Perspectives of the Double Strangeness Physics at FAIR

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Abstract.

The future complex FAIR (Facility for Antiproton and Ion Research) will allow to investigate a wide spectrum of physics items, ranging from QCD to the Nuclear Structure, from Astrophysics to Atomic Physics, from Plasma Physics to their applications. Among the other facilities the High Energy Storage Ring (HESR) will supply antiprotons in the momentum range from 1.5 to 15 GeV/c, with a resolution up to \(10^{-5}\). The PANDA experiment, located inside HESR, will study the charm and strangeness physics, the form factor in the time like region and other topics like the crossed channel Compton scattering. The idea of studying the strangeness using antiprotons is new and the investigations will be focused onto the doubly strange systems, whose physics aspects are here shortly reviewed. The production technique will be illustrated and the expected performances, in terms of statistically significant amount of data, presented.

1. Introduction

The status of art of the hypernuclear physics today presents a very rich panorama of data and theoretical models concerning the single hypernuclei. These systems, containing a \(\Lambda\) hyperon inside the nucleus, have been widely studied and a large amount of information is present in literature about the hyperon-nucleon and hyperon-nucleus interaction and about the problem of the weak decay of the bound \(\Lambda\). The strangeness contents of the single hypernuclei is \(S = -1\) and they are produced starting from \(K\) or \(\pi\) mesons. Meson factories were the basic facilities which supplied the rich statistics of the single hypernuclei.

Of course, systems with higher strangeness contents are in principle very interesting too, as it will be shown in detail in the next chapters. Nevertheless the production of strangeness \(S = -2\) or \(S = -3\) presents some peculiar features that make it very difficult. In fact the \(\Lambda\) hypernuclei are usually formed through the strange meson production from pion in the reaction \(\pi N \rightarrow \Lambda K\) or through the charge exchange reaction of strange meson \(KN \rightarrow \Lambda \pi\). Obviously, analogous procedures cannot be applied to highly strange systems because only \(S = -1\) mesons exist. The existing \(S = -2\) and \(S = -3\) particles are the baryons \(\Xi\) and \(\Omega\) respectively: the cross sections for their production are lower and their mean lifetimes shorter in comparison with \(K\) mesons. This explains why the data up to now are very scarce, in spite of the first claim of the existence of double hypernuclei came in the sixties of the past century \[1, 2\]. At present the most reliable observation of a double hyperfragment is the so called NAGARA event observed in emulsion by the experiment E373 at KEK[3]. It is evident that in order to explore the world of the highly strange matter a big step forward has to be done in a) the production technique of the strange baryons, b) the fluxes of the accelerated particles which are used, c) the efficiency...
of the detection apparatuses. FAIR complex will supply intense beams of various ion species at high energy and will contain a dedicated ring (HESR) for antiprotons in the energy range from 0.8 to 14 GeV, with luminosity up to $2 \cdot 10^{32} \text{ cm}^{-2} \text{s}^{-1}$.

PANDA Collaboration aims to use the antiprotons of HESR, among others, to produce $\Xi^-\Xi^-$ baryonic pairs, whose invariant mass is inside the energy range of the ring [4]. $\Omega^-\Omega$ pairs are in the possibility too but any project has not yet been developed up to now. In the next chapters the main aspects of the physics of the doubly strange systems will be discussed and the way to form doubly strange systems from $\Xi^-$ baryon described.

2. Systems with $S = -2$

A $\Xi^-$ baryon can form 2 doubly strange systems: the hyperatom, in which it occupies an atomic level among the electrons, and a doubly strange hypernucleus in which it occupies a nuclear level among the protons and neutrons. Inside the nucleus it can undergo a reaction with a proton producing 2 $\Lambda$'s: if these $\Lambda$'s stick to the nucleus (or to a fragment of the nucleus) a Double Hypernucleus (DH) is built. The properties of the 3 systems can shed light on some aspects of physics that are totally absent in single hypernuclei.

