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The PANDA physics programme

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Abstract The PANDA experiment at the future FAIR facility in Darmstadt, Germany, will use interactions of antiprotons with nucleons or nuclei to investigate fundamental questions of hadron and nuclear physics. Here, a brief overview of the physics programme is given, focusing on a few selected topics.

Keywords Charmed mesons · Exotic mesons · Multi-strange baryons · Proton form factors

1 Introduction

PANDA [1] is one of the major experiments at the future FAIR facility in Europe [2]. Gluonic excitations and the physics of strange and charm quarks will be accessible with unprecedented accuracy, allowing high-precision tests of strong interaction. The FAIR facility is under construction on the area of the GSI Laboratory in Germany. A primary beam of protons up to 30 GeV will be provided. A secondary beam of $\bar{p}$ in the momentum range from 1.5 to 15 GeV/c will be available at the High Energy Storage Ring (HESR), where the PANDA detector will be installed. Commissioning of PANDA is foreseen to start in 2017, but pre-assembling will start at COSY in Jülich in 2014.

The HESR will work into two different operation modes: high momentum resolution mode with $\delta p/p \sim 10^{-5}$ at a moderate luminosity $\mathcal{L} = 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, by electron cooling, and high luminosity mode $\mathcal{L} = 2 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, but with greater momentum spread ($\delta p/p \sim 10^{-4}$), by stochastic cooling.

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In the last decade most of the results on meson spectroscopy in the region of charm has been achieved at e^+e^- colliders. Nevertheless, in order to shed light on the recently discovered narrow states, a very high mass resolution is required. The use of $\bar{p}p$ annihilations allows to achieve an excellent resonance mass resolution, as was successfully demonstrated by experiments at FNAL [3]. Indeed, the precision of the resonance mass and width depends on the energy spread of the beam and not on the resolution of the detector, which is definitely used to identify and reconstruct the final state and for an efficient background rejection. In PANDA a resolution below 100 keV can be achieved, which is unbeatable with respect to the one of a few MeV of experiments at e^+e^- colliders. Moreover, all measurements will profit from the high yield of $\bar{p}$ induced reactions (2×10^7/s) and from the fact that states with all quantum numbers allowed for a $q\bar{q}$ system can be directly populate, in contrast to e^+e^- reactions, which select states with $J^{PC} = 1^{--}$. Of course, states with exotic quantum number will be observed in production measurements.

2 The PANDA physics programme

PANDA has a wide range physics programme, both in collisions of $\bar{p}p$ and $\bar{p} - $ *nucleus*, which will allow to extend our knowledge on hadron structure, quark-gluon dynamics and nuclear physics. A comprehensive discussion of the programme, with feasibility studies and benchmark channels, can be found in the PANDA physics performance report [4]. Since, the available c.m. energy for the $\bar{p}p$ system will be in the range 2.2–5.5 GeV, one of the main goals is the study of charmonium and open charm spectroscopy, where the high resolution can contribute in searching and understanding of gluonic excitations, such as glueballs and hybrids. Many other different topics, addressed to answer to fundamental questions of hadron and nuclear physics, will be pursued as well. For instance, properties of mesons with hidden and open charm in the nuclear medium will be studied to understand the origin of hadron masses [5]. In $\bar{p}p$ annihilations the production of baryon–antibaryon pairs allows to study the excitation spectrum of strange and charmed hyperons, where no data are available, and at the same time the dynamics of the $s\bar{s}$ and $c\bar{c}$ creation can be studied in the non perturbative regime of QCD. Since in PANDA the Ξ and $\bar{\Xi}$ hyperons will be copiously produced, both single-Λ and double-Λ hypernuclei can be generated allowing to study nuclear structure and hyperon-nucleon and hyperon-hyperon interactions [6] with high statistics, comparable to the one achievable at J-PARC [7].

Last, but not least, the study of nucleon structure will be investigated in electromagnetic final states (e^+e^-, $\gamma\gamma$), for instance measuring the proton form factors in the time-like region up to high q^2 values, and in Drell-Yan processes. Such an ambitious programme requires a high performance spectrometer. For this reason a multipurpose set-up, which includes innovative detectors, has been designed and it is described in details in [8].

The following sections are focused on a few selected topics.

3 Spectroscopy of charmonium and charmed mesons

In the last years charmonium spectroscopy has enjoyed a renaissance due to the discovery of several missing states and several unexpected ones at B-factories, where very large data sample have been collected.

