Λ-hyperon lifetime in very heavy hypernuclei produced in the $p+\mathrm{U}$ interaction

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The recoil shadow method for the detection of fission fragments has been used to investigate delayed fission of very heavy Λ hypernuclei produced in the p-U interaction at the projectile energy of 1.5 GeV. From the measured distribution of delayed fission events in the shadow region and the calculated momenta of hypernuclei leaving the target the lifetime of the Λ hyperon in very heavy hypernuclei was determined to be $\tau=2.40\pm60$ ps. The comparison of the number of delayed fission events with that of the prompt events leads to an estimation of the cross section for the production of Λ hypernuclei in $p+\mathrm{U}$ collisions at 1.5 GeV of $\sigma_{\mathrm{Hy}}=150^{+150}_{-80}$ μb. [S0556-2813(97)04506-8]

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The lifetime of hyperons bound in hypernuclei is affected by the nuclear environment [1]. Whereas the free Λ decay is purely mesonic, $\Lambda\rightarrow N+\pi$, in the nuclear medium the nonmesonic decay channels, $\Lambda+N\rightarrow N+N$, dominate even in light nuclei like ${}^{12}_{\Lambda}\mathrm{C}$ [2]. In heavy nuclei the mesonic decay mode is negligible such that the total decay width is due to the nonmesonic decay channels. The study of such decays as purely baryonic weak processes can shed light on the problem of the weak interaction of baryons [3].

The measurements performed for ${}^{12}_{\Lambda}\mathrm{C}$ and ${}^{11}_{\Lambda}\mathrm{B}$ nuclei [2] led to a value for the Λ lifetime, including the nonmesonic decay, which is comparable to that for the free particle. Since in-medium effects should be especially pronounced for heavy nuclei, further investigations were performed for Λ hypernuclei produced from $\bar{p}$ interactions with ${}^{209}\mathrm{Bi}$ and ${}^{238}\mathrm{U}$ nuclei [4]. The results of these investigations have shown a decrease of the Λ lifetime, however, they indicate a difference in the lifetimes for ${}^{209}\mathrm{Bi}$ and ${}^{238}\mathrm{U}$ contrary to the expectation, that the decay of a Λ hyperon captured into the $1s$ state should not be strongly influenced by nuclear structure effects in the higher shells of nuclei not very distant in (Z,A).

The aim of the present work was to measure the average lifetime of the Λ hyperon in very heavy hypernuclei produced in proton interactions with U nuclei and to determine the production cross section. In case of very heavy hypernuclei the application of direct timing methods—as used for light hypernuclei [2]—is not feasible due to the large background of light particles. However, this problem can be overcome when detecting the heavy fragments from fission processes that are induced by the Λ decay in very heavy hypernuclei. Since hypernuclei produced in proton-nucleus collisions leave the target with a recoil momentum p_R, they will subsequently decay at some distance from the target proportional to the lifetime τ of the Λ and to the momentum p_R. The recoil shadow method [5] can then be used to discriminate delayed fission against the strong background due to prompt fission. In this method (Fig. 1) only fragments from delayed fission can reach the shadow region of the detector which can be shielded against prompt fission fragments by a diaphragm placed near the detector. The distribu-

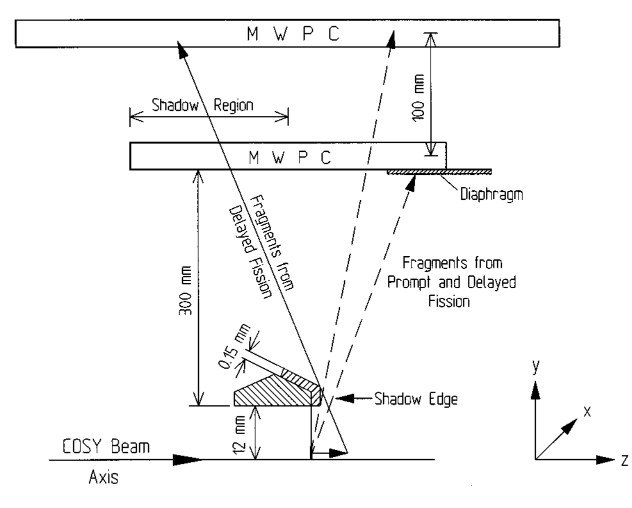

FIG. 1. Schematic presentation of the experimental setup. The thickness of the target holder is enhanced in the drawing to show the details. The real distances are given.

tion of events in the shadow region then depends on the lifetime of the Λ and on the momentum distribution of the hypernuclei recoiling out of the target.

