Feasibility study of the quasi-free creation of the $\eta'$ meson in the reaction $pn \rightarrow pn\eta'$

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Abstract: The feasibility of an investigation of the $pn \rightarrow pn\eta'$ reaction by means of the COSY-11 internal target facility is discussed. Appraisals are based on the assumption of the quasi-free reactions of beam protons, circulating in the cooler synchrotron COSY, with neutrons from a windowless deuteron cluster target.

1 Introduction\footnote{This part of the talk presents some aspects of the motivation from the COSY Proposal\#100 \[3\]}

In 1984 Maltman and Isgur \[1\] have argued on the basis of simple geometrical considerations (see Figure 1) that at the distances smaller than 2 fm the internucleon potential should begin to be free of meson exchange effects and may be dominated by the residual colour forces. However, as pointed out by Nakayama \[2\], the transition region from the hadronic to constituent quark degrees of freedom does not have a well defined boundary, and at present both approaches should be evaluated in order to test

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{A cartoon illustrating in naive geometrical terms that for $r < 2r_N + 2r_M$ meson exchange is unlikely to be appropriate to the description of the internucleon potential. Figure and caption are taken from reference \[1\].}
\end{figure}
their relevance in the description of close-to-threshold meson production in the collision of nucleons. The authors of reference [4] have shown, that for example the $K^+$ meson production via the $pp \rightarrow pK^+\Lambda$ reaction far from its production threshold can well be described in terms of either the meson-exchange mechanism or the two-gluon exchange model. Thus, a determination of the relevant degrees of freedom for the description of the nucleon-nucleon interaction, especially in case when nucleons are very close together, remains one of the key issues in the hadronic physics [5].

Close-to-threshold production of $\eta$ and $\eta'$ mesons in the nucleon-nucleon interaction requires a large momentum transfer between the nucleons and hence can occur only at distances smaller than $\sim$0.3 fm. This suggests that the quark-gluon degrees of freedom may indeed play a significant role in the production dynamics of these mesons, and especially that the $\eta'$ meson can be created directly from the glue which is excited in the interaction region of the colliding nucleons [6, 7]. A possibly large glue content of the $\eta'$ and the dominant flavour-singlet combination of its quark wave function may cause that the dynamics of its production process in the nucleon-nucleon collisions is significantly different from that responsible for the production of the $\eta$ meson (see Figure 2).

![Figure 2: Coupling of $\eta$ and $\eta'$ to two gluons through (a) quark and antiquark triangle loop and (b) gluonic admixture. The figure is taken from reference [8].](image)

![Figure 3: Diagrams depicting possible quark-gluon dynamics of the reaction $pp \rightarrow pp\eta'$. (a) — production via a fusion of gluons [3] with rearrangement of quarks. (b) — production via a rescattering of a “low energy pomeron” [13].](image)
Figure 3 depicts possible short-range mechanisms which may lead to the creation of the $\eta'$ meson via a fusion of gluons emitted from the exchanged quarks of the colliding protons [7] or via an exchange of a colour-singlet object made up from glue, which then rescatters and converts into $\eta'$ [19]. The hadronization of gluons to the $\eta'$ meson may proceed directly via its gluonic component or through its overwhelming flavour-singlet admixture $\eta_1$ (see Fig. 2). In contrary to the significant meson exchange mechanisms and the fusion of gluons of graph 3a, the creation through the colour-singlet object proposed by S. D. Bass [19] (graph 3b) is isospin independent, and hence should lead to the same production yield of the $\eta'$ meson in both reactions: $pp \rightarrow pp\eta'$ and $pn \rightarrow pn\eta'$ because gluons do not distinguish between flavours. This property should allow to test the relevance of a short range gluonic term [9] by the experimental determination of the cross section ratio $R_{\eta'} = \frac{\sigma(pn \rightarrow pn\eta')}{\sigma(pp \rightarrow pp\eta')}$, which in that case should be close to unity after correcting for the final and initial state interaction. The other extreme scenario – assuming the dominance of the isovector meson exchange mechanism – should result in the value of $R_{\eta'}$ close to 6.5 as was already established in the case of the $\eta$ meson [20].

The total cross section for the $pp \rightarrow pp\eta'$ reaction has already been measured close to the kinematical threshold by the COSY-11 [16, 15], SPES-III [13] and DISTO [14] collaborations. However, data on the near threshold production of the $\eta'$ meson in proton-neutron collisions do not exist. Thus as a first step towards the determination of the value of $R_{\eta'}$ the feasibility of the measurement of the $pn \rightarrow pn\eta'$ reaction by means of the COSY-11 facility was studied by the Monte-Carlo method and is discussed in the following section.

