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η AND η' MESONS PRODUCTION AT COSY-11

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COSY-11 Collaboration

The low emittance and small momentum spread of the proton and deuteron beams of the Cooler Synchrotron COSY combined with the high mass resolution of the COSY-11 detection system permit to study the creation of mesons in the nucleon-nucleon interaction down to the fraction of MeV with respect to the kinematical threshold. At such small excess energies, the ejectiles possess low relative momenta and are predominantly produced with the relative angular momentum equal to zero. Taking advantage of these conditions we have performed investigations aiming to determine the mechanism of the production of η and η' mesons in the collision of hadrons as well as the hadronic interaction of these mesons with nucleons and nuclei. In this proceedings we address the ongoing studies of the spin and isospin dependence for the production of the η and η' mesons in free and quasi-free nucleon-nucleon collisions.

New results on the spin observables for the $\vec{p}p \rightarrow pp\eta$ reaction, combined with the previously determined total cross section isospin dependence, reveal a statistically significant indication that the excitation of the nucleon to the $S_{11}(1535)$ resonance, the process which intermediates the production of the η meson in the nucleon-nuleon interactions, is predominantly due to the exchange of the π meson between the colliding nucleons.

Keywords: Meson-nucleon interaction; near threshold meson production.

1. Introduction

In the low energy limit, for energies lower than the Λ_{QCD} parameter[1], in the domain where the strong coupling constant is large, there exists no clear description of the strong interaction since both quark-gluon and hadron degrees of freedom become relevant. Therefore, in order to understand the phenomena governed by the strong forces in this non-perturbative regime of QCD still a lot of experimental

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[∗] E-mail address: p.moskal@fz-juelich.de and theoretical effort is required. In this energy regime, investigations of the production and decay of hadrons (objects owing their existence to the strong forces), deliver information needed to deepen our knowledge about the strongly coupled QCD, where the perturbative approach is not possible.

Here we will focus on the studies of the production of the η and η' mesons emphasising such aspects like the production mechanism of these mesons and their interaction with nucleons. We will stress mainly results obtained at the COSY-11 facility[2] operating at the cooler synchrotron COSY[3]. Yet, whenever it will be possible, investigations of the COSY-11 group will be presented in the broader context together with the relevant data obtained at other facilities. We hope to be able to demonstrate that, although there are always many possible interpretations of the determined observables, the combination of the energy dependence of the total cross section with its differential distribution and its spin and isospin dependencies, gathered during the decade of measurements, permit now conclusive statements about the studied phenomena.

2. Advantages of Threshold Kinematics

The COSY-11 facility is designed for studies of the mesons and hyperons production in the nucleon-nucleon, nucleon-deuteron, and deuteron-deuteron collisions near the kinematical threshold. For the details concerning the detection system[2,5] as well as the methods of particle identification[4], absolute normalisation[6] or multidimensional acceptance corrections[7] the interested reader is referred to the quoted publications, where the facility was described in a comprehensive way.

Exactly at the reaction threshold all ejectiles are at rest in the center of mass system. Therefore, in the case of the fixed target experiments, due to the momentum conservation, outgoing particles are confined in the laboratory in a small cone centered around the beam line and can be detected by means of relatively small detectors. In practice, it means that a full space phase coverage can be achieved even when using magnetic spectrometers which are usually limited by a small geometrical acceptance. This feature allows to combine a precise momentum reconstruction of the outgoing particles with an effectively large detection efficiency.

In the case of the studies of short-lived mesons, measured indirectly via the missing mass technique a very important advantage is that the missing mass resolution due to the uncertainties of the reconstruction of the ejectiles' momenta tends to zero at threshold. In addition, the smearing of the missing mass distribution caused by the beam momentum spread is also narrowing with decreasing beam momentum and it reaches its minimum at threshold[8]. We demonstrated empirically that the missing mass resolution is approximately proportional to the square root of the excess energy[9]. Hence, we can benefit thoroughly from the threshold kinematics as far as the acceptance, resolution of the missing mass reconstruction as well as a signal-to-background ratio are concerned. Recently at COSY by means of the GEM[10] setup the mass of the η meson was determined with precision[11], and in

