The antiproton interaction with an internal ^{12}C target inside the HESR ring at FAIR

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Abstract.
    In order to fulfill the goal of producing higher rates of doubly strange hyperons, the P̄ANDA collaboration will use the antiproton ring HESR at the future facility FAIR. The low energy hyperon production by an antiproton beam requires to insert a solid target inside the ring. Unwanted side effects of such an insertion are the overwhelming amount of annihilations, which would make the detectors blind, and the fast depletion of the bunch, which circulates inside the ring. The choice of the target material impacts the hyperon production yield: Carbon turned out to provide enough initial hyperon deceleration and keep secondary interactions below a tolerable level. The use of a very thin Diamond target, together with beam steering techniques, seems to be a satisfactory solution to the above problems and will be described hereafter.

1. Introduction
The understanding of the Strange Systems is attracting more and more the interest of the scientific community in the last years. This is due to two main aspects: on one hand the doubly strange systems represent a feasible way to investigate the interactions of strange matter with nucleons and nuclei, on the other hand the technological advancements on intense beams at new hadronic facilities allow a rich production of doubly strange hyperons as at J-PARC (Japan Proton Accelerator Research Complex) and FAIR (Facility for Antiproton and Ion Research).

    Exotic Ξ^- atoms, Ξ^- hypernuclei and $\Lambda\Lambda$ hypernuclei (also called Double Hyper-nuclei, DH) are the three possible types of strange systems, in which hyperon-nucleus, hyperon-nucleon and hyperon-hyperon interactions take place.

    The investigation of these doubly strange systems allows to shed light on the interaction of a doubly strange hyperon with the nuclear potential in the peripheral regions of the nucleus and with single nucleons [1]. Moreover, the spectroscopy of a double hypernucleus can provide information about the hyperon-hyperon potential and interactions of s quarks[2].

    In spite of their importance the available data about these systems are very scarce: only six Ξ^- hypernuclei, seven $\Lambda\Lambda$ hypernuclei and no Ξ^- hyperatoms have been observed up to now.

    This lack is due to the low probability of producing Ξ^- hyperons (e.g. in antiproton-proton collisions the cross section is $\approx 2\,\mu$b) and to the short lifetime of the hyperon ($\tau = 1.64\cdot10^{-10}$ s).
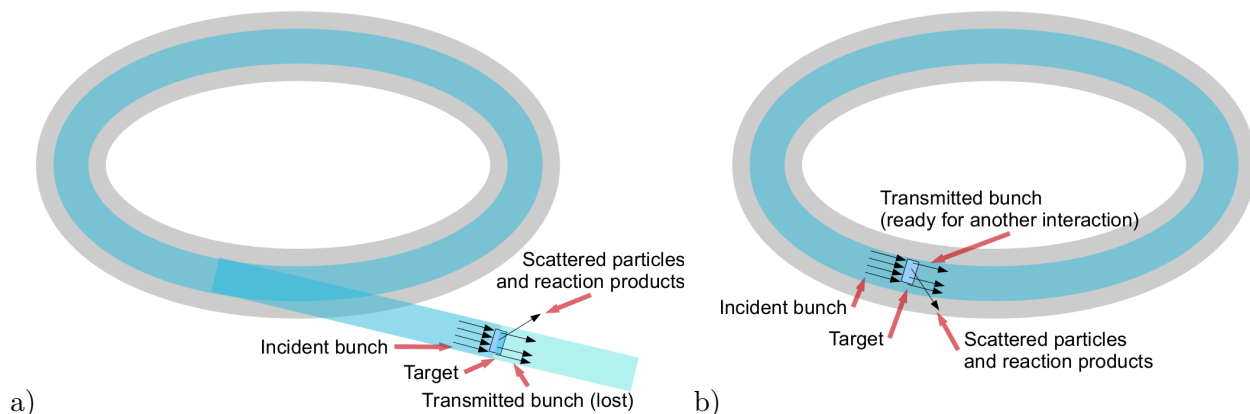
Figure 1. a) extracted beam and b) in-ring target configurations are shown for comparison; in the first case non-interacting particles are lost after crossing the target section while they are reused in the second one.

