PROCEEDINGS OF SCIENCE

Hadron Physics with PANDA

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The PANDA experiment is one of the major projects at the upcoming FAIR facility in Darmstadt, Germany. It will study interactions between antiprotons and protons or nuclei in the momentum range of 1.5 GeV/c to 15 GeV/c with a 4π state-of-the-art detector. The purpose is to learn about fundamental aspects of the strong interaction in the transition region between perturbative QCD and nuclear phenomena. PANDA covers a broad physics program ranging from hadron spectroscopy and structure, baryon/antibaryon production, hadron properties in nuclei to hypernuclei. This paper reviews some of the main physics topics together with a presentation of the detector.

XLVIII International Winter Meeting on Nuclear Physics, BORMIO2010
January 25-29, 2010
Bormio, Italy

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PoS(BORMIO2010)031

1. Introduction

Hadron physics is on the borderline between nuclear and high-energy physics dealing with particles made out of quarks and gluons. Quantum chromodynamics (QCD) is the accepted theory that describes the strong interaction on a fundamental level between these quarks and gluons as one of the four elementary forces of nature. Yet there are many aspects of QCD that are not understood, most prominently the phenomenon of confinement - the observation that quarks and gluons cannot be isolated as single particles but rather form composite objects, the hadrons. A big problem is that QCD becomes non-calculable at energies that are relevant for these bound systems. High quality experimental data is therefore needed to guide the theoretical efforts in this field. The PANDA experiment [1] at the antiproton storage ring HESR at the upcoming FAIR facility in Germany will provide such data with unprecedented precision and statistics. It is being planned by an international collaboration, currently consisting of more than 400 physicists coming from more than 40 institutions in 16 countries.

PoS(BORMIO2010)031

2. The PANDA physics program

The PANDA experiment will cover a wide range of topics, all aiming at improving our understanding of the strong interaction and hadron structure. Significant advances can be expected due to precision and high statistics in the fields of:

- Meson spectroscopy
- Baryon spectroscopy
- Baryon-antibaryon production
- Hypernuclear physics
- Hadron properties in the nuclear medium
- Electromagnetic processes

Features of some of these topics will be outlined in the following. The hypernuclear physics is covered by the contribution by J. Pochodzalla in these proceedings.

2.1 Meson spectroscopy

It is advantageous to study meson spectroscopy using antiproton-proton collisions at the HESR for many reasons. All quantum number that are allowed for $\overline{q}q$ states are accessible in formation experiments in $\overline{p}p$ collisions, where the initial $\overline{p}p$ system fuses into one mesonic state. This is in contrast to studies at e^+e^- colliders where only $J^{PC} = 1^{--}$ states are allowed in formation. Furthermore, the high momentum resolution of the $\overline{p}$ beam in HESR ($\Delta p/p < 10^{-4}$) will allow for resonance scans over particle states where the precision in mass and width is determined by the resolution of the beam and not the detector. This technique was pioneered by the E760/835 experiments at Fermilab giving a resolution of a few hundreds of keV [2].

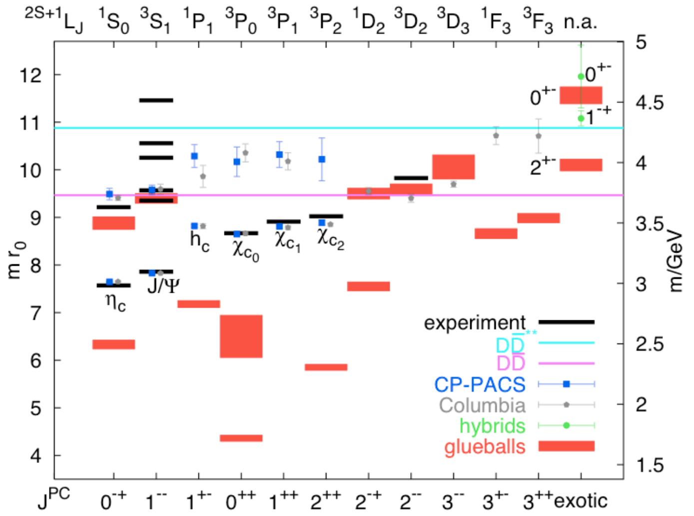

Figure 1: Lattice QCD predictions for charmonium, glueball and hybrid states together with experimental results [7].

