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Production of Ξ^- hyperons in the storage ring HESR in PANDA

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The Ξ^- hyperon is the basic tool to produce all systems containing double strangeness. These systems allow to investigate the hyperon-nucleon and hyperon-hyperon strong interaction. Moreover the non mesonic decays, in particular the hyperon induced decay of $\Lambda\Lambda$ hypernuclei, give information about their weak interaction. In spite of the great interest of these topics, data are scarce at present, due to the difficulty in producing and stopping the short living Ξ^- hyperons. The techniques exploited up to now to produce doubly strange systems are here shortly reviewed, toghether with the related physics items. Then the proposal of PANDA Collaboration to use antiprotons for the hyperon production and the design of the innovative system of two separated targets is briefly described. Finally the problems arising from the interacion of the solid target, inserted in the ring and the antiproton beam are illustrated and the possible solutions for getting high rates of stopped Ξ^-'s are indicated.

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1. Introduction

The most recent developments in the field of the Strong Interaction Physics lead the High Energy Community to investigate very rare reactions, e.g. the production of strange baryons and the formation of heavy quark systems. To fullfil the goal of getting a rich statistics, intense beams of the projectiles are requested. Two hadronic machines will supply intense beams of kaons (JPARC)[1] and antiprotons (FAIR)[2], the former being ready to take data and the latter to operate in nearly 5 years.

Concerning the production of strange baryons it must be remarked that the Λ hyperon (strangeness S=-1, isospin I=0) has been widely investigated and a lot is known about the strong and weak interaction of Λ with nucleons in the single hypernuclei. Some data from the hyper-atoms containing Σ^- hyperon (S=-1, I= 1) are available while the status of art of the investigations of the systems containing S=-2 (the so called Doubly Strange Systems, DSS) are basically at an early stage.

Nevertheless the physics items related to the electromagnetic, weak and strong interactions of the DSS are of great interest, as discussed in the next chapter and new techniques to produce a large amount of such systems are welcome.

Up to now the starting point of nearly all experiments has been the creation of the Ξ^- hyperon (S=-2, I=1/2), whose strangeness contents is transferred to a system (atom or nucleus) through absorption of the hyperon. Therefore the goal of getting high statistics for DSS has to be achieved looking for intense beams of particles which can produce large amount of Ξ^-'s and devising suitable setups to optimize their absorption in atoms and nuclei.

The project of the antiproton ring HESR at FAIR suggested PANDA Collaboration to exploit this antibaryon to produce Ξ^-'s in a totally different way with respect to the use of K^- beam, as it has been done in the past and foreseen for JPARC. This technique requires to insert a target inside the ring and this leads to a number of constraints due to a) the beam lifetime, b) the geometry of the setup, strongly dominated by the short lifetime of the hyperon, c) the overwhelming background which impinges on the detectors. Work is in progress to solve these problems and it is already stated that the performances of HESR can fit the needs of the DSS experiment.

In Section 2 the main features of the physics related to the S=-2 systems and the status of art of the data is briefly reviewed; in Section 3 the reactions which produce Ξ^- hyperon from both kaons and antiprotons are discussed; the project of the experimental setup for producing Ξ^- hyperons and DSS in PANDA is illustrated in Section 4 and the conclusions are drawn in Section 5.

2. Doubly Strange Systems: physics and status of art

The systems containing double strangeness are: I) the Ξ^- exotic atoms, which contain a Ξ^- hyperons in an atomic orbit; II) the Ξ^- hypernuclei, in which the hyperon is absorbed inside a nucleus; III) the double hypernuclei whose strangeness contents is due to a pair of Λ's bound in a nucleus. The main features of their interactions and the status of art of the available data are listed in the following.

I) Ξ^- EXOTIC ATOMS

The Ξ^- exotic atoms belong to the class of the hadronic atoms, which includes pionic, kaonic, antiprotonic, Σ^-, Ξ^- and Ω^- hyperonic atoms. They are formed by capture of the hadron nearly at rest into an atomic orbit, in general in a level with high n. After capture they cascade emitting Auger electrons or X rays. When the lowest levels are reached, the hadron wave function overlaps the low density region of the nuclear matter. The lowest levels are shifted and broadened by the strong interaction between hadron and nucleus, which adds to the Coulomb potential. The detection of the X-rays emitted during the transitions allows to measure these shift and width. When the hadron reaches a broadened level the absorption into the nucleus is fast and the level is called absorption level: therefore the first brodened level is the last of the atomic cascade and only the shift and width of the absorption level can be measured in each exotic atom. Different hadrons have different masses and different levels in which the Coulomb and strong potential start to interplay: therefore they end the cascade at different absorption levels in different atoms. It has been already pointed out [3, 4, 5] that in an atom the absorption level increases monotonically with the hadron mass and, for the same hadron, with the atomic number. Apart the Ω^- hyperon, whose production is still very difficult from the experimental point of view, the Ξ^- hyperon has the heaviest mass among the hadronic atoms and the absorption levels should be the highest ones.

