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Search for Λ–Λ hyperuclei using antiprotons in PANDA

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Abstract. The Double Hypernuclei are the only systems that allow to study the hyperon-hyperon interaction because the hyperon-hyperon scattering experiments are at present impossible. Experimental data are still very scarce, due to the difficulty of producing the doubly strange hyperon Ξ^-, from which a double hypernucleus is formed. The formation of such a hypernucleus proceeds through a multiple-step process and the measurement of the relevant parameters (e.g. energy separation and decay branching ratios) requires high statistics. The PANDA Collaboration planned to exploit the intense beam of the HESR machine at the future facility FAIR to produce Ξ^- hyperons from antiproton annihilation in nuclei. A ^{12}C target will be inserted inside the ring: the sizes of the target and the beam spot overlap play a crucial role to avoid serious damage of beam and detectors. The status of the art of the present data, the design of the optimized target and the tests on the prototype will be presented.

1. Introduction

The interest of the scientific community on Doubly Strange Systems has grown more and more in the last decade. Experiments on hyperon-hyperon scattering are not possible nowadays, thus the study of doubly strange nuclei represents the only viable way to explore Λ-Λ, Ξ-nucleon and Ξ-nucleus interactions.

The production of nuclei containing a pair of Λ's is quite cumbersome given the extremely low probability to insert two hyperons in one target nucleus. Inserting a doubly strange hyperon Ξ^- is a good alternative because, in the nucleus, Ξ^- can interact with a proton to form ΛΛ.

In a ΛΛ-hypernucleus the binding energy $B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z)$ of the ΛΛ pair within the nucleus ${}^{A}Z$ can be measured. If the Λ's do not interact together, this quantity should be equal to twice the binding energy $B_{\Lambda}({}^{A}_{\Lambda}Z)$ of one Λ in the same nucleus. Therefore the separation energy, defined as $\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) - 2B_{\Lambda}({}^{A}_{\Lambda}Z)$, can provide useful information on the Λ-Λ interaction, which is attractive if $\Delta B_{\Lambda\Lambda} > 0$ and repulsive if $\Delta B_{\Lambda\Lambda} < 0$.

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The few available data suggest an increasing trend of the binding energy $B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z)$ with the mass number A. The Λ-Λ interaction seems to be attractive: however not all experimental results are in agreement. Moreover it is not yet completely clear if the separation energy decreases with the mass number A, as expected, or not. Unluckily only single measurements are available while a high statistic is needed to find the core of Λ-Λ interaction.

2. Λ-Λ interactions

Within a double hypernucleus the two Λ hyperons may undergo strong interaction or weak decay. The separation energy is related to the hyperon-hyperon potential and measurements of $\Delta B_{\Lambda\Lambda}$ are crucial to understand the strangeness role in the strong interaction. It is worth noting that, in the double hypernuclei, strangeness interaction comes into play at quark level (*s*-*s* quark interaction) at short distance while at larger distance the One Boson Exchange picture should take into account that only non-strange mesons with zero isospin (ω, η, η'...) can be exchanged between the Λs [1]. Data about the separation energy are the only ones that might allow to discriminate among different models. The $\Lambda\Lambda$ hypernuclei could also provide the opportunity to observe the di-baryon H ($B = 2$), a system made of 6 deconfined quarks *uuddss*, predicted by Jaffe in 1977 [2] and never seen.

After formation, excited $\Lambda\Lambda$ hypernuclei can undergo fragmentation, following different break-up channels: 1) ${}^{A}_{\Lambda\Lambda}Z \rightarrow {}^{A_1}_{\Lambda\Lambda}Z_1 + X$; 2) ${}^{A}_{\Lambda\Lambda}Z \rightarrow {}^{A_1}_{\Lambda}Z_1 + {}^{A_2}_{\Lambda}Z_2 + X$; 3) ${}^{A}_{\Lambda\Lambda}Z \rightarrow \Lambda + {}^{A-1}_{\Lambda}Z_1 + X$; 4) ${}^{A}_{\Lambda\Lambda}Z \rightarrow \Lambda + \Lambda + X$. Hyperfragment distribution is suggested to depend on the hyperon-hyperon potential [3] and the detection of the fragments could provide more information on the Λ-Λ interaction.

