THE LIFETIME OF THE Λ-HYPERON BOUND IN HYPERNUCLEI PRODUCED BY p+U COLLISIONS

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The nonmesonic decay of the Λ-hyperon has been investigated by observation of delayed fission of heavy hypernuclei produced in proton–U collisions at $T_p = 1.9$ GeV. The lifetime of heavy hypernuclei with masses $A \approx 220$ obtained in the present work, *i.e.* $\tau_\Lambda = [138 \pm 6(\text{stat.}) \pm 17(\text{syst.})]$ ps, is the most accurate result for heavy hypernuclei produced in proton and antiproton induced collisions on a U target so far.

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1. Introduction

Λ-hyperons bound in hypernuclei do not decay in the same way as free hyperons because the mesonic decay $\Lambda \to \pi + N$ is strongly Pauli blocked for all but the lightest hypernuclei. This is due to the fact that the emerging nucleons have an energy smaller than the Fermi energy of the nucleons in the hypernucleus. However, another type of weak hyperon decays becomes possible in the nuclear medium due to the presence of nucleons, *i.e.* the processes $\Lambda + N \to N + N$, or $\Lambda + N + N \to N + N + N$. The energy of the final nucleons from these reactions is much higher than the Fermi energy and thus this "nonmesonic decay" is not Pauli blocked. The study of the nonmesonic decay, which proceeds via a weak interaction only (the Coulomb and strong interactions preserve the strangeness), enables one to obtain information on the weak baryon–baryon interaction which is not accessible by other means. For example, the nonmesonic decay allows to observe strangeness changing $\Delta S = 1$ weak decays whereas the weak nucleon–nucleon interaction is limited to $\Delta S = 0$ processes.

The nonmesonic decay of Λ hyperons in heavy hypernuclei is very interesting because of two reasons: *(i)* it corresponds to the decay of the hyperon in infinite nuclear matter (the hyperon decays from the S-state for which the wave function is well localized in the center of the hypernucleus and surface effects are negligible), and *(ii)* the mesonic decay in heavy hypernuclei is completely negligible. In spite of this the available experimental data for the decay of Λ hyperons in heavy nuclei are scarce and have large uncertainties, which is essentially due to the immense difficulty in producing Λ hypernuclei and subsequently detecting their decay products. Most of the measurements have been performed for light hypernuclei, *i.e.* lighter than $_{\Lambda}$Fe (see *e.g.* the review article [1] or Refs. [2–4]). An investigation of heavy hypernuclei decays has been up to now performed only using Au [5], Bi [6], and U [7–10] targets in proton or antiproton induced reactions [11, 12] or — in case of the Bi target — by electrons [13].

In the present work we report on an experiment devoted to the measurement of the lifetime of heavy hypernuclei as produced in proton collisions with an uranium target. This experiment was performed with the aim to achieve an accuracy comparable to that obtained for heavy hypernuclei produced with Au and Bi targets. The outline of the paper is as follows: in Section 2 the general concept of the experimental setup and the data analysis is presented. The third Section is devoted to a discussion of systematic errors arising from various sources while Section 4 contains a comparison of our present results with the data from the literature as well as a summary.

2. Experimental setup and data analysis

The lifetime of Λ hyperons in heavy hypernuclei may be extracted from the delayed fission channel of heavy hypernuclei, *i.e.* fission induced by the decay of a hyperon via the process $\Lambda N \to NN$. Due to very different time scales for the fission ($\sim 10^{-18}$ s) and for the decay of hyperons ($\sim 2 \times 10^{-10}$ s) it can be assumed that the delayed fission occurs almost immediately after the hyperon decay. Thus the position distribution of delayed fission events from hypernuclei, that move with known velocities in beam direction, provides unambiguous information on the lifetime distribution of the hyperon decays.

