either from the formation of the quasibound η-nucleus state or from the interaction between the final nucleons.

Indeed, a strong influence of the final state interaction (FSI) on the cross sections of π, η, η', and ω-meson production in nucleon-nucleon (NN) collisions was observed in experiments at the IUCF, COSY and CELSIUS accelerator facilities [4–11]. With the exception of the η channel, those experiments producing mesons in NN collisions can be described almost perfectly by theoretical calculations accounting only for the final state interactions between the nucleons [10,11]. In case of η production there is evidence that the ηN FSI could play a role as well [5,6]. Therefore, one might expect that the TAPS data can be understood in terms of the strong neutron-proton (np) FSI and possibly an ηN FSI.

However, recent calculations [12] that include the np as well as the ηN final state interactions underestimate the cross section for the reaction $\gamma d \to np\eta$ at photon energies close to the threshold. Within a different approach, three body calculations [13] of the reaction $\gamma d \to np\eta$ performed by the same authors reproduce the main features of the experimental data, but again do not explain the rather large total cross section near the reaction threshold. On the other hand, an older calculation of the reaction $\gamma d \to np\eta$ performed by Ueda [14], which considers the formation of a quasibound ηd state, leads to a much too strong enhancement of the production cross section close to threshold, and is ruled out by the TAPS data. Furthermore, it is possible that the effect of the FSI in the NN system might depend substantially on the employed interaction model. For example, variations in the predicted total cross sections of up to 50% or even more were found for the reaction $pp \to pp\pi^0$ [15–17] and similar uncertainties seem to be present in the reaction $pp \to pp\eta$ as well [18]. In this context let us also mention the FSI investigation of meson production in pp collisions in Ref. [19] that clearly illustrates that different NN potentials may result in fairly large quantitative differences in the enhancement of the production cross section close to threshold. Therefore, the explanation of the TAPS data is still open and needs further investigations.

Here we evaluate the reaction $\gamma d \to np\eta$ within the impulse approximation. In addition we account for the FSI between the neutron and proton by employing the most recent CD-Bonn potential [20] as well as some other realistic NN interaction models. In Sec. II we specify the elementary $\gamma N \to \eta N$ amplitude that serves as input for our calculation of the reaction $\gamma d \to np\eta$. Specifically, we assume that the elementary η production proceeds via the excitation of the N^* $S_{11}(1535)$ resonance. The free parameters of our model are fixed by a fit to available data for the reaction $\gamma p \to \eta p$ [21]. In Sec. III we provide some details about the evaluation of the reaction amplitude for $\gamma d \to np\eta$ and present results for the impulse approximation as well as for the inclusion of the FSI in the np system. Possible effects from the ηN FSI are discussed in Sec. IV. In addition we provide predictions for the angular spectrum and for the momentum spectrum of the produced η meson for selected incident photon energies in the vicinity of the η-production threshold. In Sec. V we briefly summarize our results.

II. THE ELEMENTARY $\gamma N \to \eta N$ AMPLITUDE

The dominant contribution to η-meson photoproduction from a nucleon is given by the N^* isobar excitation [22,23]. We neither consider the nucleon s-channel pole term nor t-channel vector meson exchanges, since their contributions were found to be negligible [22,23].

The square of the invariant collision energy of the reaction $\gamma N \to N\eta$ is defined as

$$s = m_N^2 + 2m_N E_\gamma, \tag{1}$$

where m_N and E_γ are the nucleon mass and the photon energy, respectively. The photon momentum k and the η-meson momentum q in the center of mass (c.m.) system are given by

$$k=\frac{s-m_N^2}{2\sqrt{s}}, \quad q=\frac{\lambda^{1/2}(s,m_N^2,m_\eta^2)}{2\sqrt{s}}, \tag{2}$$

where m_η stands for the mass of the η meson. The Källén function is defined as

$$\lambda(x,y,z)=(x-y-z)^2-4yz. \tag{3}$$

The resonant contribution is given by helicity amplitudes in the relevant partial waves [24,25], namely,

