Physics at CELSIUS and COSY

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Abstract

We review some selected experimental results achieved at the synchrotrons CELSIUS in Sweden and COSY in Germany. They concentrate on meson production with emphasis on the underlying quark structure. The project WASA at COSY is discussed and the search for symmetry breaking in decays of $\eta$ and $\eta'$ mesons is highlighted.

1 Introduction

CELSIUS at the The Svedberg Laboratory, Uppsala, Sweden and COSY at the Research Center (FZ) Jülich, Germany have a lot of features in common. Both have a cyclotron as injector, are synchrotrons with beam cooling and operate as storage rings. On the other hand there are differences. CELSIUS is slow ramping, has no external beams and its circumference is much smaller than that of COSY, leaving only space for two experiments. COSY is a rapid cycling machine with presently four internal experiments installed and three external target stations. Extraction of the beams is performed by stochastic methods. The following text is organized into two parts. First we will discuss some selected experimental results at both accelerators. Then we will discuss in the second part the WASA detector, which previously (summer 2005) operated at CELSIUS and is presently disassembled and has been shipped to Jülich. It is foreseen that the physics programme WASA at COSY will start in fall 2006.

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2 Selected Results

2.1 OZI Rule Violation

The Okubo-Zweig-Izuka (OZI) rule [1] can be summarized in simple terms that processes with continuing quark lines are favored over those with discontinued quark lines. The \( \omega \) is almost a pure \( uu + dd \) state while the \( \phi \) is almost a pure \( ss \) state. So production of the latter meson in a \( pp \) reaction should be almost impossible. But quark mixing in these two mesons makes the production of the \( \phi \) possible. From the vector mixing angle one gets \( \sigma(pp \to pp\phi)/\sigma(pp \to pp\omega) = \tan \alpha_v = 0.004 \). In \( p\bar{p} \) annihilation the OZI rule was found to be violated. More recently, DISTO measured the cross sections for both reactions at the same beam momentum and found the cross section ratio to strongly violate the OZI rule. However, different phase space for both reactions introduce a deviation of the cross section ratio from the OZI-rule. COSY TOF measured \( \sigma(pp \to pp\omega) \) cross sections and ANKE \( \sigma(pp \to pp\phi) \) cross sections. These data together with the DISTO data and earlier SPES3 data for \( \sigma(pp \to pp\omega) \) close to threshold allows the estimation of the dependencies of the cross sections as function of the excess energy \( \epsilon \) which allows a comparison that is equivalent to the same phase space. The data on \( \phi \) production follow \( s \)-wave behavior while angular distributions of \( \omega \)-production require several partial waves to be fitted. We have therefore fitted a power law to the total cross sections. The OZI-ratio is shown in Fig. Figure 1 together with the expectation value from the OZI-rule. The data show a distinct deviation from it which is increasing with increasing excess energy. There are several possible explanations why the OZI-rule fails. One of them is the \( ss \) content in the proton.
Figure 2: The ratio of associated strangeness production as function of the excess energy.

2.2 Associated Strangeness Production

Another topic associated with $s\bar{s}$ production is its production in

\[ pp \to p\Lambda K^+ \]  

and

\[ pp \to p\Sigma^0 K^+ \]  \(\text{(2)}\)

These two reactions were measured by TOF at higher energies and by COSY11 close to threshold. The ratio of both reactions is shown in Fig. 2. It reaches a value 25–30 close to threshold and decreases then to 8 at 60 MeV. This unexpected behavior is studied within several models, including pion and kaon exchange added coherently with destructive interference [2] or incoherently [3], the excitation of nucleon resonances [4,5] (labelled effective Lagrangian), resonances with heavy meson exchange ($\pi, \rho, \eta$) [6] and heavy meson exchange ($\rho, \omega$ and $K^*$) [4, 5]. 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 except the one from Ref. [5], in which the sign of the poorly known coupling constant $g_{pN(1650)}$ has been adjusted. It should be noted that $pY-fsi$ with $Y$ the hyperon is essential in reproducing the measurements.

This $fsi$ can be directly studied. HIRES at the Big Karl spectrometer measures the excitation function at zero degree for both reactions [1] and [2]. In TOF the complete Dalitz plot is filled. A $fsi$ can be seen as enhancement forming a line with constant mass of the $p\Lambda$ system. $N^*$ excitation is seen on the other hand as an enhancement as a line with constant mass of the $KA$ system. An enhancement with constant mass of the $pK^0$ system was
interpreted by the TOF collaboration as strange pentaquark $\Theta^+$ [7]. The group has in the meantime repeated the experiment in a longer beam time and with an improved efficiency of their detector.