Each Λ in a $\Lambda\Lambda$ hypernucleus can undergo different decays [4]: a) Hyperon Induced Non Mesonic Weak Decay (only possible in the double hypernuclei because the interaction with the other hyperon is necessary), $\Lambda\Lambda \rightarrow Y + N$ ($320 \leq p_Y \leq 430$ MeV/c); b) Mesonic Weak Decay, $\Lambda \rightarrow N + \pi$ ($p_N \approx 100$ MeV/c) (since the nucleus is bound, this decay is suppressed in heavy nuclei by Pauli blocking); c) Nucleon Induced Non Mesonic Weak Decay, $\Lambda N \rightarrow N + N$ ($p_N \approx 415$ MeV/c). The existence of several decay channels makes the branching ratios, $\Gamma_{\pi^0}, \Gamma_{\pi^-}, \Gamma_p, \Gamma_n$ for both Λ's, interesting quantities to be investigated in the double hypernuclei.

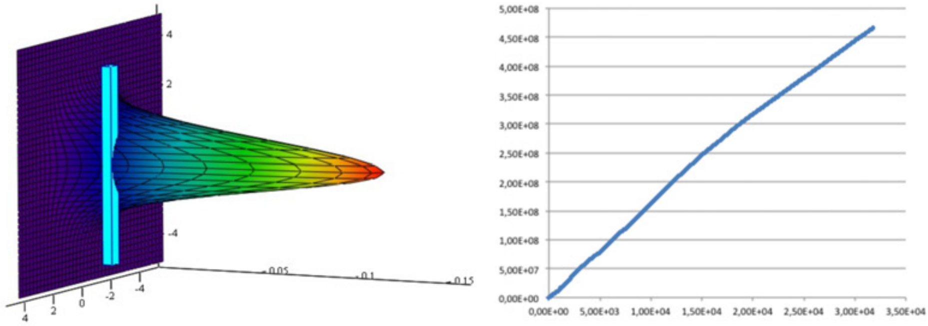
3. $\Lambda\Lambda$ hypernuclei production

In direct reactions the Ξ^- production and the $\Lambda\Lambda$ hypernucleus formation takes place in the same nucleus. These reactions require two-step processes and therefore their probability is low. Measurements at AGS [5] show a forward cross sections of ≈ 89 nb/sr for the reaction $K^- + {}^{A}Z \rightarrow K^+ + {}^{A-1}_{\Xi^-}(Z-1)$ (which requires rescattering of the hyperon inside the nucleus) and an upper limit of ≈ 10 nb/sr for $K^- + {}^{A}Z \rightarrow K^+ + {}^{A-2}_{\Lambda\Lambda}(Z-2)$ (which requires double strangeness-exchange steps inside the nucleus). Another direct reaction suggested in FLAIR is $\overline{p} + N \rightarrow K^* + \overline{K}^*$, $K^* + N' \rightarrow \overline{K} + \Xi^-$, where the $\overline{p}$ is brought to rest and the K^* has a momentum $p_{K^*} \approx 290$ MeV/c; the Ξ^- is produced nearly at rest.

In indirect reactions, the Ξ^- is produced in one nucleus while the $\Lambda\Lambda$ pair is formed in another nucleus after the capture of the Ξ^- hyperon. Such two-stage reactions are more effective [6]. At KEK and AGS kaon-beams were used in $K^- + p \rightarrow K^+ + \Xi^-$ reaction to produce Ξ^-.

The production technique designed by the PANDA (antiProton ANnihilation at Darmstadt) collaboration [7] foresees the following two stages: i) $\overline{p} + n \rightarrow \overline{\Xi} + \Xi^-$, $\overline{p} + p \rightarrow \Xi^+ + \Xi^-$ (quasi two-body reaction, $\overline{p}$ are quasi free in the nucleus), ii) $\Xi^- p \rightarrow \Lambda\Lambda$ (taking place in a different nucleus where the $\Lambda\Lambda$-pair sticks). In the first stage Ξ^- re-scatters in the residual nucleus, undergoing a strong deceleration, then exits. The $\overline{\Xi}$ annihilation $\overline{\Xi} + N \rightarrow \overline{K} + \overline{K} + \pi + ..$ can be exploited for trigger purposes.

After exiting, the Ξ^-, if it does not decay, goes to stop in ordinary matter and is captured in an atomic orbit, starting a cascade. Strong forces become relevant on the lowest atomic levels, which are



(a) (b)

Figure 1. a) Picture of the steering technique: the beam-target overlap is shown. b) The cumulative back-scattering plot produced during the target test under low energy protons: the linear trend indicates that neither structural variation nor charge pile-up occurred.

shifted and broadened [8] and the nuclear absorption occurs. Once in the nucleus the Ξ^- reacts with a nucleon (stage 2) and the produced $\Lambda\Lambda$ pair sticks there and decays (MWD, NINMWD, HINMWD).

