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Recent physics at COSY – A review

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Abstract. The COSY accelerator in Jülich is presented together with its internal and external detectors. The physics program performed recently is discussed with emphasis on strangeness physics and precision experiments.

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1. Introduction

The accelerator complex at Jülich consists of an isochronous cyclotron as injector and a strong focusing synchrotron. Injection is performed by stripping negative ions (hydrogen and deuterium) at an energy of 40 MeV*A. They can be vector polarised (protons and deuterons) and tensor polarised (deuterons). The synchrotron COSY is equipped with electron cooling at the injection energy and stochastic cooling at higher energies. It provides beams up to 3700 MeV/c momentum. COSY can be used as a storage ring to supply internal experiments with beam. The beam can also be stochastically extracted within time bins ranging from 10 s to several minutes to external experiments. The emittance of the extracted cooled beam is only $\epsilon = 0.4\pi$ mm mrad. This allows tracking of reaction particles close to the target. Hence a large fraction of the experimental program is devoted to meson production close to threshold. The maximal energy of COSY compared to other hadron accelerators is shown in figure 1. Some mesons, which can be produced in a *pp*-collision in the COSY range, are shown together with some selected nucleon resonances. Also shown is the equivalent photon energy to produce the same final systems along with maximal energies of photon facilities.

Here we will concentrate on hadron physics leaving out detectors built for different purposes like PISA, NESSI and JESSICA (see figure 1). The detectors of interest are COSY-11, ANKE and EDDA internally and TOF and BIG KARL externally. The physics at EDDA, proton–proton scattering of unpolarised on unpolarised, polarised on unpolarised and polarised on polarised [1] is terminated and is therefore neglected here. COSY-11 and ANKE are magnetic detectors. The former [2] employs an accelerator dipole magnet while the latter [3] is a chicane consisting of three dipoles with the middle one as analysing magnet. TOF [4] is a

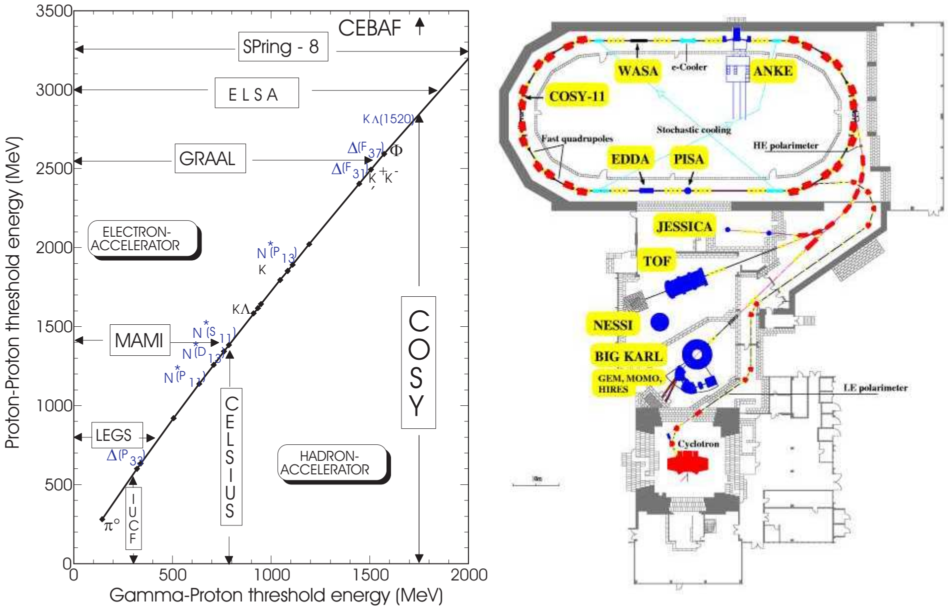

Figure 1. Left: Energy dependence of photon beams and proton beams in order to produce indicated mesons or nucleon resonances are indicated in the figure. The maximal energy of some accelerators are indicated as well. Right: Floor plan of COSY. Positions of internal experiments as well as those of external experiments are shown.

a huge vacuum vessel with several layers of scintillators. Time-of-flight is measured between start detectors in the target area and the scintillators. The target area detectors are especially suited for the identification of delayed decays and TOF is thus a geometry detector. BIG KARL [5,6] is a focusing magnetic spectrograph of the 3Q2D-type. Particle tracks are measured in the focal plane area with packs of MWDC's followed by scintillator hodoscopes allowing for a time-of-flight path of 3.5 m. Additional detectors exist. MOMO [7] measures the emission vertex of charged particles. The Germanium Wall [8] is a stack of four annular germanium diodes which are position sensitive. It acts as a recoil spectrometer.

