Investigation of near–threshold η production in the $dp \to pd\eta$ reaction

COSY-11 Collaboration

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Abstract

We propose to measure the near–threshold η meson production in the $dp \to pd\eta$ reaction for seven excess energies in the range from 1 MeV to 15 MeV. The experiment can be performed with the COSY-11 facility using the internal deuteron beam of the COSY accelerator. Momenta of the final protons will be measured with the existing detector system whereas for the determination of the deuteron momenta an additional detector has to be installed. The η mesons will be identified via the missing mass determination. Data on the $dp \to pd\eta$ reaction are needed in order to contribute to the understanding of the η meson production mechanism in a three nucleon system. They are also important for studies of the low energy η-deuteron interaction, which according to theoretical predictions can be strong enough to form quasi–bound states.

1 Motivation

1.1 Production mechanism of η mesons in three nucleon system

Recent data on the η meson production in proton–proton collisions measured by the COSY–11 collaboration [1] and earlier data from experiments at SATURNE [2, 3] and at CELSIUS [4] determine consistently the energy dependence of the $pp \to pp\eta$ cross section in the threshold region. This energy dependence is well described by the production model including the excitation of the $N^*(1535)$ resonance which subsequently decays into the $\eta - p$ pair and taking into account the p-p and p-η final state interactions [5]. The role of various heavy meson exchanges in the production mechanism is still not well fixed and possible excitation of other resonances has to be explored. An interesting question concerns contributions from higher partial waves to the production cross section near threshold, observed at higher beam energies by the PROMICE/WASA collaboration [6].

Near-threshold η meson production in a three–nucleon system is much less explored as compared to the two–nucleon case. It can be studied using the available cross sections for the $pd \rightarrow {}^3He\,\eta$ reaction originating from measurements at SATURNE [7, 8]. The analyses of further data are in progress from WASA/PROMICE at CELSIUS and from COSY–11 at COSY. Fäldt and Wilkin described these cross sections in a two–step model [9]. In the first step, a pion is produced in a $NN \rightarrow d\pi$ reaction and in the second step the η meson is produced via a $\pi N \rightarrow \eta N$ reaction. As shown by Kilian and Nann [10] the intermediate pion is close to the energy shell. The calculations of Fäldt and Wilkin include the final state interaction in the ${}^3He$–η system. The energy dependence of the $pd \rightarrow {}^3He\,\eta$ cross section is well reproduced, however, the predicted absolute value of the cross section is by a factor of 2.5 too low. As suggested by the authors of the calculations, the effect of the intermediate pion might be more clearly seen in the $pd \rightarrow pd\eta$ reaction. According to Kilian and Nann the $pd \rightarrow pdX$ reaction should show up another manifestation and further proof of the two step processes [10].

An understanding of the η meson production in a three nucleon system is very important from the point of view of heavy–ion physics since it can be considered as an archeotype of η production in heavy–ion collisions. The production of η mesons is one of the possible processes to study the high density nuclear matter. Especially promising is the observation of dileptons produced by the Dalitz decay of η mesons [11].

1.2 η–deuteron interaction

A study of the η meson interaction with nuclear matter is of special interest due to the possible existence of η–nucleus bound or quasibound states caused by the strong attractive η–nucleon interaction. There exist indications of quasibound states e.g. in η–^{3}He and η–^{4}He systems (see Ref. [12] and [13], respectively). Recently, the observation of an η–nucleus bound state (η–mesic nucleus) produced in the photoproduction on a carbon target was reported [14].

A quasibound state can exist even in the η–deuteron system as it was predicted by Ueda [15] on the basis of various η–N interaction models for the first time. Also more recent calculations performed in a multiple series formalism [16] or Faddeev–type calculations [17] support strongly the existence of a quasibound state in the η–d system. Indeed, an early SATURNE measurement on the $pn \to d\eta$ cross section suggested a very strong threshold effect, which could be due to a strong η–deuteron interaction [18]. However, more recent measurements at CELSIUS delivered a much smoother energy dependence of the $pn \to d\eta$ cross sections [19, 20].