$$A_{l\pm}=\pm F A_{1/2}^N,$$
$$B_{l\pm}=\pm F\left[\frac{4}{l(l+2)}\right]^{1/2} A_{3/2}^N, \tag{4}$$
$$C_{l\pm}=\pm F C_{1/2}^N,$$

where the factor F accounts for the resonance decay into the $N\eta$ channel. l denotes the orbital angular momentum. Taking into account the phase space factor and the relativistic Breit-Wigner propagator as introduced in Ref. [26] one obtains

$$F=\left[\frac{\Gamma_\eta}{\pi(2j+1)}\,\frac{k}{q}\,\frac{m_N}{\sqrt{s}}\right]^{1/2}\frac{\sqrt{s}}{M_R^2-s-i\sqrt{s}\Gamma}. \tag{5}$$

Here M_R is the resonance mass, and Γ and Γ_η are the total and $R\to N\eta$ partial resonance widths, respectively, while j is the spin of the resonance.

The standard relation between the Breit-Wigner helicity amplitudes and electric, magnetic, and longitudinal multipoles are given in Refs. [22,23].

Following the analysis of pion photoproduction, we account for the energy dependence of the hadronic widths [27] in order to satisfy the threshold dependence [22,28] of the multipole amplitudes of the outgoing meson momentum q_ξ. The energy dependence of the partial width for each final meson ξ is given as

$$\Gamma_\xi=\Gamma_\xi(M_R)\frac{\rho_\xi(\sqrt{s})}{\rho_\xi(M_R)}, \tag{6}$$

where $\Gamma_\xi(M_R)$ is the $R\to N\xi$ partial resonance width at the resonance pole, while ρ_ξ is given by [27]

$$\rho_\xi(\sqrt{s})=\frac{q_\xi}{\sqrt{s}}B_l^2(q_\xi R), \quad q_\xi=\frac{\lambda^{1/2}(s,m_N^2,m_\xi^2)}{2\sqrt{s}}. \tag{7}$$

Here B_l is the Blatt-Weisskopf function for the orbital angular momentum l. The interaction radius was taken as $R=1$ fm, and m_ξ stands for the mass of the meson. The function $\rho_\xi(M_R)$ in Eq. (7) is evaluated at the resonance pole $\sqrt{s}=M_R$. In addition, the total energy-dependent resonance width is given by the sum over the partial widths of all available final states.

In principle, one may consider the contributions from the resonances $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$, $S_{11}(1650)$, $D_{15}(1675)$, and higher mass resonances to the photoproduction of η mesons [22] and evaluate the resonance parameters from the available differential cross section data and recoil nucleon polarization data [23]. Contributions from S-wave resonances provide an isotropic angular spectrum $d\sigma/d\cos\theta$ of η mesons, with θ denoting the η-meson emission angle in the c.m. system. Although contributions from higher partial waves to the total photoproduction cross section of η mesons can be very small, they can be evaluated from the differential cross section $d\sigma/d\cos\theta$ with the help of interference terms involving the S wave. For example, an interference with P-wave resonances contributes proportionally to $\cos\theta$, while an interference with D-wave resonances results in a $\cos^2\theta$ dependence. However, most recent data [21] for differential cross sections of the reaction $\gamma p\to p\eta$ at photon energies from 716 to 788 MeV indicate that, within the experimental errors, the angular spectrum is dominated almost entirely by the S-wave distribution. Estimated contributions from P- and D-wave resonances can be given only at very low confidence level [29]. Furthermore, data on the nucleon recoil polarization, which in principle must be sensitive to the resonant contribution [23], have large uncertainties and are thus not significant.

Since there is no strong experimental evidence [29] for contributions to the η-meson photoproduction from resonances other than the $S_{11}(1535)$ resonance in the near-threshold region, we will consider in the following only this resonance. The partial decay widths, $S_{11}(1535)\to N\eta$ and $S_{11}(1535)\to N\pi$, are related to the relevant coupling constant $g_{RN\xi}$, $\xi=\eta,\pi$, by

$$\Gamma_\xi=\frac{g_{RN\xi}^2}{4\pi}\,\frac{q_\xi(E_N+m_N)}{M_R}. \tag{8}$$

Here the momentum q_ξ and the nucleon energy E_N are evaluated in the rest frame of the resonance at the pole position of $S_{11}(1535)$.