2. Strangeness physics

One strong item in COSY physics is the study of strangeness production in various processes in pp, pd and pA interactions. Here we concentrate on a few of these reactions.

The $pp \to pK\Lambda(\Sigma)$ reactions and associated strangeness production were measured by COSY-11 [9–11] and TOF [12]. Figure 2 shows the ratio $\sigma(pK^+\Lambda)/\sigma(pK^+\Sigma^0)$ as a function of excess energy. The ratio rises strongly to threshold. This unexpected behaviour is studied in several models, including pion and kaon exchange added coherently with destructive interference [13]

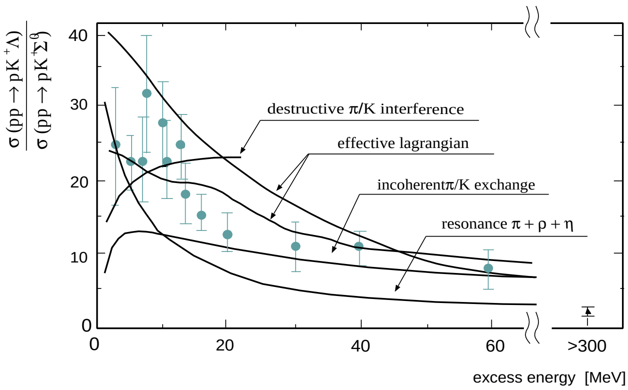

Figure 2. Ratio of the cross-sections for the indicated associated strangeness production. The curves are model calculations discussed in the text.

or incoherently [14], the excitation of nucleon resonances [15,16] (labeled effective Lagrangian), resonances with heavy meson exchange (π, ρ, η) [17] or $(\rho,\ \omega$ and $K^*)$ [15,16]. The corresponding curves are also shown in the figure. All models show a decrease of the ratio with increasing excitation energy but none of them accounts for all data.

The associated strangeness production is also a useful tool to study the nucleon–hyperon interaction via FSI. At present a high-resolution study of this interaction runs at BIG KARL (see contribution by Roy *et al* in this volume). The measurement of Dalitz diagrams enables even the investigation of the importance of intermediate N^* excitation.

Connected with the associated strangeness production is the question whether pentaquarks exist. Most of the experimental searches were performed with electromagnetic probes on the neutron, which, of course, is embedded in a nucleus. A cleaner environment is the pp interaction. The reaction studied with TOF is the

$$pp \to K^0 \Sigma^+ p \tag{1}$$

reaction. K^0 is identified via its decay into two pions and Σ via its delayed decay. The data from ref. [18] are shown in figure 3. There is evidence on a 4σ level for the production of a pentaquark

$$pp \to \Theta^+ \Sigma^+ \tag{2}$$

with a subsequent decay of Θ^+ into K^0 and p. For the enormous body of papers related to pentaquark we refer to a review given by Stancu [19].

Another interesting reaction is

$$pp \to dK^+ \bar{K}^0. \tag{3}$$

In order to reach the threshold of this reaction the maximal energy of COSY had to be raised to a value above its design value of 2.5 GeV. The data were taken at an energy of 2.65 GeV [20]. The analysis of the data [21] resulted in the dominance of the channel

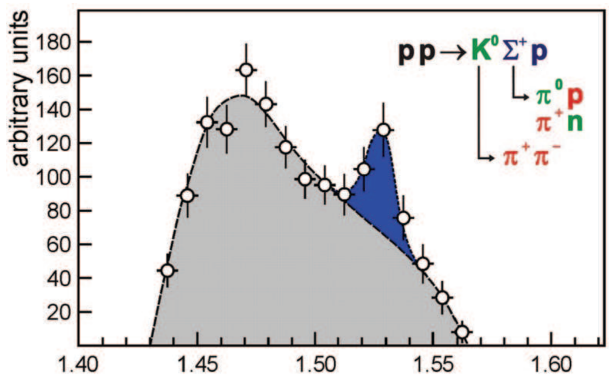

Figure 3. Evidence for a pentaquark produced in pp collision.

$$pp \to da_0^+ \tag{4}$$

with a subsequent decay $a_0^+ \to K^+\bar{K}^0$.