The (p,K) reaction for hypernucleus production has evident advantages for the recoil shadow method. In general, the strangeness exchange (K^-,π^-) reactions yield the largest cross sections; also the associated strangeness production reactions (π^+,K^+) [6] or $\bar{p}$-induced reactions [4] can be employed. The p-nucleus reaction, however, ensures the largest momentum transfer to the hypernucleus produced, which is essential for the recoil shadow method.

Even, e.g., at the energy of 1.5 GeV—still below the threshold for Λ production in nucleon-nucleon interactions—the large projectile momentum of 2.25 GeV/c results in a significant recoil momentum of 750 MeV/c of the produced hypernuclei. Furthermore, the projectile energy in the (p,K) reaction can be easily reduced to lower subthreshold energies were the hypernucleus production cross section becomes negligible. This allows for an easy determination of the background and, in particular, it permits finding out whether an ordinary fission isomer might imitate the decay of a hypernucleus. Such a test is not possible in $\bar{p}$-nucleus interactions where the cm energy is fixed for stopped antiprotons.

Hypernucleus production in the (p,K) reaction has been proposed by Yamazaki [7], however, no data exist on cross sections for energies below the nucleon-nucleon threshold (≈ 1.58 GeV). Recent calculations based on the Boltzmann-Uehling-Uhlenbeck (BUU) approach including Λ hyperon production, propagation, and rescattering [8] predicted a cross section of about 110 μb for $p+$U at 1.5 GeV for ''hot'' hypernuclei which indicated the feasibility of the hypernucleus production in the (p,K) reaction with 1.5 GeV protons. The calculations point out a 30-fold increase of the production cross section for hypernuclei due to Λ rescattering. The importance of rescattering has been confirmed in ^{12}C (π^+,K^+) experiments by Ajimura *et al.* [9]. Further theoretical calculations [10], using a statistical model for nucleon evaporation processes in competition with fission (after the nonequilibrium phase described by the BUU calculation), led to the prediction of final mass and momentum distributions of the produced hypernuclei after the evaporation stage. This information is necessary for the analysis of the recoil shadow data with the aim of extracting the lifetime of the Λ hyperon.

The present experiment was performed at the circulating proton beam of COSY-Jülich, because this offers the unique possibility of achieving sufficient luminosity, even for very thin targets, which are needed for the recoil shadow method. Optimization of the luminosity requires minimization of material other than the target material of interest. This excludes a massive backing as used in other experiments [4]. We have, therefore, used targets with a sandwich structure: 3×3 mm^2 20 μg/cm^2 UF_4 evaporated on the lower part of a 3 mm wide double layer of a 2×20 μg/cm^2 C strip covered also with a 3×3 mm^2 20 μg/cm^2 UF_4 layer on the other side. In such targets strain is largely compensated and they remain flat within $\leqslant$0.15 mm during several days of running of the experiment. The C backing was fixed at the target holder which acted as the shadow producing edge. The U layers extended from 9 to 12 mm below this edge (cf. Fig. 1). The target was positioned under vacuum by means of a manipulator which could be moved in all three directions with an accuracy of $\pm$0.1 mm. Additionally the position of the target could be fine tuned and kept constant by an electrostatic field in the y direction (cf. Fig. 1) produced by two cylindrical electrodes placed below the target. After injection and acceleration of the proton beam, slightly below the target, the beam was bumped onto the target until the proton beam was used up. Then a new cycle was started (typically every 12 s).

