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Short Note

Nonmesonic decay of the Λ-hyperon in hypernuclei produced by p + Au collisions

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Abstract. The lifetime of the Λ-hyperon for the nonmesonic decay $\Lambda\mathrm{N} \rightarrow \mathrm{NN}$ has been determined by a measurement at COSY Jülich of the delayed fission of heavy hypernuclei produced in proton-Au collisions at $T_\mathrm{p} = 1.9$ 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 $\tau_\Lambda = 130 \pm 13$ (stat.) ± 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 $\Lambda\mathrm{N} \rightarrow \mathrm{NN}$ transitions as known from the weak mesonic decays of kaons and hyperons.

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The free Λ-hyperon undergoes almost with 100% probability the mesonic decay, *i.e.* $\Lambda \rightarrow \pi^- + \mathrm{p}$ or $\Lambda \rightarrow \pi^o + \mathrm{n}$. The energy release (≈ 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 ($\mathrm{n} + \Lambda \rightarrow \mathrm{n} + \mathrm{n}$) or by protons ($\mathrm{p} + \Lambda \rightarrow \mathrm{p} + \mathrm{n}$) with an energy release much higher than in the mesonic decay (≈ 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 Λ-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 [1].

The standard model of electroweak 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) [2]. The question arises whether this is also the case for the nonmesonic decay of the Λ-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 [3], are affected by too large errors to solve this problem unambigously [4]. 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 [5]. 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 [6], agree within the errors with the data

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obtained in proton-induced reactions on these targets [7,8]. Experiments with electrons on Bi nuclei [9,10] 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 $T_\mathrm{p} = 1.9$ GeV. The details of the experimental apparatus and the data analysis are described elsewhere [11]. 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 ($\mathrm{K}^+\Lambda$) 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, hypernuclei decay in the target but the latter escape and fission —due to a rather long lifetime for the nonmesonic decay of the hyperon (≈ 200 ps)— at some distance downstream the target. Fragments from prompt fission of nuclei and hypernuclei, which emerge from the target, can hit only that part of the detector 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"). The question remains whether the particles observed in the shadow region are due to 1) a delayed fission of heavy hypernuclei —caused by the decay of the Λ-hyperon in the nucleus— or 2) are lighter particles emerging from other sources, *e.g.*, from the prompt fission fragments of target nuclei or hypernuclei. The following tests have been performed to exclude the possibility 2): i) it was checked in separate tests that the detectors used in the present experiment are not sensitive to minimum ionizing particles, ii) the measurements have been also performed with the proton beam of COSY bombarding on a ^{12}C target and with a Cf source to determine experimentally, which region of the (energy loss *vs.* time of flight) diagram is populated by fission fragments and light particles, respectively, iii) the energy distribution of the detected particles has been compared with the energy distribution as predicted by Viola systematics for fission fragments [12], iv) the measurement was performed at two proton beam energies: at 1.0 GeV, which is far below the nucleon-nucleon threshold for Λ-hyperon production (≈ 1.58 GeV), and at 1.9 GeV, where the theoretical prediction of the cross-section for Λ-hypernuclei production is quite large ($> 300\mu$b). The results of all these tests are consistent with the underlying assumption, that the particles observed in the shadow region of the detectors stem from the delayed fission of hypernuclei. Furthermore, the fission fragments detected in the shadow region might also be hyperfragments from the prompt fission of hypernuclei that have changed their direction due to the recoil induced by a subsequent Λ-hyperon decay. To investigate this possibility we have performed extensive Monte Carlo simulations for such processes. These simulations show that, due to the geometrical conditions of the present experiment, the latter fragments can hit the detectors only in a very narrow region close to the edge of the shadow region and, thus, do not contribute to the distribution which was used for the extraction of the lifetime of hypernuclei.