The proposed measurements of the $dp \to pd\eta$ reaction will make it possible to study the strength of the η–deuteron interaction on the basis of the energy dependence of the total cross section as well as using the Dalitz plot analysis for the final state particles.

To the best of our knowledge, for the reaction $pd \to pd\eta$ in the threshold region there exist only recently published data on the total cross section measured with the SPESIII spectrometer at the SATURNE accelerator [21]. Measurements were done by the coincident detection of protons and deuterons identifying the produced η mesons via the missing mass method. Unfortunately, due to the closure of the SATURNE, the measurements could only be done at two excess energies namely 1.5 and 3.8 MeV. Besides, the uncertainty in the excess energy of the measured points with $\Delta Q = \pm$ 0.6 MeV is large when taking into account the rapid rise of the cross section near threshold. It causes also an additional systematic error due to the acceptance variation.

The measured points are compared in Fig. 1 with predictions of two different theoretical models. The dashed line in Fig. 1 represents calculations of Tengblad with a two–step model [22]. In turn, the solid line corresponds to calculations of the $pd \to pd\eta$ cross sections with the final p-d pair in a spin–$\frac{1}{2}$ state using relation to the $pd \to {}^3He\,\eta$ cross sections from Ref. [23]. As it is clear from Fig. 1, further data are needed to determine the energy dependence of the $pd \to pd\eta$ cross section and to test in this way the theoretical predictions. We propose, therefore, to measure these cross sections for seven excess energies in the range from 1 MeV to 15 MeV. Due to the precise knowledge of the magnetic field in the COSY–11 dipole magnet we can determine the excess energy at least a factor of two more accurately than in the SATURNE experiment. Two alternative methods of the beam momentum determination applied at the COSY–11 in the measurements of η production in proton–proton collisions are described in Ref. [1].

2 Experiment

Measurements of the near–threshold η production in the proton–deuteron collisions can be performed with the COSY–11 experimental facility. An excellent opportunity for such measurements opens now thanks to the availability of deuteron beams at the COSY accelerator. The detection acceptance for measurements with deuteron beams scattered on a proton target ($dp \to pd\eta$ experiment) is by about one order of magnitude higher compared to the acceptance for measurement with proton beams scattered on a deuteron target

($pd \to pd\eta$ experiment). This can be explained as follows. For a given excess energy the momentum of the deuteron beam is two times larger than of the proton beam since the deuteron is about two times heavier than the proton and the velocities of the proton and the deuteron beams are the same in the labolatory system. Due to momentum conservation, on the average the momenta of the outgoing particles ($p + d + \eta$) are also about two times larger in the $d + p$ case compared to the $p + d$ reaction. However, the transversal components of momentum vectors are the same since the two cases are identical in the CM system. This means that in the $d + p$ case the outgoing particles are confined in two times narrower cones compared to the $p + d$ case and the resulting solid angles are 2x2=4 smaller. For coincident measurement of protons and deuterons one can gain a factor of up to 4x4=16 due the the solid angle. Further in addition some factor is gained due to smaller smearing of the longitudinal momenta.

A scheme of the COSY–11 experimental setup with indicated proton and deuteron tracks obtained in Monte Carlo simulations of the $dp \to pd\eta$ reaction is shown in Fig. 2. Indicated is an additional detector for measuring the deuterons which emerge with roughly two times larger momenta than the ones of the protons. The deuterons leave the COSY–11 vacuum chamber through a 10 cm wide and 5.6 cm high window. The free space between the window and the nearby quadrupole magnet can be used for the installation of a new detector for the registration of the deuterons. The proposed new detector system, shown in detail in Fig. 3, consists of three parts: a drift chamber, a threshold Cerenkov counter and a scintillation detector. The drift chamber contains hexagonal cells with a radius of 0.6 cm. The cells are grouped in four detection planes with vertical wires and three detection planes with horizontal wires. This arrangement allows for a three–dimensional reconstruction of particle tracks. The drift chamber for measuring the deuteron tracks is being built and will be ready for installation at the COSY–11 facility in May 2001.

