Heavy Meson Production in NN Collisions with Polarized Beam and Target — A new facility for COSY

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The study of near–threshold meson production in *pp* and *pd* collisions involving polarized beams and polarized targets offers the rare opportunity to gain insight into short–range features of the nucleon–nucleon interaction. The Cooler Synchrotron COSY at FZ–Jülich is a unique environment to perform such studies. Measurements of polarization observables require a cylindrically symmetrical detector, capable to measure the momenta and the directions of outgoing charged hadrons. The wide energy range of COSY leads to momenta of outgoing protons to be detected in a single meson production reaction between 300 and 2500 MeV/c. Scattering angles of protons to be covered extend to about 45° in the laboratory system. An azimuthal angular coverage of the device around 98% seems technically achievable. The required magnetic spectrometer could consist of a superconducting toroid, providing fields around 3 T.

1 Scientific Motivation

The production of heavy mesons near threshold in *pp* and *pd* collisions with stored polarized beams and internal gas targets offers the rare opportunity to study short–range features of the nucleon–nucleon interaction, at distances where the nucleons start to overlap. The identification of relevant sub–nucleonic degrees of freedom of the nucleon–nucleon system in the non–perturbative region of QCD is of great topical relevance to nuclear and particle physics. COSY represents a unique environment to perform studies of this kind, in particular measurements of polarization observables in heavy meson production reactions, as emphasized recently [1]. Measurements of those polarization observables are to be considered which are associated with the spins of the particles in the entrance channel, since the polarization of particles in a final state in most cases is difficult to access.

1.1 Meson production in proton–proton collisions

When producing a meson close to threshold, the transferred momentum is large. In addition, angular–momentum constraints require a head–on collision (small impact parameter). From this, it is clear that such a reaction is sensitive to the NN interaction at distances of less than 1 fm, while the long–range part is suppressed,

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thus the reaction acts as a filter for short–range features of the nucleon–nucleon interaction. In hindsight, we can understand why the first precise measurement of the total cross section in $pp \to pp\pi^0$ [2] resulted in a challenge for theorists. For the very same reasons, near–threshold production of mesons heavier than the pion is a promising field of nuclear research. In addition, the interaction of the produced meson with the hadrons in the exit channel can be studied, and one expects to learn about the coupling of mesons to nucleons.

The production of a meson in NN collisions close to the production threshold involves only a few transitions between a given initial and final angular momentum state. These transitions can be labeled by the angular momentum of the NN pair (L') and the angular momentum of the meson with respect to the nucleon pair (l'_{meson}) in the exit channel. Close to threshold l'_{meson} and L' can be either 0 or 1. This scheme results for $pp \to pp\pi^0$ for instance in the possible combinations Ss, Ps and Pp listed in table 1. Parity and angular–momentum conservation forbid Sp final states. As the incident proton energy is lowered further, eventually only a single transition into Ss becomes possible. These angular–momentum constraints

initial state	final state	class
$^{2S+1}L_J$	$(^{2S'+1}L'_{J'}, l'_\pi)_J$	$L'l'_\pi$
$^3P_0$	$(^1S_0, s)_0$	Ss
$^1S_0$	$(^3P_0, s)_0$	Ps
$^1D_2$	$(^3P_2, s)_2$	
$^3P_1$	$(^3P_0, p)_1$	Pp
$^3P_{0,1,2}$	$(^3P_{1,2}, p)_{0,1,2}$	
$^3F_{2,3}$	$(^3P_{1,2}, p)_{2,3}$	

Table 1. Contributing amplitudes in the process $pp \to pp\pi^0$. The angular–momentum quantum numbers in the final state are denoted by a prime.

apply also for the case of the production of heavier pseudo–scalar mesons, e.g. η and η' ($J^P = 0^-$), while for the vector mesons, like ρ, ω, ϕ ($J^P = 1^-$), analogous relations can be worked out. The total cross section can be written as an incoherent sum of the cross sections of the individual final states $\sigma_{tot} = \sigma_{Ss} + \sigma_{Ps} + \sigma_{Pp}$. Over a limited energy range close to threshold, the transition matrix element can be taken as constant. In this case, the energy dependence of the reaction is given by phase space, modified by the final–state interaction and the momentum dependence of the radial part of the wavefunction. In $pp \to pp\pi^0$, the final–state interaction is dominated by the (well–known) interaction between the two nucleons, but in the production of heavier mesons cases exist, where the (less well–known) meson–nucleon interaction plays an important role. The contribution of the radial wave functions to the energy dependence differs for different angular–momentum configurations in the exit channel. When only the cross section is measured, the energy dependence of the cross section is the only handle one has on a decomposition of

the reaction in terms of individual amplitudes. On the other hand, when polarization observables are available, a much cleaner and model–independent amplitude analysis becomes possible. A polarization analysis of particles in a final state requires a second scattering, which is difficult, except in a self–analyzing decay (e.g. $\Lambda^0 \to \pi^- p$) The polarization observables accessible are those that are associated with the spins of the two protons in the entrance channel.

