Letter of Intent

for an experiment with an

4π electro-magnetic calorimeter @ COSY

Free and quasi-free production of γ, π, η *and* η' *bosons in nucleon-nucleon collisions*

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Abstract

This letter comprises suggestions for investigations of few different physics issues by means of the measurement of the total and differential cross sections of the production of γ, π, η and η' bosons in the collisions of nucleons in various isospin combinations. It is proposed

1) to make a systematic study of the dependence of the meson production cross sections in nucleon-nucleon collisions as a function of the nucleon virtuality defined as a difference between a mass of a free nucleon and the mass of its virtual counterpart inside eg. a deuteron.

2) to study the π and η meson production in neutron-neutron collisions via double quasi-free $nn \to nnX$ reactions. A Dalitz-plot analysis of the n-n-meson system would enable eg. to study the neutron-neutron and neutron-meson scattering lengths, the first is still not well etablished and the second – in case of η – is only roughly estimated, yet highly desired as one of the key constants in hadron physics. It will also allow to determine the production cross sections in the channel of isospin equal to one without the necessity of correcting for the Coulomb interaction.

3) to investigate the η' meson structure and the isospin dependence of its creation in the nucleon-nucleon interaction by comparing its production in proton-proton and proton-neutron collisions. The excitation function for $pp \to pp\eta'$ is already established. In August 2004 the COSY-11 collaboration will start measurements of the $pn \to pn\eta'$ reaction in the excess energy range between 0 and 30 MeV and these could be extended up to the excess energy of about 150 MeV when using WASA@COSY.

4) to search for a signal from the η-proton and η'-proton interaction, which should manifest itself as a modification of events population on a Dalitz-plot of a $pp \to ppX$ reaction. At present such investigations are carried out at COSY-11, however, due to the need of the subtraction of the unavoidable multi-pion background, the available statistics allows only for the determination of one-dimensional invariant mass distributions, yet the full information of the mutual interaction between ejectiles is excessible from the two-dimensional spectra. The detection of protons and an independent identification of the produced meson via the detection of the gamma quants would allow to determine a background free Dalitz-plot.

5) to measure the nucleon-nucleon bremsstrahlung radiation. This process is highly sensitive to the nucleon-nucleon potential, and hence may serve as a tool to discriminate between various existing models. Moreover, since the interaction of γ quants with nucleons is negligibly small in comparison to the meson-nucleon one, a comparative study of the $NN\eta$, $NN\eta'$ and $NN\gamma$ systems will certainly allow to draw less model dependend conclusions of the $N\eta$ and $N\eta'$ interaction than those which might follow from the study of the meson production only.

1 Physics case

1.1 Scientific justification

ad 1) Usually we consider and measure reactions of free particles for which the difference between the squared energy and the squared momentum is equal to the square of its mass. This is not the case for the nucleons bound inside the nuclei, whose masses may differ from the mass of the free particles. In particular, in the case of the deuteron, the entire difference (summed for both nucleons) amounts to at least a value equivalent to the binding energy. The inner motion of nucleons inside a nuclei makes it even larger. Thus, principally the virtual nucleons inside a deuteron may not be identical with their free equivalent. By virtuality we would like to name the difference between the mass of the real particle and the mass calculated as a difference between the squared energy and the squared momentum of its virtual counterpart. When using a deutron as a source of neutrons for the measurement of eg. proton-neutron reactions this difference is usually regarded as an obstacle making difficult a direct comparison of a free and quasi-free scattering. Here we would like to suggest how to take advantage of this fact. Namely, we intend to make a systematic study of the dependence of the cross sections for a meson production in nucleon-nucleon collisions as a function of their virtuality, which in the first order can be deduced from the momentum of the nucleon which does not take part in the reaction.

There is a difference between the free and bound neucleon since they have different masses. Hence, it is natural to expect that they may also differ in other aspects.

ad 2) In article [1] we described a method of measuring the close to threshold meson production in neutron-neutron collisions, where the momenta of the colliding neutrons can be determined with an accuracy obtainable for the proton-proton reaction. The technique is based on the double quasi-free $nn \to nnX^0$ reaction, where deuterons are used as a source of neutrons (see figure 1).

