Verification of a novel calorimeter concept for studies of charmonium states
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Chapter 2. Charmonium and exotic hadronic states

2. Charmonium and exotic hadronic states

The PANDA experiment in the High Energy Storage Ring (HESR) at FAIR in Darmstadt will investigate proton - antiproton annihilations. The physics program of PANDA contains topics of high current interest like the study of charmonium states, the search for glueballs, hybrids, exotic mesons, and hypernuclei. Figure 2.1 compiles the focus topics of the PANDA experiment for the accessible antiproton momentum range from 1.5 – 15 GeV/c and interactions with protons from a hydrogen cluster jet or frozen pellet target.

The research goals of PANDA experiments aim at a clear understanding of QCD in the non-perturbative regime, which governs the formation and structure of hadrons. Here we will discuss two main topics of physics investigations in the PANDA experiment:

- Charmonium spectroscopy;
- Exotic hadronic states.
2.1 Charmonium spectroscopy

In 1974, the J/Ψ charmonium state was discovered in electron-positron collisions [8]. Subsequently, in electron-positron collisions also other states of the charmonium spectrum, Ψ′ and Ψ (3770) resonances, were found and the quantum numbers $J^{PC} = 1^{--}$ could be assigned, which are the quantum numbers of the photon. Charmonium states (see Figure 2.2) are bound states of a $c$ and a $\bar{c}$ quark and the $J^{PC} = 1^{--}$ states can be formed in electron-positron collisions via the coupling to a virtual photon.

![Figure 2.2: Spectrum of charmonium states [6] and transitions according to the given legend. Dashed-line transitions need further confirmation. The thresholds for $D\bar{D}$ states are indicated.](image)

Since their discovery, the charmonium states played a key role in understanding the nature of the strong interaction. The high mass ($\approx 1.5$ GeV/c$^2$) of the charm quark allows to describe the charmonium bound states rather well in a non-relativistic potential model.

In $e^+e^-$ collisions only states of charmonium with the quantum numbers of the photon can be directly formed. Meanwhile, a number of experiments (e.g. CLEO [9], BELLE [10], BES [11]) have produced charmonium states and rather well completed the charmonium spectrum (Figure 2.2). Charmonium can be produced e.g. in B-meson decays, two photon collisions, or $p\bar{p}$ interactions. In $p\bar{p}$ annihilations, all possible states of charmonium can be directly excited. Exploiting the precise knowledge of the beam momentum and the momentum scanning technique, the masses and widths of all charmonium states can be determined with excellent accuracy, limited by the very precise knowledge of the initial $p\bar{p}$ state and not limited by the detector resolution, unlike the situation of charmonium production in $e^+e^-$ collisions. The concept of the resonance scan is illustrated in Figure 2.3. The mass distribution that should be determined for the particle of interest is indicated by the green dotted curve. The nominal beam momentum is adjusted to several discrete values. Due to the finite momentum distribution of the beam, each of the nominal settings of the beam momentum excites a distribution of the center-of-mass energy $E_{CM}$ as indicated by the
red dotted curves. The measured yield distribution for a given final state is the convolution of these two types of distributions, as indicated by the filled points along the blue solid line. The power of this method is clearly recognized by comparing measurements of the total decay width of the $\chi_{c1}$. Measurements from the Crystal Ball were only able to achieve a precision better than 3.8 MeV [12] and newer measurements from the BES collaboration achieved a precision of $\Gamma = 1.39 \pm 0.40 \pm 0.26$ MeV [13]. In contrast, the E835 experiment was able to achieve uncertainties which are about one order of magnitude smaller resulting in a width $\Gamma = 0.876 \pm 0.045 \pm 0.026$ MeV [14]. In the spectrum of charmonium states, shown in Figure 2.2, the $c\bar{c}$ states below the $D\bar{D}$ threshold are well established. The properties of the triplet-P states $\chi_{c0}$, $\chi_{c1}$ of and $\chi_{c2}$ are studied well. However, the width of the charmonium ground state $\eta_c$ is determined very poorly.

![Figure 2.3](image)

**Figure 2.3**: Scheme of the resonance scan technique [15]. The mass distribution that should be determined for the particle of interest is indicated by the green dotted curve. The nominal beam momentum is adjusted to several discrete values (red curves). The measured values (blue dots) need to be corrected for the beam resolution to obtain the true mass distribution.

The $\eta_c$ state, the first excitation of the $\eta_c$ ground state, was discovered by BELLE [16] and was observed as an 8$\sigma$ deviation from the initial claims of the Crystal Ball [17]. Furthermore, different values of mass and width were established. However, the existing data on the mass only have a precision of 4 MeV and there is a 50% uncertainty in the width. These results are only marginally consistent with most predictions.

The singlet-P resonance ($h_c$) is of extreme importance to determine the spin-dependent component of the $q\bar{q}$ potential. For this state only two decay channels have been seen [18], but due to the narrow width of this state ($\Gamma < 1$ MeV) only $p\bar{p}$ formation experiments, as are proposed for PANDA, will allow measuring the width and systematically investigating the decay modes.