Considering only the contribution of the $S_{11}(1535)$ resonance, the data for η-meson photoproduction of protons can be well fitted with the following resonance parameters at the $S_{11}(1535)$ pole:

$$M_R=1544 \text{ MeV}, \quad \Gamma=203 \text{ MeV},$$
$$\Gamma_\eta/\Gamma=0.45, \quad \Gamma_\pi/\Gamma=0.45, \quad \Gamma_{\pi\pi}/\Gamma=0.1. \tag{9}$$

For the electromagnetic helicity amplitudes in Eq. (4) we use the values $A_{1/2}^p=0.124$ GeV$^{-1/2}$ and $A_{1/2}^n=-0.1$ GeV$^{-1/2}$. The result of this fit for the total cross section for the reaction $\gamma p\to p\eta$ is displayed in Fig. 1.

III. THE REACTION $\gamma D\to\eta np$

Using the impulse approximation (IA), the amplitude $\mathcal{M}$ of the reaction $\gamma d\to np\eta$ for given spin S and isospin T of the final nucleons can be written as

$$\mathcal{M}_{IA}=A^T(s_1)\phi(\vec{p}_2)-(-1)^{S+T}A^T(s_2)\phi(\vec{p}_1), \tag{10}$$

where $\phi(p_i)$ stands for the deuteron wave function and p_i $(i=1,2)$ is the momentum of the proton or neutron in the

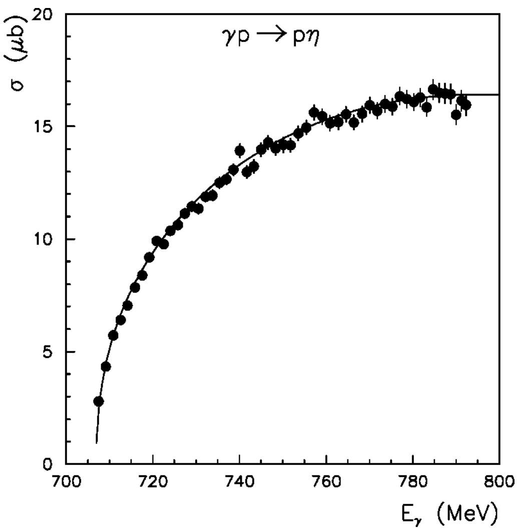

FIG. 1. Total $\gamma p \rightarrow p\eta$ cross section. Experimental data are from Ref. [1], while the solid line gives our result.

deuteron rest frame. The quantity A^T denotes the isoscalar or isovector photoproduction amplitude at the squared invariant energy s_N given by

$$s_N = s - m_N^2 - 2(E_\gamma + m_d)E_N + 2\vec{k}_\gamma \cdot \vec{p}_N. \tag{11}$$

Our calculation within the framework of the IA is shown in Fig. 2 and corresponds to the dashed line. It describes the data [1] at photon energies above $\simeq 680$ MeV reasonably well. Close to the reaction threshold, however, the IA result substantially underestimates the data. We take this as an indication that effects from the (NN and/or ηN) final state interaction play an important role here. Indeed, as already mentioned in the Introduction, it is well known from meson production in NN collisions that close to threshold FSI effects lead to a significant modification of the cross section.

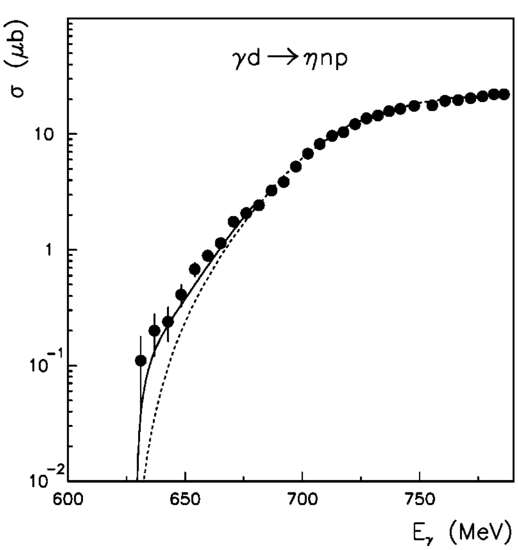

FIG. 2. The cross section for inclusive photoproduction of η mesons of deuterium. Experimental data are taken from Ref. [1]. The dashed line shows the IA calculation, while the solid line is the result with np final state interaction.