The deuteron momenta can be determined by tracing their trajectories in the magnetic field of the COSY–11 dipole magnet back to the nominal target position. The common–stop signal for the drift chamber will be derived from the scintillation detector made of 5 mm thick plastic scintillator (see Fig. 3). This detector will also be used for the time of flight measurement on a 2 m path from the target. The start for the time of flight measurement will be derived from the measurement of velocities of the associated protons on the path between the S1 and S3 hodoscopes and by tracing their movement back to the target point. This method has been proven to work very well in other analyses of data at the COSY–11. The time of flight combined with the momentum measurement will be used for the identification of deuterons.

In order to suppress intense proton background expected at forward angles where deuterons are measured, a threshold Cerenkov counter consisting of a 2 cm thick Plexiglass plate will be used.

The identification of protons will proceed using the momenta measured with the available drift chambers D1 and D2 and the time of flight measured with the S1 and S3 scintillation hodoscopes. The identification of η mesons will be done via the determination of the missing mass of the p–d pair using the information about the momentum of the deuteron beam and of the final proton and deuteron. The position of the η peak in the missing mass spectra will be used for a precise determination of the beam momentum as it is described in Ref. [1].

The luminosity in the experiment will be monitored by coincidence measurement of $d-p$ elastic scattering using the drift chambers DC1 and DC2 for the detection of the forward-scattered deuterons and the silicon pad detectors for detection of the recoil protons.

3 Counting rate estimation

In order to estimate the counting rate we assume, that the energy dependence of the cross section is given by the phase space and is normalized to the SPESIII data point at Q=1.5 MeV. The detection efficiency for a coincident measurement of the outgoing proton and deuteron from the reaction $dp \to pd\eta$ was determined via Monte Carlo simulation under the assumption of a uniform phase space distribution of the reaction products modified by the p-d-η FSI enhancement factor. The p-d-η FSI was factorized into p-d, p-η and d-η enhancement factors:

$$f_(pd\eta) = f_{pd}(q_{pd}) \cdot f_{p\eta}(q_{p\eta}) \cdot f_{d\eta}(q_{d\eta}), \tag{1}$$

where q_{pd}, $q_{p\eta}$ and $q_{d\eta}$ are relative momenta in the p-d, p-η and d-η systems, respectively. The enhancement factor for the proton–deuteron FSI was calculated according Ref. [24] using effective–range expansion of pd elastic scattering phase shifts in spin doublet and spin quadruplet state and taking into account the Coulomb interaction. The enhancement factor for the η–proton FSI was calculated in the effective–range approximation with the complex η–proton scattering length $a_{\eta p} = 0.717 + i0.263$ taken from Ref. [25] and the complex η–proton effective range parameter $r_{\eta p} = -1.50 - i0.24$ from Ref. [26]. In calculations of the η–deuteron FSI the effective range was taken the same as for the η–proton system and the scattering length was taken two times larger than for η–proton.

The acceptance of the detection system is mainly limited by the dimensions of the window for deuterons and it changes from about 43% at Q=1 MeV to 4% at Q=15 MeV (see Fig. 4). The influence of the FSI on the detection efficiency is depicted in Fig. 4 by difference between the dashed line and the solid line. This difference is highest at the highest excess energy and it corresponds to relative change of the detection efficiency of about 20 %. This effect is caused predominately by the $p-d$ FSI. The influence of $p-\eta$ and $d-\eta$ FSI is by about one order of magnitude smaller.

In spite of the fact that the detection acceptance limited especially for higher excess energies it covers the whole Dalitz plot for the final particles even at Q =15 MeV (see Fig. 5) which is crucial for the studies of FSI effects.

Numerical values of the estimated cross sections near threshold are given in Table 1 together with the detector acceptance, the expected counting rate, the planned beam time and the totally expected counts. The planned beam times amount to 1 day for each of five excess energies in the range from 2.5 MeV to 10 MeV. For the lowest excess energy of 1 MeV we plan 2 days of the beam time due to smaller expected counting rate. In turn for the highest excess energy of 15 MeV, where the FSI effects are expected to be the most pronounced, we would like to perform a 5 days long run allowing for detailed studies of the Dalitz plot. The expected counts were calculated assuming lost of 8 hours of the beam time for each energy setting necessary for the beam optimization. Including two further days for a measurement below the η production threshold to determine the shape of the multi-pion background in the missing mass spectra, a total of 14 days is required. In order to perform the proposed measurements we would like, therefore, to ask for two weeks of COSY beam time in the second half of 2001.