It has been alredy remarked [3] that Ξ^- and Ω^- are absent in the panorama of the hyperatom data even if their mass and lifetime are quite close to those ones of Σ^- hyperatom, which has been observed. The reason of this lack can be found in the specific features of the reactions used until now to produce these hyperons:

$$K^- + N = \Sigma^- + \pi^{+/0} \tag{2.1}$$

$$K^- + N = \Xi^- + K^{+/0} \tag{2.2}$$

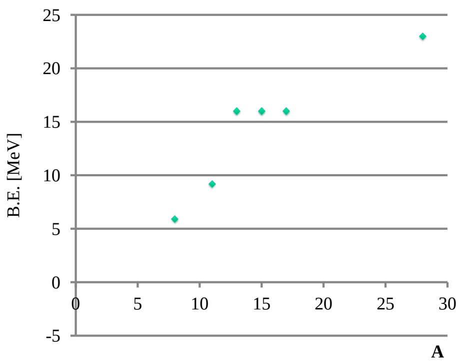
The total mass in the final state of eq.2.1 is less than in the initial state. This allows Σ^- to be produced with a low momentum using very low K^- momenta. Tipically, for K^- of 50 [MeV/c], Σ^- exits in the forward direction at ≈ 217 [MeV/c] and goes to stop in 60, 20 and 25 [ps] in carbon, lead and iron respectively. All these time intervals are quite less than the lifetime and each produced Σ^- hyperon has a good probability to be captured into an atom. On the other hand the final state of eq.2.2 has a mass greater than the initial one and the threshold of the reaction is around 1.05 [GeV/c], producing Ξ^- with forward momentum greater than 500 [MeV/c]. The Ξ^- stopping times in the above materials are 332, 127 and 133 [ps] respectively, greater or comparable with the lifetime: the probability to be captured into an atom is strongly reduced.

By measuring shift and width of the levels, the nuclear potential can be determined in the peripheral region of the nucleus where the nuclear density varies appreciably and the Coulomb and nuclear forces overlap. Data from different atoms are needed to completely describe the low density nuclear potential.

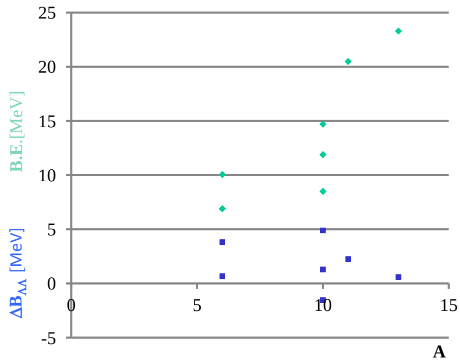
II) Ξ^- HYPERNUCLEI

A Ξ^- hypernucleus contains a Ξ^- hyperon inside the nucleus. As said above, it is formed after Ξ^- absorption from an atomic level. Inside the nucleus the hyperon interacts with the nucleons undergoing both strong interaction and weak decay.

The strong interaction presents some peculiar aspects different from the $\Lambda - N$ interaction acting in the single hypernuclei. In fact, as remarked by Motoba [6], in the OBE mechanism to describe the $\Xi N \rightarrow \Xi N$ coupling no strange meson (K..., I=1/2) can be exchanged, while all



a)



b)

Figure 1: a): Binding Energy vs mass number A of the observed Ξ^- hypernuclei; b) B.E. and ΔBE vs A of the observed $\Lambda\Lambda$ hypernuclei

non-strange mesons of $I = 0$ or $I = 1$ $(\omega, \eta, \pi, \rho..)$ can be exchanged. On the other hand, in the $\Xi N \rightarrow \Lambda\Lambda$ coupling only strange mesons can be exchanged.