2.1. Exotic Hyperatoms

The $\Xi^-$ hyperatom belongs to the class of the exotic atoms which includes the leptonic and the hadronic atoms. Leptonic atoms, which are positronium ($e^+e^-$), muonium ($\mu^+e^-$), and muonic atoms ($\mu^-$-atom), undergo to the electromagnetic and weak forces and these interactions have been used to explore basic aspects of QED. In the hadronic atoms the negative hadron replacing one electron undergoes the electromagnetic and strong forces [5]. The formation of the $\Xi^-$ hadronic atom occurs through the capture of the hyperon nearly at rest into an atomic orbit followed by the cascade with emission of Auger electrons or X rays. In the low density region of the nuclear matter the hadron and nucleus wave functions overlap and the strong interaction shifts and broads the atomic levels with respect to the values due to the Coulomb interaction only.

The strong interaction between hadron and nucleus can be described by a Klein-Gordon equation in which the neutron and proton density distribution are parameters of a complex optical potential [6]. Measuring shift and width by means of X-ray spectroscopy technique, these parameters can be evaluated by fitting the experimental data. The spectroscopy of the modified X-ray has been used for pionic, kaonic, antiprotonic and sigma atoms, i.e. for all common negative hadrons but $\Xi^-$, due to the lack of data. Finally it must be recalled that shifts and widths are changed differently in different atoms and data coming from various $\Xi^-$ hypernuclei are welcome.

2.2. Doubly Strange Hypernuclei

The $\Xi^-$ hyperon contained in a doubly strange hypernucleus plays an analogous role to that of $\Lambda$ and $\Sigma^-$ inside the single hypernuclei but with an important difference: the strangeness of this negative hyperon is $S = -2$. The spectroscopy of the $\Xi^-$ hypernuclei levels could shed light on the strangeness contribution to the hyperon-nucleus interaction in the central region.

Another aspect that could be investigated in the doubly strange hypernucleus is the $\Xi^-N$ interaction: at present data are nearly inexistent. To our knowledge the $\Xi^-$ mean free path inside a nucleus [7] is the only measurement somehow related to the cross section. Some information could be obtained from the $\Xi^-$ hypernucleus about the short and long range interaction in the reactions:

$$\Xi^- + N \rightarrow \Xi^- + N$$  \hspace{1cm} (1)
\[ \Xi^- + p \rightarrow \Lambda + \Lambda \]  \hspace{1cm} (2)

In the frame of the OBE description, in reaction (1) only non-strange mesons (\(\pi, \rho, \omega, \eta\)) can be exchanged and in reaction (2) only strange mesons with isospin \(I = 1/2\) can be exchanged [8]. An upper limit of the conversion reaction (2) has been estimated near 5 mb [9].

Possible measurements could be the gamma emission in the \(\Xi^-\) absorption into the nucleus, the \(\Xi^-\) hypernucleus decay rates and the ratio of reaction (2) with respect to reaction (1). Such measurements present a lot of experimental problems and high statistics of the produced \(\Xi^-\) hypernuclei is absolutely necessary.

### 2.3. Double Hypernuclei: Binding Energy

In the Double Hypernuclei (DH) the strangeness \(S = -2\) is shared by 2 \(\Lambda\)'s bound inside a nucleus. This system shows a very intriguing feature: 2 hyperons are simultaneously present in the nuclear field and they can interact together. Investigating this interaction is at present possible only in DH systems. In fact \(\Lambda\Lambda\) scattering experiments are not in sight for the next and far future: the short lifetime of the \(\Lambda\) hyperon makes impossible to produce fluxes enough intense to be crossed. On the other hand the \(\Lambda - \Lambda\) potential \(V_{\Lambda\Lambda}\) is one of the contributions to the total potential in a DH and can be written as:

\[-V_{\Lambda\Lambda} = \Delta B_{\Lambda\Lambda}(A_{\Lambda\Lambda}Z) \equiv B_{\Lambda\Lambda}(A_{\Lambda\Lambda}Z) - 2B_{\Lambda}(A_{\Lambda\Lambda}^{-1}Z)\]  \hspace{1cm} (3)

where \(B_{\Lambda\Lambda}(A_{\Lambda\Lambda}Z)\) is the binding energy of the double hypernucleus \(A_{\Lambda\Lambda}Z\) and \(B_{\Lambda}(A_{\Lambda\Lambda}^{-1}Z)\) is the binding energy of the single hypernucleus \(A_{\Lambda}^{-1}Z\). The binding energy of the single hypernuclei is quite well known and a suitable choice of the target for DH allows the evaluation of the difference in (3). In the experiment E373 [3] this difference has been evaluated around 1 \([MeV]\) for \(6_{\Lambda\Lambda}He\), indicating a weak attraction between the \(\Lambda\)'s. Taking into account that the previous measurements [1, 2] were quite in disagreement, more statistics is necessary to fix the parameters in the various potential models. In OBE, for instance, \(\Lambda\Lambda\) interaction can only occur by exchanging the non strange mesons with isospin 0 (\(\omega, \eta\)) [8]. Data should come from (several) different nuclei in order to extract the \(\Lambda\Lambda\) pure contribution.

