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Production of heavy hypernuclei in the p + Bi reaction and determination of their lifetime for fission induced by Λ decay

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Abstract

The production of Λ hypernuclei was studied in proton reactions with Bi nuclei and the lifetime of the produced heavy hypernuclei was measured by the observation of delayed fission using the recoil shadow method. The measurements were performed at 1.9 GeV proton energy whereas the background was determined at 1.0 GeV. From the distribution of the fission fragments in the shadow region the lifetime $\tau = [161 \pm 7(\text{statist.}) \pm 14(\text{system.})]$ ps was obtained and from a comparison of counting rates of prompt and delayed fission fragments the production cross section of hot Λ hypernuclei was determined to be (350 ± 140) μb. © 1998 Published by Elsevier Science B.V. All rights reserved.

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The lifetime of a Λ particle bound in hypernuclei differs from that in free space due to the following effects:

- the mesonic decay of the Λ particle is strongly inhibited due to the small available phase space of the decay products (Pauli blocking),
- the non-mesonic decay according to the channel $\Lambda + N \to n + N$,
- possible in-medium modifications of the Λ particle.

All these effects should be most pronounced in heavy hypernuclei. Thus the investigation of the decay of heavy hypernuclei, which proceeds only due to weak interaction, may shed some light on the problem of weak interactions of baryons in nuclear matter.

The specific property of heavy hypernuclei – their possibility to fission – enables to use for mea-

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surements of their lifetime the recoil shadow method [1] in which the fragments from delayed fission (induced by Λ decay) are detected in a detector region screened against prompt fission fragments by some diaphragm. All experiments performed up to now have applied this method of lifetime measurement using, however, different projectiles for the production of hypernuclei. At the Kharkov electron linac e^- were used for the bombardment of a Bi target and the distribution of fission fragments was detected in mica trace detectors [2,3]. At LEAR antiprotons were stopped in thick Bi and U targets [4–6] and prompt as well as delayed fission fragments were measured with two parallel plate avalanche counters. The protons from the COSY facility produced hypernuclei in collisions with a U target [7] and the lifetime for delayed fission was determined from the distribution of fission fragments detected in the shadow region of two position sensitive multiwire proportional chambers.

The measurements performed with antiprotons and protons lead to a lifetime τ somewhat lower than that for a free Λ particle $\tau(\Lambda) = [263 \pm 2]$ ps, $\tau(\mathrm{Bi}) = [180 \pm 40(\mathrm{statist.}) \pm 60(\mathrm{syst.})]$ ps, $\tau(\mathrm{U}) = [130 \pm 30(\mathrm{statist.}) \pm 30(\mathrm{syst.})]$ ps [6], and $\tau(\mathrm{U}) = [240 \pm 60]$ ps [7]. A controversial result was obtained for hypernuclei produced in e^- reactions with Bi where a one order of magnitude larger value of $\tau(\mathrm{Bi}) = [2.7 \pm 0.5]$ ns was found [2,3]. The sensitivity of the experiment with antiprotons for a possible long lived component of the Λ decay was smaller than that in the electron induced reactions due to significantly different ratios of delayed to prompt events: $\mathrm{R}(\bar{p} + \mathrm{Bi}) = 3.6 \cdot 10^{-3}$, $\mathrm{R}(e^- + \mathrm{Bi}) = 2.5 \cdot 10^{-5}$, respectively. Thus one could not exclude the possible production of long lived hypernuclei in antiproton induced reactions [5]. In the recent study of hypernuclei produced in the p + U reaction [7] the ratio of delayed to prompt fission events $\mathrm{R}(\mathrm{p} + \mathrm{U})$ was equal to $1.3 \cdot 10^{-5}$, i.e. similar to that for the $e^- + \mathrm{Bi}$ reaction. In spite of the same sensitivity of both experiments to the long lived component of Λ decay, such a component was not observed in the p + U reaction [7]. In both these studies, however, the hypernuclei were produced from different target nuclei. Moreover, the proton energy (1.5 GeV) was very close to the free nucleon-nucleon threshold for Λ production (1.58 GeV) in [7], while in the electron studies the energy was 0.3 GeV above the threshold.