Also the weak decay of the Ξ^- hypernuclei presents some different mechanisms with respect to the Λ hypernuclei. First, the Pauli principle, which is responsible for the strong decrease of the branching ratio of non mesonic weak decay in heavy Λ hypernuclei, doesn't affect the possibility of the decays: $\Xi^- + p \rightarrow \Lambda + n$, with $p_{\Lambda,n} \approx 469$ [MeV/c] and $\Xi^- + N \rightarrow \Sigma^- + N$, with $p_{\Sigma,N} \approx 366$ [MeV/c]. In fact the momenta of the final states hyperons are large enough to allow them to exit from the nucleus and in case of sticking after rescattering they have a set of quantum numbers different from those of the nucleons. Moreover the branching ratios of the decays into Λ and Σ could shed light on the role of the isospin.

The amount of Ξ^- hypernuclei data at present is very poor. Some binding energies have been measured in old experiments with bubble chambers and emulsions [7, 8, 9], which look increasing with increasing mass number (see Figure 1.a). Even though these measurements are affected by large errors, Dover and Gal [10] succeeded in calculating an attractive potential well for carbon in the range $V_{\Xi^-} \approx 21 - 24$ [MeV]. Experiments E885 at AGS and E224 at KEK found smaller values for carbon, $V_{\Xi^-} \approx 14$ [MeV] and for scintillating fibers $V_{\Xi^-} \approx 16$ [MeV] respectively. An upper limit of the total elastic cross section $\sigma(\Xi^- p \rightarrow \Xi^- p) \approx 24$ [mb] and the cross section $\sigma(\Xi^- p \rightarrow \Lambda\Lambda) \approx 5$ [mb] have been measured by Ahn et al. [11] for Ξ^- momentum of 0.5 [GeV/c].

III) $\Lambda\Lambda$ HYPERNUCLEI

A $\Lambda\Lambda$ hypernucleus ${}^{A}_{\Lambda\Lambda}Z$, also called Double Hypernucleus, contains 2 Λ hyperons inside a nucleus made of A nucleons, which are created by the reaction $\Xi^- + p \rightarrow \Lambda + \Lambda$. Other creation mechanisms have been studied, which will be discussed in the next section. Inside the nucleus both Λ's interact strongly with the nucleons and can decay weakly in both mesonic and non mesonic mode. The mesonic mode undergoes the same constraints due to the Pauli principle as the single Λ hypernucleus. Both strong and weak interactions present peculiar features.

The strong interaction binds each Λ to the nucleus, as occurs in a single hypernucleus, with a binding energy $B_\Lambda({}^{A}_{\Lambda}Z)$ related to the Λ-nucleus potential. Each Λ can interact also with the other Λ and the interaction energy $V_{\Lambda\Lambda}$ is related to the binding energy $B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z)$ of the Double

Hypernucleus by:

$$-V_{\Lambda\Lambda} \equiv \Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) \equiv B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) - 2B_{\Lambda}({}^{A}_{\Lambda}Z) \tag{2.3}$$

By measuring the binding energy of the Double Hypernucleus, if the binding energies of the 2 single hypernuclei involved in eq.2.3 are known, the $\Lambda\Lambda$ interaction energy can be obtained. Measurements of several hypernuclei are needed in order to obtain a satisfying knowledge about the core of the $\Lambda\Lambda$ interaction.

Concerning the OBE mechanism it must be recalled that the contribution to the $\Lambda\Lambda$ interaction comes only from the non-strange mesons with zero isospin (η, ω...).

The set of available data is today scarce: after the discovery in the 60's [12] in an emulsion experiment and a result from KEK-E176 [13], a recent contribution came from KEK-E373 experiment, which used a diamond target, scintillating fibers and emulsion [14, 15, 16]. Nevertheless the total collection includes less than ten double hypernuclei. Their binding energies $B_{\Lambda\Lambda}$ show an increasing trend for increasing mass number A (see Figure 1.b); their separation energies $\Delta B_{\Lambda\Lambda}$, which are expected to decrease for large nuclei corresponding to large average distances, look quite constant with A. Anyway nothing is definite because the errors are large and the statistics is very poor. It must be remarked that the $\Lambda\Lambda$ hypernucleus is the only system which allows to study the $\Lambda\Lambda$ interaction, because all the other techniques, like hyperon-hyperon scattering measurements, are at present impossible.