### 2.4. Double Hypernuclei: Weak Decay

The weak decay of \(\Lambda\)'s inside a double hypernucleus is another tool to investigate the hyperon-hyperon interaction. In fact it is well known that the free \(\Lambda\) decay:

\[ \Lambda \rightarrow \pi + N \]  \hspace{1cm} (4)

is quite suppressed in single hypernuclei, due to the Pauli principle, in favor of the Nucleon Induced Non Mesonic Weak Decays (NINMWD):

\[ A_\Lambda Z \rightarrow A_\Lambda^{-2} Z' + N + N \hspace{1cm} (E_N \approx 78MeV) \]  \hspace{1cm} (5)

where the hyperon-nucleon interaction produces a final state without any meson. The NINMWD width rapidly increases and the free one rapidly decreases for increasing mass number of the hypernuclei: as a result the total width is slightly increasing.

In a double hypernucleus the simultaneous presence of 2 hyperons might allow their interaction with the possibility of a new kind of decay, the Hyperon Induced Non Mesonic Weak Decays (HINMWD):

\[ A_{\Lambda\Lambda} Z \rightarrow A_\Lambda^{-2} Z + \Lambda + n \hspace{1cm} (402.2 \leq p_{\Lambda,n} \leq 433.0 MeV/c) \]  \hspace{1cm} (6)

or:
\[
\begin{align*}
\Lambda\Lambda Z & \rightarrow A^{-2} Z + \Sigma^{-} + p \quad (275.8 \leq p_{\Sigma p} \leq 318.9 \text{MeV/c}) \\
\end{align*}
\]  
(7)

In principle the exiting nucleons in decays (5), (6) and (7) could be distinguished from each other, thanks to their different momenta, but taking into account the possible decay of a Double Hypernucleus into single hyperfragments, each one with some kinetic energy contents, the detection of HINMWD events will be a hard experimental challenge. This confirm the needs of high production rate of double hypernuclei in addition to a good detection efficiency.

3. Production techniques of Doubly Strange Systems

Although the number of observed doubly strange systems is very scarce, nevertheless more than one technique has been devised to produce them. The processes can be divided into 2 classes: the direct formation processes, in which the hypernuclear system (\(\Xi^{-}\) or \(\Lambda\Lambda\) hypernucleus) is formed in the same nucleus where the double strangeness is created and the indirect formation, in which a \(\Xi^{-}\) hyperon is produced in a nucleus, exits and is captured in another one. In both cases a \(S=-2\) particle must be initially created and in the past the available \(K^{-}\) beams have been used to this purpose. Recently the availability of intense antiproton beams at the future FAIR complex suggested new ways. The main features of both techniques are discussed in the following.

3.1. Production techniques with kaons

Kaon beams have been used up to now in all trials to search for doubly strange systems, since the pioneering works of Danisz [1] and Prowse [2] up to the most recent results at KEK [3]. Also the JPARC program for double strangeness is based on kaon beams. The kaon momenta were generally 1.66 GeV/c at KEK, 1.8 GeV/c at BNL-AGS and will be 1.7-1.8 GeV/c at J-PARC.

Direct formation of \(\Xi^{-}\) hypernucleus can occur through the reaction:

\[
K^{-} + A Z \rightarrow K^{+} + \Lambda\Lambda (Z - 1) \quad (8)
\]

where the (quasi free) charge and strangeness exchange \(p(K^{-}, K^{+})\Xi^{-}\) is followed by \(\Xi^{-}\) rescattering inside the nucleus. A theoretical value around 4 \(\mu\)b/sr for the forward cross section has been found by Dover and Gal [10] for the \(\frac{13}{2}B\) hypernucleus direct production. Experiment E885 at BNL-AGS estimated only an upper limit of the forward cross section for (8) because of lack of statistics. This value (\(\approx 90 \text{ nb/sr}\)) is significantly smaller than the quoted theoretical prediction [11].