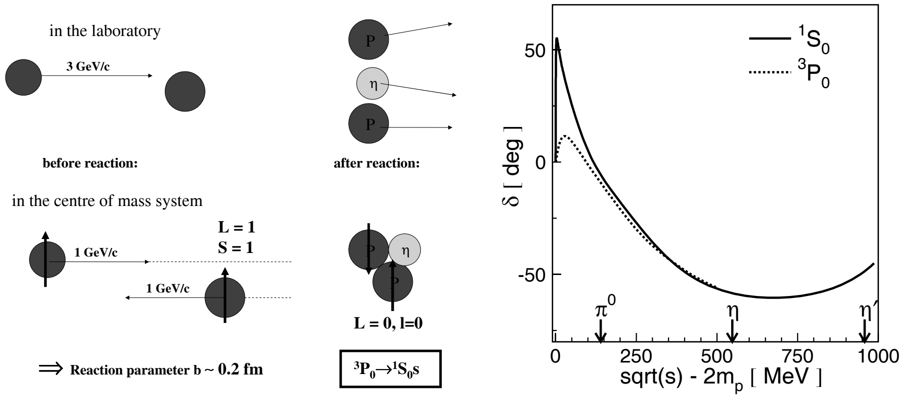

Fig. 1. **Left:** Schematic view of the $pp \to pp\eta'$ process at threshold. **Right:** The ${}^1\mathrm{S}_0$ and ${}^3\mathrm{P}_0$ phase-shifts of the nucleon-nucleon potential shown versus the centre-of-mass kinetic energy available in the proton-proton system. The values have been extracted from the SAID data base[12].

the near future, taking advantage of the threshold kinematics, using the developed monitoring methods[6] and the stochastically cooled proton beam of COSY we will use the COSY-11 setup to measure directly the natural width of the η' meson with an experimental resolution of about 0.2 MeV[8]. On the theoretical side the most crucial facilitation and attractiveness when interpreting meson production at the vicinity of the threshold is the fact that the relative angular momenta larger than $l = 0$ play no role due to the short range of the strong interaction and small relative momenta of the produced particles. Due to the conservation laws and the Pauli excluding principle for many reactions there is only one possible angular momentum and spin orientation for the incoming and outgoing particles[a]. Thus, the production of neutral mesons with negative parity – as pseudoscalar or vector mesons – may proceed in the proton-proton collision near threshold only via the transition between ${}^3\mathrm{P}_0$ and ${}^1\mathrm{S}_0\mathrm{s}$ partial waves. This means that only the collision of protons with relative angular momentum equal to $1\,\hbar$ may lead to the production of such mesons. A situation which is pictorially demonstrated in Figure 1 (left).

Thus, basing on general conservation rules one can deduce that in the case of η and η' production in proton-proton collisions the dominant transition is the one between ${}^3\mathrm{P}_0$ and ${}^1\mathrm{S}_0\mathrm{s}$ partial waves. Before coming to the experimental results let us still examine phase-shifts of the nucleon-nucleon potential (see Fig. 1 right) for

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[a] The Pauli principle for the nucleon-nucleon system implies that $(-1)^{L+S+T} = -1$, where L, S, and T denote angular momentum, spin, and isospin of the nucleon pair, respectively. For the $NN \to NNX$ reaction the conservation of the basic quantum numbers requires[13] that $(-1)^{(\Delta S+\Delta T)} = \pi_X \ (-1)^l$, where π_X describes the intrinsic parity of meson X, ΔS denotes the change in the spin, and ΔT in isospin, between the initial and final NN systems. For more circumstantial discussion on the partial waves contribution in the production of various mesons in the collisions of nucleons an interested reader is referred to Refs. 14, 15, 13.

the partial waves involved in the production process. The ${}^3\mathrm{P}_0$ phase-shift variation in the vicinity of the threshold for mesons heavier than π^0 is very weak, and hence we expect that the interaction of nucleons before the act of a primary production will not introduce a significant energy dependence to the cross section excitation function[b].