On the experimental side at present only the PINTEX group at IUCF performs studies of this kind in $\vec{p}\vec{p} \to pp\pi^0$ [3, 4, 5], $\vec{p}\vec{p} \to pn\pi^+$ [6, 7], and $\vec{p}\vec{p} \to d\pi^+$ reactions [8], while measurements in $\vec{p}\vec{d} \to t\pi^+$, $\vec{p}\vec{d} \to pd\pi^0$, and $\vec{p}\vec{d} \to {}^3\mathrm{He}\pi^0$ have not yet been published. With the apparatus described in ref. [9], it becomes possible to *experimentally* separate contributions from different angular momentum states, free of any model [4]. Theoretical estimates of polarization observables in near threshold pion production are scarce, and those available still agree not well with the measurements. While the agreement for final states with charged pions is better, in particular the measured spin correlation parameters for $\vec{p}\vec{p} \to pp\pi^0$ are not well reproduced [10]. One is inclined to state that the theoretical understanding of one of the most fundamental processes in nuclear physics is still incomplete, and that more insight must come from measurements of polarization observables.

In the case of pion production, measurements with vector– and tensor–polarized deuteron and vector–polarized proton targets are presently carried out at IUCF and will be continued into the near future. For the production of heavier mesons, COSY, due to its higher beam energies and intensities, is in a position to dominate the field during the years to come, once an appropriate detector system would be available. One purpose of such a new experimental facility, recently proposed for the internal beam of COSY [11], would be a detailed study of near threshold meson production using a cooled, stored, polarized proton (or deuteron) beam incident on an internal polarized hydrogen (or deuterium) storage cell gas target [12]. For $pp \to ppX$ reactions the production of π^0, η, ρ, ω, η' and ϕ mesons is energetically possible at COSY (see table 2).

		Threshold	
Meson X	Mass [MeV]	P_{lab} $[MeV/c]$	E_{lab} [MeV]
π^0	135.0	776.5	279.7
η	547.5	1982.1	1254.7
ρ	768.5	2627.5	1851.7
ω	781.9	2667.8	1889.7
η'	957.8	3208.3	2404.4
ϕ	1019.4	3403.9	2592.6

Table 2. Threshold values of bombarding proton momenta (and kinetic energies) required to produce the listed mesons in the reaction $\vec{p}\vec{p} \to ppX$.

1.2 Meson production in the three–nucleon system

Naïvely, one would think that near–threshold meson production in *pd* collisions can be fully understood in terms of a short–ranged NN $\rightarrow$ NNπ process, with the extra nucleon acting as a spectator. Recently, however, pion production in *pd* collisions has revealed departures from such a simple picture [13]. These studies are in their infancy and deserve more attention from the theoretical community. Since the number of participating amplitudes in this case, too, is small, even though the transferred momentum is large, we have a unique environment in which to study the interaction of more than just two nucleons, e.g. three–nucleon forces. It is likely that eventually the research on three–nucleon forces will focus on this process. Again, the role of polarization observables is important, but practically no such data are available. In the case of pion production, measurements with vector– and tensor polarized deuterons and polarized protons are carried out at IUCF. For the production of heavier mesons, COSY again is in a position to dominate the field in the years to come.

1.3 Other reactions

Even though, clearly, the main motivation in designing a new facility is arising from the need for polarization observables in meson production, one needs to also mention future possibilities, which would include the *pd* breakup reaction [14] as well as radiative transitions.

Besides what has been presented so far, a truly unique application of a gas target would be the use of polarized deuterons as an effective polarized neutron target by detection of low energetic spectator protons. The purpose of these measurements would be the generation of a solid $\vec{p}\vec{n}$ database and, as mentioned above, a detailed study of meson production in *pd* collisions. These studies hinge on the availability of a spectator detector system, by which energy *and* angle information about the spectator proton have to be measured along the extended storage cell target [15].

In addition, three body final states involving strange mesons ($K^{\pm,0}$) and baryons (Λ, $\Sigma^{\pm,0}$), for instance in the reaction $\vec{p}\vec{p} \rightarrow pK^+\Lambda^0$, could be studied with polarized beam and target.