The experimental setup is shown schematically in Fig. 1. The fission fragments were recorded by a set of two position sensitive low-pressure multiwire proportional chambers (MWPC) which detected only strongly ionizing fission fragments. The detection efficiency for minimum ionizing particles was checked with β particles from ^{90}Sr and found to be $\leqslant 10^{-11}$, which indicates that the background from light particles, i.e., protons, mesons, etc., . . . , was practically eliminated. The lower detector has dimensions of 10×20 cm^2, the upper one of 17×34 cm^2. The pulses from two planes of anode wires oriented in the x and z directions (Fig. 1) provided information on the position of the hits. The wires were read out through delay lines. The wire spacing was 1 mm. The position resolution in the direction of the beam (z direction) was equal to 1 mm in the lower detector which was placed at the distance of 30 cm above the shadow edge. The distance between both detectors was 10 cm. This geometry and position resolution of the counters enabled a good reconstruction of tracks of the recorded fission fragments. The pulse height spectra were also measured as well as the time of flight with a resolution of about 1 ns. The diaphragm below the lower MWPC was adjusted such that prompt fragments could also be recorded for on-line monitoring and calibration.

Measurements were performed at beam energies of 1.0 and 1.5 GeV. According to the calculations in Ref. [8] the expected cross section for the production of heavy hypernuclei increases by approximately three orders of magnitude when going from 1 to 1.5 GeV. Thus the measurement at 1 GeV provides information on the background in the shadow region or it can reveal an ordinary fission isomer for which the cross section would change only little with projectile energy. The trajectories of the tracks were reconstructed and only those which passed a narrow region around the target were used in the analysis. The histograms of such events along the z axis of the detector are presented in Fig. 2. The distribution of the prompt events is of identical shape for both energies. A simulation calculation (dashed line in the upper part of Fig. 2) taking into account the energy loss and straggling of fission fragments in the target, in the foil separating the ring and the detector chamber as well as in the entrance foils of the MWPC system resulted in a good description of the observed distribution of events near the shadow region.

A Λ hyperon bound in a very heavy hypernucleus, which undergoes prompt fission, can attach to one fragment forming a hyperfragment. The recoil due to the Λ decay then leads to a slight change in the direction of flight of the hyperfragment. Such kicked fragments can reach the shadow region only in its extreme near the shadow edge due to the small value of the transverse component of the recoil momentum transferred in the Λ decay. This region, where the