Due to the large momentum transfer between colliding protons needed to create a meson, the primary production amplitude is also only weakly energy dependent in the excess energy range of a few tens of MeV. Directly at threshold, where all ejectiles are at rest in the centre-of-mass frame, the momentum transfer is equal to the centre-of-mass momentum of the interacting nucleons. In the case of the η' meson production it is equal to about 1 GeV/c $\approx 5\ \mathrm{fm}^{-1}$, which according to the Heisenberg uncertainty relation implies a distance of about 0.2 fm probed by the $NN \to NN\eta'$ reaction at threshold. In contrast, the typical range of the strong nucleon-nucleon interaction at low energies determined by the pion exchange may exceed a distance of a few femtometers and hence is by one order of magnitude larger than the spatial size of the range where the production occurs. Thus, in analogy to the Watson-Migdal approximation for two-body processes[16] the complete transition matrix element of the production process may be factorized into the total short range production amplitude (M_0), and the interaction among particles in the exit (M_{FSI}) and initial (F_{ISI}) channels. In contrary to the weak energy dependence of M_0 and F_{ISI} we expect a strong variation of M_{FSI} when the excess energy changes by tens of MeV. This is due to the rapid changes of the phase-shifts for the ${}^1\mathrm{S}_0\mathrm{s}$ partial wave as it is demonstrated in Fig. 1 (right). Therefore, near threshold, the shape of excitation functions for the total cross section for meson production in the collision of nucleons will be predominantly due to the final state interaction between outgoing nucleons convoluted with the variation with energy of the phase space volume available for the reaction.

3. Signals from Final State Interaction

Now we can confront results of considerations carried out in the previous section with the experimental data. Figure 2 presents a total cross section for the $pp \to pp\eta'$ reaction as a function of the excess energy. The solid line superimposed on the data indicates calculations of the total cross section performed employing factorisation of the total production matrix element $|M_{pp\to ppX}|$ into the short range primary amplitude $|M_0|$ and the initial and final state interaction $|M_{pp\to ppX}|^2 \approx |M_{FSI}|^2 \cdot |M_0|^2 \cdot F_{ISI}$. The proton-proton FSI effects have been taken

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[b] Authors of Ref. 17 have demonstrated that the reduction factor due to the influence of the NN initial state interaction (ISI) can be estimated from the phase-shifts and inelasticities only. At the threshold for π meson production ISI makes almost no distortion since the reduction factor is close to unity. This is because at this energy the inelasticity is still nearly 1 and the ${}^3\mathrm{P}_0$ phase-shift is close to zero (see Fig. 1 right). However, at the η threshold, where the phase-shift approaches its minimum, the proton-proton ISI diminishes the total cross section already by a factor of five.

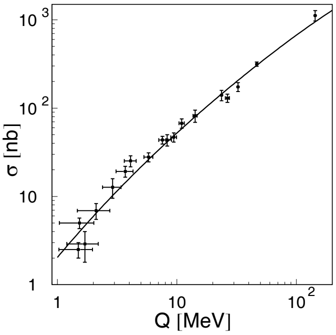

Fig. 2. Total cross section for the $pp \to pp\eta'$ reaction as a function of the excess energy. The data were obtained using COSY-11[21,22,23], SPESIII[24] and DISTO[25] experimental facilities. The line shows the result of the parametrisation described in the text. The parameters ϵ and the normalisation constant have been fixed by minimising the χ^2 value. The fit lead to the values of $\epsilon = 0.62 \pm 0.13$ MeV and $const = 84 \pm 14\, mb$.