The hypernuclei have been produced in interactions of protons from the COSY-Jülich synchrotron at an energy $T_{\rm lab}$=1.9 GeV with a U target. A very thin target has been used such that the hypernuclei — produced with some momentum distribution — can move out of the target area practically without distortions. Now the detection of delayed fission fragments, *i.e.* the position distribution of delayed fission events, allows to extract information on the lifetime of the hyperons if the velocity of the hypernuclei in the laboratory is known. It should be emphasized that, at the energy of 1.9 GeV, proton–nucleus collisions lead to various processes other than delayed fission, *e.g.* spallation, fragmentation, or — most importantly — a prompt fission of uranium nuclei. The relative cross sections and survival probabilities are shown schematically in Fig. 1. The prompt fission cross section (1.5 barn) was taken from Refs. [15,16] while the numbers at the bottom of the figure are theoretical estimates of Λ-hypernucleus cross section formation (410 μb), of P_{S} — the average survival probability against prompt fission (12%), of P_{f_Λ} — the fission probability of hypernuclei induced by $\Lambda N \to NN$ process (85%)); the cross section for delayed fission of hypernuclei 42 μb = 410 μb $\times$ 12% $\times$ 85%.

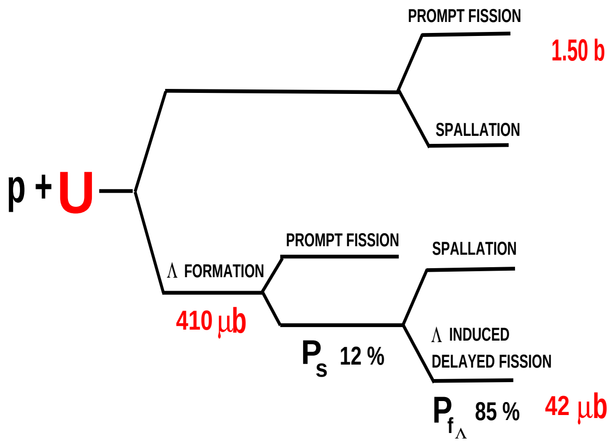

Fig. 1. Schematic view of the relative population of the delayed fission channel and competing reaction channels in p+U collisions, see description in the text.

The detection of hypernuclei and a measurement of their lifetime via an observation of delayed fission events in the presence of prompt fission events, that are more abundant by about five orders of magnitude, is a quite difficult task. This problem has been solved by an application of the recoil distance method as proposed by Metag *et al.* [14] for measurements of the lifetime of long living fission isomers in the presence of a large background of prompt fission events. It should be mentioned that this method was successfully used by Polikanov [12] in his pioneering work concerning measurements of lifetime of heavy hypernuclei.

A schematic view of the experimental setup is shown in Fig. 2. Two position sensitive detectors — operating in coincidence — are placed above the target parallel to the beam. Low pressure multiwire proportional chambers (MWPCs) have been chosen since they are sensitive to heavy fragments only. The MWPCs allowed, besides a measurement of the position of hits, also to determine the Time-Of-Flight (TOF) of the fragments between the detectors as well as the energy loss of the fragments. These detectors were partly screened by the target holder (*cf.* magnification in Fig. 2) from the prompt fission fragments which directly emerge from the target. Thus, as will be discussed below, the shadowed (left) region could be irradiated only by delayed fission fragments or long living isomers. Furthermore, to prevent an overloading of the bright (right) part of the detectors by prompt fission fragments, a diaphragm was placed below the bright region of the lower MWPC. Two slits, parallel to the beam direction, were cut in the diaphragm to allow for the registration of a reduced yield from prompt fission fragments.