After the discovery of J/Ψ in 1974, QCD-motivated quark potential models were proposed. Such models were successful in describing the gross features of the spectrum and many predicted states were confirmed by experiments. Thus, below $\bar{D}D$ threshold all states are established and the spectrum is more clear. New precise measurement of η_c mass has been achieved and the η_c' has been unambiguously observed. Nevertheless, the width of h_{1c} has not yet been measured and the high angular momentum states, which are not populated in e^+e^-, need to be measured using $\bar{p}p$ interactions. On the contrary, above the $\bar{D}D$ threshold the picture is still incomplete, only a few states among the ones predicted by potential models have been identified and many unexpected states, called "X, Y, Z", have been observed by different experiments, mainly in the hadronic decays of B mesons [9]. Interpretation of these states from the decay patterns and from their properties is still unclear and the possibility they are not simple $q\bar{q}$ states, such as molecules, tetraquarks, glueballs or hybrid mesons is under debate. Moreover, the open charm spectrum contains states for which quark model expectations do not hold. For instance, the charmed-strange mesons $D^*_{s0}(2317)$ and $D_{s1}(2460)$, discovered in 2003, are narrow states with masses below the DK and D^*K thresholds, respectively, instead of lying at higher masses as predicted. Performing fine energy scans, PANDA will be able to observe the cross section close to the threshold and to measure the width as explained in [10].

The $\bar{p}p$ annihilations is intrinsically a gluon rich process, indeed, most of the promising results for gluonic hadrons comes from $\bar{p}$ annihilation experiments. In the light meson sector more than 10 states have been classified as exotic candidates, among them the $f_0(1500)$ is the best candidate for the ground state glueball with $J^{PC} = 0^{++}$. In the charm sector glueballs and hybrid ($c\bar{c}g$) mesons are expected to be narrower than in the light meson sector, therefore identification should be easier. Lattice QCD models [11] predict heavy glueballs with $J^{PC} = 2^{+-}$ and 0^{+-} at masses ~4.1 GeV/c^2 and ~4.7 GeV/c^2, respectively, and hybrid charmonia with $J^{PC} = 1^{-+}$ and 0^{+-} in the mass range ~4.2–4.5 GeV/c^2. The identification of these states requires high statistics to have reliable spin-parity analysis. The $\bar{p}p$ production cross sections of these exotic states in the charm sector are expected to be similar to the ones of conventional states (~100 pb).

In 2003 Belle first observed the $X(3872)$ narrow state [12], which is now well established. Soon after a series of new hadronic structures, like Ys, have been observed by different experiments at mass values higher than the open charm threshold, with unusual decay patterns. For instance, the $Y(4260)$ [13] does not decay into open charm, but in final states containing J/Ψ, even if it lies above the $D\bar{D}$ threshold. Therefore, they are candidate for charmonium hybrid or multiquark states. Among the "XYZ" exotics the $Z^+(4430)$ is unique [14]. In fact, since it has a non-zero electric charge, it cannot be a simple $c\bar{c}$ state nor a $c\bar{c}g$ hybrid meson and it is a prime candidate for a multiquark meson.

PANDA will profit of the $\bar{p}$ beam at high intensity and high momentum resolution for searching new states, with high statistics and high accuracy measurements, and to determine the nature of these states, which do not fit in the expected spectrum of conventional charmonium states [4].

4 Baryon-antibaryon production

4.1 Baryon spectroscopy

In $\bar{p}p$ interactions, a large fraction of the inelastic cross section is associated to channels with a baryon-antibaryon pair in the final state, therefore a comprehensive study of baryon spectroscopy with |S|= 2, 3 and even |C|= 1 is possible in PANDA. In fact, since the HESR kinematic limit is $\sqrt{s} = 5.5$ GeV, the excitation energy for multistrange baryons reaches the continuum region and it is ~ 1 GeV, for the charmed hyperon Λ_c^+. Most of existing data is in the nucleon sector and comes from high energy pp scattering experiments. Scarce information is available for Ξ and Ω excited states for which spin-parity quantum numbers are still uncertain or unknown.

A look at the available data for excitation spectra of baryons shows that some low-lying states are not at the predicted energies and many predicted states are missing. A possible explanation is a quark-diquark structure of hadrons, which, reducing the number of degrees of freedom, would reduce the number of states. Another possibility from the chiral coupled channel dynamics approach is that the excited baryon states are dynamically generated resonances [15].

Since production cross sections for Ξ resonances in $\bar{p}p \to \bar{Y}Y^*$ interactions are expected to be of the same order as for ground state Ξ production ($\sim 2\mu b$), the study of Ξ resonances with good statistics is feasible. Final states with a baryon-antibaryon pair offer the opportunity to independently investigate the baryon excitation pattern into two charge conjugate systems reducing the systematic uncertainties.