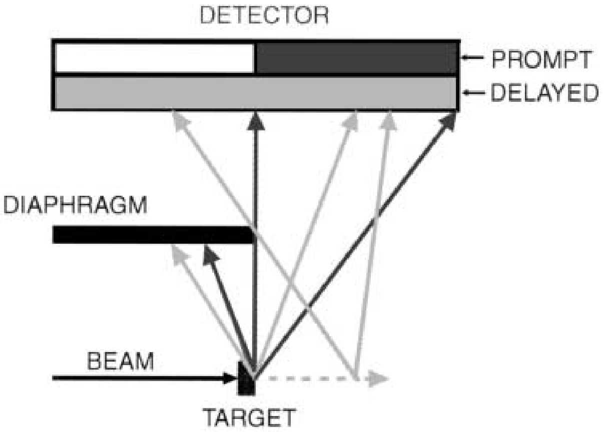

Fig. 1. The schematic view of the apparatus and the idea of the measurement.

Such a method for the separation of delayed fission fragments from the prompt fission [13] has been used in all experiments measuring the lifetime of heavy hypernuclei [6–11]. 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 the 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 [14–16]. As can be seen, the decay rate of the

Table 1. Comparison of calculated hypernuclei production cross-sections in proton-induced reactions at $T_{\mathrm{p}} = 1.9$ GeV for 3 heavy nuclei (σ_{HY}/μb), the survival probability of the produced ("hot") hypernuclei against prompt fission (P_{S}), the probability of delayed fission of ("cold") hypernuclei induced by hyperon decay (P_{f_Λ}), the cross-section for the delayed fission of hypernuclei ($\sigma_{\mathrm{del}}/\mu$b). Also given are the cross-sections for prompt fission of the target nucleus (σ_{prompt}/b) for U, Bi, and Au [14]-[16].

	Theoretical values				Exp. data
Target	σ_{HY}/μb	P_{S}	P_{f_Λ}	$\sigma_{\mathrm{del}}/\mu$b	σ_{prompt}/b
U	410	0.12	0.85	42	≈ 1.5
Bi	350	0.90	0.09	25	≈ 0.25
Au	330	0.99	0.05	16	≈ 0.10

delayed fission for Au targets is expected to be ≈ 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 the prompt fission of Au nuclei by protons at 1.9 GeV energy is ≈ 16 times smaller than for a U target.

In the present experiment a 30 μg/cm^2 thick Au target on 26 μg/cm^2 carbon backing was irradiated by the internal proton beam of COSY with 5×10^{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 [11], in which the machine was switched between the two energies every ≈ 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 energy $T_{\mathrm{p}} = 1.9$ GeV after subtraction of the distribution measured at $T_{\mathrm{p}} = 1.0$ GeV (normalized to the maximum of the distributions). The latter distribution is shown in fig. 2 by the thin solid line. The data presented as full dots were used to extract the lifetime of the Λ-hyperon by a fit of the simulated distribution of delayed fission fragments —the thick solid line. The dashed line in fig. 2 corresponds to the simulated prompt fission fragment distribution (which is the same for $T_{\mathrm{p}} = 1.9$ GeV, and for 1.0 GeV). The velocity distribution of hypernuclei —necessary for the simulation of the delayed fission fragment distributions— has been evaluated within the theoretical formalism mentioned above. The reliability of the calculations has been checked by a comparison of the experimental and theoretical momentum distributions of kaons produced together with the Λ-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 [17].

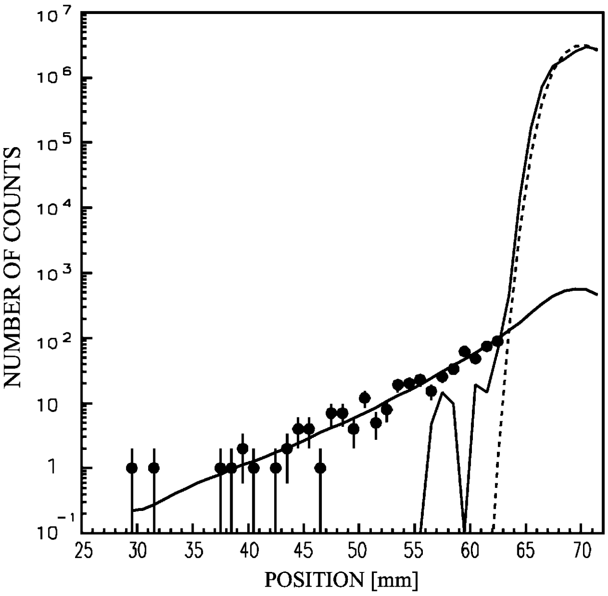

Fig. 2. The position distribution of hits of fission fragments in position sensitive detectors. Details of the figure are discussed in the text below.