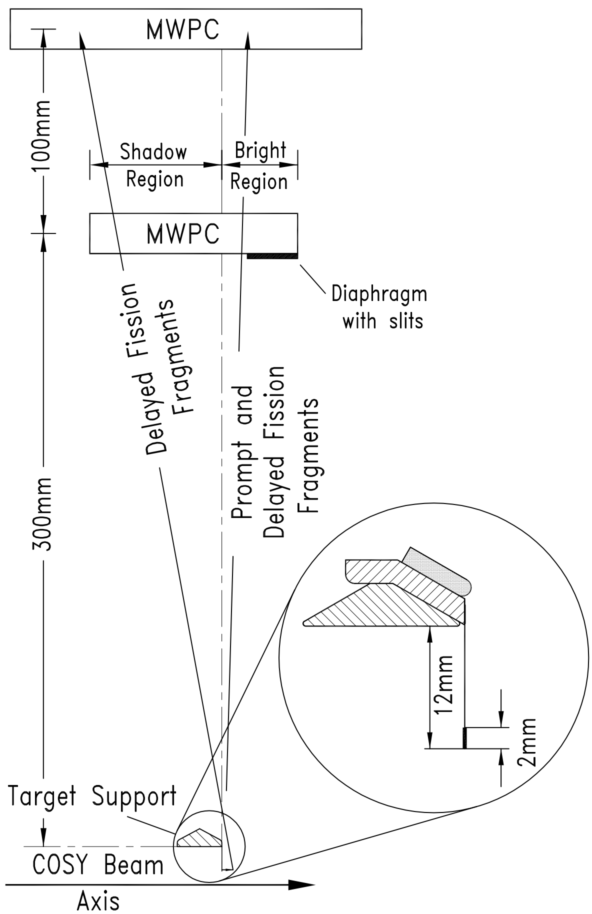

Fig. 2. Schematic view of the experimental setup and illustration of the recoil distance method (see text for a description). The target holder and the shadow edge (dark dashed part of the holder) are shown on a magnified scale.

We now come back to the physical background processes in the p+U reaction at 1.9 GeV. When a proton impinges on an uranium nucleus, the latter undergoes prompt fission with a cross section of ~1.5 barn [15,16]. The created fission fragments can (a) hit the bright part of a position sensitive detector (denoted by "MWPC" in Fig. 2) or (b) hit the shadow part of the target holder (*cf.* magnification in Fig. 2) and be stopped; some of the fragments, however, may scatter on the edge of the target holder and move into the shadowed part of the detectors. This process was found to give the dominant background in the measurements to be presented below.

On the other hand, also hypernuclei can fission promptly in the target giving a contribution to the bright part of the detectors, only. Such events are of no interest for our lifetime measurements. The "cold" hypernuclei (after deexcitation by nucleon and γ emission), that have survived the prompt fission stage, remain stable up to the time when the hyperon decays. The excitation energy released in the Λ decay can induce a delayed fission of the residual nucleus. Since the hypernuclei move approximately in beam direction — due to the momentum transferred from the impinging proton — the latter fission occurs in some distance from the target. Thus the delayed fission fragments can hit both, the bright (right) and shadowed (left) part of the detectors (*cf.* Fig. 2). The position distribution of hits on the surface of the shadowed part of the detector, measured from the shadow edge, then is just a magnified distribution of the distance between the target and the points at which the delayed fission occurs. Thus the shape of the distribution in the shadow region contains the information on the lifetime of the Λ-hyperon folded with the velocity distribution of the hypernuclei.

The distance between the target and the target holder, which defines the shadow edge, is about a factor 27 smaller than the distance from the target holder to the detectors. This leads to a significant magnification of the position scale on to the detector and, therefore, allows for an accurate measurement of the position distribution of fissioning hypernuclei.

In the actual experiment thin (30 μg/cm^2) uranium targets — in the form of UO_2 backed on a carbon foil of 28 μg/cm^2 thickness — were placed in the internal proton beam. The details of the target construction as well as other experimental techniques are described in Ref. [17].

In order to prove that the MWPCs detect the fission fragments from delayed fission of hypernuclei in the shadow region, but not lighter background particles, the following tests were performed:

- The MWPCs were irradiated with minimum ionizing particles (β^-); it was found that the counting efficiency for such particles is below 10^{-11}.