At the future facility FAIR the ring HESR (High Energy Storage Ring) will supply intense antiproton beams in the momentum range $1.5 - 15\,\mathrm{GeV/c}$ [3], which will be exploited by the experiment $\bar{\mathrm{P}}$ANDA (antiProton ANnihilation at DArmstadt) to collect rich statistics thanks to new production and detection techniques.

The reaction antiproton-carbon has been found to satisfy all the requirements to obtain a high rate of double hypernuclei [4]. For this goal the Collaboration $\bar{\mathrm{P}}$ANDA performed a feasibility study of a new experimental technique based on the use of two different targets for the creation of Ξ^- hyperons and of double hypernuclei. One of these targets should be inserted inside the HESR in order to re-use at each round the antiprotons, which did not interact in the previous one. In this way the effect of the low Ξ^- production probability and short lifetime is partially recovered (see Fig. 1). The idea of inserting a solid target inside a storage ring (in particular a ring of anti-particles) is innovative and presents several problems [5].

2. $\bar{\mathrm{P}}$ANDA experiment

Hydrogen jet or pellet targets are commonly used in High Energy Physics. Their interactions with the circulating beam affect the time and spatial structure of the projectile bunch and must be taken into account in managing the beam. In case of the $\bar{\mathrm{P}}$ANDA hypernuclear program, the internal target is required to be solid and denser than gaseous and liquid hydrogen. A nuclear target different from hydrogen is crucial to provide the initial strong Ξ^- deceleration by re-scattering inside the dense nuclear matter. Of course, this greatly increases the unwanted side effects on the antiproton beam. Drawbacks are of two types.

(i) Depletion of the antiproton bunch at each round, due to:
  - hadronic interactions with the target nuclei:
    - annihilations,
    - elastic and inelastic nuclear scattering,
    - CEX (Charge EXchange);
  - SCS (Single Coulomb Scattering) with the target nuclei;
  - Touschek effect in the beam (not depending on the target), negligible with respect to SCS and hadronic interactions;
  - Straggling effect;
  - Multiple Coulomb Scattering in the target (recovered by the cooling system of the ring if the target is sufficiently thin);

(ii) Target radiation damage, which can produce:
- heating of the target;
- mechanical stress due to the interaction with antiprotons;
- fragmentation of target nuclei with consequent embrittlement;
- accumulation of electrostatic charges, which can perturb the antiproton trajectories.

Type (i) effects require thin and narrow targets to be cared, while type (ii) ones create more problems the smaller the target is. Therefore, the sizes and the features of the target and its beam-spot overlay play a crucial role. To provide feasible measurement conditions, a proper design of the internal target and a careful study of the space-time structure of the beam in the ring are mandatory.

As previously discussed, the interaction of the antiproton beam with the target will generate high mechanical stress, embrittlement, heat and possibly charge pile-up; thus, the target structure and material must feature very good mechanical resistance, as well as large thermal and electrical conductivities.

The reaction of interest, $\bar{p} + N \rightarrow \overline{\Xi} + \Xi^-$, has a maximum cross section close to $3\,\mathrm{GeV/c}$ and a threshold at $2.65\,\mathrm{GeV/c}$, while the π production comes into play above $3.1\,\mathrm{GeV/c}$. By using antiprotons at $3\,\mathrm{GeV/c}$, the Ξ^- production is maximized and only two particles are present in the final state.

Another important issue, when using an internal target within a storage ring, is the refill and measurement cycle. The initial multiturn injection of antiprotons, with a momentum of $3.7\,\mathrm{GeV/c}$, is followed by beam cooling and deceleration in order to meet the specification on the antiproton momentum of $3\,\mathrm{GeV/c}$ for the optimal Ξ^- production. The measurement phase starts with 10^{10} antiprotons in a rich bunch (about $200\,\mathrm{m}$ long), circulating in the racetrack-shaped ring (about $550\,\mathrm{m}$ long) at a frequency $f_{ring} \approx 0.5\,\mathrm{MHz}$.

Direct exposure of the internal target to such an intense beam can create a high annihilation rate, with the risk of blinding all detectors and of wasting many antiprotons. Furthermore, the beam lifetime would shorten due to type (i) effects.

In particular, the initial bunch content would produce higher annihilation rates than the maximum tolerable by the $\bar{\mathrm{P}}$ANDA detectors in the hypernuclear program, $R^{MAX} \approx 5 \cdot 10^6\,\mathrm{ann/s}$.