References

[1] J. Smyrski et al., Phys. Lett. **B474** (2000) 182

[2] A. Boudard, Few-Body Systems Suppl. **8** (1995) 287,
F. Hibou et al., Phys. Lett. **B438** (1998) 41

[3] E. Chiavassa et al., Phys. Lett. **B 322** (1994) 270

[4] H. Calén et al., Phys. Lett. **B 366** (1996) 39

[5] E. Gedalin, A. Moalem and L. Razdolskaya, Nucl. Phys. **A650** (1999) 471,
V. Bernard, N. Kaiser and U. -G. Meißner, Eur. J. Phys. **A4** (1999) 259

[6] H. Calén et al., Phys. Lett. **B 458** (1999) 190

[7] J. Berger et al., Phys. Rev. Lett. **61** (1988) 919

[8] B. Mayer et al., Phys. Rev. **C53** (1996) 2068

[9] G. Fäldt and C. Wilkin, Nucl. Phys. **A587** (1995) 769

[10] K. Kilian and H. Nann, AIP Conf. Proc. **No 221** (1990) 185

[11] R. Holzman, Acta Phys. Polon. **B29**(1998)3051,
R. Holzman et al., Phys. Rev. **C56**(1997)2920

[12] C. Wilkin, Phys. Rev. **C47** (1993) R938

[13] N. Willis et al., Phys. Lett. **B406** (1997) 14

[14] G. A. Sokol et al., nucl-ex/0006010, Talk at CIPANP, May 2000, Quebec

[15] T. Ueda, Phys. Rev. Lett. **66** (1991) 297

[16] A. M. Green, J. A. Niskanen and S. Wycech, Phys. Rev. **C54** (1996) 1970

[17] N. V. Shevchenko et al., Phys. Rev. **C58** (1998) R3055

[18] F. Plouin, P. Fleury and C. Wilkin, Phys. Rev. Lett. **65** (1990) 690

[19] H. Calén et al., Phys. Rev. Lett. **79** (1997) 2642

[20] H. Calén et al., Phys. Rev. Lett. **80** (1997) 2069

[21] F. Hibou et al., Eur. Phys. J. **A7** (2000) 537

[22] U. Tengblad, TSL/ISV Report 96-0163, 1996 (unpublished)

[23] G. Fäldt and C. Wilkin, Phys. Lett. **B382** (1996) 209

[24] H. O. Meyer and J. A. Niskanen, Phys. Rev. **C47** (1993)2474

[25] T. -S. H. Lee, Physica Scripta **58** 15 (1998).

[26] A. M. Green and S. Wycech, Phys. Rev. **C55** R2167 (1997).