At the BIG KARL spectrograph the reaction

$$pd \to ^3\text{He}\, K^+K^- \tag{5}$$

was studied with the MOMO vertex wall. The interest in this reaction stems from the surprising behaviour of two pions in the

$$pd \to ^3\text{He}\, \pi^+\pi^- \tag{6}$$

reaction [7]. The latter reaction showed a p-wave between the two pions even near the threshold. In figure 4 the energy spectrum of two kaons for a maximal energy of 35 MeV are shown. Besides a smooth continuum the production of ϕ-mesons is visible. The energy distribution follows phase space, hence it is an s-wave. The same conclusion holds for the KK–^{3}He system. Also the excitation function for the ϕ production is in accord with the assumption of s-wave. To summarise: the KK–^{3}He behaves as expected while the $\pi\pi$–^{3}He system shows an unexpected behaviour. In order to prove the findings for this system the experiment was repeated but with inverse kinematics. The advantage of doing so is a smaller number of settings of the spectrograph. A result of this measurement is also shown in figure 4. It supports the previous findings.

One aspect of strangeness physics is the $s\bar{s}$ content in the nucleon. This is connected to a violation of the OZI rule in the ratio

$$R = \frac{\sigma(pp \to pp\phi)}{\sigma(pp \to pp\omega)}. \tag{7}$$

These two mesons have almost ideal quark mixing and hence ω has negligible $s\bar{s}$ content while ϕ is an almost pure $s\bar{s}$ state (see previous reaction). TOF measured ω production at exactly the same excess energy as the previous ϕ production, thus allowing the deduction of R as a function of excess energy. This yields $R = (3 \pm 1) \times 10^{-2}$ while the OZI rule predicts $R = 4 \times 10^{-3}$. This may point to a serious content of $s\bar{s}$ pairs in the nucleon.

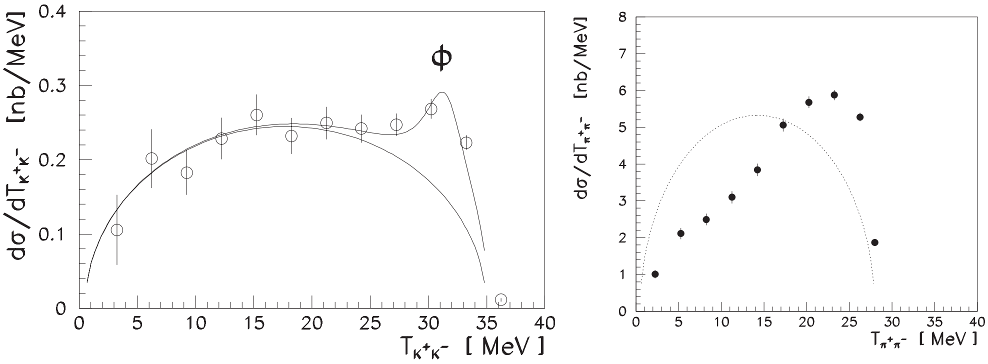

Figure 4. Left: Energy spectrum of the two kaons at a maximal excess energy of 35 MeV. Right: Same as left but for two pions for a maximal excess energy of 28 MeV.

