

PRODUCTION OF THE DOUBLE HYPERNUCLEI WITH ANTIPROTONS AT PANDA*

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After a brief review of the properties of the $S = -2$ systems and of the data collected up today, the technique that will be used in the PANDA experiment at FAIR to produce and stop the Ξ^- hyperons is illustrated and the expected rates at HESR are reported.

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1. Introduction

Since the discovery in 1963, the existence of the double hypernuclei looked like a promising tool to explore the interactions involving a double strangeness contents. The three basic systems having strangeness $S = -2$ are the double hypernuclei, the Ξ^- single hypernuclei and the exotic Ξ^- atoms. All they present very interesting aspects of their interactions with nuclei and nucleons, which are briefly reviewed in the following. A double hypernucleus contains two Λ hyperons in addition to $A - 2$ nucleons. Each hyperon is bound to the nucleus like in a single hypernucleus, with binding energy $B_\Lambda({}^{A-1}_AZ)$ related to the potential ΛN . Moreover, inside the nucleus, each Λ interacts with the other one and the interaction energy $V_{\Lambda\Lambda}$ is related to the binding energy $B({}^A_{\Lambda\Lambda}Z)$ by:

$$-V_{\Lambda\Lambda} = \Delta B_{\Lambda\Lambda}({}^A_{\Lambda\Lambda}Z) \equiv B_{\Lambda\Lambda}({}^A_{\Lambda\Lambda}Z) - 2B_\Lambda({}^{A-1}_AZ) . \quad (1)$$

Measurements of the double hypernuclei binding energy can provide the information necessary to determine the parameters of the potential models which describe the long range part of the hyperon–hyperon interaction. In the frame of the meson-exchange, the contribution to the $\Lambda\Lambda$ interaction can

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only come from zero isospin non-strange mesons ($\eta, \omega \dots$). In order to extract the core of the $\Lambda\Lambda$ interaction, several hypernuclei should be investigated. It is noteworthy that double hypernuclei are the only way to study the $\Lambda\Lambda$ system, because hyperon–hyperon scattering measurements are impossible with the today techniques.

Another source of information about the hyperon–hyperon dynamics inside a nucleus is the Non Mesonic Weak Decay (NMWD) of both Λ s inside a double hypernucleus. It is well known that in the single hypernuclei the non mesonic decay plays an important role, particularly in the heavier nuclei, due to the low momentum of the decayed nucleon ($\approx 100 \text{ MeV}/c$) in the mesonic decay. The NMWD proceeds through the reaction:

$$\Lambda + N \rightarrow N + N \quad (p_N \approx 416 \text{ MeV}/c) \quad (2)$$

and the mechanism is strongly related to the ΛN dynamics. The nucleon “induces” the reaction (2), which is called Nucleon Induced decay (NINMWD). The double hypernuclei present an analogous case because in addition to the NINMWD of each Λ independently, two other reactions are possible:

$$\Lambda + \Lambda \rightarrow \Lambda + N, \quad \Lambda + \Lambda \rightarrow \Sigma + N, \quad (3)$$

where one of the hyperon plays the role of “inducing” the decay of the other. Like in reaction (2), the mechanism of reaction (3) is related to the $\Lambda\Lambda$ interaction. From the experimental point of view, the final momenta of the hyperons and associated nucleons ($p_{\Lambda/N} \approx 433 \text{ MeV}/c$, $p_{\Sigma/N} \approx 321 \text{ MeV}/c$) of Eq. (3) are large and enough separated to be detected by the standard spectrometers. Concerning the Ξ^- hypernuclei, they are formed by absorption into a nucleus whose strangeness contents increases by 2, mass number of 1 and charge decreases by -1 . The Ξ^- hyperon interacts with protons and neutrons: in the frame of the meson exchange, the $\Xi^- N$ interaction can exchange only non strange meson while in the $\Xi^- N \rightarrow \Lambda\Lambda$ coupling only the strange meson of isospin equal to $1/2$ can contribute [1]. Finally, the Ξ^- atoms belong to the class of the exotic atoms, in particular to the hadronic atoms, as widely discussed in [2]. The unique feature of the hadronic atoms with respect to the leptonic ones is the simultaneous interaction of the Coulomb and strong field. After the hadron ($\pi^-, K^-, \bar{p}, \Sigma^-, \Omega^-$) is captured in an atomic orbit it reaches, through a cascade, the lowest levels where the wave function overlaps the peripheral low density region of the nuclear matter. These lowest levels are shifted and broad by the strong field, shift and width depending on nuclear density [3]. Optical potentials are used to describe the hadron–nucleus interaction and the parameters have to be adjusted on the shift and width data of several atoms. The data of

$S = -2$ atoms are totally missing due to the experimental difficulties in producing Ξ^- s: this results in a complete lack of information about the nuclear interaction of this hyperon with the low density nuclear matter.