2 Experimental method: Quasi-free production

In order to measure the $pn \rightarrow pn\eta'$ reaction by means of a proton beam it is necessary to use a nuclear target, since a pure neutron target does not exist. Similar to investigations of the $\eta$ meson production in the $pn \rightarrow pn\eta$ reaction [21, 12, 20], a deuteron will be considered as source of neutrons. Due to the small binding energy of the deuteron ($E_B = 2.2$ MeV), the neutron struck by the proton incoming with 2540 MeV kinetic energy may approximately be treated as being a free particle in the sense that the ma-

\footnote{after correcting for the final and initial state interaction between participating baryons.}

\footnote{Results presented in this section constitute an extended experimental part of the COSY Proposal#100 [3].}
The matrix element for quasi-free meson production on a bound neutron is identical to that for the free $pn \to pn\eta$ reaction. Measurements performed at CELSIUS [12, 20] and TRIUMF [10, 11] have proven that the off-shellness of the reacting neutron can be neglected and that the spectator proton influences the interaction only in terms of the associated Fermi motion [10]. In this approximation the proton from the deuteron is considered as a spectator which does not interact with the bombarding proton, but rather escapes untouched and hits the detectors carrying the Fermi momentum possessed at the moment of the collision. The momentum spectrum of the nucleons in the deuteron is shown in Figure 4a.

![Figure 4: (a) Momentum and (b) kinetic energy distribution of the nucleons in the deuteron, generated according to an analytical parametrization of the deuteron wave function [22, 23] calculated from the PARIS potential [24].](image)

Since the neutron bound inside a deuteron is not at rest, and its momentum may change from event to event, the excess energy in the quasi-free proton-neutron reaction will also vary from event to event. This enables to scan a large range of excess energies with a constant proton beam momentum, but simultaneously requires the determination of this energy for each registered event, which can be done only if the neutron momentum vector is known. This may be realized experimentally either by determining the four-momentum vectors of the outgoing proton, neutron, and $\eta'$ or by measuring the four-momentum of the spectator proton. Since at present none of the experimental facilities installed at COSY can fulfill the first requirement only the case with the registration of the spectator proton will be considered. From the measurement of the momentum vector of the spectator proton one can infer the momentum vector of the neutron at the time of the reaction, and hence calculate the excess energy. The distribution of the excess en-


ergy in a quasi-free $pn \rightarrow pn\eta'$ reaction is presented in Figure 5a. In the

![Figure 5](image)

**Figure 5**: (a) Distribution of the excess energy $Q_{CM}$ for the $pn\eta'$ system originating from the reaction $pd \rightarrow pspn\eta'$ calculated with a proton beam momentum of 3.350 GeV/c, and the neutron momentum smeared out according to the Fermi distribution shown in Figure 4b. The beam momentum of 3.350 GeV/c corresponds to an excess energy of $Q_{CM} = 44.7$ MeV for the free $pn \rightarrow pn\eta'$ reaction. (b) Spectrum of the off-shell mass of the interacting neutron, as calculated under the assumption of the impulse approximation.

framework of the so-called impulse approximation the spectator proton is a physical particle, hence it must be on its mass shell. This implies, however, that the reacting neutron is off its mass shell, and hence the extrapolation from the quasi-free to the free $pn \rightarrow pn\eta'$ must be done with care. The distribution of the off-shell mass of the interacting neutron is shown in Figure 5b. It can be seen that the maximum of this spectrum differs only by about 3 MeV from the free neutron mass ($m_n = 939.57$ MeV), however on the average it is off by about 9 MeV. Measurements performed at the CELSIUS and TRIUMF accelerators for the $pp \rightarrow p\eta$ \cite{12} and $pp \rightarrow d\pi^+$ \cite{10} reactions, respectively, have shown that within the statistical errors there is no difference between the total cross section of the free and quasi-free processes. The quasi-free production were realized utilizing a deuteron target. This observation allows to anticipate that in the case of the planned study of the $\eta'$ in the $pd \rightarrow pspn\eta'$ reaction, the measured total cross section for the quasi-free $pn \rightarrow pn\eta'$ reaction will not differ from the on-shell one.