3. η-Meson physics, symmetries

There is a wealth of data of light meson production measured at COSY in the threshold region. The data were taken mainly by the COSY-11 and GEM Collaborations for the nucleon–nucleon channel [22–24]. Here we will concentrate on η and η' production. First, we discuss the production in *pp* interactions. Figure 5 shows the total cross-sections as functions of excess energy Q ([25] and references therein). The dashed lines indicate a phase-space integral normalised arbitrarily. The solid lines show the phase-space distribution with the inclusion of $^1S_0$ proton–proton strong and Coulomb interactions. In the case of $pp \to pp\eta$ reaction the solid line was fitted to the data in the excess energy range between 15 and 40 MeV. Additional inclusion of the proton–η interaction is indicated by the dotted line. The scattering length of $a_{p\eta} = 0.7\,\text{fm} + i\,0.4\,\text{fm}$ and the effective range parameter $b_{p\eta} = -1.50\,\text{fm} - i\,0.24\,\text{fm}$ have been chosen arbitrarily. The dashed–dotted line represents the energy dependence taking into account the contribution from the $^3P_0 \to ^1S_0s$, $^1S_0 \to ^3P_0s$ and $^1D_2 \to ^3P_2s$ transitions. Preliminary results for the $^3P_0 \to ^1S_0s$ transition with full treatment of three-body effects are shown as a dashed–double-dotted line. The absolute scale of dashed–double-dotted line was arbitrarily fitted to demonstrate the energy dependence only. To summarise: in η' production the FSI between the two protons is of importance. In the case of η production also the FSI between the η and the two protons matters. This rather strong interaction has led to the speculation whether bound or quasi-bound η-nucleus systems exist. This will be discussed in other talks at this meeting.

Up to 2002, the PDG [26] reported a rest mass of (547.30 ± 0.12) MeV/c^2 for η-meson. Then a new measurement by the NA48 group at CERN reported a larger value [27] with a very small uncertainty: (547.843±0.030(stat.) ± 0.041(syst.)) MeV/c^2. This value does not within error bars overlap with the previous results. This measurement made use of the decay $\eta \to 3\pi^0$. GEM performed an experiment with a different technique to proof this result with uncertainties within the same order of magnitude. The idea is a self-calibrating experiment making use of the following three reactions:

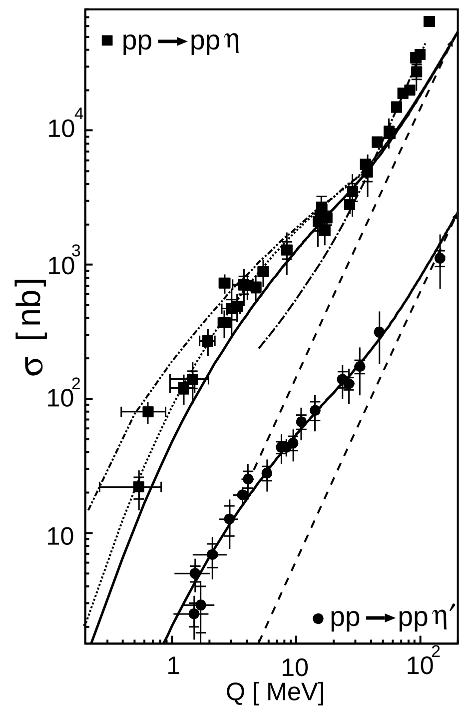

Figure 5. Total cross-sections for the indicated reactions as functions of the excess energy Q. For an explanation of the different curves, see text.

$$p + d \rightarrow {}^3\mathrm{H} + \pi^+, \tag{8}$$

$$p + d \rightarrow \pi^+ + {}^3\mathrm{H}, \tag{9}$$

$$p + d \rightarrow {}^3\mathrm{He} + \eta. \tag{10}$$

At a beam momentum around 1640 MeV/c the ^{3}H ions being emitted forward, the π^+'s being emitted backward in the centre of mass system as well as the ^{3}He ions being emitted backward are within the acceptance of the magnetic spectrograph. Reactions 8 and 9 are in principle used to calibrate the detector and the accelerator. Reaction 10 is then used to determine the η mass by the missing mass technique. It was found to be

$$m(\eta) = (547.311 \pm 0.028(\text{stat.}) \pm 0.032\ (\text{syst.}))\ \mathrm{MeV/c^2}. \tag{11}$$

Details of the experiment can be found in ref. [28]. A comparison of this new value and the previous data is shown in figure 6. It shows excellent agreement with the previously published values except the one from ref. [27].