The weak decay of the $\Lambda\Lambda$ hypernuclei has several possible final states, depending on the various combinations of mesonic and non mesonic decay of each Λ and on the fragmentation of the hypernucleus after formation. In particular the so called Hyperon Induced Weak Decays:

$$^{A}_{\Lambda\Lambda}Z \rightarrow\ ^{A}Z + \Lambda + n; \qquad 404 < p_{\Lambda/n} < 433\ [MeV/c] \tag{2.4}$$

$$^{A}_{\Lambda\Lambda}Z \rightarrow^{A} Z + \Sigma^- + p; \qquad 280 < p_{\Sigma/p} < 321\ [MeV/c] \tag{2.5}$$

are unique for double hypernuclei and could shed light on the $\Lambda\Lambda$ weak interaction. For instance it could be very interesting to test whether the relative branching ratios of the eqs. 2.4 and 2.5 present problems like the ratio Γ_n/Γ_p of the single hypernuclei. The hyperons and nucleons are emitted with quite high momenta and should be easily detectable. The momentum ranges reported in eqs. 2.4 and 2.5 are calculated under the hypothesis of recoiless, nearly at rest, residual nucleus $A = 11, Z = 5$, for $B_\Lambda \approx 11$ [MeV] and $B_\Lambda \approx 0$, neglecting $\Delta B_{\Lambda\Lambda}$.

No data about this decay are available at present.

3. Production of Ξ^- hyperons and Doubly Strange Systems

All experiments dedicated to DSS (KEK, BNL-AGS, JPARC) planned to use kaon beams in the reactions:

$$K^- + p \rightarrow\ K^+ + \Xi^-; \qquad K^- + n \rightarrow\ K^0 + \Xi^- \tag{3.1}$$

Kaons of 1.66 and 1.8 [GeV/c] were used and the targets were nuclei: reactions 3.1 could be considered quasi free inside the nucleus due to the high beam momentum. Two types of reactions can occur inside the nucleus: direct and indirect reactions. In a direct reaction the DSS is formed in the same nucleus hit by K^-. In an indirect reaction the Ξ^- hyperon exits from the hit nucleus and is captured by an other nucleus. Direct reactions are:

$$K^- + {}^AZ \rightarrow [p(K^-,K^+)\Xi^-] \rightarrow K^+ + {}^A_{\Xi^-}(Z-1); \tag{3.2}$$

$$K^- + {}^AZ \rightarrow [\pi^0 + {}^A_{\Lambda}(Z-1)] \rightarrow K^+ + {}^A_{\Lambda\Lambda}(Z-2); \tag{3.3}$$

In both cases an intermediate state preceeds the formation of DSS, suggesting low probabilities for both mechanisms. In fact two experiments at BNL-AGS, dedicated to the measurement of the forward differential cross section of the Ξ^- hypernucleus [17] and of the $\Lambda\Lambda$ hypernucleus [18], gave a low value and an upper limit (after no observations) respectively:

$$d\sigma/d\Omega_{\Xi^-} \approx 89[nb/sr]; \quad d\sigma/d\Omega_{\Lambda\Lambda} < 10[nb/sr] \tag{3.4}$$

These very low values are due to the low probability of a 2-step process inside the same nucleus. The direct reactions don't produce any Ξ^- -hyperatom during their formation process.

In the indirect reactions the Ξ^- hyperon exits from the nucleus and goes to stop losing energy by ionization in the surrounding matter. Then a) is captured in an atomic orbit forming an hyperatom, b) makes transitions down to the lowest levels and c) is absorbed inside the nucleus forming a Ξ^- hypernucleus, which d) transforms into a $\Lambda\Lambda$ hypernucleus after interaction with a proton. Ξ^- can decay in each step, mostly during the slowing down. Maximizing the number of stopped Ξ^-'s in a target is the aim of all dedicated experiments: E07 experiment at JPARC is expected to produce some 10^4 such events.

The availability of intense fluxes of antiprotons at the FAIR project suggested to produce DSS starting from the basic reactions:

$$\bar{p} + p \rightarrow \Xi^+ + \Xi^-; \qquad \bar{p} + n \rightarrow \Xi^0 + \Xi^- \tag{3.5}$$

whose momentum threshold is $p_{\bar{p}} \approx 2.6$ [GeV/c]. As for kaon beams, reactions 3.5 could be considered quasi free inside the nucleus.

