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Hadronic Threshold Reactions

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Abstract. First investigations on meson production at threshold in the strong interaction began in the fifties when sufficient energies of accelerated protons were available.
Early experiments performed with bubble chambers revealed already typical ingredients of threshold studies, which were superseded by more complete meson production investigations at the nucleon beam facilities TRIUMF, LAMPF, PSI, LEAR and SATURNE. Currently, at the cooler rings IUCF, CELSIUS and COSY the field is entering a new domain of precision and further progress. The analysis of this new data in the short range limit permits a more fundamental consideration and a quantitative comparison of the production processes for different mesons in the few–body final states. The interpretation of the data take advantage of the fact that production reactions close–to–threshold are characterized by only a few degrees of freedom between a well defined combination of initial and exit channels. Deviations from predictions of phase–space controlled one–meson–exchange models are indications of new physics. Precision data on differential cross sections, isospin and spin observables — partly but by no means adequately available — are presently turning up.

PACS. 13.60.Le Meson production, – 13.75.Cs Nucleon-nucleon interactions, – 13.85.Lg Total cross sections, – 14.40.-n Mesons

1 Introduction

The physics program at the medium energy hadron accelerators was and is focusing on studies of the production and the decay of light mesons and baryon resonances and the conservation or violation of symmetries.

Production of mesons and meson pairs at threshold will be discussed with the features depicted by the interaction view of figure 1 [1] where in the nucleon–nucleon (NN) scattering a meson X is created in a one–boson–exchange model. For the particular case the questions have to be answered: how is the distortion of the incident NN waves (ISI) included, which mesons contribute to the exchange process, is there an intermediate baryon resonance, how significant are rescattering contributions of the exchange mesons and what is a reasonable treatment of the NN and NX final state interactions (FSI)? Especially for the NN–interaction the FSI is crucial because of the nearby poles in the S–wave amplitudes corresponding to the deuteron bound state in the $^3S_1$ channel or the $^1S_0$ virtual state [1]. These poles and the phase–space factors tend to determine much of the energy dependence of the total cross section for meson production. Furthermore, in any region where these poles dominate, it is possible to link quantitatively meson production in cases where the two nucleons emerge separately or as a bound deuteron state. Even at threshold the reaction mechanism of the basic process for the interrelation between real pions and virtual exchange meson currents as for instance in the pion production ($NN \to NN\pi$) is still not fully understood. Though first data suggested that s–wave pions were produced in a heavy–meson–exchange process, later measurements resulted in an interpretation of an interference among transition amplitudes as Ss, Ps, Pp, Sd and Ds, where the capital letter indicates the NN final state wave and the small letter the angular momentum between the two nucleons and the meson produced. In addition, it has been concluded that for higher partial waves π exchange rather than a heavier meson exchange is more significant.

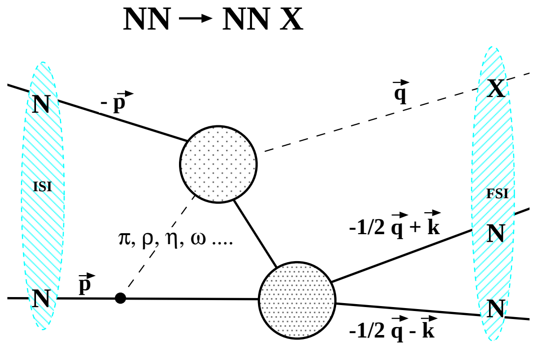

Fig. 1. Diagrammatic view of the one–boson–exchange meson production process. Produced meson = X, nucleon momentum = p, meson momentum = q, relative NN momentum = 2 k [1].