A rich spectrum of states may be expected in the energy region above the $D\bar{D}$ threshold, but up to now, this region is poorly explored. Since 2003 a number of narrow states in this mass region have been observed by the BELLE [10], BABAR [19] and CLEO [9] experiments. Many basic parameters of these states have yet to be determined. Furthermore, precision measurements of all $^1D$ and $^3D$ states are required to distinguish between models that provide different interpretations of the nature of these states.
2.2 Exotic hadronic states

The confrontation of QCD-based theoretical predictions for exotic hadronic states with experimental data will provide a deeper understanding of the QCD dynamics. On the theory side, two different approaches are generally used: (i) lattice calculations (LQCD) [20], which attempt to solve non-perturbative QCD by numerical calculations, and (ii) effective field theories [6], either with quark-gluon or with hadronic degrees of freedom, which obey the symmetries of QCD and the existence of hierarchies of scales to provide predictions from effective Lagrangians. The exotic hadronic states are classified in three main categories:

**Hybrid states:** Such states differ from conventional mesons by an explicit gluon contribution. In the simplest scenario, the quantum numbers of such states may be found by adding the quantum numbers of a gluon to those of a simple \( q\bar{q} \) pair. This procedure creates e.g. for S-wave mesons eight lowest-lying hybrid states. Exotic charmonia are expected to exist in the 3–5 GeV/c\(^2\) mass region. Predictions are provided mainly by calculations based on the bag model, flux tube model, constituent gluon model, and recently by LQCD [4, 5] calculations. These predictions qualitatively agree, and all models expect [21] that the lightest exotic state would be a \( J^{PC} = 1^{-+} \) state. Predictions for the mass and the width estimate values around 4.3 GeV/c\(^2\) and 20 MeV/c\(^2\), respectively. In addition, there are seven other hidden charmed hybrids [22] to be discovered. Therefore, the main goal would be to measure the whole pattern of charmonium exotic states. The PANDA program aims to search for charm-hybrid states in production experiments at the highest antiproton energy available (\( E_p = 15 \) GeV, \( \sqrt{s} = 5.46 \) GeV). Such measurements allow studying all possible channels, exotic and conventional. The next step would consist of formation measurements to scan the antiproton energy in small steps in the regions where promising hints of hybrids have been observed in the production phase.

**Glueballs:** Such states are composite particles consisting of gluons without any valence quarks. States of pure glue are possible since gluons carry color charge and can interact with each other according to QCD. LQCD calculations can provide predictions for the glueball mass spectrum (Figure 2.4). The glueballs are experimentally [23] hard to identify since they may mix with ordinary mesons. Therefore, glueballs with exotic quantum numbers (“odd-balls”) would be narrower and easier to be detected. LQCD predicts the presence of about fifteen glueballs in the mass range accessible to the PANDA experiment, some with exotic quantum numbers. The lightest odd-ball, with \( J^{PC} = 2^{+-} \), has been predicted with a mass of 4.3 GeV/c\(^2\).

Like charmonium hybrids, glueballs can either be formed directly in the \( p\bar{p} \)annihilation process, or produced together with another particle. In both cases, the glueball decay into final states like \( \phi\phi \) or \( \phi\eta \) would be the most favorable decay below 3.6 GeV/c\(^2\), while \( J/\Psi\eta \) and \( J/\Psi\phi \) are the first choices for the more massive states. The indication for a tensor state around 2.2 GeV/c\(^2\) was found in the experiment JETSET at LEAR [25]. The acquired statistics was not sufficient for the complementary reactions to be determined. Accordingly, the PANDA collaboration is planning to measure the \( p\bar{p} \rightarrow \phi\phi \) channel with two orders of magnitude better statistics than in the previous experiments.

**Multiquark states:** These are mesonic excitations of \( q\bar{q} \) states. These mesonic excitations are expected to be loosely bound, thus resulting in states having a large width. Nevertheless, in the vicinity of a strong threshold, this property may change, and states with a potentially large additional mesonic component can become narrower if they appear sub-threshold. This for example could be the case for the \( (a_0(980), f_0(975)) \) system, which has a
large (may be dominant) $K\bar{K}$ component in the wave function. In the case of the extremely narrow X(3872) state [26] the $D\bar{D}$ threshold could have a similar impact on the mass of this state and could explain why it is not fitting into the conventional systematic of the charmonium spectrum.

![Figure 2.4](image)

**Figure 2.4:** Predictions from LQCD calculations [24] for glueball masses with various PC quantum numbers. The masses are given in terms of the hadronic scale $r_0$ on the left vertical axis and in terms of GeV on the right vertical axis.

### 2.3 Conclusion

In conclusion, the main scientific research topics of the PANDA experiment are charmonium spectroscopy, the search for exotic hadronic states, such as hybrid states, glueballs, and multiquark states. In order to underline the importance of an excellent electromagnetic calorimeter, we discuss as an example of hybrid states the charmonium hybrid state $h_c$ [6]. The charmonium hybrid states are expected to decay mainly to charmonium final states, like in this reaction channel: $p\bar{p} \rightarrow h_c \eta \rightarrow J/\psi \pi^+ \pi^- \eta$. For this decay channel, the EMC is crucial to detect the complete final state because $J/\psi$ decays electromagnetically, the $\eta$ meson decays to three $\pi^0$ which in turn decay each to two photons. In the search for glueballs, the experiment will study final states including $\phi\phi$ or $\phi\eta$ for states below 3.6 GeV/$c^2$ and $J/\psi \eta$ and $J/\psi\phi$ for higher-mass states. As an example of charmonium spectroscopy we mention here one of the charmonium states, the $h_c$ state (see Figure 2.2). Precise information about this state will give more insight to determine the spin-dependent component of QCD bound states. One of the cleanest ways to identify the $h_c$ state is to detect its decays into the $7\gamma$ final state. This decay is discussed in Chapter 8, in order to evaluate the performance of the PANDA EMC.