QCD studies with anti-protons at FAIR: Indian participation in PANDA

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The Facility for Antiproton and Ion Research (FAIR) is a future project at GSI which will extend hadron physics studies up to the charm meson region using antiproton beams together with a state-of-the-art detector antiproton annihilation at Darmstadt (PANDA). The physics aim, in a broader sense, is to address the fundamental problems of hadron physics and aspects of quantum chromo-dynamics (QCD) at low energies. The proposed work in India will consist of several parts: R&D studies of silicon micro-strip detector, development of a scintillator hodoscope with silicon photomultiplier (SiPM) readout, studies of SiPM as photon counter and simulation studies of the detector design as well as physics case studies. The present article describes the physics motivation and initial progress made towards achieving these goals.

Keywords. PANDA collaboration, PANDA simulation, scintillator tile hodoscope, silicon microstrip detector, silicon photomultiplier.

Introduction

UNDERSTANDING the strong nuclear force in terms of the quarks and the gluons, is one of the outstanding questions in nuclear physics. Quantum chromo-dynamics (QCD) is the basic theory of strong interactions and the study of QCD will be one of the highlights of the programmes at FAIR. The field of hadron physics includes the structure of hadrons and the interactions involving hadrons. Hadron physics in some sense bridges the gap between the high-energy and low-energy nuclear physics and connects the nuclear interaction at short distances, fraction of the size of the nucleon (perturbative region) to that at long distances, comparable to the size of the nucleon (non-perturbative regime). In the case of nucleons which are made up of almost massless quarks and massless gluons, the mass is not the sum of the constituents' mass. This raises the fundamental question in hadron physics on the origin of hadron mass and that of visible universe[1]. Another fundamental question is the CP symmetry and its violation. The effect of CP violation has been observed in the decay of neutral kaons and B mesons. A significant CP violation would indicate physics beyond the standard model.

At the high-energy storage ring (HESR) of the international FAIR at GSI, Darmstadt it is proposed to accelerate antiprotons of unprecedented intensity and quality in the energy range of 1–15 GeV/c. Advanced antiproton cooling techniques will enable high-energy resolution and a versatile detector set-up (PANDA) will be employed allowing for the first time a measurement of both electromagnetic and hadronic decay modes with high precision. A brief account of the interesting nuclear physics research programmes[1] which are planned to be pursued using the PANDA and the related experimental challenges are reported here.

Charmonium ($C\bar{C}$) spectroscopy

Due to the relatively heavy mass of charm quark, spectroscopy of mesons built on charmed quark and antiquark pairs offers advantages of small non-perturbative QCD effects which is amenable to simplified theoretical treatment. On the experimental side, the high precision measurements have been performed only for ψ charmonium states which could be formed directly at e^+e^- colliders. The errors on mass and width of other known states are quite high and very little is known about the states above the $D\bar{D}$ threshold. In $p\bar{p}$ annihilations, all possible meson states can be formed and precision measurement of mass, width and decay branches of all charmonium states can be performed. High luminosity of the anti-proton beam at HESR, FAIR will take advantage of charmonium production in $\bar{p}$–p annihilations with the PANDA detector registering hadronic final states that have higher branching ratios.

Firm establishment of QCD-predicted charmed hybrids and glue balls

The fundamental building blocks of QCD are the quarks which interact with each other by exchanging gluons. QCD is rather well understood at short distance scale. At a distance comparable to the size of nucleon, the interaction between quarks becomes so strong that they can no longer be separated. This unusual behaviour, in contrast

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to the electromagnetic and gravitational interactions, is due to the self-interaction of gluons. An important consequence of the gluon self-interaction is the predicted existence of hadronic systems consisting of only gluons called glue balls and hybrids consisting of a quark, an anti-quark and excited gluons. HESR at FAIR offers an unique facility for study of these exotic states.

