

## ISOSPIN DEPENDENCE OF THE $\eta$ -MESON PRODUCTION IN HADRONIC COLLISIONS\*

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Based on recent COSY-11 results of measurements of total cross-sections for the quasi-free  $pn \rightarrow pn\eta$  reaction we determine the isospin  $I = 0$  component of the total cross-section for the  $NN \rightarrow NN\eta$  reaction down to the threshold. We show that the energy dependence of the total cross-section ratios  $\sigma_{I=0}(pn \rightarrow pn\eta)/\sigma(pp \rightarrow pp\eta)$  and  $\sigma_{I=0}(pn \rightarrow pn\eta)/\sigma(pn \rightarrow d\eta)$  can be described using the Fäldt and Wilkin analytical parametrization of the nucleon–nucleon final state interaction.

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### 1. Introduction

Studies on the  $\eta$  meson production in hadronic collisions via different isospin channels have had a large contribution to the understanding of the reaction mechanism [1–3]. From the comparison of the total cross-sections for reactions  $pn \rightarrow pn\eta$  [4–7] and  $pp \rightarrow pp\eta$  [8–15] it was derived that the production of the  $\eta$  meson with the total isospin  $I = 0$  in the initial channel exceeds the production with the isospin  $I = 1$  by over an order of magnitude, suggesting [16] the isovector meson exchange to be the dominant process leading to the excitation of the  $S_{11}$  resonance. This mechanism is considered to be predominant [17–25]. However, relative contributions to the production process of  $\pi$  and  $\rho$  meson exchange are still not well settled [26–29].

In this paper we determine contributions of the  $I = 0$  and  $I = 1$  components to the total cross-section of the  $NN \rightarrow NN\eta$  reaction taking into account the entire available data base including our recent cross-sections for the  $pn \rightarrow pn\eta$  reaction determined near the kinematical threshold [5].

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## 2. $pn \rightarrow pn\eta$ and $pp \rightarrow pp\eta$ total cross-section ratio

Denoting by  $\sigma_0$  and  $\sigma_1$  the isospin  $I = 0$  and  $I = 1$  components of the total cross-section for the  $NN \rightarrow NN\eta$  reaction, we can write that:

$$\sigma(pn \rightarrow pn\eta) = \frac{1}{2}(\sigma_0 + \sigma_1), \quad (1)$$

and that

$$\sigma(pp \rightarrow pp\eta) = \sigma_1. \quad (2)$$

The left panel of Fig. 1 shows the ratio of the total cross-sections for the  $pn \rightarrow pn\eta$  reaction to the total cross-section for the  $pp \rightarrow pp\eta$  reaction plotted as a function of the excess energy. It was surprising to observe this ratio to fall down at lower values of  $Q$ . However, as explained by Wilkin [30], to a large extent, this behavior may plausibly be assigned to the difference in the strength of the proton–proton and proton–neutron FSI. Following the reference [31] the parameterization of the isospin  $I = 0$  component of the cross-section for the  $pn \rightarrow pn\eta$  reaction, taking into account proton–neutron FSI, is given by:

$$\sigma_0(pn \rightarrow pn\eta) = A \frac{Q^2}{(1 + \sqrt{1 + Q/\varepsilon_{pn}})^2}, \quad (3)$$

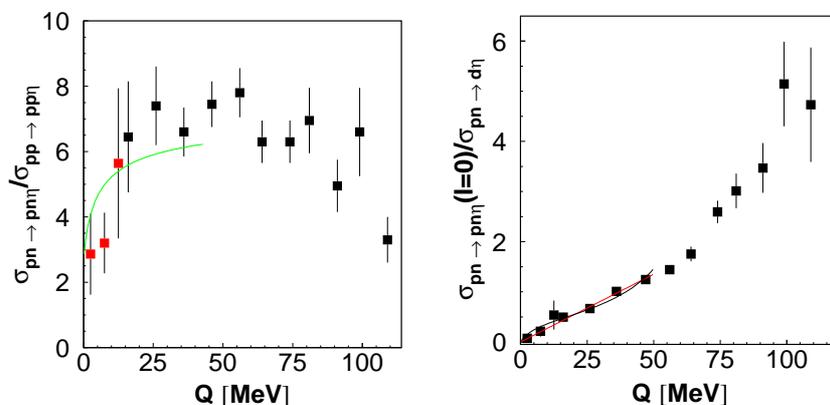


Fig. 1. Left: Ratio of the total cross-sections for the  $pn \rightarrow pn\eta$  and  $pp \rightarrow pp\eta$  reactions. The superimposed line indicates the result of the fit taking into account the final state interaction of nucleons. Right: Ratio between the  $I = 0$  component of the  $pn \rightarrow pn\eta$  total cross-section and the total cross-section for the  $pn \rightarrow d\eta$ . The superimposed lines indicate the result of fits taking into account the final state interaction of nucleons (black line), and assuming that the ratio of the total cross-sections changes linearly with the excess energy (straight line).

where  $A$  is a constant,  $Q$  is the excess energy, and  $\varepsilon_{pn} = 2.2 \text{ MeV}$  is the binding energy of the  $pn$  bound state [30].

Analogously, the parameterization of the  $pp \rightarrow pp\eta$  reaction total cross-section (pure isospin  $I = 1$ ) is given by:

$$\sigma(pp \rightarrow pp\eta) = B \frac{Q^2}{(1 + \sqrt{1 + Q/\varepsilon_{pp}})^2}, \quad (4)$$

with  $\varepsilon_{pp} = 0.68 \text{ MeV}$  being the “binding” energy of the  $pp$  virtual state [31], and  $B$  being a constant. The value of  $\varepsilon_{pp} = 0.68$  was derived [32] from the fit of formula 4 to the cross-sections for the  $pp \rightarrow pp\eta'$  reaction [33–36] for which the influence from the proton–meson final state interaction can be neglected [37].