The lifetime extracted from the fit to the experimental data is

$$\tau_\Lambda = 130 \pm 13\,(\mathrm{stat.}) \pm 15\,(\mathrm{syst.})\ \mathrm{ps}\,.$$

This result agrees with the lifetime from the p+Bi experiment, *i.e.* (161 ± 7 (stat.) ±14 ps) [8], but is not in agreement with the published data for the p+U reaction from ref. [7] of (240 ± 60 ps). We point out, however, that a later reanalysis of the uranium data [18], in which Poisson statistics of events in position distributions was used instead of Gaussian statistics, lead to a smaller value of the lifetime (194 ± 55 ps). Thus, the present value for the p+Au reaction 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) [6]. 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 (with mass numbers $A \approx (180 \pm 5)$ and atomic numbers $Z \approx (74 \pm 2)$ as found from model calculations [17]) measured with a similar accuracy as that in the p+Bi experiment.

It is known [5] that the lifetime of heavy hypernuclei is sensitive to the ratio $R_{\mathrm{n}}/R_{\mathrm{p}}$ of the neutron-induced to proton-induced Λ nonmesonic decays $\Lambda + \mathrm{N} \to \mathrm{N} + \mathrm{N}$, whereas the lifetime of light hypernuclei ($A \approx 12$) is independent of this ratio. Thus, the knowledge of the lifetime of light hypernuclei (which depends only on $R_{\mathrm{n}} + R_{\mathrm{p}}$) and the knowledge of the lifetime of heavy hypernuclei (depending both on $R_{\mathrm{n}} + R_{\mathrm{p}}$ and on $R_{\mathrm{n}}/R_{\mathrm{p}}$) enables us to determine the absolute normalization, *i.e.* $R_{\mathrm{n}} + R_{\mathrm{p}}$, as well as the ratio $R_{\mathrm{n}}/R_{\mathrm{p}}$.

Furthermore, proper constraints on $R_\mathrm{n}/R_\mathrm{p}$ allow to investigate the validity of the phenomenological $\Delta I = 1/2$ rule due to the following reasons: The ratio $R_\mathrm{n}/R_\mathrm{p}$ vanishes for final-state isospin $I_\mathrm{f} = 0$, since the neutron-induced Λ-decay leads only to neutron-neutron final states which cannot appear in an isospin zero state. On the other hand, the ratio $R_\mathrm{n}/R_\mathrm{p}$ is equal to 2 for $\Delta I = 1/2$ decays to pure $I_\mathrm{f} = 1$ final states (realized, *e.g.*, for Λ-nucleon spin state S) [19]. Therefore, in the general situation — where the observed decays correspond to an incoherent mixture of the $I_\mathrm{f} = 0$ and $I_\mathrm{f} = 1$ final state isospins— pure $\Delta I = 1/2$ decays must result in $R_\mathrm{n}/R_\mathrm{p} \leq 2$.

We recall that the mass dependence of the hypernuclei lifetimes for the one-nucleon–induced decay becomes steeper for increasing ratio $R_\mathrm{n}/R_\mathrm{p}$ [5]. Therefore, it is possible to conclude that the $\Delta I = 1/2$ rule is violated, if the experimental data indicate a steeper mass dependence as predicted by the theory. This holds true also in the case when the contribution of two-nucleon–induced decays ($\Lambda + \mathrm{n} + \mathrm{p} \to \mathrm{n} + \mathrm{n} + \mathrm{p}$) is taken into account, since it was shown by Ramos *et al.* [20] that the yield of two-nucleon–induced decays of Λ-hyperons is independent of the mass of the hypernucleus. The presence of such a mass independent contribution effects the mass dependence of lifetimes in the same way as a decreasing of the $R_\mathrm{n}/R_\mathrm{p}$ ratio. Therefore, an experimental indication for a steeper mass dependence relative to the theoretical result for the one-nucleon– induced decay —under the assumption of the validity of the $\Delta I = 1/2$ rule— becomes an even stronger argument for a violation of this rule when two-nucleon–induced decays are present.

