Design of a very thin target for hypernuclear production using antiprotons at FAIR

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Abstract. The future PANDA experiment is dedicated to hadron physics. In particular a new idea to produce doubly strange systems from $\Xi^-$ hyperons obtained from antiprotons is proposed. The developments of the hypernuclear as well as of the exotic hyperatom physics requires the production of statistically significant amounts of doubly strange $\Xi^-$ hyperons. The FAIR project will supply intense beam of antiprotons from the HESR ring. A target should be put inside the beam pipe and its features will play a crucial role in producing high rates of double hypernuclei. A new set-up with a novel idea for a hyperon production target, together with the results of some preliminary tests, will be described in this paper.

1. Introduction

The future facility FAIR (Facility for Antiproton and Ion Research) with its intense beams will include the HESR ring (High Energy Storage Ring), where the PANDA experiment will be located. This project offers new perspectives in the experimental study of hadronic physics, mainly concentrated to investigate the strong interactions. In particular special care is required for two physical programs. One is dedicated to fulfill the lack of experimental information about the $S = -2$ systems ($\Xi^-$- hypernuclei, $\Lambda\Lambda$-hypernuclei) with the goal of a unified description of the baryon-baryon interaction. The second is focused on meson spectroscopy in the charmonium energy range. For this purpose very high energy antiprotons are necessary for spectroscopy measurements. To satisfy the scientific needs, the PANDA detector was designed to have $\approx 4\pi$ acceptance together with a high detection rate capability and a particle momentum resolution of $\approx 1\%$. Moreover, two different operation modes are foreseen to be available at HESR: the so called High Resolution mode, obtained by an electron cooling system, which will provide a momentum resolution $\Delta p/p = 10^{5}$ at a luminosity of $L = 10^{31}\, cm^2 s^{-1}$, and the High Luminosity mode, obtained by a stochastic cooling system, with a worse momentum spread ($\Delta p/p = 10^{4}$) but $L = 2 \cdot 10^{32} cm^2 s^{-1}$.

Concerning the hypernuclear physics task, the main interest is focused on the doubly strange hyperon interaction with the nucleon and the nucleus at rest, the hyperon - hyperon interaction as well as on the hyperon - induced non - mesonic weak decay. Up to now, the only available way to study these processes has been the formation of $\Xi^-$ and $\Lambda\Lambda$ hypernuclei. Unfortunately the short lifetime of the hyperons puts severe constraints on the production techniques. On the other hand the availability of high statistics is a mandatory requirement in order to reach the above mentioned goals.
2. Production of Double Hypernuclei in HESR at FAIR

Up to now the strangeness physics has been explored using kaon beams. In the PANDA experiment at FAIR the double hypernuclei are planned to be produced via antiproton annihilation on nuclei [1]. Ξ⁻ hyperons will be created inside the nucleus by the quasi free reactions:

\[
\bar{p} + p \rightarrow \Xi^- + \Xi^+
\]  
(1)

and

\[
\bar{p} + n \rightarrow \Xi^- + \Xi^0
\]

with antiproton momentum \( p_{\bar{p}} = 3 \text{ GeV/c} \), just below the \( \pi \) production threshold. At this antiproton momentum the cross section of the reactions (1) and (2) is \( \sigma_{\bar{p}N} \approx 2 \mu b \) [2, 3]. The \( \Xi \), created along with \( \Xi^- \), annihilates mostly in the residual nucleus or inside the target. The annihilation products are pions and kaons and among them at least two are anti-kaons. The \( \Xi \) annihilation plays a crucial role in the detection of the whole double hypernuclei formation process, because it represents a clear tag of the \( \Xi^- \) production. The processes, which the negative hyperon undergoes, are totally different and are illustrated in Fig.1. First, it scatters against the nucleons of the residual nucleus where has been created, then, after exiting from nucleus it slows down in ordinary matter losing energy by ionization until it stops. Once at rest it is captured into some high atomic levels creating a hyper-atom and it starts the hyperatomic cascade towards lower levels. During the cascade X - rays are emitted. When the hyperon comes close enough to the nucleus it is absorbed. At this point, the \( \Xi^- \) hyperon can interact with a proton to produce two \( \Lambda \)'s through the reaction:

\[
\Xi^- + p \rightarrow \Lambda \Lambda + 28MeV
\]  
(3)

If both \( \Lambda \)'s stick to the nucleus, a double hypernucleus is formed with the emission of \( \gamma' \)'s. The weak decay of both \( \Lambda \)'s will be the last step.

During the slowing down the \( \Xi^- \)'s can decay due to their short lifetime \( \tau \approx 1.639 \cdot 10^{-10} \text{ s} \). Therefore only a fraction of the produced \( \Xi^- \) will stop in the target material. This fraction has been calculated to be in the range \((2 - 4) \cdot 10^{-3}\) stopped to produced hyperons, for production targets from \( ^{12}C \) to \( ^{207}Au \) and assuming \( ^{12}C \) as the stopping material.