The experimental conditions at PANDA will allow for almost an order of magnitude higher precision [3]. The charm quark sector is of particular interest for spectroscopy. There is a low density of narrow $c\bar{c}$ states below the open charm threshold which reduces mixing among them. This offers unique advantages for the understanding of these states. In fact, their spectrum shows a remarkable similarity with the corresponding positronium spectrum for the lower lying states. It is therefore suggestive to assume that the strong interaction potential for charmonium is Coulomb-like in shape. However, the charmonium spectrum is far from being understood. Several new and unexpected narrow states have been observed, the so-called alphabet states (X,Y,Z), which do not fit predictions by potential model calculations [4]. Some of these are candidates for hybrid states *i.e* a bound $c\bar{c}$ state with a valence gluonic content. Furthermore, several expected excited states have escaped detection. There are also many open questions in the open charm meson sector. For example, the narrow $D_{s0}(2317)$ [5] is not understood as its observed mass lies about 100 MeV below potential model predictions, which otherwise predict D_s masses accurately [6].
The search for glueballs, *i.e.* particles entirely consisting of glue, is of particular interest in this mass region. The lowest lying glueball states are expected to mix with ordinary light quark meson states which makes them very difficult to identify. The narrowness of the mesonic states in the charm sector should make it easier to pin down exotic states in this region. Lattice QCD predicts the existence of glueballs with exotic quantum numbers (oddballs) in this mass region. Such states cannot mix with normal mesons and are therefore predicted to be relatively narrow. The lightest oddball, with $J^{PC} = 2^{+-}$ has a predicted mass of 4.2 GeV/c^2 and would be well within reach at PANDA. A Lattice QCD prediction for the charmonium, glueball and spin-exotic hybrids spectrum [7] together with experimental data is given in fig. 1.

2.2 Baryon-antibaryon production

Hyperon-antihyperon pair production in $\bar{p}p$ collisions either involves the creation of strangeantistrange quark pairs or the shake-off of such pairs from the nucleon sea. Hence, the $s\overline{s}$ pair creation mechanism and their arrangement to baryons can be studied from reactions of the type $\overline{p}p \rightarrow \overline{Y}Y$, where Y denotes a hyperon. Furthermore, the parity violating weak decay of most ground state hyperons introduces an asymmetry in the distribution of the decay particles. This gives access to spin degrees of freedom for these processes: polarisation and certain spin correlations [8]. All strange hyperons are energetically accessible in $\overline{p}p$ collisions at HESR as well as single charmed hyperons. Simulations show that the spin observables can be well reconstructed in PANDA with high efficiency and statistics [3]. This opens up the possibility for a systematic investigation of these reactions to bring new information on single and multiple strangeness production and its dependence on spin observables. The many observables will allow for a partial wave analysis to pin down relevant quantum numbers and coupling constants.

2.3 Baryon spectroscopy

An understanding of the baryon spectrum is necessary for an understanding of the strong interaction in the non-perturbative region. The agreement with model predictions is small, both with respect to energies and unobserved states. It is also not clear if observed states are genuine three-quark excitations or created from baryon-meson dynamics [9]. More data are needed to guide the theoretical efforts and the data on the excitation spectrum of baryons become increasingly poor as one adds strangeness as an additional degree of freedom and the data base is particularly scarce for S = -2 and -3 baryons. The study of the $\overline{p}p \rightarrow \overline{Y}Y$ shows that ground state hyperons can be well reconstructed and this makes baryon spectroscopy in the strange sector very promising for PANDA since the excited states will primarily decay to ground state hyperons. A particular benefit of using $\overline{p}p$ reactions for these studies is that the same pattern must be found both in the baryon and antibaryon channels which will reduce the uncertainties. Given the very meagre data in the strangeness sector, in particular multiple strange resonances, there should be a large discovery potential for PANDA in this field.

2.4 Electromagnetic processes

The ground state properties of the nucleons present experimental and theoretical challenges. Several proton distribution functions are accessible with PANDA by studying electromagnetic processes in $\overline{p}p$ interactions. One example is the proton electromagnetic form factor. It has been shown that it falls off more rapidly than the standard dipole form as suggested from perturbative QCD [10]. Although progress is being made in the space-like region from elastic electron scattering experiments, there is a lack of precise data in the time-like region. PANDA offers a unique opportunity to measure the moduli of the electric, $|G_E|$, and magnetic, $|G_M|$, Sachs form factors of the proton in the time-like region by measuring the differential cross section of the $\overline{p}p \rightarrow e^+e^-$ reaction. Simulations show that the ratio $R = |G_E|/|G_M|$ can be measured with unprecedented precision up to a four-momentum transfer of 14 (GeV/c)^2 yielding 10-fold improvement on the world data [3].