γ-Ray spectroscopy of single and double hypernuclei

γ-Ray spectroscopy of single and double hyper nuclei for the study of structure of hyper nuclei, hyperon–nucleon interaction and hyperon–hyperon interaction is being planned at FAIR. In hypernucleus, the strangeness quantum number is introduced into the nucleus by replacing an up or down quark by a strange quark in a nucleon bound in a nucleus. The nucleon with a strange quark, i.e. the hyperon is not restricted by Pauli principle in populating nuclear states in contrast to protons and neutrons. These exotic nuclei offer a variety of new and exciting perspectives in nuclear spectroscopy and is a novel complement to the proposal to study the structure of nuclei with radioactive ion beams. The programme of the PANDA detector together with the high luminosity beam at FAIR opens new perspectives for hypernuclear structure studies.

Modification of meson properties in nuclear medium

Study of in-medium modification of hadron masses is one of the main research activities at various laboratories. The in-medium potential of pions has been deduced from studies of deeply bound pionic atomic states and the mass shift of kaons in nuclear matter have been observed in the studies of kaon production in heavy ion collisions. The studies, so far, have been focused in the light quark sector due to limitation in the available energy. Availability of high energy anti-protons (up to 15 GeV/c) at FAIR will allow an extension of this programme to the charm sector. A possible signal would be the reduction of $D\bar{D}$ threshold resulting in an enhancement of D and $\bar{D}$ meson production, in particular at sub-threshold energies. The detection would be through their hadronic decay modes.

A brief overview of the PANDA detector

The PANDA detector is a hybrid detector[1] designed to achieve 4π acceptance, high resolution for tracking, particle identification, calorimetry and high rate capabilities (2×10^7 annihilations/s). The detector (Figure 1) consists of two parts: a target spectrometer and a forward spectrometer. The target spectrometer surrounds the interaction region and is based on a superconducting solenoid magnet. The innermost sub-detector of the target spectrometer is a micro-vertex-detector for precise tracking information. It consists of several layers of silicon pixel detector and silicon strip detector. At larger distances from the interaction point the vertex tracking is done either by straw tubes (STT) or a high-rate time projection chamber (TPC) in the barrel part, and a set of multi-wire drift chambers (MDC) in the forward direction. For particle identification, a Cherenkov counter, detection of internally reflected Cherenkov light (DIRC) is foreseen. Following the Cherenkov detector, there will be a compact electromagnetic calorimeter made of $PbWO_4$ crystals with avalanche photodiode readout. The last layer of the target spectrometer is a muon detector which is located outside the solenoid magnet yoke. The forward spectrometer consists of a dipole magnet with a set of MDC for tracking, a RICH detector for particle identification, electromagnetic and hadronic calorimeters for charged and neutral particles, and muon counters for detection of muons. The target and forward spectrometers will provide high-resolution particle tracking, identification and momentum reconstruction for both charged as well as neutral particles that will enable us to detect the complete spectrum of final states relevant to the PANDA physics objectives.

Indian participation in PANDA

As a part of the Department of Science and Technology initiative, a few town meetings related to the Indian participation in PANDA were organized involving national laboratories, IITs and other universities; BEL and ECIL also attended some of these meetings. The initiative was supported by some of the scientists from Germany (U. Wiedner, J. Ritman and K. Peters) involved in the PANDA programme who not only attended these meetings but also provided the necessary inputs regarding the scope of the PANDA programme. They helped to identify the areas where the Indian team could participate and contribute. The Indian team consists of the following institutes and organizations: IIT-Bombay; BARC – Mumbai; TIFR – Mumbai; SINP – Kolkata; VECC – Kolkata; IIT-Guwahati; IIT-Indore; Aligarh Muslim University – Aligarh; South Gujarat University – Gujarat; University of Pune – Pune; Karnatak University – Dharwad; MSU, Vadodara; Magadh University – Bodhgaya; NIT – Jalandhar; ECIL – Hyderabad, and BEL – Bangalore. As a result of the discussions with the German PANDA team, and also taking into account the Indian interest and expertise, the following broad areas are suggested for Indian participation in PANDA.

