THE $p\,d \to p\,d\,\eta$ REACTION NEAR THRESHOLD

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Differential and total cross sections of the $p\,d \to p\,d\,\eta$ reaction are estimated in the region below the NN threshold. At the lowest energies, it is predicted that a two–step model involving an intermediate pion should be the most important but, at higher energies, a pick–up mechanism with a spectator proton should become dominant. The overall production rate is underestimated by about a factor of two compared with experimental data, which present angular distributions that are more featureless than those of the theoretical calculations. The analogous two–step model is extended to describe the low energy $p\,d \to K^+d\,\Lambda$ and inclusive K^+ production data.

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1 Introduction

The Saclay measurements of the $p\,d \to\ ^3\text{He}\,\eta$ reaction near threshold [1, 2] were the start of the modern interest in η production near threshold for at least FOUR different reasons, all of which are reflected in contributions to this Workshop:

- It involves an interesting reaction mechanism which requires some cooperative effort from all the nucleons;
- The strong final state interaction in the $\eta\,^3$He system leads to a very rapid energy variation of the production amplitude and raises the possibility of the existence of quasi–bound η–nucleus states [3];
- The two–body nature of the reaction with well established particles allows one to make precision measurements of the mass of the η meson [4, 5];
- The good signal/background ratio over a small range in the momentum of the ^{3}He recoil provides an excellent source of mesons for decay studies.

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We shall here only be concerned with the first point, using the greater flexibility of the $p\,d \to p\,d\,\eta$ kinematics to study the reaction mechanism. In Section 2 we discuss the three types of diagrams that are likely to be important in any description of the reaction and the results of calculations based upon these models are compared with experimental data in Section 3. Possible extensions of the models to describe strange particle formation in $p\,d \to K^+ d\,\Lambda$ and inclusive K^+ production in proton–deuteron collisions below the NN threshold are outlined in Section 4, with the conclusions being drawn in the final Section 5.

2 Theoretical models of the $p\,d \to p\,d\,\eta$ reaction

The three types of diagram that we have considered to describe the $p\,d \to p\,d\,\eta$ reaction are illustrated in Fig. 1.

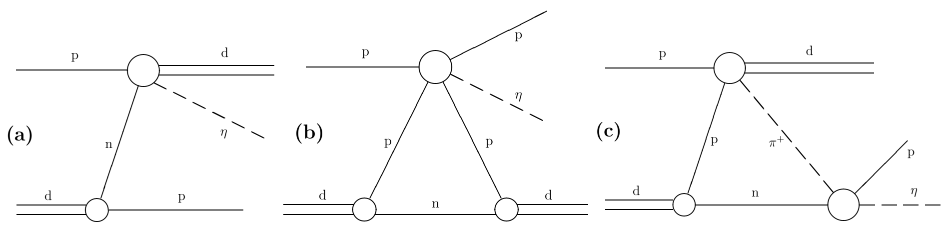

Fig. 1. Three classes of diagrams relevant for the $p\,d \to p\,d\,\eta$ reaction: (a) the pick–up term, (b) the impulse diagram, and (c) the two–step model with an intermediate pion.

The pick–up diagram (or one–neutron–exchange) of Fig. 1a corresponds to quasi–free production through a $pn \to d\eta$ reaction on a bound target neutron. Above the threshold for η production in nucleon–nucleon collisions it is precisely this model that is used to extract the $pn \to d\eta$ cross section [6]. However, the pick–up amplitude is proportional to the deuteron momentum–space wave function evaluated at the momentum $\boldsymbol{p}_{\text{sp}}$ of the final (spectator) proton in the rest frame of the target deuteron. At the $p\,d \to p\,d\,\eta$ threshold the spectator momenta are very high (≈ 440 MeV/c) and so we would expect the contribution from this term to be very small at low energies. The situation here is very similar to that of the two–body $p\,d \to {}^3\text{He}\,\eta$ reaction where the single–scattering mechanism is insufficient to explain the experimental data [7]. The formal evaluation of the amplitudes corresponding to the pick–up and the other two diagrams of Fig. 1 is to be found in Ref. [8].