into account according to the model developed by Fäldt and Wilkin[18,19], which allows to express the total cross section energy dependence for a $NN \to NN\, Meson$ reaction by a closed analytical formula[14]: $\sigma = const \cdot \frac{V_{ps}}{\mathrm{F}} \cdot \left(1 + \sqrt{1 + \frac{\mathrm{Q}}{\epsilon}}\right)^{-2}$, where Q stands for the excess energy, F denotes the flux factor[20] and V_{ps} corresponds to the volume of the available phase space[14]. The parameter ϵ and the normalisation constant have to be settled from the data. Figure 2 demonstrates that the data can indeed be very well described under the above discussed Ansatz. We can conclude also, that the interaction of the η' meson with the proton, which was neglected in the calculations, is too weak to manifest itself visibly within the statistical error bars[26]. Interestingly, when using the same model and calculating the shape for the excitation function of the η meson production we underestimated the data at the very threshold by about a factor of two[14,7] [c]. The difference could be explained when extending the factorisation by the proton-η interaction, however doing so we fail to describe the invariant mass distributions where the discrepancy is even more pronounced as can be clearly observed in Fig. 3 (left). In order to explain the structure observed in the invariant mass spectra Nakayama and collaborators[29] suggest a contribution from higher partial waves to the production process. In fact an admixture of the ${}^1S_0 \to {}^3P_0 s$ transition to the main ${}^3P_0 \to {}^1S_0 s$ one results in the very good agreement with the experimental points in the invariant mass spectra[29]. However, at the same time, this conjecture leads to strong discrepancies in the shape of the excitation function[29,14]. Till now there exists no consistent picture allowing for the simultaneous explanation of the excitation function and invariant mass distributions for the η meson production. The enhancement is visible also at Q = 4.5 MeV (see Figure 3 center)[7], where the contribution of the higher partial waves is quite improbable[32]. We deem this as an indication in favour of the hypothesis that the effect is caused by the proton-η interaction rather than by higher partial waves. In order to shed new light on these investigations we have con-

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[c] Recently an even larger enhancement has been observed in the case of the K^+K^- pair production[27,28]. It cannot be excluded that the effect is due to the strong K^+K^- interaction. The interpretation is however still open.

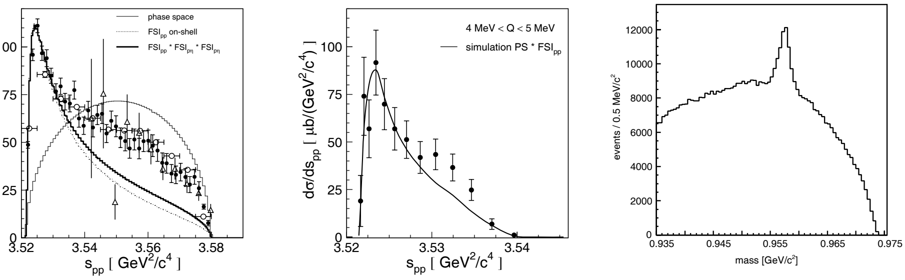

Fig. 3. **Left:** Distributions of the square of the proton-proton (s_{pp}) invariant mass determined experimentally for the $pp \to pp\eta$ reaction at the excess energy of Q = 15.5 MeV by the COSY-11 collaboration (closed circles), at Q = 15 MeV by the TOF collaboration (open circles)[30], and at Q = 16 MeV by PROMICE/WASA (open triangles)[31]. The integrals of the phase space weighted by the square of the proton-proton on-shell scattering amplitude FSI$_{pp}$ (dotted line), and by the product of FSI$_{pp}$ and the square of the proton-η scattering amplitude (thick solid line) have been normalized arbitrarily at small values of s_{pp}. The expectation for homogeneously populated phase space is shown as thin solid curve[7,14]. **Center:** Distribution of the square of the proton-proton invariant mass from the $pp \to pp\eta$ reaction measured at COSY-11 for the excess energy range 4 MeV $\leq$ Q $\leq$ 5 MeV[7]. The superimposed line shows the result of simulations assuming that the phase space population is determined exclusively by the on-shell interaction between outgoing protons[7,14]. **Right:** Missing mass distribution for the $pp \to ppX$ reaction measured using the COSY-11 facility at an excess energy of Q = 15.5 MeV above the threshold for the η' meson production.

ducted a high statistics measurement of the η' meson creation at an excess energy of Q = 15.5 MeV. Our purpose is to determine an invariant mass distribution of the $p\eta'$ system at exactly the same value of excess energy as it was done in the case of the η meson. If for the η' meson case a similar enhancement appears it will indicate that its origin cannot be assigned to the meson-proton interaction and hence it would strengthen the hypothesis suggesting a significant contribution from higher partial waves[29]. On the other hand, if the enhancement disappears this will raise the confidence to the hypothesis that the observed bump is due to the proton-η interaction acting in the $pp\eta$ system. The data are being analyzed, and presently as a herald of the forthcoming invariant mass distribution we show a missing mass spectrum (Fig. 3 right) where a clear signal with about 17000 events corresponding to the $pp \to pp\eta'$ reaction is clearly visible.