Now we will proceed to $pd \rightarrow {}^3AX$ reactions with $A = \mathrm{H}$ or He and $X = \pi, \eta$. Here we will start with pion production. A series of angular distributions was measured by GEM, in order to study possible violations of isospin symmetry [29,30]. Two components were found: one depending strongly on the emission angle and thus on the momentum transfer, and another one which is almost isotropic. In

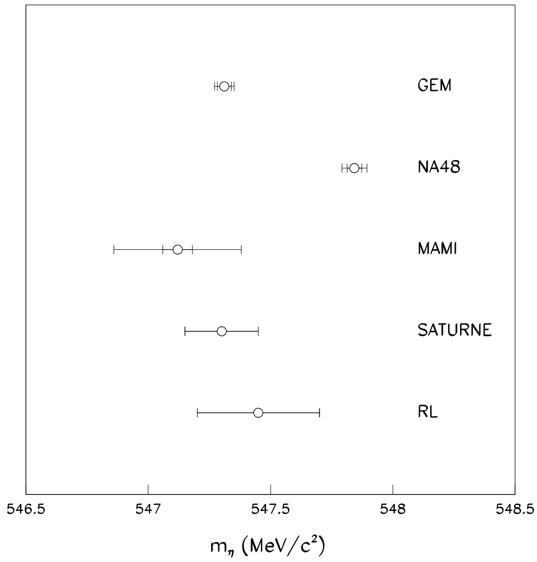

Figure 6. The η-meson rest mass as published by different experiments in the order of their publication. The references given can be found in the particle data book.

the first component a violation of isospin symmetry was found. The data also serve to investigate the production mechanism. This has to be understood before more complicated reactions such as multi-pion production or η production can be understood. A calculation which goes beyond the Locher–Weber type calculations [29,31] was performed recently by Canton and Levchuk [32]. They treated the three nucleon wave functions in the ISI within the AGS formalism. Their results are compared with GEM data in figure 7. One can see that the isotropic component strongly depends on ISI. The Paris NN potential seems to slightly underestimate the experiment.

We now proceed to the $p + d \to {}^3\text{He} + \eta$ reaction which is of great interest, since the η–nucleus interaction should be more attractive than in the pp case. From the differential cross-sections one can deduce a matrix element f as

$$|f(\theta)|^2 = \frac{k^2}{q^2}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(\theta) = |f_p|^2 |T\,(q)\,|^2. \tag{12}$$

The right-hand side is valid for s-wave production with FSI in the exit channel. With f_p the production matrix element and with T the FSI matrix element are denoted. Willis *et al* [33] analysed the near-threshold data in this way. Later, Sibirtsev *et al* [34] extended the range to the then available data. Their value for the η–^{3}He scattering length is $a(\eta\text{–}{}^3\text{He}) = (-4.3\pm0.3) + i(0.5\pm0.5)$. The resulting angle integrated matrix element is shown in the left part of figure 8 as a function of the η momentum q. This is in agreement with model calculations, for instance, of Khemchandani *et al* [35]. They calculated the cross-section in a two-step model. In the first step a pion is produced in a nucleon–nucleon interaction while in the

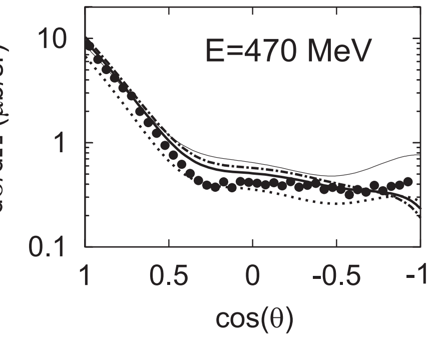

Figure 7. Angular distribution of the $p + d \rightarrow {}^3\text{He} + \pi^0$ reaction at the indicated beam energy. Solid, dashed-dotted and dotted lines denote the calculations for Bonn-B, Bonn-A, and Paris NN potentials, respectively, while thin solid line corresponds to the plane-wave calculation (without the pd ISI).