Another way to directly produce a doubly strange system is the reaction:

\[
K^{-} + A Z \rightarrow K^{+} + \Lambda\Lambda (Z - 2) \quad (9)
\]

which proceeds through a first charge and strangeness exchange:

\[
K^{-} + p \rightarrow \pi^{0} + \Lambda \quad (10)
\]

followed by another one:

\[
\pi^{0} + p \rightarrow K^{+} + \Lambda \quad (11)
\]

after \(\pi^{0}\) rescattering inside the nucleus. The forward cross section for (9) has an upper limit of \(\approx 8 \text{ nb/sr}\), found by the experiment E885 at BNL-AGS [11].

The reason of these low values lies mainly in the 2 step process reactions required to form the double hypernucleus. Moreover it must be remarked that the tagging of the hypernucleus formation is given by the measurement of the \(K^{+}\) momenta, which are \(\approx 1.39 \text{ GeV/c}\) and \(\approx 1.42 \text{ GeV/c}\).
GeV/c for Ξ⁻ and ΛΛ hypernuclei respectively, for $K^-$ of 1.8 GeV/c. For the KEK beams at 1.66 GeV/c the corresponding values are $\approx 1.24$ GeV/c and $\approx 1.28$ GeV/c. These differences in momentum could be easily detected but the excitation levels of the formed hypernuclei could overlap and therefore high statistics is required to distinguish among them.

The indirect production using $K^-$ beams is based on the creation of the Ξ⁻ hyperon in the reaction:

$$K^- + p \rightarrow K^+ + \Xi^-$$ (12)

quasi free in nucleus. The Ξ⁻'s exiting from the nucleus are slowed down until they stop and are captured by an atom, forming an hyperatom in a highly excited atomic level. The de-excitation leads the hyperon to the lowest levels where can be absorbed by the nucleus, forming a Ξ⁻ hypernucleus. When the reaction (2) occurs and both Λ's stick up to the nucleus, a ΛΛ hypernucleus is formed. The Ξ⁻ momentum in (12) is $\approx 0.5$ GeV/c for the BNL-AGS and KEK beams: during the slowing down a part of the hyperons decay due to their short lifetime. The number of surviving until stop is a parameter to estimate the efficiency of the production technique. Up to now the stopped Ξ⁻'s in BNL-AGS and KEK experiments has been of the order of some thousands, while at JPARC some hundreds thousands are foreseen.

3.2. Production techniques with antiprotons at FAIR

The future facility FAIR will provide, among others particles, antiprotons in a wide range of momentum, from 15 GeV/c down to rest, offering new perspectives to the production of doubly strange systems.

In the technique proposed by the FLAIR facility, an amount of $K^*$ mesons is produced from the annihilation in nuclei of antiprotons previously brought to rest: through the reactions ($K^*, \bar{K}$), analogous to (8) and (9), the Ξ⁻ can be created and $S=-2$ systems formed in the same nucleus. The large mass $K^*$ has a 'magic momentum' at which Ξ⁻ is produced at $\approx 0.2$ GeV/c with high probability to stick up to the nucleus [12]. As a counterpart, the cross section of the 2 step reaction can be expected quite low.

At the opposite extreme of the antiproton energy range there is the possibility to produce Ξ⁻'s with momentum not too much higher than $\approx 0.5$ GeV/c: in this way a result analogous to the final state of reaction (12) is obtained and the efficiency in terms of stopped hyperons depends on the specific experimental setup. From the detection point of view it must be remarked that a lot of particles can be produced together with Ξ⁻ in the high momentum antiproton annihilation, requiring a very efficient particle identification system.

The middle energy range antiprotons are used in the project of the PANDA Collaboration, which aims, among others, to create and detect doubly strange systems with different nuclei and atoms. The particular designed setup and the results of the achievable Ξ⁻ rates are discussed in the next chapter.