In the present work very precise measurements of the lifetime of heavy hypernuclei and the ratio of delayed to prompt fission events were performed for p + Bi collisions at a proton energy of 1.9 GeV, which is also 0.3 GeV above the free nucleon-nucleon threshold. This enabled us to obtain an upper limit for a possible long lived component of a delayed decay from hypernuclei.

We note that a very thin target is essential for achieving high precision with the recoil shadow method. Then a large luminosity could be obtained practically only when placing the target in the circulating beam. This permits a multiple passing of protons through the target. The COSY facility [8] is very well suited for the application of such a multipass method where the achievable luminosity is independent of the target thickness. The experiment (see Fig. 1) was installed in the middle of the straight, telescope section of the COSY ring. The proton beam was accelerated when passing slightly below the target and then bumped vertically onto the target and passed through it until it was completely used up. The target consisted of a sandwich structure formed by three layers of 14 $\mu\mathrm{g/cm}^2$ of Bi, 30 $\mu\mathrm{g/cm}^2$ of C and 14 $\mu\mathrm{g/cm}^2$ of Bi suspended on a carbon strip of 13.1 mm length (Fig. 1). The target spot had dimensions of 2.4 mm $\times$ 2.65 mm. This structure of the target assures its flatness during the experiment. The position and shape of the target was monitored during the whole measurement by a close circuit TV system. An electrostatic field of two cylindrical electrodes placed at relative distance of 2.6 cm and 6 cm below the target stretched the target and enabled the adjustment of its position along the beam. Fission fragments were recorded with two multiwire proportional chambers (MWPC) operated at a pressure of 4 mbar. They were position sensitive in x and z direction. This system allowed track reconstruction as well as energy loss and time of flight (TOF) measurement for each detected fragment. The target and its support establish a shadow region at the MWPC's. This region is screened from prompt fission fragments originating in the target. Thus in the shadow region only the fragments which originate downstream of the beam outside of the target are detected. They are due to delayed fission,

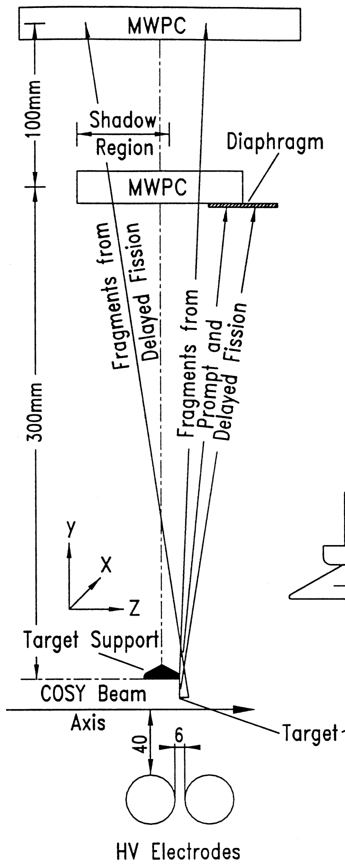

Fig. 1. Sketch of the experimental arrangement. Details of the target are shown in an enlarged scale. High voltage electrodes are located below the target support. The detector system for recording prompt and delayed fission fragments from the interaction of 1 and 1.9 GeV protons with Bi is indicated in the upper part of the figure.

induced by Λ decay, of hypernuclei which recoil out of the target with momenta transferred by protons during the reaction. Prompt fission fragments can reach the MWPC's between the shadow region and the edge of the diaphragm and in the region of a narrow slit cut in z-direction in the diaphragm in order to reduce the load of prompt fragments on the detectors and thus the dead time losses. The simultaneous detection of prompt and delayed fission fragments allows for normalization of delayed fission cross sections.