The impulse or triangle diagram of Fig. 1b is the one that is normally used to describe elastic scattering or the coherent production of particles on the deuteron at very high energies. The integration of the two deuteron wave functions over the internal loop momentum of the triangle leads to a form factor which is generally maximal when the momentum transfer q is the smallest. However, the minimum momentum transfer from a particle of mass m_i to one with mass m_f is approximately

$$q_{\text{min}} \approx \frac{m_f^2 - m_i^2}{2p_{\text{lab}}} > \frac{2m_p m_\eta + m_\eta^2}{2p_{\text{lab}}}\,. \qquad (2.1)$$

Near threshold, where the laboratory momentum $p_{\rm lab} = 1.58$ GeV/c, the minimum value is 420 MeV/c. This decreases only slightly by the NN threshold, and just for those events where the $p\eta$ effective mass is small. It is therefore not surprising that the contribution from the impulse approximation remains small throughout the region that we have investigated.

The most intriguing model is the two–step process represented by Fig. 2c. Here a virtual pion beam is produced on say the proton through the $pp \to d\pi^+$ reaction, with the observed η being formed through a secondary $\pi^+ n \to p\eta$ process. Though such terms were included in the microscopic approach of Laget and Lecolley for the analogous $p\,d \to {}^3\mathrm{He}\,\eta$ reaction [9], it was noted by Kilian and Nann [10] that near threshold the intermediate pion can get very close to its mass shell, which allows the two steps to be separated by some distance in configuration space. This does not mean that the off–shell part of the propagation can be neglected and the real part of the integral over the triangle in Fig. 2c is significant in certain regions [11].

The *magic kinematics* extends also to the $p\,d \to p\,d\,\eta$ reaction near threshold though, as the energy is increased, the fraction of phase space where the pion is almost real gets smaller. A decrease in the total cross section at higher energies is also induced by the energy variation of the $pp \to d\pi^+$ and $\pi^+ n \to p\eta$ inputs.

3 Comparison with experiment

The predictions of the $p\,d \to p\,d\,\eta$ total cross sections from the three driving terms, as well as their incoherent sum, are shown in Fig. 2 as functions of the excess energy Q.

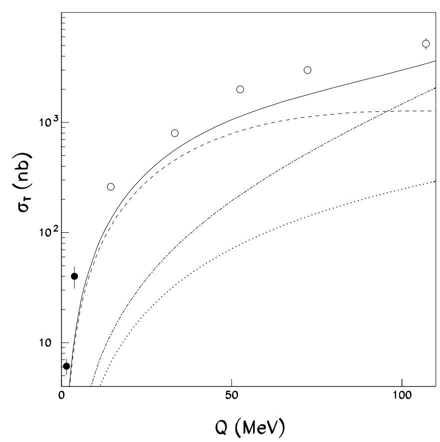

Fig. 2. Experimental values of the $p\,d \to p\,d\,\eta$ total cross sections from Refs. [12] (solid circles) and [13] (open circles). These are compared with the predictions of the impulse approximation (dots), the pick–up contribution (chain), the two–step model (dashes), and their incoherent sum (solid curve).

As expected, the impulse approximation gives only a very small contribution and will be neglected for the differential observables. The two–step process dominates near threshold, though this is eventually overtaken by the pick–up mechanism as the NN threshold at $Q \approx 190$ MeV is approached. The incoherent sum lies about a factor of two below experiment [12, 13], though this is very similar to the $p\,d \to {}^3\mathrm{He}\,\eta$ case [11].