3. PANDA experimental set-up

The full understanding of the nuclear processes requires measurements with instruments having excellent energy resolution together with reasonable efficiency. The PANDA Collaboration has proposed a general purpose detector system which allows the measurement of charged particles as well as neutral ones with very good precision. The planned PANDA detector will be divided into two parts, the so-called target spectrometer (TS), consisting of a solenoid providing 2T magnetic field, surrounding the target, and a forward spectrometer (FS) covering most forward angles. The combination of these two spectrometers will allow measurements in a full solid angle coverage with good particle identification and momentum resolution. Such a solution seems to be sufficiently flexible to be modified by adding other elements needed for each specific experiment such as for the case of the double hypernuclei measurements.

3.1. Double Hypernuclear set-up within PANDA

A new technique based on a system of two separated targets for the \( \Xi^- \) production and the double hypernuclei formation has been designed by the PANDA Collaboration. In this way the production rate is optimized by a suitable choice of the parameters of the primary target,
Figure 1. Two step production technique for the double hypernuclei at PANDA

independently of the characteristics of the secondary one. Therefore different materials can be chosen for the latter in order to study several different hypernuclei. The whole set-up is shown in Fig. 2: it is made of a primary target, to be inserted inside the beam pipe of the HESR, for the production of the $\Xi^-$ hyperon from reactions (1,2) and a secondary target located around the beam pipe, where the $\Xi^-$ will be stopped.

The second important component of the double hypernuclear set-up is the assembly of High Purity Germanium crystal (HPGe) dedicated to the gamma and X rays detection.

The HPGe detectors are assembled in a configuration of 15 clusters where each cluster is made of 3 crystals. They are located upstream of the hypernuclear target in order to cover almost $2\pi$ of solid angle and to maximize the acceptance. These detectors will operate inside the fringing field of the central solenoid of PANDA whose non negligible effects on the crystal performances have been accurately measured [4].
4. The Antiproton beam and the primary target

The HESR ring will supply intense antiprotons beam with momentum range from 1.5 to 15 GeV/c. Inside the ring the antiprotons circulate at a frequency $\nu \approx 5 \cdot 10^8$ Hz. The antiprotons are produced and cooled outside HESR at a maximum rate of $2 \cdot 10^7 \bar{p}/s$ and are injected in discrete bunches into the ring every repetition time $T_{\text{cycle}}$. At present the interval is foreseen to be $T_{\text{cycle}} \approx 10$ s but a method to decrease it down to few seconds is under study. The bunch length is $L_B \approx 200$ m [6].

4.1. The Antiproton beam structure

The presence of the primary target inside the beam pipe changes the time structure of the beam between two consecutive injections. In fact, the bunch containing $I_0$ antiprotons at injection, is depleted at each passage through the target because each antiproton can undergo the following processes: a) the Coulomb scattering by the target nuclei, b) the strong interaction (annihilation, nuclear scattering, CEX reactions, meson production...) and c) ionization.

Coulomb scattering by the nuclei (Single Coulomb Scattering) can deviate the antiproton trajectory in such a way that they cannot be recovered by the cooling system. The cross section for these deviated antiprotons at various energies in the range of the HESR has been evaluated by Lehrach et al.[6] for a hydrogen target of density $4 \cdot 10^{15}$ atom/cm$^2$. For a $^{12}$C target and antiprotons of 3 GeV/c the corresponding value is $\sigma_{\text{SCS}} \approx 1$ barn.

Concerning the antiproton-nucleus strong interactions, it must be remarked that the biggest contributions at 3 GeV/c come from the annihilation, scattering and Charge EXchange processes. The cross sections of the elementary reactions $\bar{p}N$ can be found in [7]. By using the scaling law $\sigma(A) = \sigma(N) \cdot A^{2/3}$ the cross section for nuclei can be estimated with a good approximation.
Ionization is basically a transfer of energy from the antiprotons to the electrons of the target without appreciable change of direction nor $\bar{p}$ destruction. If the target is very thin, as will be discussed in the next paragraph, the amount of transferred energy is small and the $\bar{p}$ momentum is recovered by the cooling system of HESR.

Therefore only processes a) and b) affect the beam content. Defining $\sigma_T^A$, their total nuclear cross section, the bunch contents $I_n$ after the $n$–th passage is given by:

$$I_n = I_0 \cdot e^{-n \cdot \sigma_T^A \cdot f_b \cdot (\rho \cdot N_A/A) \cdot W_t}$$

where $W_t$ is the thickness of the target of the density $\rho$, $N_A$ is the Avogadro number and $f_b$ is the fraction of the beam spot illuminating the target.