In fact, the difference between off-shell and on-shell cross section of the $\eta'$ meson production should be even smaller than in the case of the $\eta$ and $\pi$, since in the former case the total energy of the interacting nucleons is much larger than in the latter one, and the mean difference between the off-shell and on-shell neutron mass remains the same.
Other nuclear effects in case of the production on the neutron bound in the nucleus are rather of minor importance. The effect of the reduction of the beam flux on a neutron due to the presence of the proton in the deuteron, referred to as a shadow effect, decreases the total cross section by about 4.5% in case of $\eta$ production [21]. Thus it should also have a minor influence on the evaluation of the total cross section for the $pn \rightarrow pnn'$ reaction. Similarly the reduction of the total cross section due to the reabsorption of the produced $\eta'$ on the spectator proton should be negligible due to the weak [17] proton-$\eta'$ interaction. Even in case of the $\eta$ meson, which interacts with protons much more strongly, this effect was found to be only about 3% [21].

In order to identify the production of the $\eta'$ meson in a proton-deuteron collision it is necessary either to measure the decay products of the meson or to register the outgoing nucleons and nuclei. At present only the second possibility can be considered at COSY experiments due to the lack of an appropriate detector. The requirement to register the spectator proton excludes the possibility of performing such an experiment by means of any external facility which utilize liquid or solid targets.

Figure 6: Schematic view of the COSY-11 detection setup [26]. Only detectors needed for the measurements of the reaction $pd \rightarrow pspmn\eta'(\eta')$ are shown. D1, D2 denote the drift chambers; S1, S2, S3, S4 and V1 the scintillation detectors; N1 the neutron detector and $Si_{mon}$ and $Si_{spec}$ silicon strip detectors to detect elastically scattered and spectator protons, respectively.

4A photon detector is planned to be build and installed at the ANKE facility, however, first experiments with this apparatus are foreseen for the end of the year 2004 [25].
At present, COSY-11 is the only internal facility at COSY, where the outgoing proton and neutron can be measured simultaneously. Since for the proposed study the ratio $R_{\eta'} = \sigma(pn \rightarrow pn\eta')/\sigma(pp \rightarrow p\eta')$ has to be determined it would be extremely advisable to perform both the production on protons and on neutrons by means of the same detection system in order to minimize systematical uncertainties.

During the last years close to threshold total cross sections for the $pp \rightarrow pp\eta'$ reaction have been successfully measured at the COSY-11 facility [13, 16]. Thus the proposed investigation is planned to be performed using the COSY-11 detection system with an additional silicon strip detector for the registration of the spectator proton. The shape of the COSY-11 scattering chamber close to the target allows for the installation of the spectator detectors [18] which were already used successfully at the CELSIUS accelerator for tagging of quasi-free proton-neutron interactions.

In Figure 6 a schematic view of the COSY-11 detection system together with the spectator detector is presented. The spectator detector consists of four modules with two layers of 0.3 mm thick silicon strips. Each module is further divided into six parts each of them with 3 strips of 20 mm x 5 mm. The physical properties of the detector were implemented into the COSY-11 Monte-Carlo programme and detailed simulations of the $pd \rightarrow p_sp_p\eta'$ reaction were performed, taking into account the momentum and dimension spread of the COSY beam [27], as well as the dimensions of the cluster target [28] and the known resolution of the time and position measurements of the standard COSY-11 detectors.

Figure 7a depicts the spectrum of the spectator proton momentum which will be registered in coincidence with the forward flying proton and neutron. The fact that spectator protons with momenta larger than 130 MeV/c will not be registered has the advantage that events with neutron masses differing much from its on-shell value will be omitted (compare figures 5b and 7c). A 300 $\mu$m thick silicon detector can absorb protons up to a momentum of about 106 MeV/c corresponding to a kinetic energy of $T_s \approx 6$ MeV. Both layers together can absorb protons up to a momentum of 130 MeV/c ($T_s \approx 9$ MeV), however, protons with momenta lower than 30 MeV/c ($T_s \approx 0.5$ MeV) cannot be distinguished from noise. Thus this detector allows the registration and identification of about 70% of the spectator protons hitting its sensitive area (see Figure 3). On the other hand, Figure 7b shows that the fraction of spectator protons having kinetic energy larger than 6 MeV and registered simultaneously with the forward scattered neutron and proton is very small. Consequently, most of the spectator protons will be fully stopped already in the first layer. This gives the opportunity to get rid of the background
Figure 7: (a) Momentum and (b) kinetic energy distributions of the spectator protons registered in coincidence with the forward scattered neutron and proton. (c) Spectrum of the off-shell mass of the interacting neutron, provided that all nucleons from the $pd \rightarrow p_{sp}p_{pn}\eta'$ reaction have been measured with the COSY-11 detection system.

due to fast protons and pions crossing both layers of the detector, just by considering in the off-line analysis only those events which have no signal in the second layer.