2 A new facility for COSY

Near threshold only a limited angular range in the forward direction needs to be covered. However, the momenta of the particles in the exit channel increase with the threshold of the mesons under study. While for pion production near threshold the involved proton momenta are small and a scintillator detector is sufficient, heavier meson production experiments with high proton momenta require magnetic separation[1]). Especially for experiments involving polarized beams and targets, the azimuthal angular distribution of the ejectiles depends on the spin orientation of

[1]) The range of a proton of 1 GeV kinetic energy, e.g. in plexiglass (Lucite) is about 2.8 m and the hadronic interaction probability is ~ 0.97 [16].

beam and target polarization. Thus, measurements of polarization observables in meson production reactions require a cylindrically symmetrical detector which is able to measure the momenta and the directions of outgoing charged hadrons. It should be pointed out that for this task a toroidal field configuration is advantageous, compared to e.g. a solenoid, because residual field components along the beam axis are absent. Thus the polarized gas target can be operated in a weak magnetic guide field. For the same reason distortions of the beam closed orbit due to the magnetic field of the toroid are avoided to a large extent.

The IUCF pion production experiments have shown that in particular large values of the kinematical η parameter[2]) are of interest. For instance in $\vec{p}\vec{p} \to pp\pi^0$, only for values of $\eta \sim 0.5 \ldots 1$ higher partial waves begin to play a role. Large values of $\eta \sim 1$ correspond typically to proton scattering angles $\theta_{lab} \sim 30°$. Consequently, if for the production of heavy mesons, η is the relevant parameter, in order to study the onset of higher partial waves, the new apparatus should be capable to accept a large range of scattering angles of the outgoing hadrons up to about $\theta_{lab} \sim 45°$. Based on the boundary conditions outlined above, an axially symmetric toroidal magnetic spectrometer seems appropriate[3]). The first concept of such a device is depicted in Fig. 1.

3 Conclusion

The recently approved upgrade of the beam injection system, once installed, will supply COSY with high polarized proton and deuteron beam intensities up to the acceptance limit of the machine. An intense polarized light–ion beam stored in COSY, bombarding a purely polarized internal gas target, surrounded by a toroidal magnetic spectrometer, capable to detect charged hadrons of high momentum, will allow us to fully exploit the machines scientific potential. Such a device would be ideally suited as one of the *next generation* experiments at COSY, providing a *Short Range Laboratory of Meson Production.*

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[2]) η is defined as the maximum meson momentum divided by the meson mass, $\eta = 0$ characterizes threshold.

[3]) Similar magnet constructions of two recently commissioned devices, HADES at GSI [17] and CLAS at Jefferson Lab [18], are based on six single helium cooled superconducting loops arranged such as to form a toroid. The BLAST setup [19] employs warm coils.

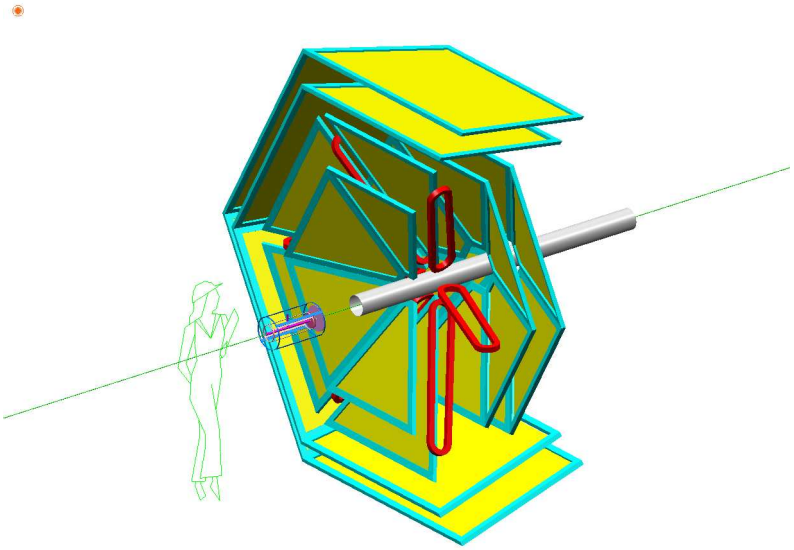

Fig. 1. 3D view of a detector system based on a toroidal magnetic field configuration. Six superconducting coils form a toroid, particle tracking is accomplished by a system of drift and proportional chambers before and behind the deflecting magnet. The polarized storage cell gas target is located in front of the detector.

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