- A pure carbon foil was used as a target, leaving all the other experimental setups unchanged; the measured spectra in the shadowed part of the detectors were found to be empty.

- A ^{252}Cf source was placed in the target position and two–dimensional energy loss (ΔE) versus TOF spectra (between the two MWPCs) were recorded; the measured ΔE–TOF distributions were found to be in full agreement with Monte Carlo calculations taking into account the mass, charge and velocity of fragments according to the Viola systematics [18] for the fission of californium.

Another type of background is expected from hypernuclei, which undergo prompt fission in the target. The hyperon, which is bound in one of the fission fragments, decays in flight and can "kick" the fragment towards the shadow region. However, it has been shown by Monte Carlo simulations that these hyperfragments can hit the shadowed region of the detectors only in a very narrow region of 1–2 mm 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.

In this experiment special precautions have been taken to decrease the background, which mainly stems from prompt fission fragments that scatter at the edge of the target holder or in the entrance foils of the multiwire proportional counters:

The edge of the target holder, which served as a diaphragm — defining the shadowed region of the detector as shown in Fig. 2 (the dark dashed part of the holder) — was shaped cylindrically in the present experiment. This geometry assured that the prompt fission fragments, which enter into the material of the holder at larger angles with respect to the direction perpendicular to the beam, were absorbed in the holder and could not contribute to scattering into the shadowed region. This modified shape was found to be particularly important for measurements with an uranium target since the prompt fission cross section reaches ~ 1.5 barn, which is ~ 36000 times larger than the delayed fission cross section (*cf.* Fig. 1).

A new data acquisition system has been applied allowing for the acceptance of a higher event rate than in the previous experiments. This enabled us to collect a higher number of delayed fission events before the internal structure of the thin target became distorted. Furthermore, the shape of the target was continuously recorded by a TV camera and photos of the target were stored every several minutes. This allowed for corrections in the *off-line* analysis, which were necessary because the uranium targets changed their shape during irradiation.

The background of the position distribution of events in the shadow region of the detectors has been estimated performing the measurements at T_p=1.0 GeV, which is much lower than the threshold energy for the Λ-hyperon production in nucleon–nucleon collisions. Thus at this energy the cross section for hypernucleus formation is negligible ($\sim$ 4 orders of magnitude smaller than at T_p=1.9 GeV) whereas the prompt fission yield is about the same. The COSY accelerator was operated in the supercycle mode, *i.e.* there were three cycles (each of $\sim$ 18 s duration) of acceleration and irradiation of the target; two of them at the higher energy of 1.9 GeV and one at 1.0 GeV. This allowed to study the effect and the background almost concurrently, *i.e.* for the same shape and thickness of the target.

The distribution of hit positions of the fission fragments in the surface of the detector were projected on to the beam direction. These experimental distributions were then compared with simulated distributions, which have been evaluated from the velocity distribution of the hypernuclei and the lifetime of the Λ-hyperon in the hypernuclei. In these simulations the lifetime was treated as a free parameter whereas the velocity distribution was taken from a theoretical analysis performed in the framework of the coupled channel Boltzmann–Uehling–Uhlenbeck model [19–21] (for the first — fast stage of the reaction) and the Hauser–Feshbach model (for the second — slow reaction stage). It was not possible to determine experimentally the velocity distribution of heavy hypernuclei because this would involve coincidence measurements for the fragments. Such measurements — in the presence of prompt fission fragments being more abundant by about five orders of magnitude — would be completely obscured by random coincidences.