4.2 Non-perturbative QCD dynamics

In hadron physics the identification of relevant degrees of freedom is important for an effective description of the reactions. In the quark picture hyperon pair production involves either the creation of a $q\bar{q}$ pair or the knock-out of such pairs out of the nucleon sea. Hence, the creation mechanism of $q\bar{q}$ pairs and their rearrangement into hadrons can be studied by measuring the reactions of the type $\bar{p}p \to \bar{Y}Y$ with strange or charmed hyperons and antihyperons in the final states. By comparing several reactions involving different quark flavours, OZI rule violation effects can be tested.

The parity violating weak decay of hyperons introduces an asymmetry in the distribution of the decay particles, which gives access to spin degrees of freedom for these reactions (polarisation and spin correlations), with the exception of Σ^- and the Ω^- for which the decay asymmetry is close to zero.

The $\bar{p}p \to \bar{\Lambda}\Lambda$ reaction has been investigated at LEAR by PS185 experiment [16] from threshold up to 2 GeV/c and the spin analysis has shown that the $s\bar{s}$ pair is predominantly produced in a triplet state. Data for this reaction and for other channels with strangeness are scarce above 2 GeV/c and they are missing above

7 GeV/c. No data exist for channels with charmed hyperons. The LEAR data were taken near threshold, it is interesting to verify whether the same features are valid increasing the momentum transfer into more perturbative region. In PANDA the same spin analysis can be extended to other $\bar{Y}Y$ channels and also for $\bar{\Lambda}_c^- \Lambda_c^+$ channel, to study whether the creation of $c\bar{c}$ pair shows the same features as the $s\bar{s}$ pair for $\bar{\Lambda}\Lambda$ channel.

A systematic measurement of total and differential cross sections for these reactions will give new information on single and multiple strangeness or charm production mechanism and its dependence on spin observables. This may help to disentangle the perturbative contributions from the non-perturbative ones, since the charm production probes mainly the hard processes, while the strangeness one is influenced by non-perturbative effects.

5 Proton electromagnetic form factors in the time-like region

Nucleon electric (G_E) and magnetic (G_M) form factors play a fundamental role in our understanding of hadron dynamics. Therefore, for over 40 years many attempts have been made to get a theoretical description in the whole complex q^2 plane and to measure them with different experiments. In the time-like region ($q^2 > 0$) the proton form factors can be studied using the crossed reactions $\bar{p}p \leftrightarrow e^+e^-$. Since analiticity requires a continuous transition of the form factors from space-like to time-like region and equality for $|q^2| \to \infty$, the measurements of the form factors at large q^2 allow to verify the asymptotic behaviour. The possibility to cover a large kinematical domain is interesting to investigate the transition region from soft to hard scattering mechanisms dominated by perturbative QCD, which describes the nucleon in terms of quark and gluon degrees of freedom. Therefore, different theoretical approaches can be tested. The high intensity and high momentum of the $\bar{p}$ beam at HESR, together with the performance of the PANDA detector will allow to investigate the proton form factors in the time-like region up to large values of q^2, where the data are scarce and affected by poor statistics [17].

Recent experiments of the form factors in the space-like region ($q^2 < 0$), using polarised beam or targets in elastic ep scattering, are in disagreement with unpolarised measurements. Indeed, at large values of $-q^2$ the ratio $\mu G_E/G_M$ shows a linear trend as a function of $-q^2$. Such a deviation has been attributed to radiative corrections, as two photons exchange or higher order ones, but needs further investigations in both regions [18, 19].

In the time-like region an independent determination of G_E and G_M form factors requires the measurement of the angular distribution of the outgoing leptons at fixed energy. Previous experiment have measured cross sections up to $q^2 = 18$ (GeV/c)^2 and extracted G_M by using the hypothesis $G_E = G_M$ or $G_E = 0$ (affecting G_M up to 30%). Attempts to determine the ratio $\mathcal{R} = |G_E|/|G_M|$ have been done by the old PS170 experiment at LEAR and, recently, in the BABAR experiment through initial-state radiation reaction. However, the results are affected by large errors and show a different trend. The sensitivity to $\mathcal{R}$ decreases at increasing values of q^2, due to the falling of the cross section and to the relative weight of the magnetic term, which is growing as q^2. With the PANDA experiment such a measurement can be performed up to $q^2 \sim 14$(GeV/c)^2, with a precision at low-q^2 one order of magnitude better than for existing data. At increasing q^2, where $\mathcal{R}$ cannot be determined, it will be possible to extract an effective form factor, under the usual hypothesis of $\mathcal{R} = 1$, up to $q^2 \sim 28$ (GeV/c)^2.

6 Conclusions

The PANDA experiment will study many physics topics in the field of QCD, aiming to achieve a better understanding of the structure and dynamics of hadrons, using the $\bar{p}$ beam with high intensity and high momentum resolution of the HESR at the future FAIR facility. This will allow to have an unprecedented accuracy in various key experiments such as measurements of meson spectroscopy or of proton form factors in the time-like region.

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