For a background determination the measurement was performed at a proton energy of 1.0 GeV, sufficiently low to inhibit hypernucleus production [9]. In order to assure the same conditions for the effect and background measurements the COSY ring was operated in a supercycle mode in which the cycle time was equally split into 10 seconds shots at 1.0 and 1.9 GeV. The acquisition system ensured event-by-event storage of data on the computer discs and streamer tapes. The data were monitored on-line for inspection of the performance of the experiment.

The track reconstruction in the off-line analysis allowed a determination of the target position and the dimension of the target spot. Gates on this target spot image were applied reducing the accepted number of events to 99 %, rejecting particles which do not come from the region in the vicinity of the target. Time of flight was measured between both MWPC detectors while the energy loss ΔE was measured in the lower MWPC. Gates were then set in the TOF – ΔE two dimensional plot on the region corresponding to fission fragments (region ''b'' in the scatter plot shown in the upper part of Fig. 2). This condition rejects particles which are emerging from reactions different from nuclear fission.

The results of the experiment are shown in Fig. 3 presenting the projected distribution of events in the detector plane on the axis parallel to the beam direction. In the upper part of the figure the data obtained at 1.0 GeV are displayed, in the lower one the data at 1.9 GeV. Three distinct regions are visible: A) the shadow region (channels [1–54] in Figs. 3 and 4) – strongly populated for 1.9 GeV, but almost empty for 1.0 GeV, B) the region of the shadow edge (channels [55–62]) where a strong increase in the number of fission events is seen, and C) the region open for prompt fission fragments where the number of counts is saturating (channels [63–90]), however, for larger channel numbers the number of counts is reduced by 2 orders of magnitude in the region of the narrow slit in the diaphragm. The distributions and number of events in the regions B) and C) are practically the same for both proton energies. This is clearly seen from comparison of the lower and upper parts of Fig. 3. Therefore the distribution of events measured for 1.0 GeV in the shadow region was used (after normalization) to determine background events at 1.9 GeV in the shadow region A). The event distribution in the shadow region – originating from the delayed fission at 1.9 GeV – depends on the geometry of the experimental ar-

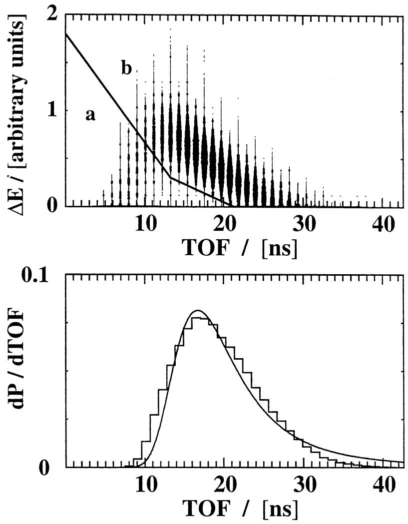

Fig. 2. The upper part of the figure shows the scatter plot of experimental events in the TOF – energy loss plane. The prompt and delayed fission events taken for further analysis are defined by gate ''b''. The events present in the gate ''a'' correspond to fast particles with small charge and are produced probably in processes other than fission. The lower part of the figure shows the histogram obtained by projection of the experimental events from the gate ''b'' of the two dimensional scatter plot on the time of flight axis. The full line shows the time of flight distribution of fission fragments evaluated from the mass distribution of fission fragments (assumed to have a gaussian shape with average mass and standard deviation equal to 95 and 11 mass units, respectively) while the total kinetic energy of fragments was taken from Viola systematics [10]. In the calculation the loss of energy of fragments in the foils of the detector was taken into account. This distribution was normalized to represent the same total number of events as that contained in the experimental histogram.

rangement, the recoil momentum distribution of hypernuclei emitted from the target and the lifetime τ of the Λ hyperon. Adopting the momentum distribution from calculations performed in the framework of a BUU plus Hauser–Feshbach model [11,12], the lifetime τ was determined from a χ^2 fit to the experimental data (cf. Fig. 4). These data were obtained as the difference of counts at 1.9 GeV and the background found according to the prescription discussed above. The fit was restricted to channels in the range from 1 to 54 (cf. Fig. 4) and it was checked that diminishing the range of fitted channels does not change the results within the limits of the estimated errors. The statistical error of the lifetime was found by the standard method from the fitting procedure as the range of the lifetime corresponding to an increase of the χ^2 value by 1 with respect to the minimal value. Two main sources of systematic errors were taken into account i) the uncertainty in the recoil momentum distribution and ii) the uncertainty in the target position, its dimension and deformation. Contributions from these two sources to the systematic error were estimated to be in total less than 10 %.