Especially the pion–nucleon interaction went through several stages of increasing sensitivity for tests of nuclear

theory. More than a decade after the initial work [2,3] only in the sixties explicit calculations on cross sections of the $pp \to pp\pi^0$, $pn\pi^+$ transitions were possible [4,5] which, however, failed the total cross section [6–8] by a factor of five. After further theoretical developments, see e.g. reference [9], only recently detailed calculations were provided within the Jülich meson exchange model [10–12] including transitions in the threshold region beyond $l_\pi = 0$ and predicting analyzing powers and spin correlation coefficients making use of i) the basic diagrams, ii) final state interactions, iii) off–shell effects, iv) the exchange of heavier mesons and v) influences of intermediate excitation of the Δ resonance. On the other hand, the Jülich model does not account for quark degrees of freedom i.e. calculations within the framework of the χPT which, in fact, predict cross sections too small [13] compared to experiments.
The heavier the meson produced in nucleon–nucleon scattering the larger the momentum transfers and thus in such processes the short–range parts of the production operators are tested.

Double meson production processes with both mesons being either identical (e.g. $\pi^0\pi^0$ or $K^0\overline{K^0}$) or different (e.g. $\pi\eta$) are in principle similar to the single ones, however, the possibly associated baryon resonances as intermediate states differ significantly. For instance, the two–pion production very likely is dominated by either the P_{11} $N^*(1440)$ resonance — via an effective σ exchange giving information of a scalar meson excitation of the P_{11} $N^*(1440)$ resonance — or the simultaneously excited P_{33} $\Delta(1232)$ resonances. Due to selection rules here the choice of definite quantum numbers in the initial and final state might help to sort out the reaction mechanism.

Much knowledge about the π–π interaction has been obtained by the $\pi N \to \pi\pi N$ reaction, whereas data employing proton beams just start to come.

As long as only S–wave processes are involved, which is the privilege of threshold production studies, scattering length and effective range approaches are used to describe the interaction sign and strength. In case of strong attractive interactions a distinction between the final state scattering and the formation of a baryonic resonance leading to bound or quasi–bound states can not be made uniquely.

Isospin violation or charge symmetry breaking processes are a topical and interesting field of threshold production physics. The essential contribution to isospin breaking is the possible $\pi^0 - \eta$ mixing. Therefore experiments around the η threshold as e.g. $dd \to \alpha\pi^0(\eta)$ or $pd \to {}^3He\pi^0({}^3H\pi^+)$ should identify the $\pi^0 - \eta$ mixing angle which in turn might give hints to the mass difference of the up and down quarks.

There is an exciting field of physics studying the threshold production of mesons in the fundamental processes of $NN \to NNX$. There is work for the years to come and thus it is a very positive sign that the Research Centre Jülich is presently upgrading COSY by projecting a new linear injector for higher intensities and especially for polarized beams of high quality.

2 Aspects of threshold production

Threshold production experiments are characterized by excess energies which are small compared to the produced masses. Consequently, in fixed target experiments the momenta of the final state particles transverse with respect to the direction of the incoming beam are small compared to the longitudinal components. Thus, ejectiles are confined to a narrow forward cone in the laboratory system around the centre–of–mass movement and — close–to–threshold — an experimental acceptance covering the full solid angle is feasible with comparatively small dedicated detector arrangements.

Small relative momenta in the final state effectively limit the number of partial waves contributing, simplifying the theoretical interpretation of experimental results. It should be noted, that already three–body final states require — in principle — a three–body Faddeev like approach, which has not been accomplished so far [14, 15]. However, as first described by Watson [16], with two strongly interacting particles in the final state, the energy dependence of the total cross section close–to–threshold is essentially determined by the (three–body) phase–space and the energy dependence of the on–shell final state interaction (FSI). Due to small relative velocities FSI effects are inherent to the experimental observables. Thus, the interpretation of data in terms of reaction dynamics requires a correct treatment of both initial (ISI) and final state interactions [17] (for a review see [18]). On the other hand, FSI effects might provide access to low–energy scattering parameters, which are difficult to obtain otherwise in case of unstable particles.