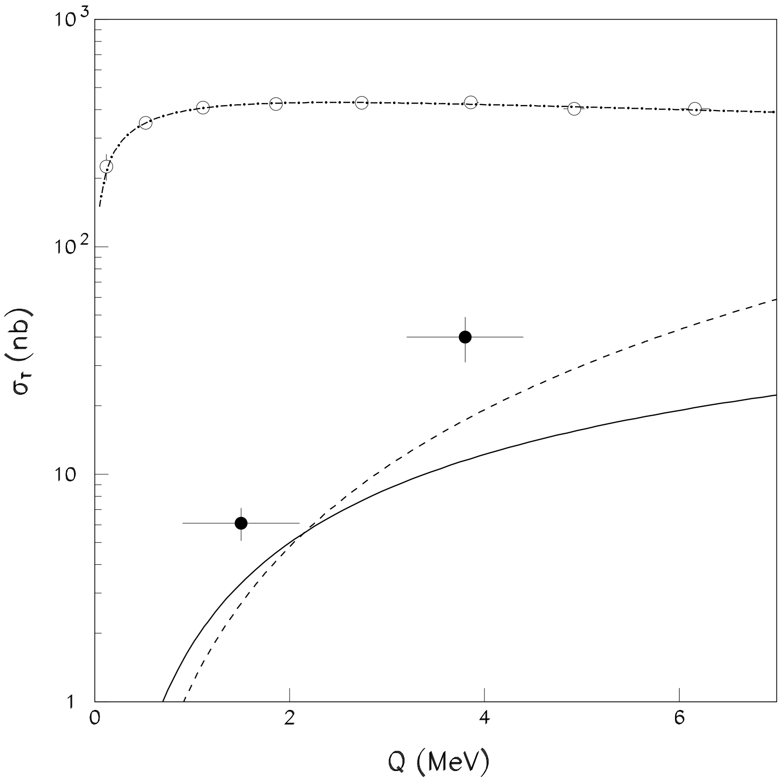

Figure 1: Two data points for the total cross sections of the $pd \to pd\eta$ reaction measured with the SPESIII spectrometer (full circles). The additional errors arising from the influence of the uncertainty in the absolute value of the excess energy Q are not indicated since, due to the $Q - \sigma$ error correlation, they have much smaller components perpendicular to the theoretical predictions. The solid curve is the prediction for the spin–$\frac{1}{2}$ p–d final state in the final state interaction model of Ref. [23] and the dashed curve corresponds to the two-step model of Ref. [22]. The open circles show the $pd \to {}^3He\,\eta$ data of Ref. [8] and the dot-dashed curve is the parametrization of these data of ref. [21]. The figure is reprinted from Ref. [21].