Luminosity monitor: silicon micro-strip detector

The physics processes to be used is based on the premise that the differential cross-section for $\bar{p}$–p elastic scattering can be exactly calculated in the Coulomb region. Owing to low momentum transfer, in extremely forward direction

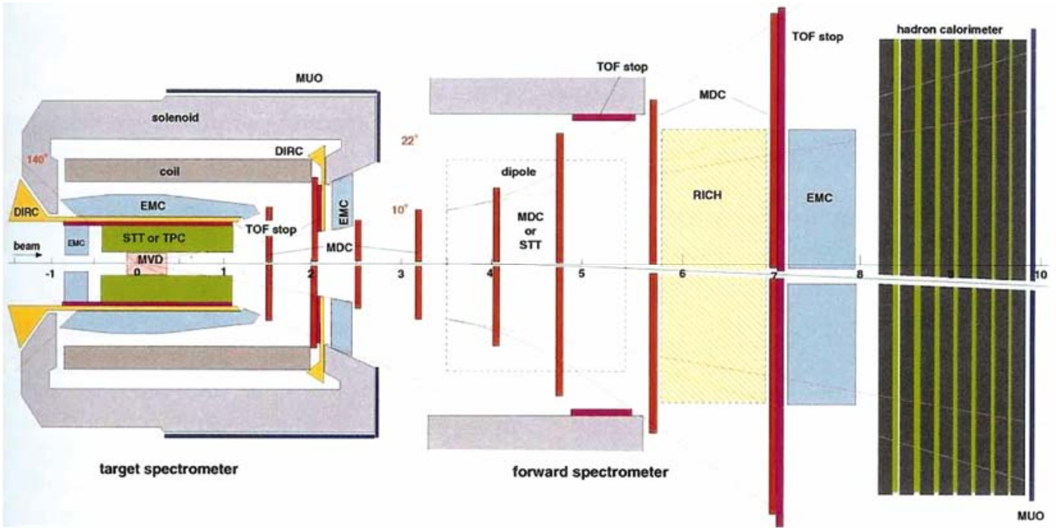

Figure 1. A schematic view of the PANDA detector. The HESR beam enters the detector from the left, interacts with the target at 0 m on the horizontal scale. The surrounding and forward detectors are indicated as MVD, Micro vertex detector; STT, Straw tube tracker; TPC, Time projection chamber; TOF, Time-of-flight stop counters, DIRC and RICH, Cherenkov counters; EMC, Electro magnetic calorimeter; MDC, Multi-wire drift chamber; MUO, Muon counter and hadron calorimeter[1].

the angular distribution can be uniquely transformed into the *t*-distribution, giving the luminosity for normalization. It is envisaged that the luminosity monitor would be placed about 15 m downstream of the target. It will consist of double-sided silicon strip detectors 200–300 μ thick with about 50 μ pitch. It is envisaged that these will be rectangular sensors and will be located very close to the beam axis for extreme forward angle measurement. There will be four sensors at a given position downstream from the target and four such stations at different distances from the target (separation of about 15 cm between stations). This will be sufficient to measure the angle of the antiproton with respect to the direction of the beam. Detailed simulation studies within the PandaRoot software have been undertaken for visualization and geometry optimization of such a microstrip detector.

Scintillator tile hodoscope with SiPM readout

A hodoscope based on plastic scintillator tiles with SiPM as photon detector has been proposed for the PANDA experiment. The detector will serve for precision time measurements for triggering and the determination of time-of-flight. The detector will consist of about 15,000 scintillator tiles readout by SiPM and will be mounted in front of the crystals of the electromagnetic calorimeter (EMC). The concept provides the use of a minimum amount of material and a good spatial resolution due to its granularity. The timing detector concept is based on $2 \times 2 \times 0.5\ cm^3$ scintillator tiles matching the front face of the calorimeter crystals. The scintillator tiles are readout by SiPMs of appropriate size. In addition to timing and position information, the hodoscope will allow clean detection of gamma-conversions in front of EMC in particular within the region of DIRC. Also, it is best suited for charged-neutral discrimination. The concept of the scintillator hodoscope with SiPM as readout with the whole system operating at very low temperature is a new concept and requires detailed R&D studies. Simulation studies are being planned for optimal arrangement of scintillator tiles and SiPM array. On the hardware side, studies will be carried out with SiPM on its low temperature (~ –25°C) behaviour and radiation hardness. In addition, development of ASIC electronics for SiPM readout is being planned.