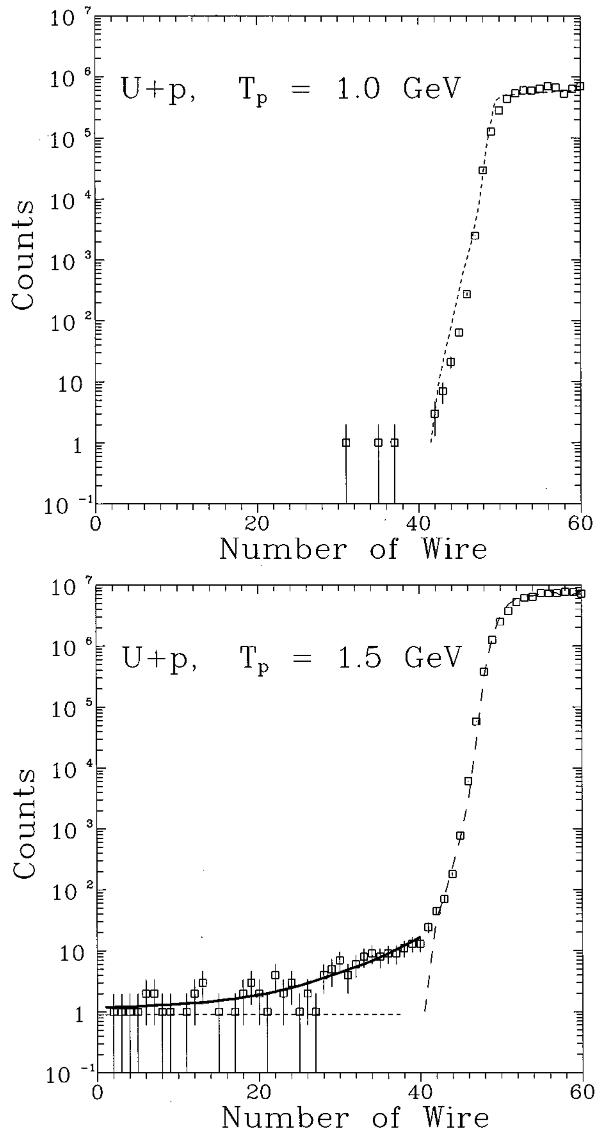

FIG. 2. Histograms of fission fragments measured at proton energies $T_p = 1.0$ GeV (upper part) and 1.5 GeV (lower part). The shadow region includes the channels up to 40; the prompt fission fragments are recorded in channels 41–60. The dashed line in the upper part results from a simulation calculation taking into account the energy loss and straggling of fission fragments in the target, in the foil separating the ring and the detector chamber as well as in the entrance foils of the MWPC system. The dotted line in the lower part of the figure displays the (constant) background taken from the measurement at 1.0 GeV, while the solid line is the result of our calculations for $\tau = 240$ ps. The dashed line in the lower part shows the (normalized) spectrum at 1.0 GeV (upper part) for comparison.

intensity of prompt fission fragments increases drastically, was excluded in the present analysis.

The 1.0 GeV data show little background and no evidence for an ordinary fission isomer. In fact, no such fission isomer is expected for nuclei with masses below uranium. In the measurement at 1.5 GeV events were also observed in the shadow region (channels $\leqslant 40$) which correspond to fragments from fission of hypernuclei induced by the nonmesonic weak decay of the Λ.

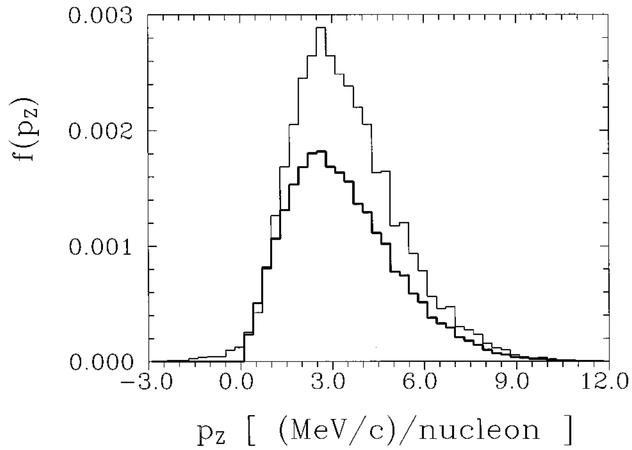

FIG. 3. Distribution of momenta per nucleon parallel to the proton beam, p_z, for hypernuclei produced in $p+\mathrm{U}$ collisions at $T_p = 1.5$ GeV (thin line) as evaluated in Ref. [10]. The thick line shows the momentum distribution for hypernuclei that escape from the target after energy loss and absorption (in total 25%).

From the distribution of events in the shadow region the lifetime of the Λ hyperon was determined. For this one needs to know the recoil momenta of hypernuclei when they exit from the target. For this purpose the momentum distribution of hypernuclei produced in the $p + {}^{238}\mathrm{U}$ collision, as calculated in Ref. [10], was corrected for energy loss in the target. The resulting distribution is shown by the thick line in Fig. 3 in comparison to the result of the BUU calculation (thin line). It was used in the Monte Carlo simulation of the distribution of fission fragments in the shadow region. The lifetime of the Λ hyperon was treated as an adjustable parameter in this calculation. The simulated event distribution was compared with the 1.5 GeV data after subtraction of the background taken from the 1.0 GeV run (dotted line in the lower part of Fig. 2). The analysis based on the χ^2 fit led to the average value of the lifetime of the Λ hyperon in very heavy hypernuclei produced in the proton interaction with ${}^{238}\mathrm{U}$ of

$$\tau = 240 \pm 60 \text{ ps}.$$

In Fig. 2 (lower part) we display the result of our fit for $\tau = 240$ ps in terms of the solid line.

The quoted error of 60 ps is mainly due to statistics (45 ps), while the systematic error was estimated to be about 10% due to uncertainties in the momentum distribution $f(p_z)$ (Fig. 3) and 5% due to possible deformations of the target. The estimate of the systematic error is based on detailed simulations by varying $f(p_z)$ and the target deformation within physical limits.