In meson production in NN collisions FSI effects result predominantly from strong S-wave interactions in the outgoing NN system. Therefore, we will take into account this contribution for the reaction $\gamma d \rightarrow np\eta$. The corresponding amplitude is given by

$$\mathcal{M}_{FSI} = m_N \int dk k^2 \frac{T(q,k) A^T(s_N) \phi(p_i)}{q^2 - k^2 + i\epsilon}. \tag{12}$$

Here q is the nucleon momentum in the final np system and $T(q,k)$ is the half-shell np scattering matrix in the $^1S_0$ and $^3S_1$ partial waves. In the calculations presented here, the half-shell t matrix is obtained at corresponding on-shell momenta q from the latest CD-Bonn potential [20], which describes the NN data base with a χ^2/datum of about one. In order to find out if a high precision description of the NN data, in our specific case the NN S-waves, is crucial, we carried out the calculations with an older one-boson-exchange model [30], also describing the S waves reasonably well. We found the difference of those two calculations being negligible. In addition, we employed some other realistic NN models from the literature but also those models did not produce any noticable differences in the cross-section prediction. Thus, we conclude that in contrast to η production with hadronic probes [18], the reaction $\gamma d \rightarrow pn\eta$ near threshold is not very sensitive to the details of the NN interaction. Indeed, this is not too surprising. The amplitude for the latter reaction contains also the deuteron wave function in the loop integral involving the FSI, see Eq. (12). This wave function drops rather rapidly with increasing momentum for all realistic NN models, and therefore strongly suppresses contributions from higher off-shell momenta in the integral of Eq. (12), i.e., those momenta where the half-off-shell T matrices of the different NN models show larger variations.

The total cross section $\gamma d \rightarrow np\eta$ including the np FSI in S waves is displayed in Fig. 2 as solid line. Now the model calculation describes the data [1] reasonably well and lies, in fact, within the experimental uncertainties. As expected, the FSI interaction gives rise to a significant increase of the production cross section close to threshold as is required for getting agreement with the data.

IV. DISCUSSION

In η-production experiments in pp as well as in np collisions one has observed that there is an even stronger enhancement of the production cross section close to threshold, which cannot be explained by FSI effects from the NN interaction alone [5,6,10]. This additional enhancement is, in general, seen as an indication of FSI effects due to the ηN interaction [31,32]. Thus, it may be suggested that similar effects are seen in the reaction $\gamma d \rightarrow np\eta$. In order to expose a possible influence from the ηN FSI we again show the experimental data in Fig. 3, but now divide them by our model calculation, which includes the enhancement from the FSI between the nucleons. Any effects from the ηN FSI present in the data would then reveal themselves as addi-

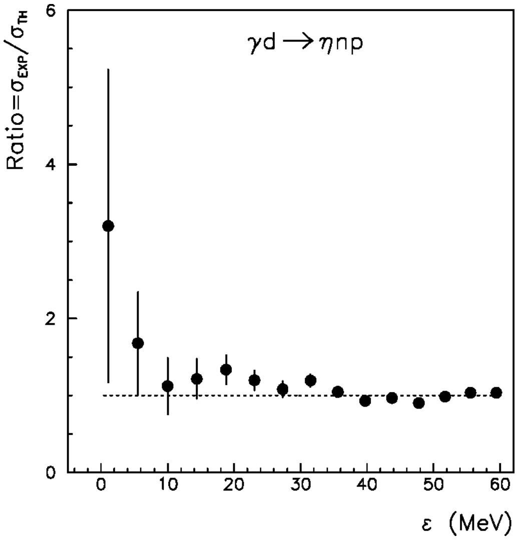

FIG. 3. The cross section for inclusive photon production of η mesons of the deuteron as a function of the excess energy ε. Shown is the experimental cross section divided by the full calculation given in Fig. 2.