2.3 A precision measurement of the $\eta$ mass

Compared to other light mesons, the mass of the $\eta$ is surprisingly poorly known. Though the Particle Data Group (PDG) quotes a value of $m_\eta = 547.75 \pm 0.12$ MeV/$c^2$ in their 2004 review [8], this error hides differences of up to 0.7 MeV/$c^2$ between the results of some of the modern counter experiments quoted. The PDG average is in fact dominated by the result of the CERN NA48 experiment, $m_\eta = 547.843 \pm 0.051$ MeV/$c^2$, which is based upon the study of the kinematics of the six photons from the $3\pi^0$ decay of 110 GeV $\eta$-mesons [9]. In the other experiments employing electronic detectors, which typically suggest a mass $\approx 0.5$ MeV/$c^2$ lighter, the $\eta$ was produced much closer to threshold and its mass primarily determined through a missing-mass technique where, unlike the NA48 experiment, precise knowledge of the beam momentum plays an essential part. GEM performed a high precision determination of the $\eta$ meson mass. The idea of the experiment is as follows. Three reactions were measured at the same time at a beam momentum, where products of all three reactions are detected simultaneously in the acceptance of the Big Karl spectrometer. The reactions are

\begin{align*}
p + d &\rightarrow ^3H + \pi^+ \\
p + d &\rightarrow \pi^+ + ^3H \\
p + d &\rightarrow ^3He + \eta.
\end{align*}

The experiment simultaneously detected forward emitted pions and backward emitted tritons in the c.m. system together with backward emitted $^3He$ ions (doubly charged) as at a proton beam momentum around 1640 MeV/c. Details of the experiment are found in Ref. [10]. The final result of this measurement is

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

Our value of the mass of the $\eta$ meson is compared in Fig. 3 with the results of all other measurements reported in the current PDG compilation [8]. Though significantly smaller than that reported in the NA48 experiment [9], it is in excellent agreement with the other results.
Figure 3: The results of the $\eta$-mass measurements, in order of publication date, taken from the Rutherford Laboratory (RL) [11], SATURNE [12], MAMI [13], NA48 [9], and GEM [10]. When two error bars are shown, the smaller is statistical and the larger total.

2.4 $\eta$ and $\eta'$ production in proton-proton collisions

A comparison of neutral pseudoscalar meson production in $pp$ collisions should shed light on the reaction mechanism and the interactions among the reaction partners. The $\eta$ and $\eta'$ mesons are the isospin zero partners of the $\pi^0$ which has isospin one. The latter has a very weak interaction with nucleons with respect to the nucleon-nucleon interaction. Furthermore, the influence of an intermediate nucleon resonance, the $\Delta(1332)$, was found only in the $Pp$ partial wave [14]. In contrast to this case, the $\eta$-nucleon and even more the $\eta$-nucleus interaction is not that small. The $N^*(1535)$ has a strong coupling to the $\eta$-nucleon channel. On the other hand no resonance is known to couple to the $\eta'$-nucleon channel. The meson-nucleon interaction in all three cases can only be studied in $f_{si}$ because of the short lifetime of the mesons. In Fig. 4 the total cross section for the reactions as a function of the center-of-mass excess energy $Q$ are shown. The sources of data are given in Ref. [15].

The dashed lines indicate a phase-space integral normalized arbitrarily. The solid lines show the phase-space distribution including the $^1S_0$ proton-proton strong and Coulomb interactions. In the case of the $pp \rightarrow pp\eta$ reaction, the solid line was fitted to the data in the excess energy range between 15 and 40 MeV. Additional inclusion of the proton- $\eta f_{si}$ is indicated by the dotted line.
Figure 4: Excitation functions of the total cross sections for $pp \rightarrow \eta pp$ (circles) and $pp \rightarrow \eta' pp$ reactions (squares). The different curves are discussed in the text.
The scattering length and the effective range parameter have been arbitrarily chosen. The dash-dotted line represents the energy dependence taking into account the contribution from the \(^3P_0 \rightarrow ^1S_0s\), \(^1S_0 \rightarrow ^3P_0s\), and \(^1D_2 \rightarrow ^3P_2s\) transitions [16]. Preliminary results for the \(^3P_0 \rightarrow ^1S_0s\) transition with the full treatment of the three-body effects are shown as a dashed-double-dotted line [17]. The absolute scale of dashed-double-dotted line was fitted with an arbitrary strength in order to demonstrate the energy dependence. While the \(\eta'\) production is nicely reproduced by phase space plus \(pp-fsi\) this is not the case for \(\eta\) production. Most importantly the Dalitz plot can not be explained by \(p\eta\) and \(pp-fsi\). The necessity for a rigorous three body calculation was found [15].