From the performed analysis described above the lifetime τ of the Λ hyperon bound in heavy hyper-

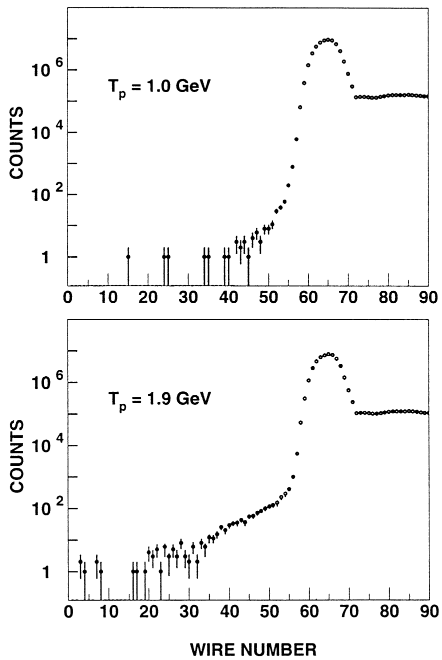

Fig. 3. In the upper part of the figure a distribution of hits is shown in the lower MWPC detector in coincidence with upper MWPC for collisions of 1.0 GeV protons with the Bi target. The abscissa is the distance (in 1 mm wide channels) along the lower MWPC, parallel to the COSY beam direction (cf. Fig. 1). The reduced number of events for channels $>$ 70 is due to the presence of a diaphragm with the narrow slit along the beam direction. In the lower part of the figure the analogous distribution is presented, obtained for 1.9 GeV protons bombarding the target. A striking similarity of the shape of the distributions is visible for channels $>$ 54, whereas the shadow region i.e. channels $\leq$ 54 is significantly more populated in the case of 1.9 GeV than for 1.0 GeV showing the presence of fragments originating from the delyed fission induced by the Λ hyperon decay.

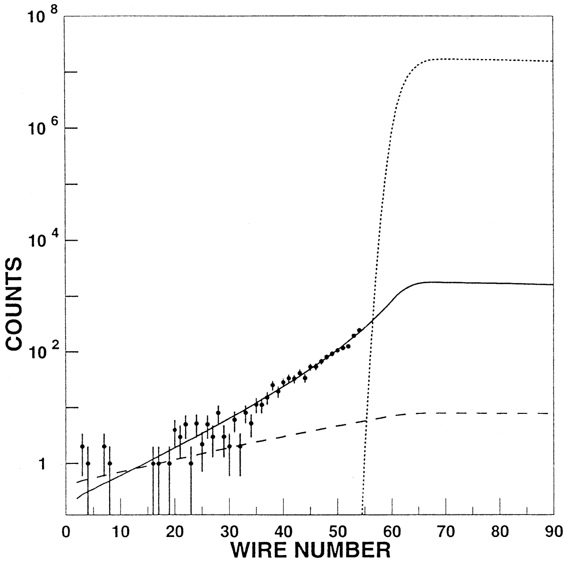

Fig. 4. The experimental points shown for channels $<$ 55 were obtained by subtracting the distribution measured at 1.0 GeV (after normalization to the same number of events in the plateau – i.e. channels >70 – as in the distribution measured at 1.9 GeV) from the distribution for 1.9 GeV. The full line presents the result of the fit of delayed fission fragments for a hypernucleus lifetime of 161 ps and the momentum distribution calculated in the BUU model [11] for 1.9 GeV protons bombarding the Bi target. The dotted line is the distribution of prompt fission events modelled taking into consideration scattering of fission fragments in the target and in the foils of detectors. The dashed line was evaluated for a lifetime of hypernuclei equal to 2700 ps [3] and was normalized in such a way as to reproduce the number of events in channels [1–11] after subtraction of the fitted curve with a lifetime of 161 ps from experimental data and addition of $3\cdot\sigma$ for these events. Thus it represents an upper limit for long lifetime component.