Since the number of events in the position distributions was not very large, a Poisson (instead of Gaussian) probability distribution $p(n_i)$ has been used to simulate the number of counts n_i for each position bin:

$$p(n_i) = \frac{\Lambda_i^{n_i}\exp(-\Lambda_i)}{n_i!}\,, \tag{1}$$

$$\Lambda_i(\tau) = \alpha(\tau)l_i(\tau) + b_i\,, \tag{2}$$

where $\Lambda_i(\tau)$ is the expected number of counts in the bin "i" for the detection of delayed fission events — depending on the lifetime τ. In (2) $l_i(\tau)$ is the number of events from the simulated (non normalized) distribution, $\alpha(\tau)$ is a normalization factor to be found from the fit procedure, whereas b_i is the number of counts of the background.

The distributions measured at T_p=1.0 GeV were employed for an estimate of the background in the shadowed region of the detector (after normalization to the same number of events in the bright part of the detector as for T_p=1.9 GeV). The search for the normalization factor $\alpha(\tau)$ has been performed by means of the "maximum likelihood method", which amounts to finding a value of $\alpha(\tau)$ that maximizes the logarithmic likelihood function $L(\alpha)$,

$$L(\alpha) = \ln(\Pi_i \; p(n_i; \alpha(\tau))) \,, \tag{3}$$

for a given value of the lifetime τ. Then the best lifetime τ was extracted by the same — maximum likelihood — prescription, which allows also for an estimate of the error for τ as the difference between the solution for τ and its value τ' corresponding to the likelihood function

$$L(\tau') = L(\tau) - \tfrac{1}{2} \tag{4}$$

(see *e.g.* Ref. [22]).

The results of the fit are presented in Fig. 3 by the solid line in comparison to the data for T_p=1.9 GeV (full dots with error bars). The triangles show the background events measured at T_p=1.0 GeV and normalized to T_p=1.9 GeV data in the bright region of the detector.

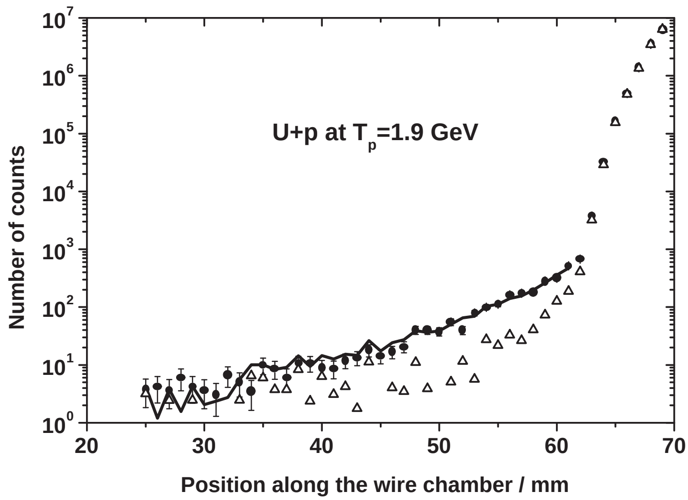

Fig. 3. Experimental position distribution (full dots), background (triangles) and results of the simulation (solid line). The fitted line is not smooth because the background — added to the theoretical distribution — fluctuates due to small statistics. The fit was performed for the position range from 25 mm to 62 mm along the wire chamber. For positions larger than 62 mm the experimental points are perfectly reproduced by the background itself since the effect of delayed fission is orders of magnitude smaller than that of the prompt fission.

Within the analysis described above the following value for the lifetime was found:

$$\tau_\Lambda = 138 \pm 6\,(\mathrm{stat.})\;\mathrm{ps}.$$

3. Discussion of systematic errors

The statistical error quoted in this result was determined from the maximum likelihood method described above. It only depends on the statistics of the experimental position distributions. The systematic errors in addition have various origins; they emerge from

1. uncertainties in the velocity distribution of hypernuclei,
2. an anisotropic emission of the fission fragments in their rest frame,
3. a not uniform irradiation of the target by the proton beam,
4. a modification of the position and shape of the targets during the measurements,
5. the background treatment,
6. the search procedure for the best lifetime.

These sources of errors will be separately discussed in more detail below.