Both the position of the spectator detector and the proton beam momentum were optimized such that most of the registered events have an excess energy between 0 MeV and 25 MeV. This is the range for which the total cross section of the $pp \rightarrow pp\eta'$ has been studied at COSY-11 [15]. Increasing the beam momentum in general shifts the maximum of the excess energy distribution (fig. 7a) to larger values, but simultaneously installing the spectator detector upstream the target (see Figure 6), such that the spectator proton is moving opposite to the proton beam, the excess energy is decreasing, since the neutron is escaping the beam proton. Positioning of the tagger detector upstream the target also reduces drastically its irradiation. The distribution of the excess energy for events registered under the chosen geometry is shown in Figure 8a. In the first approximation it
reflects the dependence of the COSY-11 acceptance on the excess energy. Figure 8b depicts the difference between the generated and reconstructed excess energy. The standard deviation of the obtained resolution amounts to 2 MeV, and is due to the finite dimension of the beam and target and the granularity of the spectator detector. In these simulations the distance between the beam and the detector was adjusted to be 5 cm as an optimum regarding both the coverage of the solid angle and the angular resolution. However, the accuracy of the excess energy reconstruction may be improved significantly if needed, since the scattering chamber allows for the installation of spectator detectors at a distance of 10 cm from the beam. Apart from

Figure 8: (a) Distributions of the excess energy \( Q_{CM} \) for the quasi-free \( pn \rightarrow pn\eta' \) reaction as would be measured with the COSY-11 detection system at a beam momentum of 3.350 GeV/c. The shape corresponds roughly to the energy dependence of the detection efficiency. The Figure shows the number of reconstructed events per 1 MeV bin out of the \( 5 \cdot 10^6 \) events generated in the target. (b) Difference between the generated and reconstructed excess energy. Calculations were performed assuming a target diameter of 0.9 cm [28], and standard deviations of 0.2 cm and 0.4 cm for the horizontal and vertical beam spread, respectively. The applied values correspond to a realistic estimation of the beam parameters based on the data from previous COSY-11 experiments [27]. The spectator detector modules were positioned behind the target, five centimeters from the beam, as it is indicated in Figure 6.

the excess energy, in order to identify the reaction it is necessary to determine the momentum vectors of the registered protons and neutrons. Proton momenta will be reconstructed by tracking back the proton trajectory to the target point, and the neutron momenta will be determined from the time of flight between the target and neutron detector and the angle defined by the middle of the hit segment. The granularity of the neutron detector allows to determine the horizontal position with an accuracy of ±4.5 cm.
For the time resolution of one segment (11 scintillation and 11 lead plates) a conservative value of 0.5 ns (standard deviation) was assumed. The missing mass spectrum, reconstructed from events for which signals from the spectator detector as well as the forward scattered protons and neutrons were registered, is shown in Figure 9. An obtained mass resolution amounts to 7.6 MeV (FWHM) which is only 3 times the resolution of the measurements for the $pp \rightarrow pp\eta'$ reaction at an excess energy of 23.6 MeV.

Assuming a luminosity of $3 \cdot 10^{30}$ cm$^{-2}$s$^{-1}$, and taking into account i) the detection efficiency which decreases with excess energy as shown in Figure 8a and ii) the energy dependence of the total cross section as determined for the $pp \rightarrow pp\eta'$ reaction, we calculate the number of quasi-free $pn \rightarrow pn\eta'$ events which will be measured per day. The calculation can be performed modulo the absolute cross section which in the one extreme scenario should be equal to the cross section of the $pp \rightarrow pp\eta'$ reaction, and in the other extreme case should be enhanced by factor of about 6.5, as discussed in the introduction. The estimation results in 30 and 195 measured and reconstructed events per day for the extreme scenarios. The energy dependence of the total cross section is predominantly determined by the nucleon-nucleon final state interaction [2, 29], which approximately has the same influence for $\eta$ and $\eta'$ production. Thus, the observation that the excitation function for the $pp \rightarrow pp\eta$ and $pn \rightarrow pn\eta$ reaction is approximately the same justifies our assumption of the cross section dependence for the estimation of the counting rate.

A natural extension of the experiments with the close to threshold production of $\eta$ and $\eta'$ mesons in proton-proton and proton-neutron collisions would be the creation of these mesons in neutron-neutron reactions. This is a challenge for the future, however, a first consideration concerning this
possible study by utilizing a double quasi-free reaction has already been described in reference \[30\].

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