Nonmesonic decay of the $\Lambda$-hyperon in hypernuclei produced by p+Au collisions

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Abstract. The lifetime of the $\Lambda$-hyperon for the nonmesonic decay $\Lambda N \rightarrow NN$ has been determined by a measurement at COSY Jülich of the delayed fission of heavy hypernuclei produced in proton - Au collisions at $T_p\approx 1.9$ GeV. It is found that heavy hypernuclei with mass numbers $A\approx (180\pm 5)$ and atomic numbers $Z\approx (74\pm 2)$ fission with a lifetime $\tau_A=130 \pm 13$(stat.) $\pm 15$(syst.) ps. This value together with the results obtained for other heavy hypernuclei in previous investigations indicates – on the confidence level of 0.9 – a violation of the phenomenological $\Delta I=1/2$ rule for the $\Lambda N \rightarrow NN$ transitions as known from the weak mesonic decays of kaons and hyperons.

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The free $\Lambda$-hyperon undergoes almost with 100% probability the mesonic decay, i.e. $\Lambda \rightarrow \pi^- + p$ or $\Lambda \rightarrow \pi^0 + n$. The energy release ($\approx 40$ MeV) and its sharing among pion and nucleon implies (due to momentum conservation) that the energy of the nucleon is much smaller than the Fermi energy of nucleons in the nucleus. Therefore, such a process is strongly suppressed in nuclei and a different type of the hyperon decay – nonmesonic decay – dominates for all but the lightest hypernuclei. This decay can be induced by neutrons ($n+\Lambda \rightarrow n+n$) or by protons ($p+\Lambda \rightarrow p+n$) with an energy release much higher than in the mesonic decay ($\approx 180$ MeV). The higher nucleon energy, due to an equal sharing of the energy among both nucleons, implies that this process is not blocked by the Pauli principle.

The nonmesonic $\Lambda$-decay represents an example for the nonleptonic weak interaction of baryons with a change of strangeness ($\Delta S = 1$) and isospin ($\Delta I= 1/2$ or 3/2). Thus it is an analogue of the weak nucleon - nucleon interaction, but it involves a new degree of freedom, i.e. strangeness. The strong and Coulomb interactions preserve strangeness and therefore the weak interaction responsible for the nonmesonic decay is not masked by contributions from these two interactions. Therefore the nonmesonic decay enables to study both parity violating and parity conserving amplitudes in contrast to the nucleon-nucleon interaction, where the latter amplitudes are completely masked by strong and Coulomb forces.

The standard model of electro-weak interactions favors neither $\Delta I= 1/2$ transitions nor the $\Delta I= 3/2$ transitions, but experimental investigations on the properties of mesonic decays of kaons and hyperons lead to the obvious dominance of the $\Delta I= 1/2$ part (the so called $\Delta I= 1/2$ rule). The question arises whether this is also the case for the nonmesonic decay of the $\Lambda$-hyperon. Data from the nonmesonic decay of light hypernuclei, which were used to test this hypothesis in the phenomenological model proposed by Block and Dalitz, are affected by too large errors to solve this problem unambiguously. Another possibility for testing the validity of the $\Delta I= 1/2$ rule is an investigation of the dependence of the hyperon lifetime for the nonmesonic decay on the mass of the hypernucleus in which the hyperon is embedded. Such a test requires, besides the knowledge of the lifetimes of light hypernuclei, also the precise knowledge of the lifetimes for heavy hypernuclei. The existing experimental results on the lifetime of heavy hypernuclei, which have been produced in antiproton interactions with Bi and U nuclei, agree within the errors with the data obtained in proton induced reactions on these targets. Experiments with electrons on Bi nuclei lead to an order of magnitude longer lifetime, however, one has to note that the detection conditions of these experiments were not suitable for a measurement of such short lifetimes as quoted in antiproton and proton experiments.

