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PRODUCTION OF HEAVY HYPERNUCLEI WITH ANTIPROTONS

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1. INTRODUCTION

At the Low-Energy Antiproton Ring (LEAR) at CERN, experiment PS177 is studying heavy hypernuclei produced in the annihilation of antiprotons. The decay mode, i.e. delayed fission, makes it possible both to identify them and to measure their lifetime.

In this paper I present:

- 1) a brief recall of the principle of the experiment and of the main features of the experimental set-up;
- 2) the results obtained up to now, and the arguments demonstrating the interpretation of the delayed fission observed as decay signature of heavy hypernuclei;
- 3) the next step of the experiment, with particular emphasis on the new detectors implemented in order to i) sign strangeness production, ii) differentiate the hypernuclei of masses ≈ 200 from the fission fragments, with a Λ attached, of masses around 100. This will improve the precision of the lifetime measurements as well.

2. PRINCIPLES OF EXPERIMENT AND SET-UP

The production of Λ particles in the annihilation of antiprotons stopped in nuclei is mainly through the two-step process:

$$\bar{p}N \rightarrow K\bar{K} + \pi_s \quad \text{followed by} \quad \bar{K}N \rightarrow \Lambda\pi.$$

Some experimental data are consistent with this idea, in particular the most recent ones on $\bar{p}D$ annihilation [1, 2]. Nevertheless the yield of Λ particles observed in the annihilation of $\bar{p}$ on heavier nuclei (C to Ta) [3, 4], is as high as 2%. This has led to the conjecture of another possible mechanism, the annihilation on two nucleons:

$$\bar{p}NN \rightarrow K\Lambda + \pi_s.$$

Our results will be discussed in terms of these two mechanisms.

In a heavy hypernucleus a Λ particle will decay mainly according to the non-mesonic process $\Lambda N \rightarrow NN$ releasing about 170 MeV energy; this, in a nucleus of mass ≈ 200 , readily induces fission. Therefore, the observation of fission delayed by the lifetime of the Λ particle in the nucleus will identify heavy hypernuclei and allow the measurement of their lifetime.

The detection of delayed fission is performed using the recoil-distance method [5] which is schematically shown in Fig. 1. The antiprotons stop in the target after being slowed down in the backing. The hypernuclei recoiling in the forward direction decay in flight and their decay products give hits on the shadowed area of the position-sensitive detectors (Parallel-Plate Avalanche Counters) placed perpendicularly to the target plane and at a distance large compared to the target size. The path lengths of the hypernuclei, on the average a tenth of a millimetre, are thus magnified and can be well measured. On the area of the detectors downstream of the target, hits come from delayed fission as well as from prompt fission induced by the annihilation. All these hits are identified as fission fragments by selecting coincidences between the two detectors and measuring TOF and energy loss.

The distance travelled by the recoils before decay depends on their lifetime and also on their velocity. The distribution of their momenta can be deduced from the measured distribution of the opening angles of the fission fragments.

3. RESULTS

We have observed delayed fission following antiproton annihilation in the two targets used, U [6] and Bi [7]. From the 209 and 156 events (respectively) finally recorded, we can evaluate the probability for producing one hypernucleus per stopped antiproton.

First, the probability for delayed fission is given by:

$$P(\text{DF}) = N(\text{DF})/[N(\bar{p}) \times E(s) \times E(e) \times E(g)] ,$$

where $N(\text{DF})$ is the number of delayed-fission events observed and $N(\bar{p})$ the number of antiprotons on target (the backing is a scintillator); $E(s)$ is the antiproton stopping efficiency of the target; $E(e)$ is the escaping efficiency of the recoils, evaluated on the basis of the stopping power program of Ziegler; $E(g)$ is the geometrical detection efficiency deduced from a Monte Carlo simulation. From this formula we evaluate:

$$\begin{aligned} P(\text{DF}) &= (6.5 \pm 2) \times 10^{-4} && \text{in uranium ,} \\ P(\text{DF}) &= (2 \pm 0.6) \times 10^{-4} && \text{in bismuth .} \end{aligned}$$

(The main error comes from $E(e)$.) Then the probability for the formation of a hypernucleus $P(\Lambda A)$ can be calculated according to:

$$P(\text{DF}) = P(\Lambda A) \times P(\text{NF}) \times P(\text{FD}) ,$$

where $P(\text{NF})$ is the probability for the hypernucleus to be stable against prompt fission, and $P(\text{FD})$ is its probability of fission when the Λ decays. In a first approximation we can take for $P(\text{NF})$ the value measured for a nucleus of mass near to that of the hypernucleus. We have measured in the case of a Bi target $P(\text{NF}) \approx 0.90$. In the same way we can take for $P(\text{FD})$ the fission probability which can be estimated for a nucleus with 170 MeV excitation energy. For a Bi target it is evaluated between 0.05 and 0.25 [8] depending on the fission code used.