Experimental investigations of the close to threshold production in neutron-neutron collisions have not yet been carried out.

The suggested meson production via a double quasi-free neutron–neutron reaction with precisions comparable with the proton-proton and proton-neutron reactions, opens the possibility of studying for example the charge symmetry breaking by comparing cross sections for the $pp \to pp\eta$ and $nn \to nn\eta$ reactions, similarly to investigations performed via the π-deuteron reactions [2]. The Dalitz-plot analysis of the $nn \to nn$ Meson would allow to study the neutron-neutron and neutron-Meson scattering lengths, the first being still not well established [3] and the second being unknown. In principle when studying the meson production in proton-proton and in proton-neutron collisions one has access to all possible isospin combinations, which can be derived after the correction for the electromagnetic interaction. Exceptionally, close-to-threshold meson production via the neutron-neutron scattering represents a pure $T = 1$ isospin channel without an accompanying Coulomb interaction and consequently no need for its correction.

ad 3) The most remarkable feature – in the frame of the quark model – distinguishing the η' meson from all other pseudscalar and vector ground state mesons is the fact, that the η' is predominantly a flavour singlet combination of quark-antiquark pairs and therefore can mix with a purely gluonic state.

Close-to-threshold production of η and η' mesons in the nucleon-nucleon interaction requires a large momentum transfer between the nucleons and occurs at distances in the order of $\sim$0.3 fm. This implies that the quark-gluon degrees of freedom may

play a significant role in the production dynamics of these mesons. Therefore, additionally to the mechanisms associated with meson exchanges it is possible that the η' meson is created from excited glue in the interaction region of the colliding nucleons [4, 5], which couple to the η' meson directly via its gluonic component or through its SU(3)-flavour-singlet admixture. The production through the colour-singlet object as suggested in reference [4] is isospin independent and should lead to the same production yield of the η' meson in both the $pn \to pn\eta'$ and $pp \to pp\eta'$ reactions after correcting for the final and initial state interactions between the nucleons.

Since the quark structure of η and η' mesons is very similar we can – by analogy to the η meson production – expect that in the case of dominant isovector meson exchange the ratio $R_{\eta'}$ should be about 6.5 as measured at CELSIUS [6]. If, however, the η' meson was produced via its flavour-blind gluonic component from the colour–singlet glue excited in the interaction region, the ratio $R_{\eta'}$ should approach unity after corrections for the interactions between the participating baryons.

A very important result of theoretical investigations is that – independent of whether it is a mesonic-, nucleonic- or resonance current – the contributions from the exchange of isovector mesons (ρ or π) is much larger from the ones from isoscalar mesons (ω or η) [7, 8, 9]. This unequivocally entails that if the ratio $R_{\eta'}$ – corrected for FSI and ISI distortions – will be found to be close to unity we will have a clear indication that the η' is produced directly by gluons. Gluons, may hadronize to η' either via its $SU(3)_F$ flavour singlet component or via its gluonic content. In order to disantangle these two effects a substantial theoretical input is required. If, however, the measured ratio $R_{\eta'}$ will not be equal to one, a quantitative determination of the contribution from gluonic mechanism to the production process will require a better understanding of the meson exchange currents. And also in this case, if the magnitude of meson exchange currents is once understood, we will be able to infer the contribution from gluons. The subject is at present vigorously studied (see for example a very recent publication of Nakayama and Haberzettl [10]).

ad 4) The aim of these investigations is to determine an entirely unknown η'-nucleon scattering length and to established more precisely still poorly determined scattering length of the η-nucleon potential. Both constituting crucial quantities of hadron physics. A comprehensive physics motivation for this study can be found in the COSY proposal No. 123 [11] accepted for realisation by the COSY Program Advisory Committee. Here we would like to stress that the measurements by using WASA@COSY would allow to determine the Dalitz-plot distributions of the $pp\eta(\eta')$ systems free of (or at least with drastically reduced) multi-pion background. The reduction of the background from multi-pion production would be especially important in the case of the η' meson production, where the signal to background ratio is very weak as it is demonstrated in a spectrum (see figure 2) obtained in October 2003 by the COSY-11 collaboration [12]. A background free Dalitz-plot distribution comprises full empirically accessible information about the mutual interaction between particles of the NNX system. In case of the η' meson, an installation of the WASA detector at COSY opens an unique possibility to determine a background free Dalitz-plot of the $NN\eta'$ system for the first time.