A solution to these problems has been found by overlapping only partially the beam spot with the target. In order to reduce the number of interactions at each passage through the target, only the periphery of the bunch (whose radial distribution is nearly Gaussian) will overlap the target. This will be achieved slowly steering the beam toward a wire-shaped, thin, solid target (see Fig. 2). In this way the interaction rate can be controlled to maintain it close to an optimal level.

A proper choice of the material must also account the dependencies of type (i) cross sections on the mass A and atomic Z numbers of the target.

Summing-up, the initial Ξ^- deceleration requires a high enough mass number while keeping unwanted interactions below an acceptable level sets a limit on the same quantity. The best compromise has been found in Carbon [4].

Diamond turns out to be the best material to comply also with mechanical and heat specifications [6]. To the best of our knowledge, the production of alternative Carbon materials, like multilayer graphene samples and nanotube bundles, in a suitable size is still out of reach for nowadays technology. A target has been prototyped with CVD techniques: a free-standing diamond membrane has been produced on a Si ring [6]. The method ensures high purity (99.9%), homogeneous thickness ($3\,\mu\mathrm{m}$) and areal density ($5 \cdot 10^{19}\,\mathrm{cm}^{-2}$). Then the target prototype has been wire shaped ($100\,\mu\mathrm{m}$ wide) by femto-edge laser cut ($1064\,\text{Å}$, $3\,\mathrm{W}$).

In each cycle, during the data taking phase, the bunch is depleted at each passage through the target. At the n-th round, the bunch content is given by I_n antiprotons; only a fraction
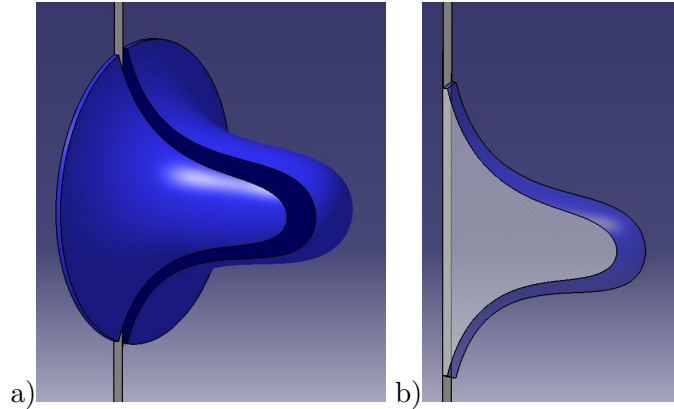
Figure 2. Picture of the steering technique: a) the circular Gaussian represents the beam distribution overlapping the wire target with its peripheral region where the antiproton density is lower; b) the distribution slice, corresponding to the beam-target overlap, is shown.

N_n of them ($N_n = f_n I_n$, $0 < f_n < 1$), will go through the target thin wire, depending on the relative position of the beam spot.

Among the N_n antiprotons a smaller subset, N_n^i, will actually interact with the target through one of type (i) processes. Labeling by the index α each interaction (α = annihilations, elastic nuclear scattering, inelastic nuclear scattering, CEX, SCS, Ξ^- production, ...), the number N_n^α of antiprotons undergoing interaction α is given by:

$$N_n^\alpha = N_n \frac{\sigma_\alpha^A}{\sum_\alpha \sigma_\alpha^A}(1 - e^{-\Sigma}) \approx N_n \frac{\sigma_\alpha^A}{\sigma_{SCS}^A + \sigma_h^A}(1 - e^{-\Sigma}) \tag{1}$$

where σ_α^A are the cross sections of each interaction, $\sum_\alpha \sigma_\alpha^A$ is the total cross section, which is approximated with the sum of the dominant ones by SCS and hadronic processes. The term Σ accounts for all factors coming into play in the exponential decay of the antiproton flux through the solid target thickness, l:

$$\Sigma = \frac{\rho N_{Av}}{A}\left(\sum_\alpha \sigma_\alpha^A\right)l \approx \frac{\rho N_{Av}}{A}(\sigma_{SCS}^A + \sigma_h^A)l \tag{2}$$

where ρ is the target mass density, N_{Av} the Avogadro number, A the target nucleus mass number.