R&D activities on SiPM

SiPMs are a new type of photon counting devices that show great promise to be used as detection device in combination with scintillators/Cherenkov radiators. SiPM is essentially an avalanche photo-diode operated in limited Geiger mode. They have been considered as potential readout devices for DIRC Cherenkov counter of the PANDA detector[1] and the proposed scintillator tile hodoscope. In addition, the potential use of SiPM includes medical diagnosis, fluorescence measurement and high-energy physics experiments. The SiPM module is a photon counting device capable of low light level detection. It is essentially an opto-semiconductor device with excellent photon counting capability and possesses great advantages over the conventional PMTs because of low voltage operation and insensitivity to magnetic fields. In many of the high-energy physics experiments, the photon sensors are required to operate in high magnetic fields precluding the use of conventional PMTs. This problem can be overcome with the use of SiPMs. SiPM operating in Geiger mode a very large gain (~ 10^6), magnitude of which is determined by the internal diode capacitance and applied over-bias voltage, comparable to that of PMTs can be achieved. A SiPM consists of matrix of microcells (known as pixels), typically between 100 and 10,000 per mm^2. Each microcell acts as a digital device where the output signal is independent of the number of photons absorbed. When all the cells are connected in parallel, SiPM becomes an analogue device thereby allowing the number of incident photons to be counted. Different types of SiPM manufactured by Hamamatsu and Zecotek with different sizes of pixels and active area have been tested using a pico-second pulsed diode laser of 660 nm wavelength as well as LED with $\lambda = 460$ nm. Single photon and multi-photon peaks have been seen by adjusting the laser intensity (Figure 2). The photo-detection efficiency of SiPM was studied as a function of wavelength of the incident photons using a monochromator that spans wavelength from 200 to 800 nm. The photo-sensitivity of different SiPMs was normalized with a PIN diode which itself was calibrated by the producer. At present, several prototype Cherenkov detectors with different readout systems are being developed by the PANDA collaboration for R&D studies. One such prototype detector with Geiger-APD readout has been built at Giessen and was tested in-beam at GSI. The radiator used was Plexiglas in rectangular bar-shaped and was coupled to a focusing element for guiding the Cherenkov photons onto several silicon photomultipliers. The beam was a proton beam of kinetic energy 2 GeV with a spill length of 5 s and intensity about 50,000 per spill. The beam was defined by scintillator hodoscopes mounted in a cross-geometry at several locations. Coincidence signals from these finger counters were used as trigger. Initial test shows a satisfactory result (Figure 3). This part of the work was performed in collaboration with GSI and Giessen university using the test set-up at GSI, Germany, and at Frankfurt University[2]. The in-beam test experiment reported here was performed with the prototype detector built in Giessen, Germany and using 2 GeV proton beam from the GSI accelerator[3].

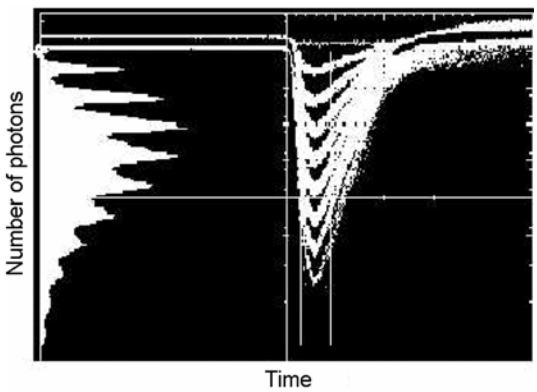

Figure 2. A typical SiPM spectrum from Hamamatsu MPPC triggered by laser light. Different peaks correspond to different photo peaks, hence, the number of pixels fired. In this case, up to eight photon peaks are seen. Photograph is taken from digital oscilloscope with the histogramming mode on.