ad 5) One of the reasons to study the nucleon-nucleon bremsstrahlung radiation is connected to the issue discussed above in item 4. The determination of the event-population-density over the Dalitz-plot of the $NN\gamma$ system would allow to corroborate or to refute – in the model independent manner – commonly anticipated conjecture that the discrepancy between observed and calculated invariant mass distributions [13, 14] is due to the neglect – in computations – of the unknown meson-nucleon interaction.

If this assumption is correct the Dalitz-plot distribution of the $NN\gamma$ system should conform the predictions since the $N\gamma$ interaction can be safely neglected in comparison to the hadronic interaction between any meson and nucleon.
Measuring excitation functions for the nucleon-nucleon bremsstrahlung radiation we may also address an issue of the verification of the nucleon-nucleon potentials. This process is claimed to be highly sensitive to the nucleon-nucleon potential [15, 16, 17] and therefore may be used as a tool to discriminate between various existing models.

1.2 Existing data

ad 1) There exist no data concerning this issue.
ad 2) Experimental investigations of the close-to-threshold production in neutron-neutron collisions have not been carried out yet.
ad 3) Close to threshold meson production in proton-neutron collisions were already investigated by means of a technique based on a quasi-free scattering of the proton off the neutron bound in the deuteron [18, 19, 20, 21]. Pioneering experiments of the π^0 meson creation in the proton-neutron reaction with the simultaneous tagging of the spectator proton resulted in a resolution of the excess energy (σ) equal to σ = 1.8 MeV [18]. Similar studies including the production of heavier mesons are carried out at the COSY-11 and ANKE facilities [20, 21].

Investigations of the η-meson production in collisions of nucleons allowed to conclude that, close to the kinematical threshold, the creation of η meson from isospin I = 0 exceeds the production with I = 1 by about a factor of 12. This was derived from the measured ratio of the total cross sections for the reactions $pn \to pn\eta$ and $pp \to pp\eta$ ($R_\eta = \frac{\sigma(pn\to pn\eta)}{\sigma(pp\to pp\eta)}$), which was determined to be $R_\eta \approx 6.5$ in the excess energy range between 16 MeV and 109 MeV [6]. The excitation function for the $pn \to pn\eta$ reaction was established by the PROMICE/WASA collaboration and the gap between the threshold and the 16 MeV point will be filled by the data taken by the COSY-11 group. Tentative results can be found in reference [19].

The excitation function for the $pp \to pp\eta'$ reaction is already established [22, 23, 24, 25, 26], however, **at present there exist no data on the $pn \to pn\eta'$ reaction.** A first attempt to measure this process is planned for August 2004 by the COSY-11 collaboration. If successful it will deliver data in the excess energy range between 0 and 30 MeV.
ad 4) Excitation function for the $pp \to pp\eta$ reaction as well as the invariant mass distributions of the produced pp and pη subsystems have been intensively studied eg. at COSY [14, 13] and at CELSIUS [27]. The data revealed signal which are most likely due to the influence of the proton-η interaction. However, **in the close-to-threshold excitation function for the $pp \to pp\eta'$ reaction a signal from the proton-η' force has not been observed** [28, 29]. The search is continued and at present invariant mass distributions of the proton-η' interaction are studied by the COSY-11 collaboration. From the high statistics run finished in October 2003 about 15000 events are expected which will allow to determine the invariant mass distribution of the $p\eta$ and pp systems [12]. Unfortunately, large multi-pion background as seen in figure 2, render impossible the background-free determination of the Dalitz-plot distribution, unless the binning were made so large that the possible effect would be smeared out completely.
ad 5) The bremsstrahlung radiation in nucleon-nucleon and nucleon-deuteron collisions have been already studied at both laboratories CELSIUS [30] and COSY [31]. In both cases total and differential cross sections have been determined. In the case

of the $pp \to pp\gamma$ reaction the TOF result together with the previous data from TRIUMF [32] establish the excitation function up to slightly above the pion threshold. An experimental background and rather poor statistics did not allow for conclusive statements concerning the influence of the interactions between the outgoing particles on the observed distributions. However, as shown for the example of the $dp \to dp\gamma$ reactions a background free measurements of this kind can be carried out with the WASA detection system [30].