2.5 Proton-neutron final state interaction

There has been an extensive search for spin-singlet contribution in \(pn-fsi\). Favorite reactions were \(dp \rightarrow p\{pn\}\) and \(dp \rightarrow \pi^+\{pn\}\). In both cases the pole (i.e. the deuteron) can also be measured. There is a theorem due to Fälldt and Wilkin which connects the pole to the continuum [18]. Thus the absolute height of the spin-triplet contribution in the continuum is given. The residual cross section is usually attributed to the spin-singlet fraction, however, the resolution and background conditions of most experiments were not sufficient to unambiguously extract the spin-singlet contribution. The characteristic feature of this contribution is a very narrow peak due to an unbound pole at 60 keV, which under these unfavorable conditions could not be seen directly. Therefore, at COSY and CELSIUS the \(\pi^+d\) final state. Therefore, one had to rely on Monte Carlo simulations [19].

At GEM they measured the pions from \(pp\) interactions with extremely high resolution due to a 2 mm thin liquid hydrogen target and a stochastically extracted beam which was electron cooled at injection energy [21]. A missing mass resolution of \(\sigma = 97\) keV was achieved for the deuteron. In addition an almost halo-free beam resulted in a very small background. The Fälldt and Wilkin \(fsi\) -theorem yielded only 50% of the yield in the \(pn\) continuum. In Fig. 5 a fit of the spin-singlet \(fsi\) to the data is shown. Obviously, that calculated cross section can not account for the data. The reason for the discrepancy is not clear at the moment. One explanation is that this is due to \(D\)-state effects in the \(pn\) system [21]. Another possibility might be a failure of the Fälldt and Wilkin theorem which is exact only at the pole position.
Figure 5: Comparison of the measured $pn$ excitation energy spectrum on a linear scale with the prediction the singlet cross section folded with the present resolution. The error bars contain a tiny contribution from the uncertainty in the acceptance correction.

3 Physics with WASA at COSY

3.1 Pseudoscalar meson mixing

The QCD Hamiltonian can be split into parts

$$H_{QCD} = H_0 + H_m$$

with $H_0$ the Hamiltonian for massless quarks. In flavor SU(3) the term containing the mass is given as

$$H_m = \int dx^3 (m_u \bar{u}u + m_d \bar{d}d + m_s \bar{s}s).$$

The latter term breaks chiral symmetry. The neutral pseudoscalar mesons $\tilde{m}$ in ideal mixing are connected to the physical mesons $m$ via

$$\begin{pmatrix} \tilde{\pi} \\ \tilde{\eta} \\ \tilde{\eta}' \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}} (u\bar{u} - d\bar{d}) \\ \frac{1}{\sqrt{6}} (u\bar{u} + d\bar{d} - 2s\bar{s}) \\ \frac{1}{\sqrt{3}} (u\bar{u} + d\bar{d} + s\bar{s}) \end{pmatrix} = A \begin{pmatrix} \pi \\ \eta \\ \eta' \end{pmatrix}.$$ 

The matrix $A$ consists mainly of the $\pi^0 - \eta$ mixing angle and the $\eta - \eta'$ mixing angle. The former is given by

$$\sin \theta_{\pi\eta} \equiv \frac{\sqrt{3}}{4} \frac{m_d - m_u}{m_s - \tilde{m}}.$$
with \( \hat{m} = (m_d + m_u)/2 \). A measurement of the \( \pi^0 - \eta \) mixing angle would therefore provide information about the up quark and down quark mass difference.

A first attempt to measure this mixing angle was put forward by Magiera and Machner [22]. They proposed to measure the ratio of backward emitted pions from the two reactions \( pd \rightarrow ^3He\pi^0 \) and \( pd \rightarrow ^3H\pi^+ \) in the vicinity the \( \eta \) threshold (below and above) in the reaction \( pd \rightarrow ^3He\eta \). They argued that in the case of \( \pi^0 \) production this channel could be enhanced below threshold due to \( \pi^0 - \eta \) mixing. Indeed an effect was found in an experiment leading to \( \theta_{\pi\eta} = 0.006 \pm 0.005 \) [23]. However, Baru et al. [24] claimed that a possible effect is not solely due to the mixing but also \( \eta - ^3He \) should contribute. The problem might be solved more cleanly by not measuring meson production but studying meson decay instead. This can and will be done with the WASA detector at COSY.

3.2 The WASA detector

The WASA detector operated until summer of this year at the CELSIUS facility. It is presently disassembled and has been shipped to Jülich where it will be installed at COSY in late fall and spring of next year. Fig. 6 shows a cross section through WASA. WASA consists of a forward part (right) for measurements of charged target-recoil particles and scattered projectiles and...
a central part (left) designed for measurements of the meson decay products. The forward part consists of eleven planes of plastic scintillators and of proportional counter drift tubes. The central part consists of an electromagnetic calorimeter of CsI(Na) crystals surrounding a superconductive solenoid. Inside of the solenoid a cylindrical chamber of drift tubes and a barrel of plastic scintillators are placed. The arrows indicate a typical reaction \( pp \rightarrow pp\eta' \) with a subsequent decay of the \( \eta' \) into an \( \eta \) and two charged pions. Finally, the \( \eta \) decays into two \( \gamma \)'s. The two protons will be measured in the forward detector, the charged pions in the volume of the magnetic field and the \( \gamma \)'s in the CsI crystals.