Simulation and reconstruction for barrel DIRC

One of the crucial points for any high-energy physics experiment is to obtain a good pion/kaon separation, i.e. particle identification (PID). For particles in minimum ionizing range, the conventional methods of PID using energy loss and time-of-flight become insufficient. In such a situation, the measurement of velocity of particles using Cherenkov radiation is an effective tool for PID in combination with momentum information from a tracking detector. The PANDA experiment at FAIR/GSI plans to use a novel technique for PID with DIRC light. DIRC uses, in contrast to the conventional gas Cherenkov detectors, a solid radiator and total internal reflection to guide Cherenkov photons onto a detection plane where it will be detected by advanced photon counters. A detailed simulation study is a must for the design of such a photon counter, to get reliable reconstruction of the Cherenkov angle and for overall performance study of the PANDA detector. Such a simulation study has been performed[4] in the framework of the existing PandaRoot software with an additional implementation of a C^{++} class that includes the following realistic detector information.

- Pixelization of the photon detector (6.5 mm grid).
- Convolution with detection efficiency of photocathode.
- Gaussian smearing of time ($\sigma = 50$ ps).

A typical *x–y* distribution of the hits in the photon detector plane for an incident kaon of momentum 2 GeV/c, after efficiency correction and pixelization of the detector plane, is shown in Figure 4. A ring-like structure in the photon detector plane, as expected, is seen which forms the input for further reconstruction. The reconstruction in DIRC is quite challenging due to the compactness of the

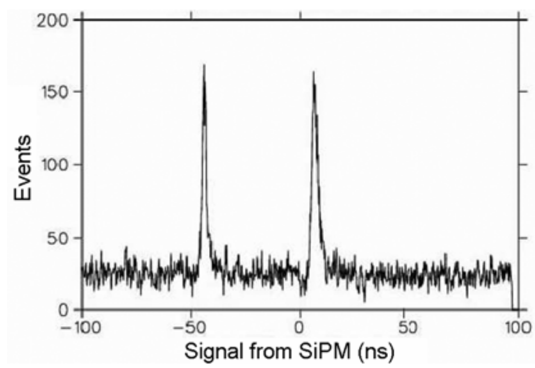

Figure 3. Histogram output from one of the SiPMs that was positioned to see maximum Cherenkov light for an angle setting of 7.5° of radiator with respect to the beam. The two peaks are due to triggering from both the leading edge and the trailing edge.

detector. It uses charged track information provided by the tracking detectors along with the position of the photon detector hits. The photon propagation time t_p provides additional constraint and gives a powerful tool to reject the backgrounds. The possible reconstruction algorithm in barrel DIRC motivated by BaBar DIRC[5], is as follows: (i) initial fast θ_c reconstruction based on look-up table approach and then (ii) followed by detail likelihood methods. The fast reconstruction is necessary to consider DIRC in the triggering decision. From the information of the spatial position of the bar through which the track passed and the PMT hit position, a three-dimensional vector can be constructed from the centre of the bar end to the centre of each pixel. This vector is then extrapolated inside the radiator bar using Snell's law. Conjugating with the track direction available from tracking detectors, this defines the Cherenkov photon direction θ_c and ϕ_c with some ambiguity due to last reflections from different bar surfaces and mirrors. For fast triggering, this information could be read from a look-up table produced and tested off-line.

One of the important factors that limits the resolution of the Cherenkov angle reconstruction is the chromatic dispersion. However, the angle resolution and hence the particle identification resolution of DIRC can be improved if one can determine the colour of the Cherenkov photon. As the Cherenkov photon flight time depends upon its wavelength, as $v_{\mathrm{red}} > v_{\mathrm{blue}}$ which gives $t_{\mathrm{red}} < t_{\mathrm{blue}}$, it may be possible to determine the colour of the photon through its flight time. The present simulation for incident kaons with momentum of 2 GeV ($\beta = 0.97$) shows (Figure 5) a time distribution plot in different wavelength band 300–350 nm (blue) and 500–550 nm (red). The study reveals the possibility to reduce the smearing due to chromaticity and hence improvement of PID if the photon detector has a time resolution better than ~ 100 ps.