4. Production of Doubly Strange Systems in PANDA

The Double Hypernuclei experiment in PANDA will use the antiprotons of the HESR ring, choosing the momentum 3 GeV/c for the reaction:

$$\bar{p} + N \rightarrow \Xi + \Xi^-$$ (13)

quasi free in nucleus[13], below the $\pi$ production threshold. The project foresees 2 different targets: the primary target for the Ξ⁻ production in (13), located inside the beam pipe of HESR and the secondary target around the beam pipe where Ξ⁻'s go to stop. The goal is to design shape and material of the primary target in order to maximize the Ξ⁻ rate and satisfy the inside-beam constraints independently on the choice of the hyperatoms and hypernuclei that
have to be studied. Of course the distance between the targets causes further $\Xi^-$ decays before the stopping. A detailed evaluation has been made of the ratio: stopped $\Xi^-$’s to produced $\Xi^-$’s, in the antiproton annihilation (13), taking into account also the $\Xi^-$ slowing down in the nuclear matter [14]. Assuming a compact secondary target of $^{12}\text{C}$ around the beam pipe, for different primary target materials this ratio is of the order of $10^{-5}$. This value can be considered as a lower limit for compact secondary targets: in fact heavier nuclei will produce a faster slowing down due to the higher charge and (in general) higher density. Therefore the design of the primary target will play a crucial role in the stopped $\Xi^-$ rate achievable in PANDA. Some evaluations of this rate have been already done assuming a nearly continuous injection capability of HESR, obtaining a value of the order of $2 \cdot 10^4$ stopped $\Xi^-$/day [15]. Taking into account that the project of HESR is not yet definite in all details, they have to be considered as preliminary indications and the study is still in progress. Nevertheless this rate is a significant improvement in statistics with respect to the total number of stopped $\Xi^-$ ($\approx 10^4$) expected in the Hybrid Emulsion Experiment E07 (“$\Lambda\Lambda$ Hypernuclei”) at J-PARC. The total statistics ($\approx 7.5 \cdot 10^5$ stopped $\Xi^-$) foreseen in the $\Xi^-$ Atom Spectroscopy Experiment E03 with a Fe target could be reached at FAIR in less than 2 months of data taking. Moreover different targets can be explored in PANDA by changing only the secondary target without modifying the $\Xi^-$ production set-up. In fact the internal target will supply a $\Xi^-$ source of constant characteristics for all hypernuclei and hyperatoms, thus minimizing the systematic error. It must be noticed that the PANDA set-up allows to detect signals from all the 3 steps along which the $\Lambda\Lambda$ hypernucleus is formed: $\Xi^-$ absorption in hyperatom, $\Xi^-$ capture in nucleus, $\Lambda\Lambda$ conversion. In this way each stopped $\Xi^-$ event is a potential source of these processes. Last but not least, the antiproton beam will offer in future the possibility to produce also the $\Omega^-$ baryon, opening new perspectives to the hypernuclei investigations. Also, on the side of the detection, the design of a detector for prongs around the beam pipe (a layered active/passive secondary target) is in progress. The performances of a HPGe crystal, to be used as gamma detector, have been studied inside the magnetic fringing field of PANDA and seems guarantee high resolution and efficiency, enough to allow hyperatomic and hypernuclear spectroscopy measurements of good precision [16].

5. Conclusions
The doubly strange systems (hyperatoms, $\Xi^-$ and $\Lambda\Lambda$ hypernuclei) may supply a rich amount of information about the interplay of the Coulomb and strong force between hyperon and nucleus and about the hyperon-hyperon interaction. Most features are peculiar of these systems and can be studied only in atoms and nuclei containing baryons of total strangeness $S = -2$. In spite of this interest after more than 40 years since the first claim of the evidence of double hypernuclei only their existence is confirmed today, because not enough statistics has been obtained in the existing data. This situation goes to be strongly improved with the very intense beams available in the new hadron facilities. The high antiproton fluxes at FAIR allow to design new techniques for the production of $\Xi^-$ and $\Lambda\Lambda$ in nuclei. In particular in the PANDA experiment the indirect production of double hypernuclei using 2 separate targets will produce all the 3 hyper-systems from each created $\Xi^-$. Even though the design of the detector assembly is still in progress, the stopped $\Xi^-$ rates per day that can be expected to be of the order of some $10^4$. In one month a factor 10 with respect the total data up today collected could be reached, thus fulfilling the present lack of statistics.

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