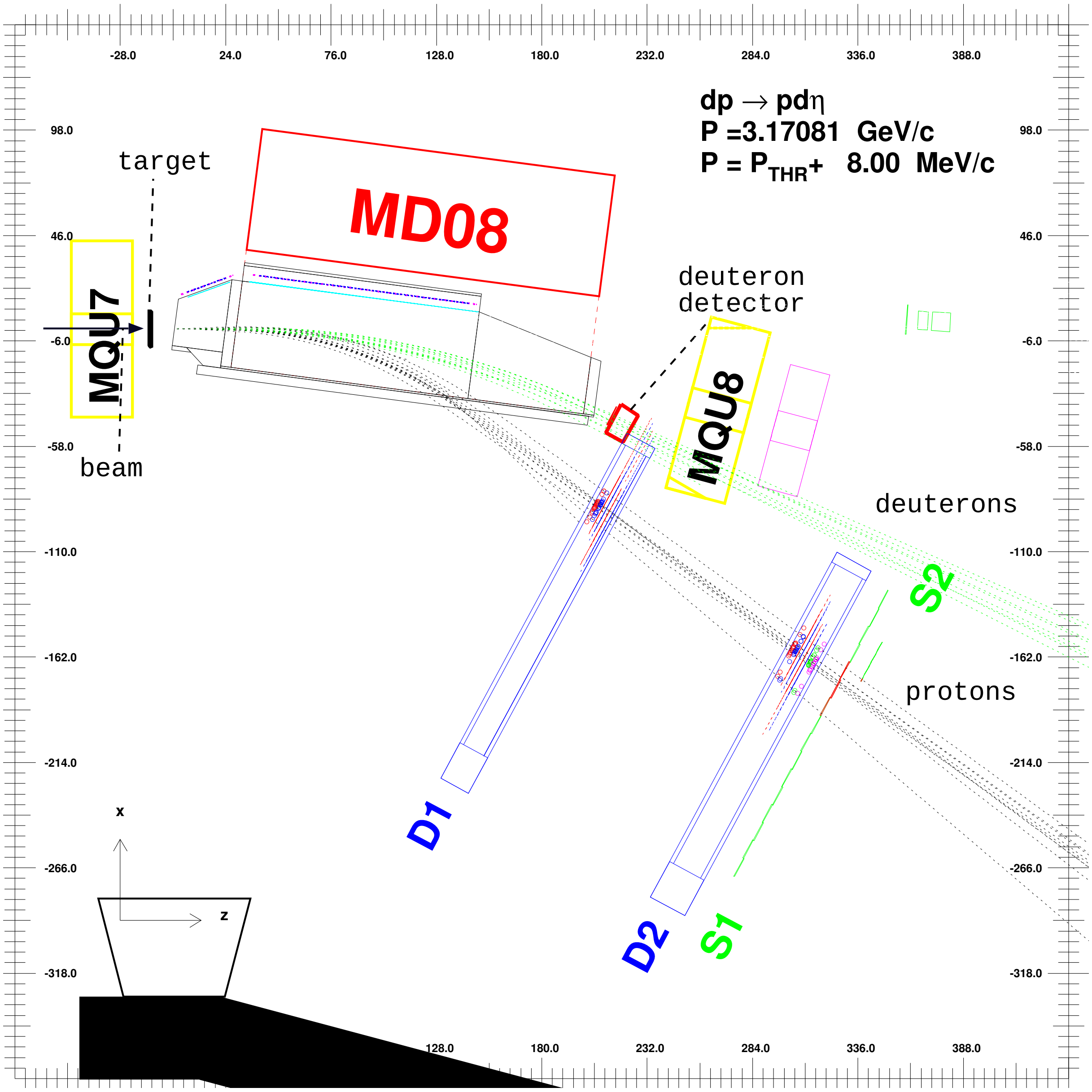

Figure 2: Scheme of the COSY–11 experimental setup with indicated particle tracks obtained in Monte Carlo simulation of the $dp \to pd\eta$ reaction at the beam momentum exceeding by 8 MeV/c the threshold momentum equal to 3170.81 MeV/c.

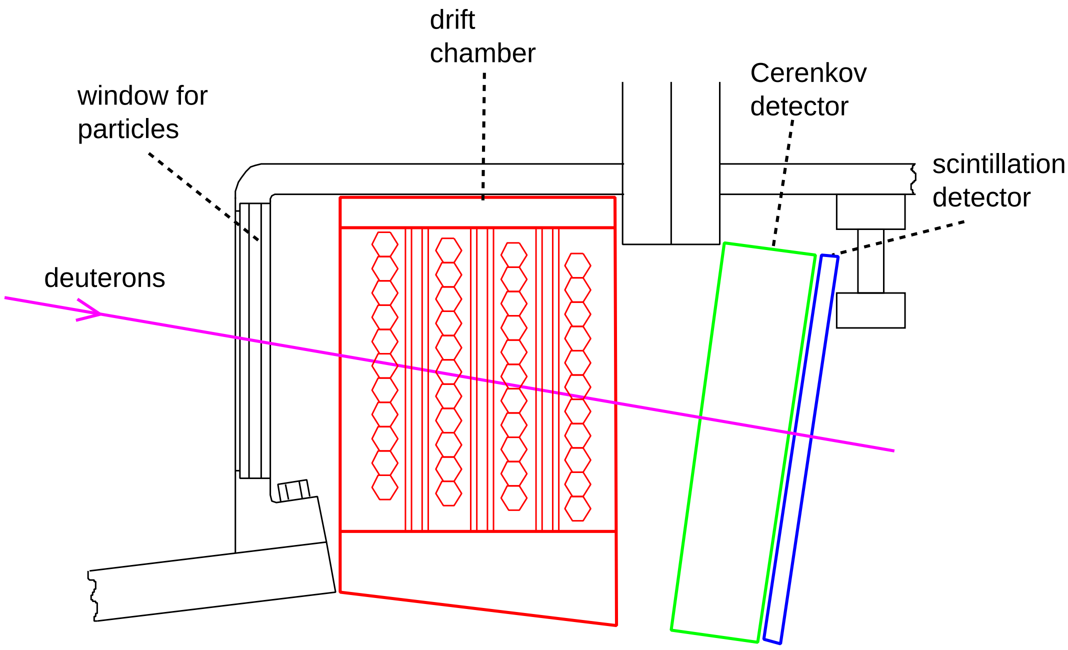

Figure 3: Deuteron detector consisting of drift chamber, Cerenkov and scintillation detector.