In Fig. 4 the value of τ for the very heavy Λ hypernuclei from the present work is compared with that for the free Λ decay (+), with results for the nonmesonic decay in ${}^{12}\mathrm{C}$ [2] and with results of Ref. [4] for heavy hypernuclei $\sim$Bi and $\sim$U. The actual lifetimes indicate that the nonmesonic decay in heavy hypernuclei is comparable to the free mesonic decay. The value of the lifetime obtained in the present work is larger than that for nuclei in the vicinity of uranium obtained in Ref. [4]. However, if one takes into account the systematic

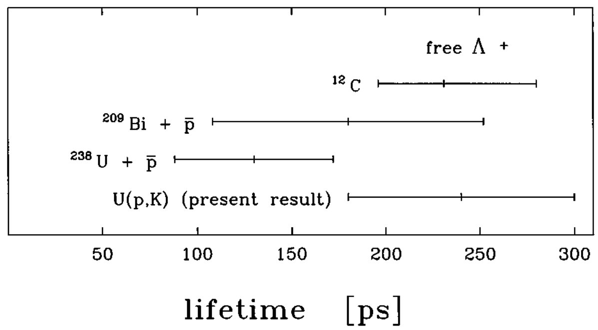

FIG. 4. Lifetime of the very heavy Λ hypernuclei measured in the present work in comparison with the lifetime for the free Λ decay (+) and those for nonmesonic decays of the Λ in ^{12}C [2] and in very heavy hypernuclei produced in $\bar{p}$ interactions with ^{209}Bi and ^{238}U from Ref. [4]. The solid lines include the systematic error of the data.

uncertainty of the latter measurements (as given in Table I of Ref. [4]), the discrepancy is diminished.

The comparison of the observed number of delayed fission events (channels 10–40) with that of the prompt fission fragments (channels 56–60) was used to evaluate the total cross section for the hypernucleus formation in the $p+\mathrm{U}$ collision at 1.5 GeV. The total number of observed delayed fission fragments was equal to 166 ± 30, while the number of prompt fission fragments per channel amounted to 8.1×10^6. The partial cross section $\sigma_{f\Lambda}$ for the production of hypernuclei, which undergo delayed fission, was evaluated from these numbers of counts by taking into account the absorption of recoiling hypernuclei in the target, the calculated ratio of solid angles for the detection of events of both types, and the value of 1.5 b [11] for the total cross section of prompt fission of ^{238}U in collisions with 1.5 GeV protons. Our analysis yields $\sigma_{f\Lambda}=20\pm4$ μb. Since the effective solid angle for the detection of delayed fission fragments in the shadow region depends on the Λ hyperon lifetime, which has some substantial statistical errors so far, the uncertainty in $\sigma_{f\Lambda}$ amounts to a factor of 2.

The total cross section for the production of ''hot'' hypernuclei σ_{Hy} in the interaction of 1.5 GeV protons with ^{238}U then can be calculated by taking into account the survival probability P_s of the hypernuclei against prompt fission and the probability for fission $P_{f\Lambda}$ induced by the nonmesonic decay of the Λ. With $P_s=0.12$ and $P_{f\Lambda}=0.85$ from Ref. [10], we get

$$\sigma_{\mathrm{Hy}}=150^{+150}_{-80}\ \ \mu\mathrm{b}.$$

This cross section is in line with the prediction $\sigma_{\mathrm{Hy}}\approx110$ μb of Ref. [10] thus confirming the importance of Λ rescattering for an increase of the hypernucleus formation in the (p,K) reaction.

Summarizing, we have shown experimentally that the (p,K) reaction is an effective method to produce heavy hypernuclei with large cross sections (≈150 μb) even at the subthreshold bombarding energy of $T_p=1.5$ GeV. Compared to $\bar{p}$-induced reactions the laboratory momenta of the hypernuclei produced are significantly larger which allows one to exploit effectively the recoil shadow method. Though the mesonic decay ($\Lambda\rightarrow\pi+N$) is strongly suppressed in heavy hypernuclei due to Pauli blocking, we find the lifetime of the hyperon in heavy hypernuclei to be roughly of the same magnitude as for the free decay.

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