4. The Power of Analysing Power - η Production with Polarized Beam

A precise data set[7,24,33,34,35,36] on the total cross section of the η meson production in the $pp \to pp\eta$ reaction allowed to conclude that the reaction proceeds through the excitation of one of the protons to the $S_{11}(1535)$ state which subsequently deexcites via emission of the η meson. The crucial observations were a large value of the absolute cross section (forty times larger than for the η' meson) and isotropic distributions[7,30] of the angle of the η meson emission in the reaction center-of-mass system. In practice, in the meson exchange picture the excitation of the intermediate resonance can be induced by the exchange between the nucleons of any of the pseudoscalar or vector ground state mesons. Based only on the total cross section and its dependence on the excess energy it was however impossible to falsify or confirm any of the proposed hypothesis. In fact due to the negligible variation of the production amplitude in the range of few tens of MeV the full information available from the excitation function is reduced to a single number[37].

Theoretical collaborations[38,39,40,41,42,43,44,45] reproduce the magnitude of the total cross section, though their models differ significantly as far as the relative contributions from the exchange of various mesons are concerned. The ambiguity was solved partially by the determination of the isospin dependence of the total cross section by the WASA/PROMICE collaboration[46]. From the comparison of the η meson production in proton-proton and proton-neutron reactions it could be inferred that η is by a factor of 12 more copiously produced when the total isospin of the nucleons is equal to zero than when it is equal to one. As a consequence only an isovector mesons exchange is conceivable as responsible for such a strong isospin dependence. It was a large step forward but still the relative contributions of ρ and π mesons remained to be disentangled. The spin averaged observables are consistent with the calculations based upon ρ meson exchange dominance[40] as well as upon π meson exchange dominance[29,43]. Yet, the conclusions drawn for the angular dependence of the beam analysing power are significantly different depending on whether π or ρ meson dominance is assumed as a leading mechanism for exciting one of the colliding nucleons[29,43]. Encouraged by the discovery potential given by the contradicting predictions we have performed an experiment aiming to determine the angular dependence of the analysing power for the $pp \to pp\eta$ reaction. After a successful test run[48] we have conducted measurements at excess energies of Q = 10 MeV and Q = 36 MeV[49]. As a result we have established that the analysing powers for both excess energies are consistent with zero. The χ^2 analysis excludes correctness of the assumption about a pure vector meson dominance (ρ exchange) with the significance level larger than four standard deviations, and provides strong evidence for the correctness of the supposition that the production of η mesons in nucleon nucleon collision is dominated by the pion exchange. Selected results are shown in Fig. 4, and for more details the reader is referred to a report of Czyżykiewicz[47] in these proceedings.

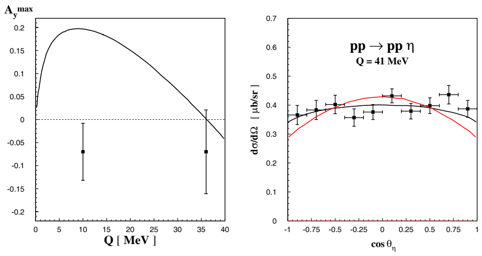

Fig. 4. **Left:** Amplitude of the analysing power as predicted upon vector dominance model[40] (line) and as measured by the COSY-11[47] (data). **Right:** Center-of-mass angular distribution of the η meson emission. Data were measured by the COSY-TOF[30]. Less and more bend lines correspond to π and ρ dominance, respectively[43].