second step this pion is scattered at the spectator nucleon $\pi + N \rightarrow \eta + N$ with eventual fusion of the three nucleons. The agreement between data and 12 is good up to $q_\eta \approx 1$ fm^{-1} (the data from COSY-11 are still preliminary). Also shown in the figure is the matrix element of a resonance model [36] without FSI enhancement. Therefore, it underestimates the data close to threshold. There are ambiguities between the data. Angular distributions close to threshold are isotropic as expected. At higher energies the data from refs [36–38] show a strong forward peaking while the data from [39] peak at $\cos\theta_\eta \approx 0.5$. This could be reproduced by the calculations performed by Stenmark [40]. However, this approach is based on the *ad hoc* assumption of the intermediate pion to be limited into a narrow forward cone, as was pointed out in ref. [41].

The GEM Collaboration studied isospin symmetry breaking by comparing neutral and charged pion production in $pp \rightarrow d\pi^+$ and $np \rightarrow d\pi^0$ [5] reactions, and $pd \rightarrow {}^3\text{H}\pi^+$ and $pd \rightarrow {}^3\text{He}\pi^0$ reactions [30]. For the latter reactions it was found that the angular distribution of the matrix elements consists of two parts. One is an exponential part showing scaling which is attributed to a one-step reaction. This part shows isospin symmetry breaking. The second component is isotropic and is related to two-step processes. It does not show isospin symmetry breaking. The origin of isospin symmetry breaking is, in addition to the Coulomb force, a difference in the masses of the up and down quark. It was suggested [42] to study the $pd \rightarrow {}^3\text{He}\pi^0$ reaction at maximal momentum transfer around the η-production threshold. This channel should be sensitive to π^0-η mixing with the mixing angle being dependent on different quark masses. On the contrary the $pd \rightarrow {}^3\text{H}\pi^+$ reaction should not show such an interference effect. This was indeed found in an experiment [43] and the ratio of both reactions is shown in figure 8. Baru *et al* [44] claimed this effect to be most probably due to FSI between the ^{3}He and the virtual η. However, if the data are analysed in terms of the model from ref. [42] the mixing angle results into $\theta = 0.006 \pm 0.005$. Green and Wycech used a K-matrix formalism and derived $\theta = 0.010 \pm 0.005$. From this formalism a rather large η–nucleon scattering length is extracted making a bound η–nucleus very likely. The search for such a system is in progress (see contributions by Jha and Chatterjee in

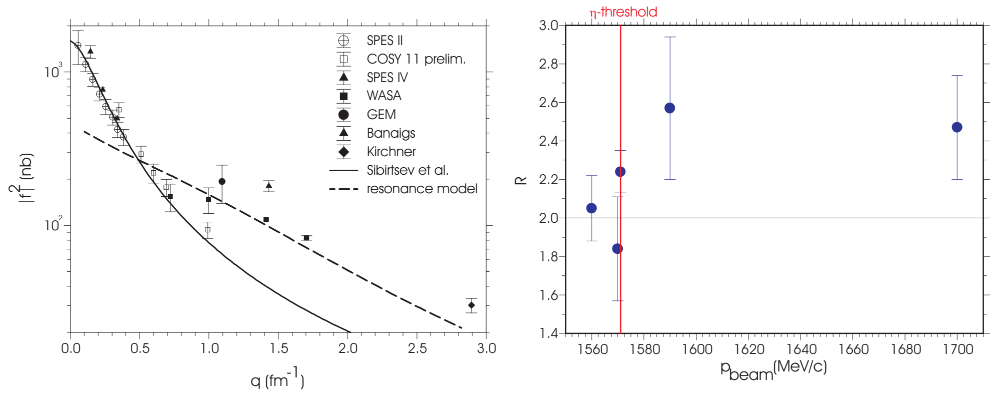

Figure 8. Left: Excitation function for the $pd \to {}^3\mathrm{He}\eta$ reaction. The references can be found in ref. [34]. Right: Excitation functions for the ratio of the two pion production reactions at maximal momentum transfer (zero degree in the lab. system). The η-production threshold is indicated as a line.

this volume). Also the question of π^0–η mixing will be further studied via isospin forbidden decays of η and η' mesons with WASA at COSY [45].

Acknowledgments

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