Consequently, the production probability of one hypernucleus per stopped antiproton is estimated between 8×10^{-4} and 4×10^{-3} . I should like to point out that this estimate is based on our experimental data, which were taken with the main purpose of measuring the lifetime.

For the following discussion, it is necessary to recall that the lifetimes measured [6, 7] for the two targets are in the range of 10^{-10} s, close to the lifetime of the free Λ . They have been determined by comparing the experimental distributions with the results of a Monte Carlo simulation. This simulation is based on the assumption that the delayed fission results from the decay in flight of heavy nuclei slowly recoiling out of the target (mean recoil momentum of the order of 700 MeV/c).

4. DISCUSSION

First we would like to demonstrate that the delayed fission observed in our experiment cannot be a nuclear structure effect.

Delayed fission is known to occur following beta decay or pion or muon absorption but in these cases, the time scale is much longer, 10^{-6} – 10^{-8} s. It is a decay mode known also for shape isomers and is well understood in terms of shell effects stabilizing a non-spherical shape of the nucleus. Several features of the delayed fission observed in the antiproton annihilation are inconsistent with what is known on these fission isomers: i) the yield compared to that of prompt fission is 3 orders of magnitude higher. In particular the observation of delayed fission in a Bi target with a yield 2×10^{-4} per stopped antiproton is in complete disagreement with both experimental data and theoretical understanding on fission isomers for nuclei with $Z < 92$; ii) the symmetric mode of fission observed implies a high excitation energy of the fissioning nucleus, about 10 MeV, and no metastable states in nuclei exist at this energy.

On the other hand, some arguments are in favour of the interpretation of delayed fission in antiproton annihilation as hypernuclear decay: i) Λ particles have been observed in the annihilation

on complex nuclei [3, 4]; ii) the lifetime measured is in the range of the free Λ lifetime; iii) the yield of hypernuclei can be understood in terms of reasonable assumptions on the hypernuclear production in antiproton annihilation. As we will show, it is in agreement with what can be expected from the two-step process mentioned at the beginning.

The particular interest of this process for producing hypernuclei is the kinematics (see Fig. 2) [9]. The momentum distribution of the kaons emitted in the $p\bar{p}$ annihilation (lower part of Fig. 2) peaks closely to the momentum of recoilless production of Λ particles (upper part). About 80% of the kaons have an energy between 200 and 700 MeV/c, to which corresponds a mean free path in nuclear matter of the order of one fermi. This means that all kaons inside the nucleus will form a Λ in the first interaction. Therefore we can write the probability for the production of one hypernucleus per annihilation:

$$P_n(\Lambda A) = P(\bar{p}N \rightarrow K\bar{K}) \times \Omega \times P(\bar{K}N_R \rightarrow \Lambda A\pi),$$

where $P(\bar{p}N \rightarrow K\bar{K})$ is the fraction of the annihilation cross-section going into $K\bar{K}$ pairs plus pions:

$$P(\bar{p}N \rightarrow K\bar{K}) = \sigma(p\bar{p} \rightarrow K\bar{K} + \pi_s) / \sigma(p\bar{p} \text{ ann.}) ;$$

for $\bar{p}$ at rest this ratio has the value 0.06 [10]; Ω is the solid angle for the $\bar{K}$ interaction within the nucleus: the annihilation taking place on the surface, we can assume $\Omega \approx 0.30$; $P(\bar{K}N_R \rightarrow \Lambda A\pi)$ is the probability that, once in the residual nucleus, the kaon interacts with one nucleon in order to form a hypernucleus, i.e. a Λ hyperon bound to a nucleus:

$$P(\bar{K}N_R \rightarrow \Lambda A\pi) = \langle \sigma(\bar{K}N_R \rightarrow \Lambda A\pi) \rangle / \langle \sigma_{\text{tot}}(\bar{K}N) \rangle .$$

Both the numerator and denominator are an average over four possible states and over the available energy in the $\bar{K}N$ centre-of-mass system. We can consider the cross-sections identical for the four channels (which is experimentally demonstrated for the excitation functions $\sigma_{\text{tot}}(K^- p)$ and $\sigma_{\text{tot}}(K^- n)$ above 500 MeV/c [11]) and write:

$$P(\bar{K}N_R \rightarrow \Lambda A\pi) = \langle \sigma(K^- n \rightarrow \Lambda A\pi^-) \rangle / \langle \sigma_{\text{tot}}(K^- n) \rangle$$