5. Isospin Dependence of the Hadronic Production of the η' Meson

In the preceding section based upon spin and isospin observables for the $NN \to NN\eta$ reaction we deduced that in collisions of nucleons the η meson is primordially created through the exchange of pion leading to the excitation of one of the nucleons to the $S_{11}(1535)$ state which subsequently decays into the η meson and a nucleon. In the case of the η' meson our understanding of the process is still much poorer and unsatisfactory. We attempt to apprehend this process since there are many indications that the wave function of the η' meson comprises a significant gluonic component[50,51], distinguishing it from other ground state mesons, and we hope that the comprehension of the mechanism leading to the creation of the η' meson in collisions of hadrons may help to determine its quark-gluon structure. A potentially large glue content of the η' and the dominant flavour-singlet combination of its quark wave function may cause that the dynamics of its production process in nucleon-nucleon collisions is significantly different from that responsible for the production of other mesons. In particular, the η' meson can be efficiently created via a "contact interaction" from the glue which is excited in the interaction region of the colliding nucleons[52,54,53].

At present the models can be confronted with the values of the total cross section only, and until now it has not been possible to satisfactorily estimate the relative contributions of the nucleonic, mesonic, and resonance current to the production process[43]. Therefore, in order to disentangle the ambiguities it is mandatory to determine experimentally spin and isospin observables.

As a first step we have conducted measurements of the $pn \to pn\eta'$ reaction in order to establish an isospin dependence of the total cross section[60,61]. We expect that the result will help to judge about the isospin nature of the objects exchanged which intermediate the production process. On the other hand a very important theoretical result is that regardless of whether it is a mesonic, nucleonic, or resonance current the contribution from the exchange of isovector mesons (ρ or π) is much larger compared to that of isoscalar ones (ω or η)[55,56,57]. Hence, our conviction is that on the hadronic level the process should have a rather strong isospin dependence, unless there is a fortuitous cancellation of the dominating amplitudes[d]. This entails that if the ratio $R_{\eta'} = \frac{\sigma(pn\to pn\eta')}{\sigma(pp\to pp\eta')}$ – corrected for FSI and ISI distortions – will be found to be close to unity we will have an indication that the η' is produced directly by gluons. On the way towards the determination of the value of $R_{\eta'}$ by means of the COSY-11 facility a test experiment of the $pn \to pn\eta$ reaction – suspected to have by at least a factor of thirty larger cross section than the one for the $pn \to pn\eta'$ reaction – was performed[60,62]. In this test measurement, using a beam of stochastically cooled protons and a deuteron cluster target, we

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[d] This can only be verified from spin observables in further studies which we intend to conduct at the WASA-at-COSY facility[59,58].

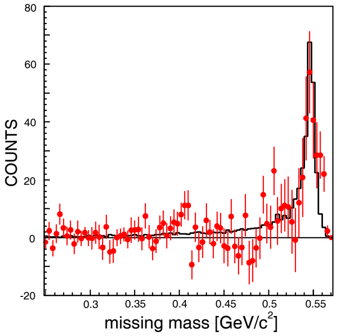

Fig. 5. Missing mass distribution of the quasi-free $pn \to pnX$ process determined for $Q > 0$ with respect to the $pn \to pn\eta$ reaction[62]. The sum for all ΔQ intervals is shown. The points denote the experimental data for $Q > 0$ after subtraction of the multi-pion background. The superimposed solid line, normalised in amplitude to the data points, results from a Monte-Carlo simulation.

have proven the ability of the COSY-11 facility to study the quasi-free creation of mesons via the $pn \to pnX$ reaction. In Fig. 5 a clear signal originating from the quasi-free $pn \to pn\eta$ reaction is visible. In the data evaluation a spectator model was employed and the background was subtracted according to the recently developed method[62]. The experimental distribution is fully consistent with expectations determined taking into account all effects introduced by the instrumentation system and the known physical processes which particles undergo when passing through the detectors. In March this year we have completed data taking for the $pn \to pn\eta'$ reaction. The obtained integrated luminosity is by factor of 50 larger than this of the test measurement of the $pn \to pn\eta$ with the signal presented in Fig. 5. Presently the data are under analysis. In order to measure the $pn \to pnMeson$ reactions we use a proton beam and a deuteron target. The main conjecture of this approach is that the bombarding proton interacts exclusively with one nucleon in the target nucleus and that the other nucleon affects the reaction by providing a momentum distribution to the struck constituent only[e]. In the case of the η' meson production, due to the large centre-of-mass velocity ($\beta \approx 0.75$) with respect to the colliding nucleons, a few MeV wide spectrum of the neutron kinetic energy inside a deuteron is broadened by more than a factor of thirty. Therefore, to achieve an accuracy of the excess energy in the order of few MeV it is important to reconstruct the four-momentum vector of the interacting neutron on the event-by-event basis. Such an accuracy is mandatory for close-to-threshold studies where the cross sections vary by few orders of magnitude within the range of excess energy of few tens of MeV[32]. For this purpose, the spectator proton is registered and its four momentum vector is reconstructed[63,14]. Subsequently, energy and momentum conservation permit to determine the four-momentum vector of the reacting neutron.