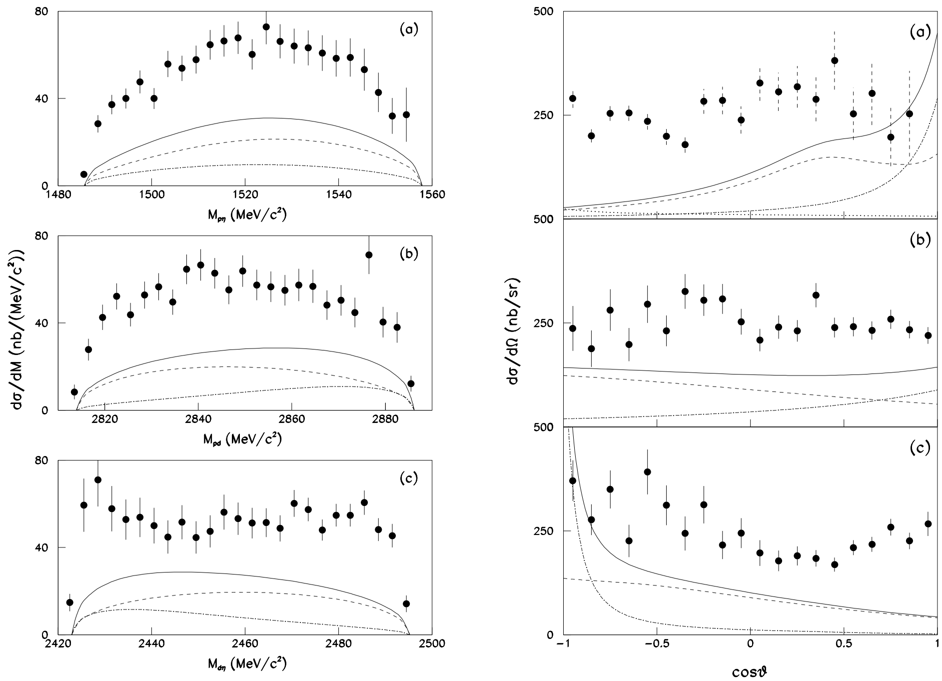

Fig. 3. Effective mass (left side) and c.m. angular (right side) distributions for the $p\,d \to p\,d\,\eta$ reaction at $Q = 72.3$ MeV, the data being taken from Ref. [13]. The panels (a), (b), and (c) refer respectively to outgoing d, η, and p. The predictions of the pick–up term, the two–step model, and their incoherent sum are shown by the chain, dashed and continuous curves respectively.

The predictions for the effective mass distributions at $Q = 72.3$ MeV, shown on the left of Fig. 3, do not deviate dramatically from phase space. Of the experimental spectra, only that corresponding to the $d\eta$ variable has significant structure, with a threshold enhancement associated with a large $d\eta$ scattering length. The models do not show such a behaviour because final state interaction (*fsi*) effects were not included. Surprisingly there is no sign of any pd *fsi* despite the fact that the ratio of the $p\,d \to {}^3\mathrm{He}\,\eta$ to $p\,d \to p\,d\,\eta$ total cross sections is as if the pd spin–doublet S–wave were dominant [13].

All three experimental angular distributions shown on the right of Fig. 3 are rather flat and there is little sign of the backward proton peak predicted from the pick–up diagram. It should, however, be noted that in this model both the proton and deuteron are produced preferentially along the beam direction and, if either of these goes down the beam pipe, the event is lost.

4 Extensions of the two–step model

Data on the $p\,d \to K^+ d\,\Lambda$ reaction taken below the NN threshold at COSY are currently being analysed [14]. This meson production reaction is very similar to that of the η except that the pick–up diagram of Fig. 1a is absent. Though there is more ambiguity in the spin and isospin dependence of the input amplitudes in the equivalent of Fig. 1b, the impulse approximation also gives a small contribution to the $p\,d \to K^+ d\,\Lambda$ cross section. In the two–step diagram of Fig. 1c, one needs only to replace the final $\pi^+ n \to \eta p$ by $\pi^+ n \to K^+\Lambda$ in order to get a model for the $p\,d \to K^+ d\,\Lambda$ reaction. This predicts cross sections that are typically an order of magnitude smaller than for η production. Of this a factor of about three comes from the energy dependence of the $pp \to d\pi^+$ cross section and most of the rest from the relative weakness of K^+ production in $\pi^+ p$ collisions. The results are shown in Fig. 4 as a function of excess energy Q.