3.1. The velocity distribution of "cold" hypernuclei

A velocity distribution in v and a lifetime τ enter the simulations of the position distributions via the product $v\tau$, *i.e.* the relative error of the lifetime is approximately equal to the relative error in the average velocity. The velocity distributions in these investigations have been taken from our theoretical calculations [23] that are based on the transport code of Wolf *et al.* [24] and Maruyama *et al.* [25]. Thus it is extremely important to check whether these calculations are reliable with respect to the momentum transfer of the proton to the residual nucleus.

We show in Fig. 4 the longitudinal momentum distribution of the residual nuclei from our coupled channel Boltzmann–Uehling–Uhlenbeck (CBUU) + evaporation calculation (solid histogram) for $p+^{238}$U at $T_{\rm lab} = 475$ MeV [23] in comparison to the data of Fraenkel *et al.* [26] (full dots). Of course, there is no hypernucleus formation at the energy of 475 MeV. However, when subtracting the kaon energy and the nucleon–hyperon difference in mass for the proton beam energy $T_{\rm lab} \approx 1200$ MeV, this should lead to similar kinematical conditions as for the system considered.

In the energy range up to 3.0 GeV the momentum transfer to the residual nucleus in the reaction p + ^{238}U was measured by Kotov *et al.* [27]. As pointed out by these authors the average values for the momentum transfer show a very weak energy dependence. Also in Fig. 4 the CBUU + evaporation calculations [23] are presented for $T_{\rm lab}$= 1.0, 1,5, 2.9 GeV and compared

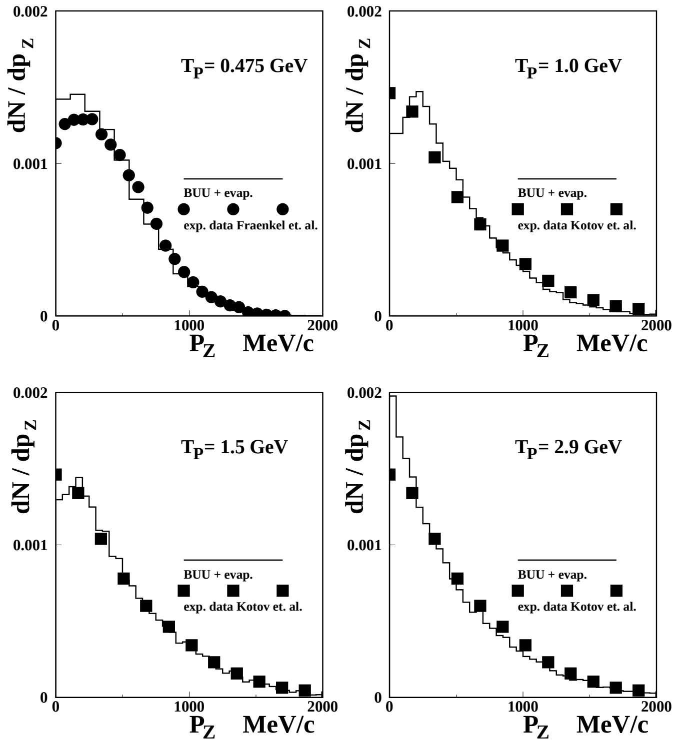

Fig. 4. Comparison of the longitudinal momentum distribution for p+^{238}U at $T_{\rm lab}$ = 0.475 GeV, 1.0 GeV, 1.5 GeV, and 2.9 GeV from the CBUU calculation (solid histograms) with the data from Fraenkel *et al.* [26](full dots) at 0.475 GeV and Kotov *et al.* [27] at 1.0 GeV (full squares).

to the experimental distributions (full squares) measured by Kotov *et al.* [27] for $T_{\rm lab}$ = 1.0 GeV. It is evident that the calculations show a rather weak energy dependence, too, and describe well the experimental distributions. The good agreement with the data in this wide kinematical regime demonstrates the accuracy of the theoretical approach, which should be of the same quality when gating on events with hypernucleus formation.