3. The PANDA detector

The PANDA detector [11] will be located at the High Energy Storage Ring, HESR, for an-

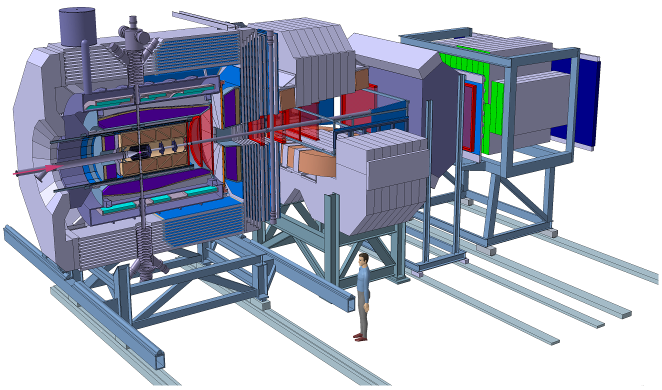

Figure 2: Layout of the PANDA detector with the Target Spectrometer surrounding the interaction region (left) and the Forward Spectrometer (right).

tiprotons at the future FAIR facility [12]. It is designed as a state-of-the-art multipurpose detector to accommodate the planned versatile physics program. It will be installed at the HESR ring and be equipped with internal targets of the pellet or the cluster-jet type. With the anticipated 10^{11} stored antiprotons they will provide a luminosity of 2×10^{31} cm^{-2} s^{-1} over the 1.5 GeV/c - 15 GeV/c momentum range of the HESR. This will lead to a reaction rate of $\sim 10^7$ s^{-1} which the detector must be capable to handle with good particle identification and momentum resolution for γ, e, μ, π, K and p. It should also be capable to measure displaced vertices from D and K_s mesons and Λ's. An almost 4π cover is necessary to make exclusive measurements of the final states. The detector is therefore divided into a target and a forward spectrometer as depicted in Figure 2 with an overall length of 12 m. The target spectrometer (TS) is based on a 2 T superconducting magnet surrounding the interaction point measuring large angles and a forward spectrometer (FS) based on a 2 Tm dipole magnet for small angle tracks.

3.1 Target spectrometer

The detectors in the TS are arranged in an onion-layered structure. The innermost detector is the micro-vertex detector (MVD) which is optimised for the detection of D mesons and Λ hyperons. It is based on radiation hard silicon pixel and strip detectors arranged in four barrel layers for the large angle tracks and six planar layers in the very forward region. The inner layers will be $100 \times 100\mu$m pixel detectors whereas the outer ones will consist of strip detectors. The MVD will allow for a vertex reconstruction to a precision of 50 μm and provide dE/dX information for particle identification. Two options are presently considered for the central tracker, a straw tube tracker (STT) or a time projection chamber with a GEM read out. Both should provide a momentum resolution at the percent level. The STT is based on proven technology whereas the TPC is a more challenging project. The latter has the advantage of a lower material budget and better tracking and particle identification. The tracking in the forward direction is complemented with three planar GEM detectors. The tracking is followed by two quartz based DIRC detectors for particle identification. Electromagnetic calorimetry is provided by $\sim$ 16000 PWO crystals. They will cover an energy range from a few MeV up to several GeV. The crystals will be cooled to $-25°$

C to increase the light yield, providing an energy resolution of 2% at 1 GeV photon energy. The magnet yoke will be interleaved with tracking detectors for muon identification. The backward end-cap calorimeter can be removed to allow for the insertion of an active secondary target and germanium-array for the hypernuclear studies.

3.2 Forward spectrometer

Trajectories of forward going particles will be measured with a set of drift chambers in the dipole magnet giving a momentum resolution of 0.2% for 3 GeV/c protons. A RICH detector will enable π/K and K/p separation at the highest momenta and a Time-of-Flight wall from plastic scintillator material will provide this separation at the lower momenta. A forward electromagnetic calorimeter of the shaslik-type will measure photons in the forward region with a resolution of $4\%/\sqrt{E}$. The last detector is a range tracking system of interleaved absorbers and drift tubes to measure muons, neutrons and antineutrons.

4. Conclusions

The PANDA collaboration will realize a very rich and versatile program with $\overline{p}$ interactions at the HESR storage ring at the upcoming FAIR facility [12]. There is a unique potential to advance our understanding of the strong interaction in the transition region between perturbative QCD and strong QCD. Only a part of the exciting physics could be presented here. A more comprehensive overview can be found in ref [3].

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