Assuming that the absolute scale of the lifetimes is fixed by their values for light hypernuclei, *e.g.*, ^{11}B, ^{12}C, and assuming the validity of the phenomenological $\Delta I = 1/2$ rule, it is possible to predict values for the lifetime of heavy hypernuclei. According to the above considerations concerning $R_\mathrm{n}/R_\mathrm{p}$ and using the formulae from ref. [5], it turns out that the lifetime of heavy hypernuclei with mass numbers $A \approx 180$ (expected to be produced in p+Au collisions) should be larger than ≈ 180 ps. The present experiment shows that the lifetime of these heavy hypernuclei is significantly shorter. Thus, it indicates that the phenomenological rule —claiming that strange particles decay only with the change of isospin equal 1/2— is violated in the nonmesonic decay of Λ-hyperons. Since this conclusion is based on experimental values for lifetimes of light and heavy hypernuclei, which are biased by statistical and systematic errors, it cannot be interpreted as an ultimate test of the $\Delta I = 1/2$ rule, but it is correct with some probability —the confidence level. To estimate this probability, we followed the procedure described in ref. [5] using the present value of the lifetime of heavy hypernuclei (130 ps) with the error evaluated as a sum of statistical and systematic errors (28 ps). Such a procedure leads to a confidence level ≈ 0.95. This estimation was repeated using average lifetime (154 ± 16 ps) of heavy hypernuclei as obtained from averaging results of proton-induced reactions on Au (130 ± 28 ps —present work), Bi (161 ± 21 ps [8]) and U targets (194 ± 55 ps [18]). The confidence level extracted from this average lifetime was found to be ≈ 0.9. Inclusion of antiproton data [6] does not modify this result. The question arises whether the conclusions of the present investigation can be reconciled with results obtained for light hypernuclei [21], where the ratio $\Gamma_\mathrm{n}/\Gamma_\mathrm{p}$ was measured by straightforward detection of nucleons from the decay of hypernuclei. For example, results obtained by Szymanski *et al.* [22] for $^{5}_{\Lambda}$He (0.93 ± 0.55) and for $^{12}_{\Lambda}$C ($1.33^{+1.12}_{-0.81}$) or $^{11}_{\Lambda}$B ($1.04^{+0.59}_{-0.48}$) are smaller than 2. However, it was pointed out by Ramos *et al.* [23] and Alberico *et al.* [24] that the conclusions from such experiments are strongly dependent on the proper treatment of the contribution of two-nucleon–induced nonmesonic decays. They found that the shape of low-energy part of the experimental spectra of protons can be significantly influenced by the contribution of two-nucleon–induced decays and the comparison of the calculated spectra with the experimental ones favors $\Gamma_\mathrm{n}/\Gamma_\mathrm{p}$ ratios around 2-3 or higher. The large spread of the lifetimes obtained from p+Au, p+Bi and p+U experiments does not allow to conclude unambiguously whether the mass dependence of the lifetimes saturates at values measured for lighter hypernuclei (with $A < 56$). More precise experiments —especially for U target— would be desirable for this purpose.

The success of the experiment relied very much on the high quality of the Au targets which were prepared by Dr. B. Lommel and her target laboratory at GSI Darmstadt, Germany. We are indebted to Prof. OWB Schult for stimulating discussions and interest in these investigations. The project has been supported by the DLR International Bureau of the BMBF, Bonn, and the Polish Committee for Scientific Research (Grant No. 2P03B 16117).

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