2. Status of art: brief review of the data

In spite of the interest for the physics of the doubly strange systems, as illustrated in a previous chapter, the amount of data after more than 40 years after the discovery of the first double hypernucleus is still very scarce. The discovery of the double hypernuclei is commonly attributed to the experiment of Danysz *et al.*, [4]. The separated K^- beam of momentum 1.5 GeV/c was used at CERN to produce Ξ^- hyperons inside an emulsion. In one event three stars were observed and interpreted as a sequence of: (a) the slowing down and absorption of Ξ^- in a nucleus which decays into a double hyperfragment and a charged particle, (b) the weak mesonic decay of the double hyperfragment into $\pi^- + \text{charged particle} + \text{single hyperfragment}$, (c) the weak mesonic decay of the single hypernuclei into $\pi^- + 3$ prongs. Only track and range of each charged particles were measured: the absence of a magnetic field did not allow to know sign and momentum of not stopped prongs, for example the exiting K^+ . Even without further information the interpretation of the event as formation of $^{10}_{\Lambda\Lambda}\text{Be}$ or $^{11}_{\Lambda\Lambda}\text{Be}$ was quite reliable against other possible configurations. The $\Lambda\Lambda$ interaction energy was obtained as $\Delta B_{\Lambda\Lambda} \approx 4.2 \pm 0.4 \text{ MeV}$ assuming $^{10}_{\Lambda\Lambda}\text{Be}$ and $\Delta B_{\Lambda\Lambda} \approx 3.2 \pm 0.4 \text{ MeV} + (\text{spin contribution} \approx 0.5 \text{ MeV})$ assuming $^{11}_{\Lambda\Lambda}\text{Be}$. This experiment basically indicated the way for the $\Lambda\Lambda$ hypernuclei production (through Ξ^-) and the interpretation and analysis of the sequence of phenomena (hyper-fragmentation, double weak decay) occurring after the $^A_{\Lambda\Lambda}Z$ formation.

Apart an observation at BNL [5], whose reliability was strongly criticized [6], a confirmation of the double hypernuclei existence came in 1991 from the experiment E176 [7] which observed a weak decay by tagging the Ξ^- with a hybrid setup containing emulsion and spectrometer. The binding energy of $^{10}_{\Lambda\Lambda}\text{Be}$ or $^{13}_{\Lambda\Lambda}\text{B}$ fixed a lower limit to the mass of the H dybarion. Always using the hybrid setup, Aoki *et al.*, [8] measured in 1998 the mean free path of Ξ^- inside a nucleus without observing any double hyperfragment out of ≈ 800 (K^-, K^+) reactions in emulsion. In 2000 the E885 Collaboration at AGS [9] searched for double hypernuclei in the particular channel $\Xi^- + ^{12}\text{C} \rightarrow ^{12}_{\Lambda\Lambda}\text{B} + n$ using a diamond target: out of 20 000 Ξ^- brought to stop, no neutron was observed. An upper limit of the $^{12}\text{C}(K^-, K^+) ^{12}_{\Lambda\Lambda}\text{Be}$ forward cross-section ($\leq 10 \text{ nb/sr}$) has been measured by the same collaboration [10], while Ahn *et al.* [11] obtained an upper limit of the $\Xi^- p \rightarrow \Lambda\Lambda$ total cross-section ($\leq 5 \text{ mb}$).

Finally, the experiment E373 at KEK [12] observed one event (named NAGARA) in emulsion, showing $2\pi^-$ exiting from a double hyperfragment. A hybrid emulsion scintillating fiber set up was used and the Ξ^- -s well tagged. The results were $B_{\Lambda\Lambda}({}^6_{\Lambda\Lambda}\text{He}) \approx 7.25 \text{ MeV}$ and $\Delta B_{\Lambda\Lambda} \approx 1.01 \text{ MeV}$, quite in disagreement with the evaluation of [4].

From this short review it can be inferred that only the existence of the double hypernuclei is up to now confirmed. In order to step forward in the physics items of chapter 1 the amount of data should be largely increased. The main limit comes from the difficulty of producing and stopping a great number of Ξ^- baryons. A solution to this problem is offered at present by the advent of the new facilities J-PARC and FAIR, which will supply intense beams of K^- and antiprotons respectively. FAIR project will cover several fields of physics with various experiments [13]. One of them, PANDA, is aimed to produce also the $S = -2$ systems using antiprotons.

3. Double hypernuclei production rates at PANDA

In PANDA experiment the Ξ^- hyperons will be produced in the reaction:

$$\bar{p} + N \rightarrow \Xi^- + \bar{\Xi} \quad (4)$$

quasi free inside a nucleus of a primary target (located inside the antiproton beam pipe) at $\bar{p}$ momentum of $3 \text{ GeV}/c$. The slowing down of Ξ^- will occur partially in the residual nucleus and partially in a secondary target where it will be stopped and then captured by another nucleus. The ratio $R_s(A)$ of stopped to produced Ξ^- -s has been evaluated for a suitable arrangement of the targets and for different primary target materials [14]. The stopped Ξ^- rate I_{Ξ} , which is the commonly used parameter to compare the efficiency of different techniques for double hypernuclei production, is proportional through $R_s(A)$ to the rate of reactions (4) achievable in the $\bar{p}$ ring (HESR) of FAIR. This rate depends on the primary target material, the beam characteristics and the PANDA set-up constraints.