Meson production at threshold implies high momentum transfers $\Delta\mathrm{p}$, given by $\Delta\mathrm{p} = \frac{1}{2}\sqrt{\left(\mathrm{m}_N + \mathrm{m}_B + \mathrm{m}_X\right)^2 - 4\,\mathrm{m}_N^2}$ for the reaction type $NN \to NBX$ with N, B and X denoting a nucleon, baryon or meson in the initial and final state and m_N, m_B and m_X as the respective masses. With momentum transfers in the range of 0.37 GeV/c to 1.10 GeV/c for π^0 and ϕ meson production, threshold production probes with corresponding distances between 0.53 fm and 0.18 fm the short range part of the nucleon–nucleon interaction. Consequently, the energy dependence of the primary production amplitude is expected to be weak, motivating Watson's approach [16].

Theoretical studies have been carried out mainly within the framework of hadronic meson exchange models, i.e. with baryons and mesons as effective degrees of freedom (for a recent review see [19]). Chiral perturbation theory has been applied for the description of data on π production close–to–threshold [20]. However, in view of the characteristic distances mentioned above, QCD inspired models [21,22] with constituent quarks and gluons or instantons as relevant degrees of freedom, might turn out to be appropriate. High quality exclusive data on close–to–threshold meson production in the energy range of non–perturbative strong interaction physics will be crucial for exploring the boundary between effective meson exchange models and (so far phenomenological) approaches based on quark–gluon degrees of freedom.

3 Features of hadronic probes

It seems that the χPT is of limited value once strangeness is involved in the hadronic systems and non–perturbative coupled–channel considerations beyond χPT are on the market [23,24]. High quality data on the meson ($\pi, \eta, \eta', \omega, K^+, K^-$) production at threshold have been and are being produced at the hadronic beam cooler rings using the baryon number B = 2 systems (essentially pp and pn). At least equally important are studies with hadronic interactions in the B = 1 sector. However, most measurements with π– or K–beams used bubble chamber techniques which naturally suffer from very poor statistics.

Accurate investigations of differential cross sections for meson production from the initial π plus proton or K plus proton systems are needed at several momenta to study the s– and p–wave dynamics and their interplay. There are indications that both the S_{11} resonance and the $K\Sigma$ quasi–bound state — followed by a final state interaction leading to nucleon and meson — are essential and could be investigated best via the B = 1 sector.

Until now, most of the data for threshold meson production were observed with proton beams. The use of antiprotons has contributed considerably to the knowledge of the meson spectroscopy up to serious candidates for glueballs and exotic hybrids but is still suffering from the lack of unique interpretations.

A comparison of the meson production in the fundamental process to productions on heavier nucleons would give constraints to eliminate uncertainties in the basic interactions. As outlined in ref. [25], precise measurements of such processes set the necessary constraints for the effective Lagrangian of low–energy QCD with strange quarks. Its knowledge has impacts on several other important issues, such as the strange quark content of the nucleon.

Cross sections are very small in the threshold region down to eight orders of magnitude compared to the total yield. Due to the rapid growth of the phase–space volume the total cross section of the meson production reactions increases by orders of magnitudes in a few MeV range of excess energy. Such studies have been made possible only due to the low emittance and small momentum spread proton beams available at the storage ring facilities. Figure 2 demonstrates threshold production measurements of light mesons in the proton–proton interaction.

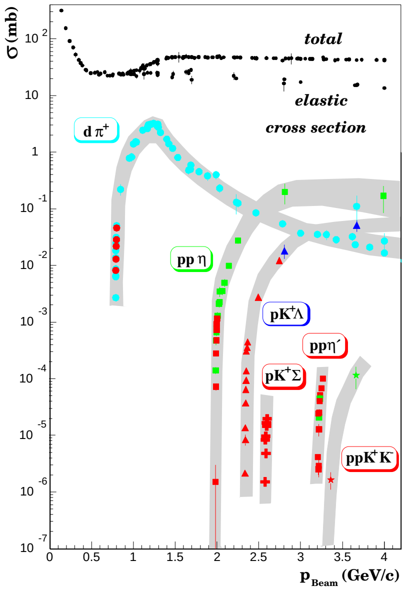

Fig. 2. Proton–proton cross sections for different reactions of the light meson production in the threshold region. For comparison also the total and elastic cross sections of proton–proton scattering are shown. Relevant references to the data will be given throughout the present article at the appropriate sections.

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