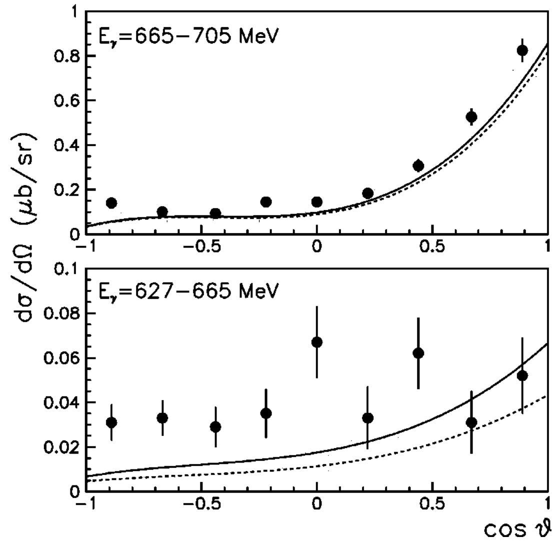

FIG. 4. The angular spectra of the η meson in the photon-deuteron rest frame at different photon energies. Experimental data are taken from Ref. [1]. The dashed line shows the IA calculation, while the solid line is the result with np FSI. The theoretical results represent an average over the given finite energy interval.

tional enhancement. Indeed, as can be seen in Fig. 3, there is a deviation from our calculation for energies very close to threshold, which may be interpreted as being caused by an ηN FSI, though the errorbars are large. In this regard it is interesting to notice that the magnitude and also the energy range of this deviation are comparable to the effects seen in η production via hadronic probes. Let us recall here that in the reactions $pp \rightarrow pp\eta$ as well as in $pn \rightarrow d\eta$ the observed additional enhancement very close to threshold is a factor of 2 to 3 (see Refs. [6] and [5]), and the enhancement is limited to excess energies belowm, roughly, 15 MeV for the former and, roughly, 10 MeV for the latter reaction.

A theoretical understanding of this additional enhancement would require a consistent inclusion of the FSI in the NN and also in the ηN systems, e.g., in the framework of Faddeev equations, which, however, is beyond the scope of the present investigation. However, we want to mention that calculations in this direction can be already found in the literature, for hadron- [32–34] as well as for photoinduced [13,35] η production processes. These studies indicate that the enhancement in the total production cross section for energies close to threshold can be indeed understood in terms of a ηN FSI, at least qualitatively. A quantitative description of the data, however, has so far not been achieved. Besides our insufficient knowledge of the ηN interaction there are also some technical aspects with regard to the application of the Faddeev theory to the ηNN system that are still under debate. Furthermore, it goes without saying that it would be very important to have data with higher statistics available at those energies very close to threshold in order to chart the possible enhancement due to the ηN FSI more accurately [3].

Angular spectra of η mesons in the photon-deuteron rest frame are shown for different photon energies in Fig. 4. The IA calculation underestimates the data at $E_\gamma = 627–665$ MeV, but already reasonably reproduces experimental results at 665–705 MeV.

Momentum spectra of the η mesons in the γ-d rest frame at different photon energies are displayed in Fig. 5. At the lower photon energy, 627–665 MeV, the IA calculation differs considerably from the full calculation including FSI. The latter leads to a significant enhancement of the yield for larger η momenta. This is not surprising because in this case the η meson carries away much of the available kinetic energy and the NN system emerges with a small relative momentum, and the interaction is particularly strong. This en-

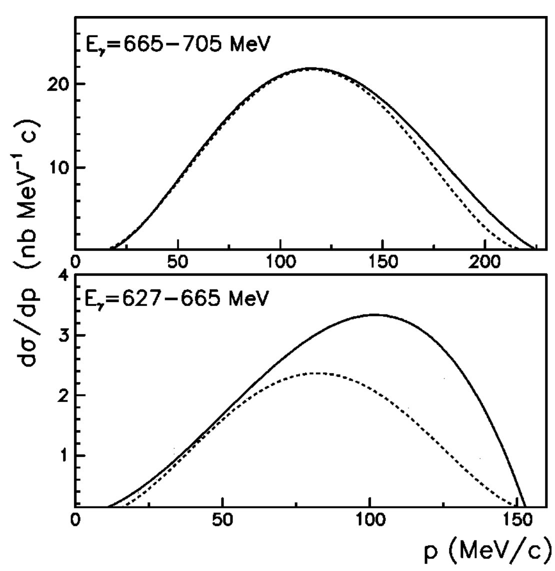

FIG. 5. The η-meson momentum spectra in the photon-deuteron rest frame at different ranges of the photon energies. The dashed line shows the IA calculation, while the solid line represents the result with np FSI. The theoretical results represent an average over the given finite energy interval.