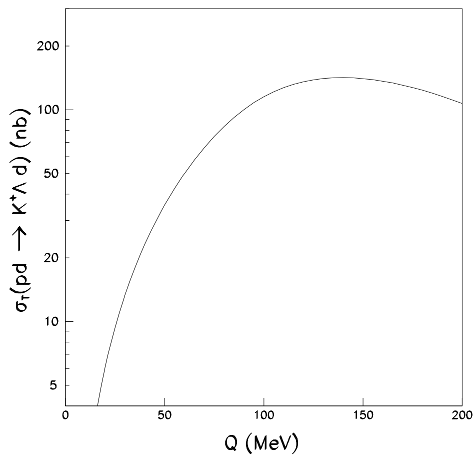

Fig. 4. Predicted values for the $p\,d \to K^+ d\,\Lambda$ total cross section in the two–step model.

If the two–step model can explain most of the $p\,d \to p\,d\,\eta$ and $p\,d \to K^+ d\,\Lambda$ production near threshold then, by replacing the $pp \to d\pi^+$ amplitude in Fig. 1c by one for $pp \to pn\pi^+$, we obtain a model for $pd \to K^+\Lambda pn$, and hence inclusive K^+ production. The resulting cross section can be estimated very simply if we consider only final pn spin–triplet S–wave pairs and use the *fsi* theorem relating this to the amplitude for deuteron production [15]. Generalising the technique used to relate two– and three–body reactions [16], we find the rough estimate:

$$\frac{\sigma(pd \to K^+\Lambda pn)}{\sigma(pd \to K^+\Lambda d)} \approx \frac{2}{\pi\sqrt{x}}\left[\frac{5}{6}+\frac{4x}{15}+\frac{1}{2x}-2\sqrt{x}\left(\frac{1+x}{2x}\right)^2 \arctan\sqrt{x}\right]\,, \tag{4.2}$$

where $x = Q/\varepsilon$, with ε being the deuteron binding energy. Though the validity of this formula is questionable at high excess energies, as shown in Fig. 5, it predicts that at $Q \approx 110\,\text{MeV}$ the ratio of $K^+\Lambda pn$ to $K^+\Lambda d$ production should be about 70%. Taking this together with the predictions of Fig. 4 it suggests that the inclusive K^+ cross section at this energy should be around 200 nb, which may be something of an underestimate compared to experiment [14].

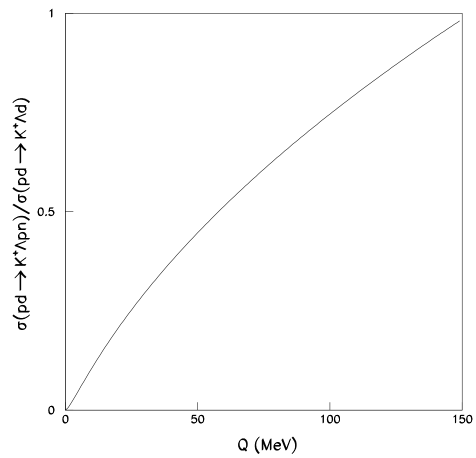

Fig. 5. The prediction of eq. (4.2) for the ratio of the production of four– and three–body final states.

5 Conclusions

We have shown that near threshold a two–step model with an intermediate pion beam dominates the $p\,d \to p\,d\,\eta$ reaction but that quasi–free production on the neutron is equally dominant around the NN threshold. The energy dependence of the total cross section is reasonable though it underestimates the data by a factor of two. There is also scope for improvement in other aspects. In particular the models predict more structure in the angular distribution than that observed. Furthermore, since there is no accepted way to introduce interactions between more than one pair of final particles, we cannot reproduce the threshold $d\eta$ enhancement. Initial state interactions have been similarly neglected, as have interferences between different amplitudes.

When the model is applied to the $p\,d \to K^+d\,\Lambda$ reaction, only the two–step term is significant. Data on this as well as inclusive K^+ production are in the final stages of analysis and they will be a useful test of our approach.

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