PANDA Collaboration designed a specific assembly of detectors to be arranged all around the antiproton beam of HESR [19]. A target dedicated to the production of Ξ^-'s is foreseen to be inserted inside the beam pipe. Using $\bar{p}$'s of 3.0 [GeV/c] (below the π production threshold), a thin target and a suitable geometry of the beam pipe, it has been calculated [20] that a fraction of some 10^{-3} Ξ^-'s (per produced Ξ^-) go to stop in a ^{12}C target surrounding the pipe. With this configuration the choice of the internal target for maximizing the stopped Ξ^-'s is independent upon the design of the external target, allowing different nuclei to be explored with the same efficiency. In this way both requirements of the DSS physics, high statistics and several hypernuclei, can be satisfied.

4. The internal target of PANDA inside HESR

At FAIR $\bar{p}$'s are accumulated in the Collector Ring (CR) and then injected, as a bunch of initial contents I_0, into the High Energy Storage Ring (HESR). A target located inside the beam pipe is illuminated at the beginning by the full bunch, then the contents I_n decreases after each $n-th$ revolution as:

$$I_n = I_0 \cdot e^{-\frac{n}{f\cdot\tau}} \tag{4.1}$$

where f is the revolution frequency and τ is the beam lifetime. The Ξ^-'s and the background produced in each revolution are proportional to I_n. After a number n_c of revolutions the survived bunch is small and a new injection is required. After each injection a time must be spent for pre-cooling, accelerating (decelerating), steering and squeezing the bunch before the target is inserted in the beam pipe: this time (constant in all cycles) is called 'preparation time' t_p and $t_d \equiv n_c/f$ is the time for data acquisition [21] . During the interval $t_T \equiv t_p + t_d$, CR accumulates a new bunch at a rate of 10^7 $\bar{p}$/s. If t_T is long, the bunch contents is big and the background initially makes blind some detectors. The maximum tolerable background in PANDA is $\approx 5\cdot 10^6$ [annihilation/s]. Since the beam lifetime is related to the target density ρ, thickness s, width w, and to the total hadronic cross section σ_T and Single Coulomb Scattering cross section σ_{SCS} of the target material by:

$$(f\cdot\tau)^{-1} = [\frac{\rho\cdot N_{Av}}{A}\cdot s\cdot w\cdot r_B]\cdot[A^{2/3}\cdot\sigma_T + Z^2\cdot\sigma_{SCS}] \tag{4.2}$$

where A, Z and r_B are mass number, charge and overlapping fraction of beam and target, it is convenient to choose light, thin, wire-shaped targets. Choosing a carbon wire of thickness $s \approx 3$ [μm] and width $w \approx 100$ [μm] the annihilation constraint is satisfied for I_0 up to $6\cdot 10^7$ $\bar{p}$ but the beam lifetime at 3 [GeV/c] is very small and the bunch is consumed in ≈ 3 [s]. Taking into account that $t_p > 15$ [s], the average rate of stopped Ξ^-'s becomes of few thousands per day. In order to increase this rate, the technique of decreasing strongly the factor r_B by steering the beam during the cycle is under study, in order to overlap the target with the less dense part of the beam spot. This solution, likely feasible at HESR, could make nearly negligible the ratio and allow a production of Ξ^-'s at a rate of the order of some 10^4 per day.

5. Conclusion

The doubly strange systems open wide perspectives to study the role played by the strangeness in the strong and weak interactions. In particular the $\Xi^- - N$ and $\Lambda\Lambda$ potentials and the interplay of the Coulomb and nuclear potential in the periphery of the nucleus can be investigated. Moreover the rich variety of mesonic and non mesonic (in particular the hyperon induced) decay modes of the double hypernuclei could help in understanding the hyperon-hyperon weak interaction. To fullfil this goal high statistics is required and the data should be spread along the periodic table. Since these systems are formed starting from Ξ^-, efforts have to be done in order to increase as much as possible the production of this hyperon.

PANDA Collaboration proposed to profite of the intense fluxes of antiprotons at HESR, in the FAIR complex, to produce high rates of stopped Ξ^- and form doubly strange systems. A system of two separated targets, for Ξ^- production and for hypernucleus formation, has been designed, with one target to be inserted inside the beam pipe and interacting with the beam. This setup requires to maximize the hyperon rate under some constraints due to the beam lifetime and the background on the detectors. The required features of the target and performances of the beam have been singled out: a solution of the problem has been identified and rates of several 10^4 stopped Ξ^-'s per day can be expected.

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