The reliability of our CBUU calculations has been tested — besides the analysis of prompt fission data — also by differential kaon spectra [10] since the kaons are emitted in associated strangeness production reactions together with the hyperons. Furthermore, by varying the hyperon-nucleon elastic cross section [19,20] within a factor of two we verified that the impact on the velocity distribution of hypernuclei is small, since the U target leads to a large number of rescattering processes. We found that the average velocity does not change by more than 3% what leads to $\sim$ 2 ps for the standard deviation of the lifetime.

3.2. Anisotropic emission of the fission fragments

The angular distributions of fission products show a rather small anisotropy ($\approx$ 10–20 %) even when gating on mass and charge of fission fragments as shown in Refs. [28, 29]. A twofold averaging is performed in our experiment, *i.e.* *(i)* over different fissioning hypernuclei and *(ii)* over different fission fragments. Thus, it is expected that the assumption of isotropic angular distributions is well justified. The influence of possible anisotropies on the lifetime was estimated by geometrical considerations to be approximately 2 ps.

3.3. Non-uniform irradiation of the target

The length of the active part of the target, *i.e.* the UO_2 layer, was about 2 mm, whereas the full length of the target was 12 mm. The assumption of a uniform irradiation of the active part of the target is justified by the fact that the vertical radius of the beam was about 3 mm. The magnification of the position scale due to a different distance from the active part of the target to the target holder and from the target holder to the detector ($\approx$ 300 mm) thus was on average $\approx$ 27. The difference between the average magnification factor, corresponding to a uniform irradiation of the target, and the smallest magnification, corresponding to an irradiation of the lowest part of the target, is $\approx$ 7% which corresponds to a $\sim$10 ps deviation for the lifetime obtained in the present experiment. We note, however, that the accelerated proton beam has been moved upward on the target to achieve a uniform counting-rate distribution over an irradiation cycle. Taking this experimental boundary condition into account, the error arising from a non-uniform irradiation of the target in the present experiment is about 4 ps.

3.4. Modifications of position and shape of the targets

The uranium targets in form of UF_4 (as used in the previous experiments) and UO_2 (in the present work) were mechanically not very stable, *i.e.* they changed their shape during irradiation. Two high voltage electrodes were placed closely to the target and used to straighten it. Due to the continuous control of the position and the shape of the target it was possible to introduce corrections in the off-line analysis, if the position or shape of the target had been changed. In the first case, *i.e.* a change of the target position, such a correction was done in shifting the scale of the position distribution. This procedure involved a negligibly small error. The following methods were used to correct for the change of the target shape; *(i)* the simulated distributions were calculated for several observed shapes of the target and the resulting theoretical distributions were averaged over the shapes to simulate the experimental distribution, or *(ii)* the average shape of the target was taken for the simulation. Both methods of correction lead to almost the same values of the lifetime and the inaccuracy involved in this procedure was ≈ 4 ps.

3.5. Background treatment

In the present work the data measured at $T_p = 1.0$ GeV served — after normalization of the counts to the 1.9 GeV data in the bright part of the detectors — to estimate the background in the shadow region of the detectors. It was found that the inaccuracy of background estimation, as arising from the small statistics of the data at 1.0 GeV, might introduce an error of about 3 ps for the lifetime.

3.6. Search procedure for the lifetime

The fitting procedure of the simulated distributions to the experimental distribution could be performed either with the minimum χ^2-method (normally related to the assumption of Gaussian statistics for the number of events in the individual position bins) or with the maximum likelihood method (which is not limited to Gaussian statistics and can be used also for a Poisson distributions of events). It was checked that both methods work well in the case of high statistics data and lead to the same value for the lifetime. However, for a small number of events the maximum likelihood method with a Poisson distribution of events is preferable [9]. In this case the reanalysis of the low statistics data [7] led to a significant modification (see Table I).