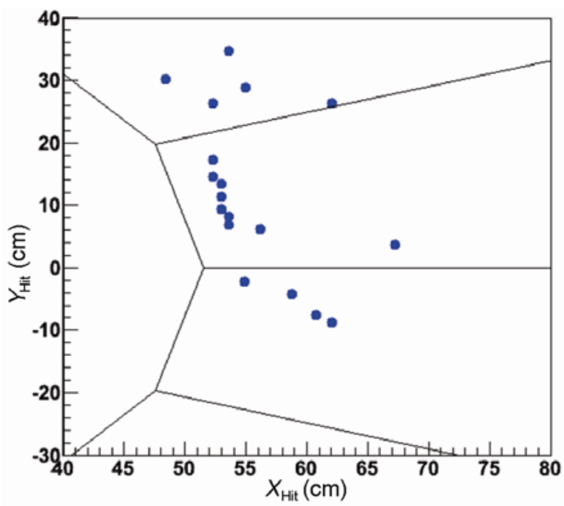

Figure 4. The expected ring structure in the photon detector plane for an incident kaon with momentum 2 GeV/c.

Analysis tools and physics simulation

The simulation of a given physics case is performed in several steps inside the software framework PandaRoot developed for the PANDA experiment. Event generation with accurate decay models for individual physics channels (using EVTGEN[6]) as well as various or background channels (using DPM[7] and UrQMD) event generators have been incorporated. The particles in the generated events are tracked inside the complete PANDA detector using the transport codes GEANT3/GEANT4. In the next step, the response of the individual detectors and the signals generated processing in the front-end electronics is modelled and digitized. The track reconstruction and particle identification of charged and neutral particle candidates are performed for further physics analysis.

High-level physics analysis tools which allow to make use of vertex and kinematic fits and to reconstruct full decay chain in various physics cases have been developed. Apart from the efficient reconstruction of the primary and secondary vertices, the possibility to include other kinematic constraints such as mass constraint, total momentum constraint, total energy constraint, four momentum constraints, etc. have been developed for the data analysis. The fitting procedure provides the quality of the vertex and kinematic fits in terms of a normalized χ^2 probability distribution for applying the cuts to improve the signal to background ratio.

The physics programme of PANDA has been enlivened by the exciting new experimental observations of states in the charmonium and open charm mesons spectrum at the B and charm factories. The discovery of the surprisingly light and narrow open charm meson states such as D_s^* (2317)[8] and D_s (2460)[9], in recent years, have questioned the validity of the 'naive quark potential model' to describe these states. The intrinsic width of these states are small enough so that only the upper limits have been measured ($\Gamma \le 4.6$ MeV and $\Gamma \le 5.5$ MeV for the D_s^* (2317) and D_s (2460) respectively). Experimental measurements

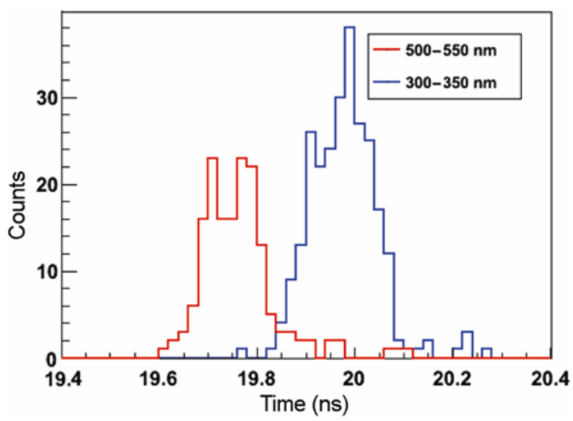

Figure 5. Time distribution for the different wavelength band for a incident kaon with momentum 2 GeV/c.