nuclei produced in p + Bi reactions at 1.9 GeV was obtained as

$$\tau = [161 \pm 7(\text{statist.}) \pm 14(\text{system.})] \text{ ps}. \quad (1)$$

The ratio R(p + Bi) of the cross sections for delayed (full line in Fig. 4) and prompt fission (dotted line in Fig. 4) was found as the quotient of the numbers of events per channel corresponding to both processes determined in the region of the plateau C) where the solid angles for both processes are equal with an accuracy of 1 %. The prompt fission events in this region are directly observed while those for delayed fission are found from the modelling of the experimental distribution by the Monte Carlo method for the lifetime of Λ hyperon and geometrical conditions of the experiment. The statistical error was obtained via the fitting procedure as the error of the normalization of the modelled event distribution of delayed fission to the experimental points in the shadow region and the statistical error of the measured number of prompt fission events. The systematic error of the ratio is caused by the systematic error of the Λ hyperon lifetime and the uncertainty in the geometrical conditions of the experiment.

The ratio of delayed to prompt fission events obtained in the present experiment is equal to

$$\text{R(p + Bi)} = [9.8 \pm 2.5] \cdot 10^{-5}. \quad (2)$$

The cross section for delayed fission calculated from this ratio and the known [13,14] cross section for prompt fission σ(prompt) = [255 ± 40] mb is equal to

$$\sigma_{f\Lambda} = [25 \pm 10]\ \mu\text{b}. \quad (3)$$

The BUU and Hauser–Feshbach model calculations performed for the determination of the recoil momentum distribution of produced hypernuclei [11] provided also values for the survival probability P_S of the hypernuclei against prompt fission and the probability of fission $P_{f\Lambda}$ induced by the non-mesonic decay of the Λ. Using the extracted values $P_S = 0.80$ and $P_{f\Lambda} = 0.09$, as well as $\sigma_{f\Lambda}$ obtained above the production cross section $\sigma_{\text{Hy}} = \frac{\sigma_{f\Lambda}}{P_S \times P_{f\Lambda}}$ for (hot) hypernuclei was found to be

$$\sigma_{\text{Hy}} = [350 \pm 140]\ \mu\text{b}. \quad (4)$$

This value agrees very well with the theoretical estimate of the production cross section for hot hypernuclei of 330 μb obtained in the framework of the BUU model [9].

The ratio of delayed to prompt fission events from the present experiment agrees well with that found in a recent study of the proton + U reaction [7] taking into account different fissibilities of Bi and U nuclei and the mass and energy dependence of the cross section of hypernucleus production [9]. Since this ratio is of a similar order of magnitude as in the electron + Bi reaction studies, it is possible to estimate the upper limit of the cross section for a conceivable long-lived component of delayed fission induced by protons on Bi nuclei. From the inspection of Fig. 4 it is evident that there are some events in channels [1–10] which are above the line representing our results from modelling the delayed fission with the lifetime determined in the present study. Taking into consideration the statistical inaccuracy of our background determination as well as that of modelling the delayed fission component, the presence of a long-lived component of the delayed fission (dashed line in Fig. 4) cannot be ruled out on the confidence level of 99 %. Assuming for this component a lifetime of 2700 ps – as found in electron + Bi reactions [2,3] – the cross section for such delayed fission events can be estimated to be less than 80 nb.

In summary, the performed experiment has lead to the most precise value of the lifetime of Λ hyperons in very heavy nuclei known up to now. It agrees well within the limits of errors with the lifetime obtained in antiproton + Bi experiments [6], however, it differs significantly from the value quoted in Refs. [2,3] originating from electron + Bi studies.

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