The other problem, which appears when fitting the simulated distribution to the experimental one, is related to the position range of the detector chosen for the fit procedure. Neglecting the position bins, that are placed closely to the shadow edge, decreases significantly the statistics of events. However, these bins are most strongly affected by the background originating from small angle scattering of prompt fission fragments on the diaphragm as discussed above. Thus, some compromise had to be reached, which was most difficult in the case of uranium targets, that are plagued by the largest background (as compared to Au and Bi targets). With good statistics data both problems introduce a rather small error of 2 ps.

In summary, the systematic errors discussed above sum up for the present experiment to 17 ps.

TABLE I

The lifetime of heavy hypernuclei measured at COSY-Jülich with a proton beam and uranium targets.

τ_Λ/ps	Ref.	Comment
240±60	[7]	low statistics, Gaussian distribution in the number of events, χ^2 fit
194±55	[9]	reanalysis of the data from [7], Poisson distribution in the number of events, maximum likelihood method
239±26	[8]	moderate statistics, several targets, Gaussian distribution in the number of events, χ^2 fit
218±35	[9]	reanalysis of the data from [8], Poisson distribution in the number of events, maximum likelihood method
152±10(stat.) ±25(syst.)	[10]	moderate statistics, large background, Poisson distribution in the number of events, maximum likelihood method
138±6(stat.) ±17(syst.)	present work	good statistics, Poisson distribution in the number of events, maximum likelihood method

4. Summary & conclusions

The present work reports results on the lifetime measurement of very heavy hypernuclei produced in p+U collisions. This lifetime is determined almost completely by the nonmesonic decay of the Λ-hyperon in the heavy hypernucleus. The lifetime τ_Λ obtained in the present experiment is compared in Table I with the results of previous experiments performed by the COSY-13 collaboration using the internal proton beam at COSY-Jülich and an uranium target.

The statistical error of the present data is significantly smaller than those obtained in all previous experiments with uranium targets because the statistics achieved in the present experiment is the best (around 3000 events as compared with several hundreds events in Ref. [8,10] and less than two hundred events in Ref. [7])

The errors given in Ref. [9] were evaluated by adding squares of the statistical and systematic errors. Using this method of error presentation the result of Kulessa *et al.* [10] has an error of 27 ps and the lifetime measured in the present work has a total error of 18 ps. Both values are significantly smaller than the errors of the previous measurements, *i.e.* 55 ps and 35 ps, respectively. Since the present data are obviously the most accurate, we recommend for future analysis to use as the lifetime of very heavy hypernuclei, *i.e.* $A > 200$, the value from our present work:

$$\tau_\Lambda = [138 \pm 6\,(\text{stat.})\ \pm 17(\text{syst.})]\text{ps}.$$

This result agrees very well with the lifetime found from experiments using antiproton annihilation on U targets [11,12], where $\tau_\Lambda = 130 \pm 30$(stat.) $\pm$ 30(syst.)] ps was quoted. Since the energy involved in antiproton annihilation is similar to the transfered energy in the present experiment, which studied p+U collisions at T_p=1.9 GeV, one can expect that roughly the same (A, Z) range of hypernuclei was produced in both experiments.

We point out that proton induced hypernucleus production has a couple of advantages in comparison to antiproton annihilation: *(i)* it was possible to obtain a larger statistics of events, *i.e.* a smaller statistical error; *(ii)* due to a larger momentum transfer in proton induced collisions the hypernuclei decay at a larger distance from the target than in the antiproton experiment, which improves the spatial resolution; *(iii)* one can vary the kinetic energy of protons, *i.e.* switching on and off the production of hypernuclei, which is not possible in antiproton induced strangeness production since even for antiproton annihilation at rest the center-of-mass energy is above the strangeness production threshold.

The above points enabled us to more accurately observe the position distributions and thus — apart from a better statistics — to reduce also the systematic error.

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