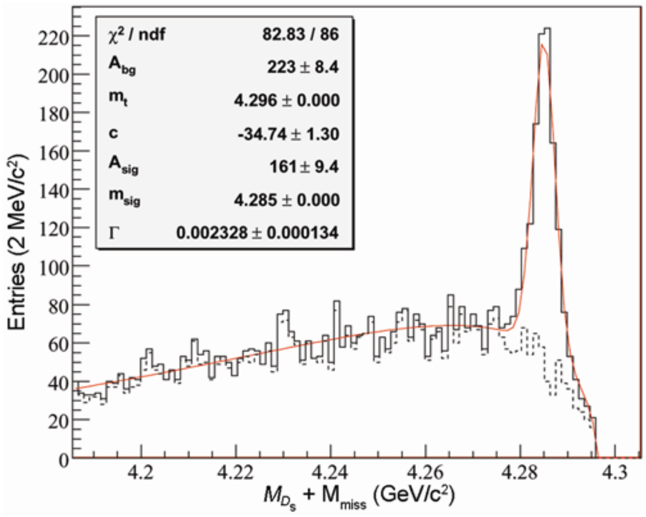

Figure 6. The sum of missing mass for the D_s^* (2317), M_{miss} and mass of $D_s^{\pm}$, M_{D_s} candidates for the background (dashed histograms) and signal plus background (solid histograms). The fit is performed by a combination of Argus function (for the background) and a Gaussian (for the signal).

with precise determination of mass and widths are required to understand the true nature of these states. The PANDA experiment at FAIR will provide a suitable environment to measure the width of these states with much higher precision because of the high-quality phase space cooled antiproton beam. Simulations have been performed for the reaction $p\bar{p} \to D_s^{\pm} D_s^*$ (2317)$\mp$ and associated background channels by reconstructing the primary $D_s^{\pm}$ in the $D_s^{\pm} \to \phi\pi^{\pm}$ $(\phi \to K^+K^-)$ decay mode. The distribution M_{sum}, which represents the sum of missing mass (M_{miss}) and mass of reconstructed D_s (M_{D_s}) candidates as shown in Figure 6 can be used to achieve a good discrimination between the signal and the background events. The widths of narrow resonance states can be finally extracted from the measurement of energy dependent cross-section in the vicinity of the threshold.

Theoretical study

On the theoretical front, there is a keen interest among the Indian theory community to undertake the theoretical work related to the PANDA physics. As mentioned here, one of the major goals of PANDA is to perform detailed study of the spectrum of charmonia and charmonium hybrids that includes determination of their masses, widths, quantum numbers and decay properties. Another important goal of PANDA is to look for detail structural information of the observed states, i.e. whether they are simple charmonium, meson–meson molecular, quark–gluon hybrid or tetra-quark states. Numerical evaluation of charmonium and charmonium-hybrid production cross-sections are evidently crucial for the PANDA physics programme. These calculations can be performed within an effective Lagrangian model framework. This would require the knowledge about the coupling strengths of the various charmonium resonances to the proton–antiproton channel which is a crucial issue for the PANDA project.

Summary

The facility for antiproton and ion research will be an unique facility for the study of hadron structure and QCD in the charm sector. There is a strong interest among the Indian hadron physics community to be a part of this exciting physics programme. Initiatives have been taken to finalize various detector components where Indian scientists can contribute and an initial R&D programme towards this has been started. The proposed work will give Indian scientists an opportunity to work at the frontier area of nuclear physics, a region in which no facilities exist in the country and to get involved in the construction of state-of-the-art detection system. The know-how gained in the experiments in constructing and handling large-scale detectors and working with advanced data processing software will certainly be very beneficial and useful in planning future facilities in the country.

Those individuals, groups and institutions who wish to contribute to this programme may contact the following: S. Kailas, BARC (kailas@barc.gov.in), Raghava Varma, IIT(B) (varma@phy.iitb.ac.in) and B. J. Roy, BARC (bjroy@barc.gov.in).

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