### 3.3 \( \eta \) and \( \eta' \) decays

One possibility of studying the meson mixing angles are the decays of \( \eta \) and \( \eta' \) mesons. We will first concentrate on the isospin forbidden decays of the \( \eta' \) into three pions. Instead of measuring the decays alone it was proposed by Gross, Treiman and Wilczek [25] to measure the ratios of the forbidden decays to the allowed decays into \( \eta \) and two pions:

\[
R_{ch} = \frac{\Gamma (\eta' \rightarrow \pi^0\pi^0\pi^-)}{\Gamma (\eta' \rightarrow \eta\pi^+\pi^-)} = PS_{ch} \sin^2 \theta_{\pi\eta} \\
R_{neut} = \frac{\Gamma (\eta' \rightarrow \pi^0\pi^0\pi^0)}{\Gamma (\eta' \rightarrow \eta\pi^0\pi^0)} = PS_{neut} \sin^2 \theta_{\pi\eta}.
\]

(11)

\( PS \) denotes the ratio of the three body phase. From the branchings given by the PDG [8] one estimates for the charged pions \( R_{ch} < 0.11 \) while Gross et al. give an estimate of \( 1.49 \times 10^{-3} \). The upper limit means that no events for this isospin forbidden decay have been observed so far. For the neutral channel the numbers are \( (7.4 \pm 1.2) \times 10^{-3} \) while the theory predicts \( 1.37 \times 10^{-3} \). The experimental number is based on two experiments with a count rate of \( \approx 150 \) counts in total. One can expect that with the high luminosity anticipated at COSY more than an order of magnitude more events will be recorded in a couple of weeks.

The same information can in principle also be gained from the study of the decay \( \eta \rightarrow \pi^+\pi^-\pi^0 \). However, here Coulomb corrections and theory input, both with some uncertainties [26, 27], are necessary.

Another approach is the study of the Dalitz plot of the decay \( \eta \rightarrow 3\pi \). Here we will concentrate on the decay into three neutral pions. The amplitude can be written as

\[
|A(\eta \rightarrow 3\pi^0)|^2 = 1 + 2\alpha z
\]

(12)

with \( z = \rho^2/\rho_{max}^2 \) the relative radial distance. The distance to the center of the Dalitz plot is \( \rho \). A recent measurement of the angle at WASA/CELSIUS
Figure 7: The slope parameter $\alpha$ from various measurements and calculations. The references are given in [29] except for the preliminary results.

[28] yielded a preliminary value of $\alpha = -0.027$±0.015 (stat.)±0.010 (syst.). This value is compared in Fig. 7 with previous measurements and model calculations. The result is based on 37 thousand events. A much richer data sample can be expected at WASA/COSY.

In QCD with $N_f = 3$ there exists a non-Abelian anomaly which breaks the chiral symmetry explicitly. In the effective chiral Lagrangian this anomaly is appropriately reproduced by introducing the Wess-Zumino action [30, 31]. The expansion of the Wess-Zumino-Witten Lagrangian is shown in Fig. 8.

Some interactions of the neutral pseudoscalar mesons have matrix elements with the wrong parity. These are called anomalous interactions. Among them are the two photon decay (triangle anomaly) and the decay $\eta/\eta' \rightarrow \pi^+\pi^-\gamma$ (box anomaly). These diagrams can be calculated within the model of hidden local symmetry. Details can be found in a recent review [32]. Benayoun et al. [33] constructed a set of equations defining the amplitudes for $\eta/\eta' \rightarrow \pi^+\pi^-\gamma$ and $\eta/\eta' \rightarrow 2\gamma$ at the chiral limit, as predicted from the anomalous HLS Lagrangian and appropriately broken. For the decay
$\eta' \rightarrow \pi^+\pi^-\gamma$ they predict an invariant mass distribution which is the same as the one from $\rho\pi^+\pi^-$ while for $\eta \rightarrow \pi^+\pi^-\gamma$ the center of gravity of the distribution is shifted to $\approx 350 \text{ MeV}/c^2$. In these calculations the $\eta - \eta'$ mixing angle enters. The WASA detector at COSY will allow one to measure the corresponding two pion distribution with high statistics.

In the decay studies other rare decays will be measured. Most of them violate $\mathcal{C}$-symmetry. The decay $\eta \rightarrow \pi^+\pi^-e^+e^-$ violates $\mathcal{CP}$-symmetry outside the CKM mechanism. Since this decay is flavor conserving, it is outside the standard model. In a first run at WASA/CELSIUS already 25 candidates were seen compared to 5 events in total in the literature.

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