1.3 Why a 4π detector?

Existing experimental facilities at COSY allow for the determination of the considered reactions via the registration of the outgoing baryons and the utilisation of the missing mass techniqe for the identification of the produced mesons. Using this method it is principally impossible on the event-by-event basis to differentiate between the production of few pions and a single heavier meson. The reduction of the multi-pion background is doable only if the number of registered events is large enough to observe a statistically significant signal over a background for each interesting phase-space partition. In practice, it is not possible to go beyond one-dimensional differential distributions without the loss of the required accuracy. A qualitative improvement of the data basis can only be made if additionally to the registration of outgoing baryons the gamma quants from the decay of the meson will be detected. A simultaneous determination of four-momentum vectors of the outgoing baryons and the independent identification of the created meson via its decay products would allow to obtain a multi-dimensional differential distributions free of background. Needless to say that the more particles are registered in coincidence the more crucial becomes the detection acceptance. Therefore, with the presently achievable luminosities (around $10^{31} cm^{-2} s^{-1}$) a scan of the phase space of the reactions characterized by $1\mu b$ cross section is feasible only at a detector facility possessing an acceptance close to 4π. Moreover, measurements performed with a 4π detector possesses exceptional advantages for they can be analyzed without the need of any presumption of the dynamics of the studied reaction.

2 Experimental details

The WASA detector, in its present form, is dedicated predominantly for the study of the η meson decays, and its forward part is desinged to detect protons with kinetic energies up to 300 MeV only [33]. This is enough to stop protons from the $NN \to NN\eta$ reactions studied at the beam energies available at CELSIUS, however this limit would need to be extended up to about 550 MeV in order to enable the study of the η' meson in nucleon-nucleon collisions.

Investigations proposed in item 1) can be realized eg. by the measurement of the $pd \to ppXn_{sp}$ or $pd \to pnXp_{sp}$ reactions, where the subscript $_{sp}$ denotes the spectator nucleon, and X stands for the mesons π^0, η, or η'. The feasibility to study these reactions at WASA – in the case of the π^0 and η mesons – has already been demonstrated by the PROMICE/WASA collaboration [6, 18]. Without a spectator detector, the excess energy could have been reconstructed with the precision of 8 MeV (rms) and 5 MeV (rms) for the quasi-free reactions $pn \to pn\eta$ and $pp \to pp\eta$, respectively [6]. This corresponds roughly to the accuracy of ± 20 MeV/c and ± 12 MeV/c for the determination of the Fermi momentum of nucleons inside a deuteron. Thus, with this precision – if the spectator nucleon is not registered – the experiment could be realized

with the present WASA detector at internal or external target stations, without any extra counters. In the case of the $pn \to pn\pi^0$ reaction one could improve the precision using the deuteron beam and detecting the spectator proton in the forward detector. For the production of η and η' mesons the maximum beam momentum available at COSY is too low in this kinematical configuration.

A significantly better accuracy, in the case of the η and η' mesons, can be achieved only at the internal target if additionally a spectator detector was used. Furthermore, the accuracy could be increased when endowing the forward detector by a neutron counter. An installation of a neutron detector would be necessary for the realisation of the study proposed in item 2) and will help to increase the accuracy and decrease the background when studing the excitation function for the $pn \to pn\eta'$ reaction.