4. PANDA experiment

Noteworthy PANDA will be the first experiment using an intense antiproton beam to produce $\Lambda\Lambda$ hypernuclei. The beam will be provided by HESR (High Energy Storage Ring) in the future complex FAIR (Facility for Antiproton and Ion Research) [9].

The facility includes: a) a p-LINAC (proton LINear ACcelerator to 70 MeV) feeding a SIS (SchwerIonen Synchrotron) by multiturn injections from which single bunches are extracted at 29 GeV, b) a target for the $\overline{p}$ production at a rate of $10^7\ \overline{p}$/s, c) a collector ring, CR, and a storage ring, HESR, where antiprotons are injected at 3 GeV with a revolution frequency of $\sim 5 \cdot 10^5$ Hz.

The reaction $\overline{p} + N \rightarrow \overline{\Xi} + \Xi^-$ has a maximum around $p_{\overline{p}} \approx 3$ GeV/c [10] and a threshold at $p_{\overline{p}} \approx 2.65$ GeV/c, while the π production starts at $p_{\overline{p}} \approx 3.1$ GeV/c. Using antiprotons at 3 GeV/c, the Ξ^- production is maximized and only two particles are present in the final state. With this choice the $\overline{p}$ beam has to be decelerated in HESR.

To exploit at best the $\overline{p}$ bunch to produce Ξ^-, the choice to insert the target (named "internal target") along the ring was taken. This avoids wasting non-interacting $\overline{p}$s since they remain within HESR and contribute to the interaction with the target in multiple bunch passages.

The interaction between the intense antiproton beam and the internal target can create a high rate of $\overline{p}$ annihilations, with the risk of blinding detectors. Moreover the beam lifetime shortens, since the bunch is depleted by the hadronic interactions and the Single Coulomb Scattering [11].

A solution to these problems has been found using a wire shaped diamond target, which overlaps only partially the beam spot. In order to further reduce the number of beam-target interactions at each passage through the target, it has been planned to overlap only the tail of the radial Gaussian distribution of the bunch, slowly steering the beam toward the wire (see Fig. 1a). In this way the interaction rate can be maintained low and nearly constant.

5. Design of the internal target

A target prototype has been produced with CVD techniques [12] to create a diamond disk (3 μm thick) on a Si ring. The thin disk has been wire shaped (100 μm wide) by femto-edge laser cut (1064 Å, 3 W).

It features high purity (99.9% ^{12}C), homogeneous thickness, areal density $\approx 5 \cdot 10^{19}\,\mathrm{cm}^{-2}$ (higher than graphite), high thermal conductivity and mechanical resistance. Furthermore it provides electrostatic charge removal thanks to the graphitised edges along the laser cuts, as detected by Raman spectroscopy.

The prototype target has been thoroughly tested under multi-cycle low energy proton beam at LNL (Laboratori Nazionali di Legnaro). The p beam current has been chosen to reproduce the worst energy-loss conditions in PANDA ($dE/dx \approx 1.8\,\mathrm{MeV/(g/cm)}^2$ for $\overline{p}$ at 3 GeV/c at HESR, while $dE/dx \approx 111\,\mathrm{MeV/(g/cm)}^2$ for $\overline{p}$ at 2.75 MeV/c at LNL). The proton current having energy loss equivalent to the $\overline{p}$ beam is $I_p \approx 2.7\,\mathrm{nA}$. Actually the irradiation has been performed with $I_p \approx 4\,\mathrm{nA}$, in order to operate in worse conditions than at HESR and it was simultaneously monitored with Back Scattering (BS) techniques. BS measurements are reported Fig.1b and show a linear trend, indicating that neither structural variation nor charge pile-up occurred.

6. Conclusions

The physics of doubly strange systems presents interesting aspects concerning strong interactions (hyperon-hyperon, hyperon-nucleus) as well as weak interactions (mesonic and non-mesonic decay).

Present worldwide data are really scarce, thus the experiment PANDA aims to investigate Strangeness Physics in a thorough way thanks to the intense $\overline{p}$-beam of the future facility at FAIR.

The production of $\Lambda\Lambda$ hyper-nuclei is one of the main aspects on which the set-up is focused. Antiprotons at 3 GeV/c will produce Ξ^- and then $\Lambda\Lambda$ hypernuclei with indirect reactions: a “steering technique” will be adopted to handle the intense $\overline{p}$ beam while a two-target system separates the Ξ^- production from the hypernuclei formation.

The internal target has been prototyped and its performances have been successfully tested with a low energy p-beam.

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