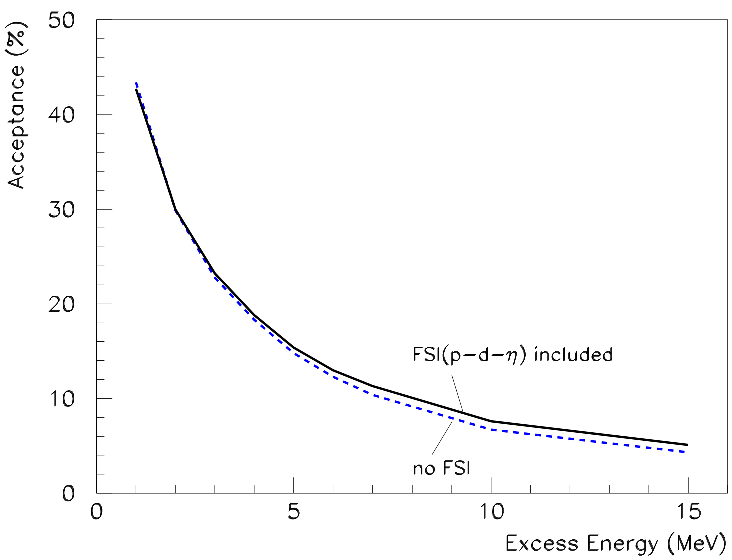

Figure 4: Acceptance of the detection system for a coincident measurement of the outgoing proton and deuteron from the reaction $dp \to pd\eta$.

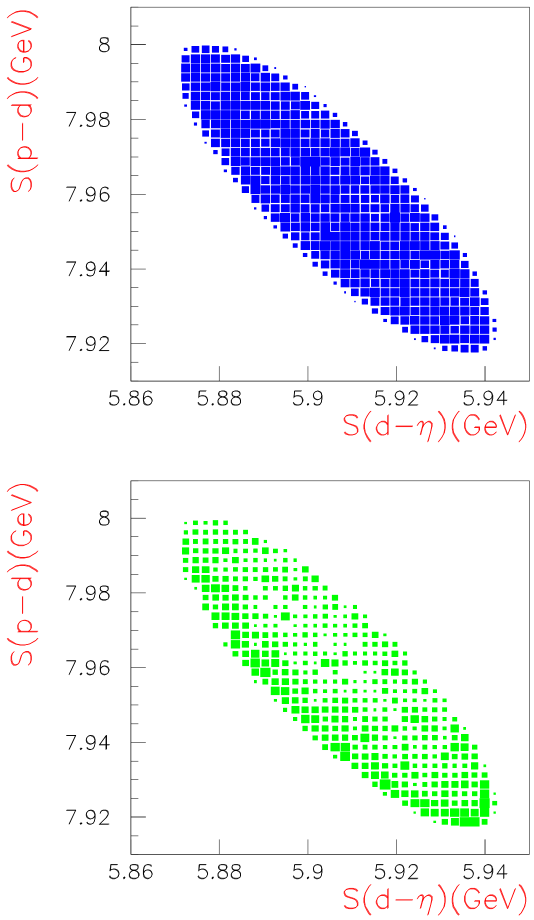

Figure 5: Dalitz plot for $dp \to pd\eta$ events generated uniformly over available phase–space for excess energy of 15 MeV (upper plot) and for events accepted by the COSY–11 (lower plot).

excess energy [MeV]	cross section [nb]	acceptance[a] [%]	counts[b] [1/day]	beam time [day]	expected counts
-1.0	–	–	–	2	–
1.0	2.9	43	322	2	537
2.5	19	26	1278	1	852
4.0	46	19	2268	1	1512
5.5	86	14	3123	1	2082
7.0	137	11	3905	1	2603
10.0	280	6.7	5514	1	3676
15.0	630	4.3	8325	5	38850
				$\Sigma = 14$	

[a] for detection of the outgoing proton and deuteron in coincidence
[b] assuming the luminosity of $3 \cdot 10^{30} cm^{-2} s^{-1}$

Table 1: Estimated cross sections, detector acceptance, counting rate, requasted beam time and expected counts for measurements of the reaction $dp \rightarrow pd\eta$ near threshold.