Employing equations (4), (3), (2), and (1) one obtains for the cross-sections ratio the following closed analytical formula which accounts for the interaction between nucleons [31, 38]:

$$\frac{\sigma(pn \rightarrow pn\eta)}{\sigma(pp \rightarrow pp\eta)} = 0.5 + C \left( \frac{\sqrt{\varepsilon_{pp}} + \sqrt{\varepsilon_{pp} + Q}}{\sqrt{\varepsilon_{pn}} + \sqrt{\varepsilon_{pn} + Q}} \right)^2. \quad (5)$$

We have fitted the function given by Eq. (5) (with  $C$  as the only free parameter) to the data in the excess energy range from 0 to 40 MeV where the higher partial waves of the nucleon–nucleon system are suppressed [37]. The result is presented in Fig. 1 (left) as the solid line, and explains to some extent the observed decrease of the ratio at threshold. The parameter  $C$  was found to be  $6.85 \pm 0.63$  and the  $\chi^2$  of the fit was equal to 1.6.

A slight bump-like structure observed in the ratio presented in the left panel of Fig. 1 — with a flat maximum at the excess energy of about 50 MeV — could be due to the fact that the production of the  $\eta$  meson in hadronic collisions proceeds via the intermediate resonance  $N^*(1535)$  ( $m(N^*) - m_\eta - m_{\text{nucleon}} \approx 49 \text{ MeV}$ ). This may indicate that the coupling of this resonance to the neutron– $\eta$  may be stronger than to the proton– $\eta$  channel. This interpretation is however controversial since it would imply a strong isospin breaking effect [39].

### 3. $pn \rightarrow pn\eta(I = 0)$ and $pn \rightarrow d\eta$ total cross-section ratio

The total cross-section for the  $pn \rightarrow d\eta$  reaction is a pure isospin  $I = 0$  channel since both deuteron and the  $\eta$  meson have isospin equal to zero. In the case of the  $NN \rightarrow NN\eta$  reaction the  $I = 0$  component of the cross-section can be extracted from cross-sections for the reactions  $pn \rightarrow pn\eta$  and  $pp \rightarrow pp\eta$  employing Eqs (1) and (2).

In order to compare the production of the  $\eta$  meson associated with the proton–neutron bound state ( $d\eta$ ) to its production with the proton and neutron in continuum ( $pn\eta$ ) in a way independent of the initial state interaction we have extracted the experimental values of the  $\sigma_0(pn \rightarrow pn\eta)$  component, and compared them to the total cross-sections for the  $pn \rightarrow d\eta$  reaction. The ratio of these two cross-sections is presented in the right panel of Fig. 1, plotted as a function of the excess energy  $Q$ . An interesting observation is that this ratio rises nearly linearly with the excess energy up to circa 60 MeV, and above this value it starts to grow more steeply. This may suggest that from about 60 MeV the influence of higher partial waves in the  $pn\eta$  system is more pronounced than in the case of the  $d\eta$  system.

According to the reference [24] the low energy cross-section for the  $pn \rightarrow d\eta$  reaction may be parameterized in the following way:

$$\sigma(pn \rightarrow d\eta) \approx a\sqrt{Q}(1 + bQ), \quad (6)$$

where parameters  $a$  and  $b$  are calculated from the nucleon mass, the  $\eta$  and  $\rho$  meson masses, and also the  $\rho$  meson coupling constant [24]. As the latter is still not well known, and the values of parameters  $a$  and  $b$  are model dependent<sup>1</sup> we have treated  $a$  and  $b$  as free parameters of the fit.

Dividing Eq. (3) by Eq. (6) we get:

$$\frac{\sigma_0(pn \rightarrow pn\eta)}{\sigma(pn \rightarrow d\eta)} = \frac{DQ^{3/2}}{(1 + bQ)(1 + \sqrt{1 + Q/\varepsilon_{pn}})^2}, \quad (7)$$

with  $D$  being a constant. We have fitted formula (7) in the range between the threshold and  $Q = 50$  MeV (see Fig. 1 (right)<sup>2</sup>), treating  $D$  and  $b$  as free parameters of the fit. The fit procedure resulted in  $D = 0.35 \pm 0.03$  [1/MeV<sup>3/2</sup>] and  $b = -0.013 \pm 0.001$  [1/MeV]. The value of reduced  $\chi^2$  of the fit was equal to 1.4.

On the other hand, the assumption that the  $\sigma_0(pn \rightarrow pn\eta)$  to  $\sigma(pn \rightarrow d\eta)$  ratio is a linear function of  $Q$  in the close-to-threshold region (up to the excess energy of  $Q = 50$  MeV):

$$\frac{\sigma_0(pn \rightarrow pn\eta)}{\sigma(pn \rightarrow d\eta)} = KQ, \quad (8)$$

yields  $K = 0.027 \pm 0.001$  [1/MeV], with a reduced value of  $\chi^2$  equal to 0.3. The best linear function fitted to the experimental data is presented in Fig. 1 (right).

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<sup>1</sup> In reference [24] they are calculated in the framework of the vector meson dominance one boson exchange model, where the  $\rho$  meson exchange current dominates the production amplitude.

<sup>2</sup> This corresponds to the close-to-threshold reaction region, where higher partial waves should not be present, and formulae (3) and (6) apply.

One should, however, be careful in the interpretation of the cross-section ratios presented in Fig. 1 due to the rather low energy resolution for measurements of the  $pn \rightarrow pn\eta$  reaction which was equal to about 5 MeV for the COSY-11 experiment and circa 8 MeV for experiments performed with the WASA/PROMICE detector [4].

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