The time needed for measurements of the above discussed quasi-free reactions will depend on the final detector configuration, eg. installation or noninstallation of the spectator detectors. However, in first order we can assume that the measured count rate of these reactions will be more or less the same as the one for the $pp \to ppX$ process. The supposition is based on the fact that the total cross section for the meson production in proton-neutron collisons is, eg. in the case of the η meson, six times larger than the one for the $pp \to pp\eta$ reaction and if the quasi-free reactions will be studied with a simultaneous detection of the spectator nucleon then the acceptance will be few times smaller. The detection rate for the $pp \to pp\eta \to pp\gamma\gamma$ reaction can be roughly estimated from the known total cross sections, branching ratio of η meson into 2γ (39%) [34], and the WASA detection efficiency for the registration of the final state protons ($\approx$ 90%) and two gamma quants ($\approx$ 66%) [35]. For details the reader is referred to the accompanying Letter of Intent [36] regarding the polarization observables of the $\vec{p}\vec{p} \to pp\eta$ reaction.
For an excess energy of eg. Q = 40 MeV and a luminosity of $10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ we expect to register about 14 $pp \to pp\eta$ events per second. Thus for the reactions with the η production we could detect more than 10^6 events per day and per energy point. A similar rate is expected for the nucleon-nucleon bremsstrahlung radiation.

Assuming further, that the efficiency for the registration of the gamma quants, originating from the $pp \to pp\eta' \to pp\gamma\gamma$ reaction sequence, will be the same as in the case of the $pp \to pp\eta \to pp\gamma\gamma$ process, and taking into account the fact that i) the cross section is thirty times smaller and ii) the branching ratio of η' meson into to 2γ is (2%) [34], with the luminosity of $10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ we expect to register about 0.024 events per second. This count rate would allow to determine a background free Dalitz plot with 10^5 events within seven weeks of beamtime. The above appraisals of the count rate should be treated as an upper limit since in the calculations other than $\gamma\gamma$ decay modes of the η' meson have been neglected. Yet for the η' meson identifications one can use also for instance a decay sequence $\eta' \to \pi^0\pi^0\eta \to 6\gamma$.

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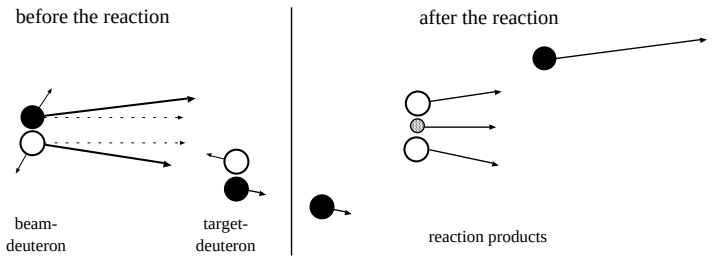

Figure 1: Schematic depiction of the double quasi-free $nn \to nnX$ reaction. During the collisions of deuterons (left hand side of the figure, with the total momentum (solid arrow) resulting from the sum of the beam momentum (dotted arrow) plus the Fermi momentum (short arrow)) a double quasi-free neutron-neutron reaction may lead to the creation of mesons (small gray circle). The spectator protons (black circles) leave the reaction region with their initial momentum plus the Fermi momentum, which they possessed at the moment of the reaction. Neutrons are plotted as open circles. Due to the large relative momenta between spectators and the outgoing neutrons ($\sim$ 1 GeV/c close to the threshold for the η meson production) a distortion of the nnX system by the accompanied protons can be neglected.

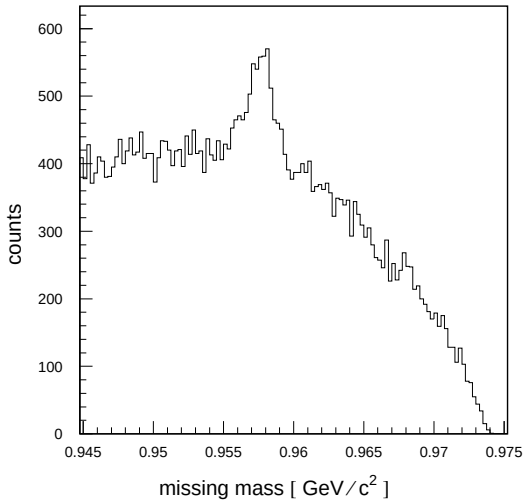

Figure 2: On-line missing-mass distribution of the $pp \to ppX$ reaction measured by means of the COSY-11 detection system in October 2003 [12].