averaged on the available energy. We know that $\langle \sigma_{\text{tot}}(K^- n) \rangle \approx 60$ mb. In order to evaluate $\sigma(K^- n \rightarrow \Lambda A\pi^-)$ we use as a starting point the experimental data of Bertini et al. [12] on the reaction $^{209}\text{Bi}(K^- \pi^-)^{209}_{\Lambda}\text{Bi}$. The production cross-section was measured to be $(10.5 \pm 3.7)\text{mb/sr}$ at (0 ± 5) degree for 640 MeV/c K^- . In this cross-section all hypernuclear states are included, even those that are unstable against direct Λ emission. We can expect most of the states populated by substitutional transitions to be stable against Λ decay plus a fraction of those populated by quasi-free transitions (ground states and deep lying states). A calculation of Bouyssy [13] gives the fraction of the cross-section corresponding to the substitutional states (14%) so that we can estimate that at least 25% of the cross-section feeds Λ bound states. The strength of the substitutional states decreases at larger angles whereas the strength of the quasi-free (including the ground state) will increase. We can therefore assume the overall cross-section constant over an angle of 20 degrees. The integration gives ≈ 1 mb. In our case the mean kaon momentum is close to 400 MeV/c. Since the elementary cross-section increases by about a factor of 2 from 700 to 400 MeV/c, we have to multiply the cross-section for hypernuclear production by this factor of 2.

We finally reach the probability of formation of a hypernucleus in the two-step process:

$$P_{N(\Lambda)} \approx 0.06 \times 0.3 \times 0.03 \approx 6 \times 10^{-4}.$$

This estimate, while based on experimental data, must be taken with some care and cannot be more accurate than within a factor of 2. Therefore, it can be considered, because of its large uncertainty, to be in agreement with the experimental determination presented above.

If this value, calculated with the assumption of annihilation on one nucleon, appears to be somewhat small, one can speculate about the necessity to include the two-nucleon annihilation. Following Cugnon et Vandermeulen [14] we can write the probability for the formation of a hypernucleus in the annihilation of an antiproton on two nucleons:

$$P_{2n(\Lambda)} = PA(B = 1) \times PB(\Lambda) \times P(\text{trap}),$$

where $PA(B = 1)$ is the probability for an annihilation on two nucleons; $PB(\Lambda)$ is the probability to produce a Λ particle in this process; $P(\text{trap})$ is the probability that this Λ stays trapped in the nucleus. From a statistical model [14] a value of $PB(\Lambda) = 4.8 \times 10^{-2}$ has been calculated. The trapping probability depends on the energy of the Λ and is not well known; 10% is an optimistic estimate. Then, for the $B = 1$ annihilation to contribute substantially to the production of hypernuclei (i.e. at least at the same level as $B = 0$) would require a probability for the annihilation on two nucleons higher than 10%. However, at this stage, experimental data as well as theoretical estimates are not more precise than a factor of 2 and all definite conclusions would be premature.

5. NEXT STEP

The main purposes of the second-generation experiment are:

- 1) to improve significantly the precision of the hypernuclear lifetime measured;
- 2) to show unambiguously that the observed delayed fission originates from hypernuclear decay, which means that it is associated with strangeness production;
- 3) to look for a lifetime component in the nanosecond range, which has been seen in an experiment performed in Kharkov with 1.2 GeV electrons [15].

We have identified two main sources of uncertainties in our previous experiment: i) the correlation between the lifetime and the momentum of the recoiling hypernucleus; ii) the possible existence of hypernuclear fission fragments which could not be differentiated from the actual heavy hypernuclei. These uncertainties could have accounted for the different lifetimes measured in U and Bi. These problems are being studied by measuring the amplitude signal of the secondary electrons escaping the target with the recoils [16]. About 180 electrons are ejected simultaneously with a fission-fragment pair whereas about 30 to 40 are ejected with a slow heavy recoil. A special ring-shaped microchannel-plate detector has been built and placed very close to the target. It should also make possible a direct lifetime measurement in the nanosecond range.

In order to demonstrate that the delayed-fission events are associated with strangeness, we use the fact that a K^+ is always produced in association with a Λ . Then each delayed fission must be correlated with the emission of a K^+ . A Kaon Range Telescope has been constructed in order to stop a significant fraction of these kaons which are identified through the detection of their muon or pion decay. Owing to the expected yields and to the detection efficiency, for both the delayed fission and the K^+ identification, this demonstration requires a large number of antiprotons [16].

The results will definitely show the interest of antiproton annihilation for producing strangeness in nuclei. If meson beams ($K^- \pi$) are the best tool for all spectroscopic experiments, the qualities of the antiproton beam and the high yield provided by the annihilation can well be appropriate for some other peculiar experiments. Lifetime studies or the production of baryonic systems with one or two units of strangeness are only two examples.

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Fig. 1 Principle of the recoil-distance method as used in experiment PS177.

Fig. 2 Lower part: The phase-space momentum spectrum of the reaction $p\bar{p} \rightarrow K\bar{K}$. The curves are weighted with the known branching ratios of the corresponding channels. Upper part: the kinematics of the reaction $K^- N \rightarrow \Lambda \pi^-$ for different $K\pi$ angles. (From Ref. 9.)