In the present note new results on the lifetime measurements are presented which were obtained at COSY.
Jülich in proton collisions with gold nuclei at $T_p = 1.9$ GeV. The details of the experimental apparatus and the data analysis are described elsewhere [1]. We briefly recall the physics of the measurement and the detection principle. The interaction of the proton beam with an energy above the $(p,K^+)$ threshold with heavy target nuclei causes prompt fission of target nuclei as well as the associated $(K^+\Lambda)$ production and for some fraction of reactions the production of hypernuclei. The hypernuclei will promptly fission with large probability – similarly to target nuclei – or they can survive the prompt fission. In the first case hypernuclear decay in the target but the latter escape and fission – due to a rather long lifetime for the first case hypernuclei decay in the target but the latter get nuclei – or they can survive the prompt fission. In the promptly fission with large probability – similarly to target nuclei – or they can survive the prompt fission. In the first case hypernuclear decay in the target but the latter escape and fission – due to a rather long lifetime for the nonmesonic decay of the hyperon ($\approx 200\mu s$) – at some distance downstream of the target. Fragments from prompt fission of nuclei and hypernuclei, which emerge from the target, can hit only that part of the target which is not shielded by a diaphragm, denoted as "PROMPT" in Fig. 1. The fragments from the delayed fission of hypernuclei are able to reach also the remaining part of the detector, not accessible by the prompt fission fragments. Therefore the distribution of hits of the delayed fission fragments in the shadow region of the detector is separated from the distribution of the prompt fission fragments by a sharp edge and contains information on the lifetime of hyperons folded with the velocity distribution of the hypernuclei (technique known as "recoil shadow method").

Such a method for the separation of delayed fission fragments from the prompt fission [2] has been used in all experiments measuring the lifetime of heavy hypernuclei [9,10,11]. Experiments with a thin target in an internal proton beam have the advantage that the recoiling hypernuclei escape with larger velocities compared to hypernuclei produced by electrons or antiprotons and therefore allow for the most accurate determination of the lifetime. However, it was observed in Ref. [11] that the experiments in the internal beam are very sensitive to mechanical properties of the targets, which must be very thin. Especially the uranium target, which is the most efficient for production of hypernuclei, is rather unstable both, in the form of UF$_4$ and UO$_2$. It changes its shape during experiments causing rather large background in the shadow region of the detector. By contrast in the present note we report on the experiment performed with a gold target, which is mechanically stable. An additional advantage gives a favorable ratio of the delayed fission events to the background appearing from prompt fission. This is illustrated in Table 1, where all factors influencing the ratio of the delayed fission cross section to prompt fission cross sections are listed for U, Bi, and Au.

The theoretical quantities presented in Table 1 have been evaluated in the coupled channel Boltzmann-Uehling-Uhlenbeck approach for the first, fast stage of the reaction, accompanied by the statistical model for the second, slow stage of the reaction. The last column contains experimental data taken from the literature [13,14,15]. As can be seen, the decay rate of the delayed fission for Au targets is expected to be $\approx 3$ times smaller than that for U targets. However, the lower statistics for Au targets can be compensated to some extent by a smaller background from the prompt fission fragments, because the cross section for prompt fission of Au nuclei by protons at 1.9 GeV energy is $\approx 16$ times smaller than for a U target.

In the present experiment a 30 $\mu$g/cm$^2$ thick Au target on 26 $\mu$g/cm$^2$ carbon backing was irradiated by the internal proton beam of COSY with $5 \cdot 10^{10}$ protons circulating in the ring. The measurements were done at 1.9 GeV – to observe the decay of hypernuclei, and at 1.0 GeV – to determine the background (the latter energy is low enough so that the production of hypernuclei is negligible). COSY has been operated in the so called supercycle mode [16], in which the machine was switched between the two energies every $\approx 18$ s. Thus the properties of the target were the same for both energies. Other details of the experimental apparatus and the data analysis were the same as described in Ref. [11].