Finally, for the comparison of the results obtained from a quasi-free and free reactions, we need to make a second assumption namely that the matrix element for quasi-free meson production off a bound neutron is identical to that for the free $pn \to pn\,Meson$ reaction.

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[e] A detailed description of the application of this technique can be found e.g.in Refs. 63, 64, 32.

6. Is the Spectator Model Valid ?

The title of this section constitutes a frequently expressed concern in the context of the investigations of the meson production in the proton-neutron collisions where the neutron is bound in the nucleus. A positive answer to it must be justified if we are to trust the results derived employing the spectator model. Below we list a few simple arguments which build our confidence to this model and more important we quote empirical results which confirm the validity of the spectator hypothesis on the few per cent level and set limits of its applications.

(1) Based on intuition from classical mechanics the assumption *that only a hit nucleon takes part in the collision* is justified if the kinetic energy of a projectile is large compared to the binding energy of the nucleus. Indeed, the deuteron is relatively weakly bound with a binding energy of $\mathrm{E}_B \approx 2.2\,\mathrm{MeV}$, which is more than three orders of magnitude smaller than the kinetic energy of the bombarding proton needed for the creation of the η' meson in the proton-neutron interaction.

(2) In case of meson production off the deuteron, one can also justify the assumption of the quasi-free scattering with a geometrical argument, since the average distance between the proton and the neutron is in the order of 3 fm. Certainly, the other nucleon may scatter the incoming proton and the outgoing meson. Yet, this nuclear processes referred to as a shadow effect and reabsorption, respectively, decrease the total cross section (e.g. for the η-meson production) by about a few per cent only[65,66].

(3) Comparisons of the quasi-free and free angular distributions for the $pp \to d\pi^+$ reaction done at the TRIUMF facility[67] have confirmed the validity of both crucial hypotheses of the spectator model. It was demonstrated that the experimental spectator momentum distribution conforms very well expectations based upon spectator model. The experiment revealed also that the magnitude of the differential cross sections for the quasi-free $pp \to d\pi^+$ process agree on the few per cent level with the free differential cross sections, thus proving also that the matrix element for the free and quasi-free process are equal at least to this level level. It is important to note that the energies of projectiles in this experiment were few times lower than needed to produce η or η' meson, and at higher energies the approximation should work even better.

(4) The WASA/PROMICE collaboration has compared quasi-free and free production cross sections for the $pp \to pp\eta$ reaction. As a result it was shown that within the statistical error bars there is no difference between the total cross section of the free and quasi-free process. Thus confirming the validity of the assumption regarding the equality of the production matrix elements for free and bound nucleons.

(5) A dedicated empirical test of the first assumption of the spectator model has been performed recently using the high acceptance COSY-TOF facility[68]. The shape of the angular distributions for the quasi-free $np \to pp\pi^-$ and $pn \to pn$ reactions as well as the form of the momentum distributions of the spectator have

been measured. Calculations based upon the hypothesis of the spectator model yield results consistent with the experimental data with an accuracy better than 4% up to 150 MeV/c of the Fermi momentum and with about 25% up to a momentum of 300 MeV/c.

7. Conclusion

Due to the limited space we could give only a brief account of a few chosen aspects of our investigations concerning the η and η' physics. We did not mentioned e.g. the issues of the η meson production in the few nucleon system[69,70] or the search for a possible bound state of the η meson with the nucleus of Helium[71]. The interested reader is thus referred to the mentioned references.

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