The HESR is a storage ring where a $\bar{p}$ bunch I_0 is injected and circulates with frequency $\approx 5 \times 10^5 \text{ s}^{-1}$. At each round the primary target is crossed and the bunch depleted due to the strong interactions, single Coulomb scatterings, energy straggling and Touschek effect [15]. After n_c rounds, *i.e.* a period $T_c = n_c/f_c$, a further injection of $\bar{p}$ s restores the bunch to the initial value I_0 and a new cycle starts. It can be easily shown that in each cycle the number N_c of produced hyperons is given by:

$$N_c = I_0 \exp \left[-\frac{\rho N_{AV}}{A} \sigma_{\Xi} w_t f_b n_c \right], \quad (5)$$

where $\sigma_{\Xi} \approx 2 \mu\text{b}$ is the total cross-section of (4), ρ , A and w_t are the density, mass number and thickness of the target and f_b is the fraction of the beam spot which overlaps the $20 \mu\text{m}$ wide target.

The stopped Ξ^- rate, given by $I_{\Xi} = N_c/T_c$, has to be maximized choosing material and sizes of the primary target. The choice of the target material is determined by the beam losses. In nuclei the strong interaction cross-section behaves like $\approx A^{2/3}$ while the single Coulomb scattering like $\approx Z^2$. Straggling and Touschek effect contributions are smaller and can be neglected. Since the parameter $R_s(A)$ goes like $\approx A^{1/5}$ [2], the heaviest nuclei will produce beam losses higher than the gain due to $R_s(A)$: therefore a ^{12}C primary target has been chosen. All the PANDA detector system can tolerate a maximum background rate which, at present, is estimated around 5×10^6 annihilation/s. This limit has been and could be in future updated, following the progress of the tests of the detector prototypes. In order to maximize the Ξ^- rate, both initial bunch I_0 and target thickness w_t should be increased without exceeding the background limit in each round, which is a more severe requirement than in average on the cycle.

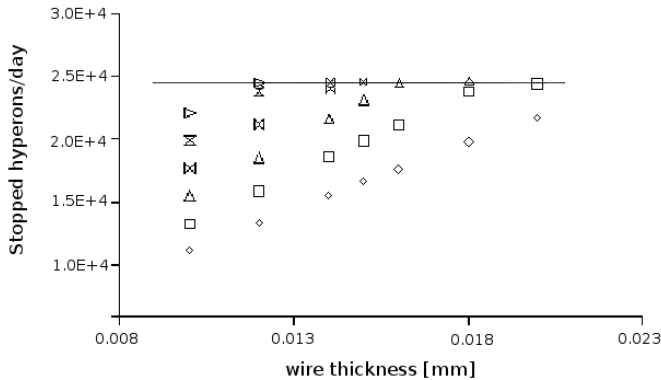


Fig. 1. Stopped Ξ^- rates for $I_0 = 1 \times 10^7$ ($\diamond$), $I_0 = 1.2 \times 10^7$ ($\square$), $I_0 = 1.4 \times 10^7$ ($\triangle$), $I_0 = 1.6 \times 10^7$ ($\bowtie$), $I_0 = 1.8 \times 10^7$ ($\times$), $I_0 = 2 \times 10^7$ ($\triangleright$).

In Fig. 1 I_{Ξ} is reported as a function of the wire thickness for different values of the initial bunch. Self sustained ^{12}C targets of thickness and width in the range $10\text{--}20 \mu\text{m}$ are feasible with the present deposition and etching techniques. The continuous line indicates the upper limit for I_0 not exceeding the maximum annihilation rate in the first round (and consequently in the following rounds). Another constraint is the maximum $\bar{p}$ production rate at FAIR, which is foreseen at $2 \times 10^7 \bar{p}/s$. It is satisfied choosing T_c long enough to allow the machine to produce a $\bar{p}s$ number equal to the number of the lost ones in the cycle. Fig. 1 shows that, under these conditions, rates of stopped Ξ^- close to $23\,000/\text{day}$ can be reached with different combina-

tions of bunch initial contents and target sizes. This allows some degrees of freedom in designing the target and managing the $\bar{p}$ beam. The hypothesis of a continuous refilling of the bunch at the $\bar{p}$ production rate has been also evaluated giving results very close to the discrete refilling.

4. Conclusions

The existence of the double hypernuclei is today confirmed as well as the Ξ^- -atom and Ξ^- -hypernucleus formation during the process in which they are produced. Nevertheless any sound evaluation of their properties could not be done up to now because the data are scarce due to the difficulty of producing large amount of Ξ^- hyperons. The new J-PARC and FAIR facilities will supply enough intense beams to provide good statistics. PANDA experiment at FAIR will use antiprotons instead of the traditional kaons and will locate the primary target inside the $\bar{p}$ ring HESR. The design of the target and the features of the machine allow to estimate that more than 2×10^4 stopped Ξ^- per day will be produced. This rate largely overcome the whole statistics present today worldwide and will start to measure the main quantities related to the nuclear interactions of the $S = -2$ systems.

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