The projections of the two dimensional position distributions of the hits of delayed and prompt fission fragments in the multiwire proportional chambers along the beam direction are presented in Fig. 2. The dots with error bars represent the distribution measured at the proton

**Table 1.** Comparison of calculated hypernuclei production cross sections in proton induced reactions at $T_p = 1.9$ GeV for 3 heavy nuclei ($\sigma_{HY}/\mu b$), the survival probability of the produced ('hot') hypernuclei against prompt fission ($P_{\text{f}}/\mu b$), the probability of delayed fission of ('cold') hypernuclei induced by hyperon decay ($P_{\text{f}}/\mu b$), the cross section for the delayed fission of hypernuclei ($\sigma_{\text{del}}/\mu b$). Also given are the cross sections for prompt fission of the target nucleus ($\sigma_{\text{prompt}}/\mu b$) for U, Bi, and Au [9,10,11].

| Target | $\sigma_{HY}/\mu b$ | $P_{\text{f}}$ | $P_{\text{f}}$ | $\sigma_{\text{del}}/\mu b$ | $\sigma_{\text{prompt}}/\mu b$ |
|--------|---------------------|---------------|---------------|------------------|------------------|
| U      | 410                 | 0.12          | 0.85          | 42               | $\approx 1.5$    |
| Bi     | 350                 | 0.90          | 0.90          | 25               | $\approx 0.25$   |
| Au     | 330                 | 0.99          | 0.05          | 16               | $\approx 0.10$   |
This also holds true for antiproton induced hypernuclei within the limits of errors with the reanalyzed p+U data. 

Gaussian statistics, lead to a smaller value of the lifetime of events in position distributions was used instead the analysis of the uranium data [17], in which Poisson statistics with the published data for p+U reaction from Ref. [8], but is not in agreement with the experimental and theoretical momentum distributions of kaons produced together with the A-hyperons (in the associated production) and by a comparison of experimental and theoretical momentum distributions of the fragments from the proton induced prompt fission of the U target [16].

The lifetime extracted from the fit to the experimental data is:

\[ \tau_A = 130 \pm 13 \text{(stat.)} \pm 15 \text{(syst.) ps}. \]

This result agrees with the outcome of the experiment p+Bi (161 ± 7 (stat.) ± 14 ps) [6], but is not in agreement with the published data for p+U reaction from Ref. [6] (240 ± 60 ps). We point out, however, that a later re-analysis of the uranium data [7], in which Poisson statistics of events in position distributions was used instead the Gaussian statistics, lead to a smaller value of the lifetime (194 ± 55 ps). Thus, the present value for p+Au agrees within the limits of errors with the reanalyzed p+U data. This also holds true for antiproton induced hypernuclei production on Bi (180 ± 40 (stat.) ± 60 ps) and U targets (130 ± 30 (stat.) ± 30 ps) [8]. All these published data are biased with large errors – with the exception of the p+Bi experiment. The present p+Au experiment provides a new value for the lifetime of heavy hypernuclei, measured with a similar accuracy as that in the p+Bi experiment.

It is known [5], that the shape of the mass dependence of the lifetime of hypernuclei is sensitive to the ratio \( R_n/R_p \) of the neutron induced to proton induced \( \Lambda \) nonmesonic decays, which results from the isospin structure of the decay amplitudes. The absolute scale of the lifetimes is fixed by their values for light hypernuclei, e.g. \(^{11}\)B, \(^{12}\)C, where lifetime is independent of the \( R_n/R_p \) ratio. Thus, a validity of the phenomenological \( \Delta I = 1/2 \) rule, which implies that \( R_n/R_p \leq 2 \), put constraints on the lifetimes of heavy hypernuclei. According to this rule the lifetime of heavy hypernuclei should be larger than \( \approx 180 \) ps for mass numbers \( A \approx 180 \). The present experiment shows that the lifetime of these heavy hypernuclei is significantly shorter. Thus, it indicates (together with p+Bi data) that the phenomenological rule claiming that strange particles decay decay only with the change of isospin equal 1/2 is violated in the nonmesonic decay of \( \Lambda \) hyperons. The confidence level for this statement has been determined - following the procedure given in Ref. [8] - to be equal \( \approx 0.9 \).

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Fig. 2. The position distribution of hits of fission fragments in position sensitive detectors. Details of the figure are discussed in the text below.