The Single Coulomb Scattering and hadronic cross sections, σ_{SCS}^A and σ_h^A, of the antiproton-nucleus interactions can be obtained from the corresponding elementary antiproton-nucleus ones, σ_{SCS} and σ_h, scaling by Z^2 (SCS) and $A^{2/3}$ (hadronic) respectively. The result is:

$$\sigma_{SCS}^A = Z^2 \sigma_{SCS} \approx 1030\,\text{mb} \qquad \sigma_h^A = A^{2/3}\sigma_h \approx 367\,\text{mb} \tag{3}$$

The Ξ^- production cross section turns out to be lower [9].

$$\sigma_{\Xi^-}^A = A^{2/3}\sigma_{\Xi^-} \approx 10.5\,\mu\text{b} \tag{4}$$

The adoption of the steering technique is meant to mantain N_n almost constant. This condition implies that each rate of type (i) reactions does not vary with time, as well as the depletion rate of the bunch, given by $f_{ring}\sum_\alpha N_n^\alpha$. In particular the annihilation rate remains at the same level as well as the Ξ^- hyperon production rate. The aim of the experiment is a Ξ^- production rate of about 100 per second.
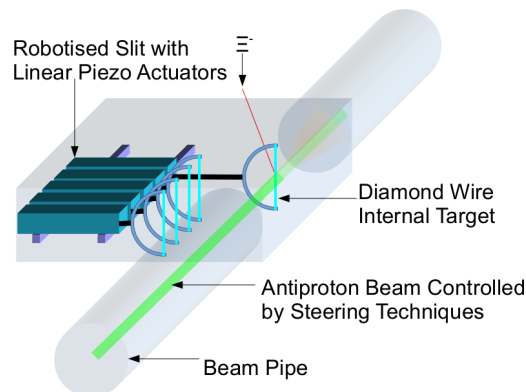
Figure 3. A transparent view of the in-vacuum interaction area shows the inner target array together with its robotised holder. Beam depletion requires a periodic refill of the ring. During antiproton injection the target is moved aside from the beam line by an automatic system based on linear piezoelectric actuators and then set back. An array of diamond wires allows to change the target when degraded by radiation damage.

The diamond atom density of the primary target, $\rho_D \approx 5 \cdot 10^{19}\,\mathrm{cm^{-2}}$ (much higher than the one of liquid hydrogen: $\rho_{LH_2} \approx 4 \cdot 10^{15}\,\mathrm{cm^{-2}}$), helps to reach this goal [10]. The expected ratio of stopped Ξ^-, with respect to the produced ones, turns out to be $R_{\Xi^-} \approx 2.2 \cdot 10^{-3}$ while the stopped Ξ^- fraction that produces $\Lambda\Lambda$ hypernuclei would be $R_{\Lambda\Lambda/\Xi^-} \approx 5 \cdot 10^{-2}$. This will provide about $2.5 \cdot 10^4$ $\Lambda\Lambda$ hypernuclei per month.

A reliable system to precisely move the target to the desired position inside the beam pipe has to be built. The particle injection and measurement cycle within the storage ring requires to set the target along the beam line only during the measurement time and to remove it in the refill time. Furthermore, the target itself will degrade due to the nuclear reactions taking place under the exposure to the beam and it must be substituted from time to time in a quick way. Figure 3 shows the sketch of the target region with an inner view of the beam line where the internal target array and the robotised holder system are positioned [11].

The device must be compatible with high vacuum. Feedback should be provided for external positioning control as well as the possibility to carry different sensors and electric signals intended to monitor the target itself. To satisfy all these constraints, the best solution has been found in linear step motors based on piezoelectric actuators.

3. Conclusions

Hadronic systems with double strangeness are interesting topics of particle Physics. New experiments at FAIR and J-PARC are aiming to investigate them to overcome the present scarceness of data. In particular, the use of antiproton beams at FAIR seems to be a promising technique for doubly strange hyperon production.

This technique requires inserting a thin solid target inside a ring with an intense beam, leading to severe constraints.

The proper design of the dimensions and features of the target and the beam-spot overlap play a crucial role to provide feasible measurement conditions. A wire shaped diamond target, which overlaps only partially the beam spot, together with the beam steering technique will be used.

A robotic control of the target within the beam pipe will be implemented to allow the measurements and the ring-refilling stages.

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