hancement at large η momentum is clearly seen in the new still preliminary data of the TAPS collaboration [3]. As the photon energy increases, the difference between the IA and the calculation including the NN FSI becomes smaller. At a photon energy of 665–705 MeV, the effect of the FSI has basically vanished, is consistent with the observations in Fig. 2.

We would like to emphasize that the theoretical results displayed in Figs. 4 and 5 represent an average over a finite energy interval. This is done in order to make the predictions comparable to the experiments where likewise an averaging over energy bins is made [1,3]. Specifically for the momentum distribution of the η meson this averaging has a significant influence on the results. The maximal η momentum available at a given fixed photon energy for the reaction $\gamma d \to np\eta$ is defined by

$$p_\eta^{max} = \frac{\lambda^{1/2}(s,[m_p+m_n]^2,m_\eta^2)}{2\sqrt{s}}, \tag{13}$$

where s is defined in Eq. (1). Averaging over the photon energy leads to a smearing of p_η^{max}. Since the NN FSI is most strongly felt for η momenta close to p_η^{max} its effect is also smeared out by averaging over E_γ as is the case with the results shown in Fig. 5. Predictions for a sharp incident photon energy show a much stronger structure due to FSI as is exemplified in Fig. 6. Clearly, this suggests that a high energy resolution in the experiments is very desirable if one wants to see and study effects from the FSI.

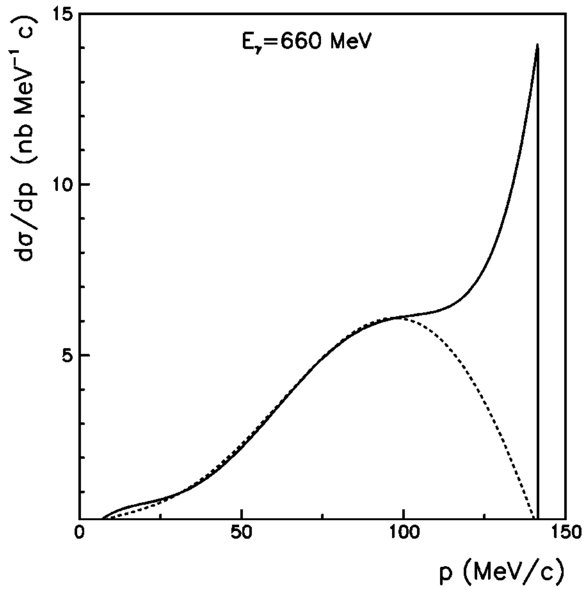

FIG. 6. The η-meson momentum spectrum in the photon-deuteron rest frame at the sharp photon energy of $E_\gamma = 660$ MeV. The dashed line is the result without NN FSI whereas the solid line includes it.

V. SUMMARY

We calculated the reaction $\gamma d \to np\eta$ including the dominant $S_{11}(1535)$ resonance and the neutron-proton final state interaction. We find that the impulse approximation reproduces the cross section for inclusive photoproduction of η mesons and the η-meson angular spectrum quite well for energies around 680 MeV and higher. At lower energies the consideration of the FSI between the outgoing nucleons is necessary to describe the relative enhancement of the cross-section data with respect to the impulse approximation. The magnitude of those FSI effects turned out to be practically the same for different realistic NN interaction models considered. Though the NN FSI accounts for a large part of the observed enhancement, our analysis suggests that there is still a remaining discrepancy with regard to the data for very small excess energies. This discrepancy is of similar size as found in the η production in NN collisions and may be taken as signature of the ηN final state interaction very close to threshold.

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