After the $n$-th passage, the $\bar{p}$ annihilations, whose total number is given by:

$$I_n^a = I_n^a(W_t) = \frac{\sigma_T^A}{\sigma_T^2} \cdot I_{n-1} \cdot \left[1 - e^{-\sigma_T^A f_b \cdot (\rho \cdot N_A/A) \cdot W_t}\right]$$

produce a large amount of neutral and charged particles which can blind the detector assembly. The average multiplicity of the annihilation products, mainly pions and kaons, is $m \approx 5$ part/ann. At present it has been estimated that the annihilation rate in PANDA cannot exceed $5 \cdot 10^6$ ann/s. The maximum rate in the cycle is given by the $I_1^a \cdot \nu$ and the exponent in (5) must be lowered with a suitable choice of the target material and size in order to satisfy this constraint.

4.2. Primary target

The choice of the material of the primary target is determined by the efficiency for producing $\Xi^-$ (which has been estimated to be higher for larger $A$ [8]) and the effects on the annihilation rates. On the other hand the product $\sigma_T^A \cdot \rho/A$ in (5) vanishes quickly for increasing $A$, keeping the annihilation rate high. Therefore low mass number materials are more suitable and a $^{12}C$ target has been chosen. Problems of machinability suggest a ribbon shape of length close to the diameter of the beam pipe ($\phi \approx 15 \, mm$). A suitable choice of the thickness and the width of the target should minimize the exponent in (5) minimizing also the annihilation number $I_n$'s. Since the $\bar{p}$ beam spot at HESR has a diameter of $\phi \approx 2.5 \, mm$, the factor $f_b$ is proportional to the width $W_w$ of the ribbon and the product $W_w \cdot W_t$ has to be kept low in (5). The value $W_w \cdot W_t \approx 300 \, \mu m^2$ satisfies the annihilation rate constraint for $T_{cycle} \approx 1 \, s$ and $I_0 = 2 \cdot 10^7$.

At present, a ribbon target of $W_w \approx 100 \, \mu m$ and $W_t \approx 3 \, \mu m$ is under construction and tests. Ribbon targets of such dimensions can be made by the "thin film deposition" technique or by diamond growth and in both cases the ribbon width can be easily reduced, with laser technique, in case the repetition time will be longer than 1 s. Also the effect of the ionization process have to be taken into account in designing the primary target, because part of the energy of the electrons is deposited inside the target, as well as part of the lost momentum. As a consequence the target is heated and mechanically stressed. Although the energy lost in $^{12}C$ by an antiproton of 3 GeV/c is quite low ($E_p^{loss} \approx 1.2 \cdot 10^{-3}$ MeV), the total number $S_n^{cross}$ of antiprotons which have crossed the target after the $n$–th passage is quite high and can be calculated by:

$$S_n^{cross} = \sum_{(k=0)}^n I_k = I_0 \cdot \frac{e^{-(n+1) \cdot \sigma_T^A \cdot f_b \cdot (\rho \cdot N_A/A) \cdot W_t} - 1}{e^{-\sigma_T^A f_b \cdot (\rho \cdot N_A/A) \cdot W_t} - 1}$$

obtaining a total energy loss of $E_p^{loss} \cdot S_n^{cross}$. Calculations of the thermal equilibrium conditions and the mechanical stress are in progress and tests with a proton beam of equivalent energy loss are foreseen in order to design the cooling system and the mechanical frame of the target.
5. Conclusions
One of the goals of the PANDA Collaboration is to produce a large number of Double Hypernuclei using the intense antiproton beam of HESR at FAIR. This innovative technique requires that the target for the production of the $\Xi^-$ hyperons be inserted inside the beam pipe. The interaction of the beam with this target places some severe constraints on the material and size of the target in order to avoid damage to the detector and the target itself, while maximizing the hyperon production. The expected features of the beam lead us to choose carbon as the target material, which will be ribbon shaped for machinability reasons. The values of the thickness and width are at present foreseen as 3 $\mu$m and 100 $\mu$m respectively. These values will satisfy the beam and detector constraints if the repetition time of the bunch injections will be around 1 s; otherwise the width will be reduced, with a consequent decrease of the hyperon production rate. The effects of the target ionization, due to the antiproton passages through the target, will be measured using a proton beam of suitable energy and intensity, in order to design the frame and cooling system.

6. References
[1] J. Pochodzalla et al., Nucl.Instr.Meth.B 214 (2004) 149
[2] B. Musgrave et al., Nuovo Cimento 35 (1965) 735.
[3] G. P. Fisher et al., Phys. Rev. C 161 (1967) 1335.
[4] K. Szymańska et al., Nucl.Instrum. Meth. A592 (2008) 486.
[5] F. Iazzi, Few-Body Systems, vol.43, no.1 (2008) 97.
[6] A. Lehrach et al., Nucl. Instr. Meth. A561 (2006) 289.
[7] G. Bendiscioli, D. Karzeev, La Rivista del Nuovo Cimento17 No. 6 (1994) 1.
[8] F. Ferro et al., Nucl.Phys. A789 (2007) 209.