Measurement of the ${}^{3}_{\Lambda}$H lifetime and of weak decay partial widths of mirror p-shell Λ-hypernuclei

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A proposal to accurately measure the hypertriton lifetime and to determine weak decay partial amplitudes for few selected neutron-rich Λ-hypernuclei belonging to the p-shell is outlined. The basic idea is to exploit for the first time the two-body ${}^{A}Z(\pi^{-},K^{0})^{A}_{\Lambda}(Z-1)$ reaction at the J-PARC K1.1 beam line and to add some specific detection capabilities to the existing SKS complex.

1 The physics cases

The accurate determination of the hypertriton (${}^{3}_{\Lambda}$H) lifetime ($\tau({}^{3}_{\Lambda}\mathrm{H})$) is today one of the key issues in strangeness nuclear physics [1]. Actually, this statement sounds surprising in itself. ${}^{3}_{\Lambda}$H is the lightest and, apparently, the simplest known Λ-hypernucleus. It is a bound nuclear system consisting of a proton, a neutron and a Λ hyperon. However, the Λ separation energy is $(0.13 \pm 0.05_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}})$ MeV only [2] and then the ${}^{3}_{\Lambda}$H is the weakest bound Λ-hypernucleus as well.

On the basis of these considerations, it seemed plausible to assume that the behavior of the Λ inside the ${}^{3}_{\Lambda}$H should not be very different from that in vacuum. In particular, the ${}^{3}_{\Lambda}$H lifetime value was expected to be very close to the one of the free Λ particle (263.2 ± 2.0) ps [3]. Such a naïve expectation was supported also on the theoretical ground [4, 5].

The first $\tau({}^{3}_{\Lambda}\mathrm{H})$ measurements were carried out in the decade 1963–1973 by exploiting two different visualizing techniques, namely photographic emulsions and He filled bubble chambers. Figure 1 shows the obtained results. The really poor quality of the data prevented to draw any firm conclusion about the effective $\tau({}^{3}_{\Lambda}\mathrm{H})$ value. Anyway, the weighted averages of the results turn out to be 203^{+40}_{-31} ps and 193^{+15}_{-13} ps in the case of emulsion and, respectively, of bubble chamber data [20]. Moreover, it is worth to note that these two mean values amount to $\approx 77\%$ and, respectively, to $\approx 73\%$ of $\tau(\Lambda_{\mathrm{free}})$. Since then, by taking into account also the measurements available for heavier Λ-hypernuclei, the assumption was that $\tau({}^{A}_{\Lambda}Z)$ was a smooth function of A starting from a value close to the $\tau(\Lambda_{\mathrm{free}})$ and asymptotically approaching the 80% of such a value. Nevertheless, none of the theoretical approaches which were attempted was able to provide a satisfactory description of the experimental data trend over the overall A range of the observed Λ-hypernuclei.

More recently, nearly 40 years after the last bubble chamber measurement, counter experiments originally designed to study heavy-ion collisions provided more precise values of $\tau({}^{3}_{\Lambda}\mathrm{H})$ (see again Fig. 1). These results were claimed to be unexpected and/or surprising, but their average value is actually 185^{+28}_{-33} ps (i.e. $\approx 70\%$ of $\tau(\Lambda_{\mathrm{free}})$), in total agreement with the old sets of measurements. However, these results had the merit of reopening the dormant debate about the ${}^{3}_{\Lambda}$H lifetime.

Moreover, the puzzle has been further fed by two recently achieved results.

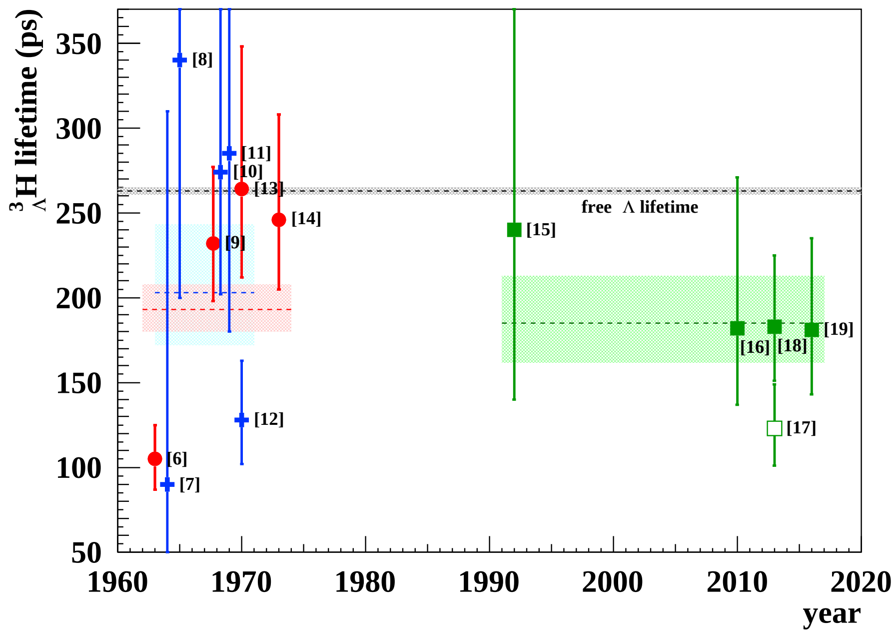

Figure 1: Chronological sequence of the published experimental data on $\tau(^{3}_{\Lambda}\mathrm{H})$. Red circles indicate results from He bubble chambers, blue crosses results from photographic emulsions and green squares results from counter experiments. For each point its Reference is given. Colored dashed lines and hatched areas represent the corresponding weighted averages with their errors. The open green square represents a result still classified as preliminary. (from Ref. [20])

The first one was announced by the STAR Collaboration, engaged in the analysis the Au-Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV collected at BNL/RHIC. By adding to the $^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{H} + \pi^{-}$ data sample the $^{3}_{\Lambda}\mathrm{H} \rightarrow d + p + \pi^{-}$ events, they got $\tau(^{3}_{\Lambda}\mathrm{H}) = 142^{+24}_{-21} \pm 31_{\mathrm{syst}}$ ps [21]. Such a value, if confirmed, is $\approx 22\%$ lower compared to the previously published $\tau(^{3}_{\Lambda}\mathrm{H})$ value [16] and it amounts to $\approx 54\%$ only of $\tau(\Lambda_{\mathrm{free}})$.
Of completely opposite sign is the conclusion of the ALICE Collaboration, committed to the study of the Pb-Pb collisions observed at CERN/LHC at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The analysis of the $^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{H} + \pi^{-}$ channel led to $\tau(^{3}_{\Lambda}\mathrm{H}) = 237^{+33}_{-36} \pm 17_{\mathrm{syst}}$ ps. This result, announced during the HADRON 2017, Quark Matter 2018 and HYP 2018 Conferences but still unpublished, is higher than the previous ALICE determination [19] by $\approx 31\%$ and it is as high as the $\approx 90\%$ of $\tau(\Lambda_{\mathrm{free}})$ and fully compatible with it within the error.

The underlying doubt is then whether something could be wrong in the new measurements, in the sense that heavy-ion collisions where hypernuclei, especially $^{3}_{\Lambda}$H, are like “snowballs in Hell” [22] could not be the right context where to perform such a delicate measurement. Otherwise, the point could be that our present understanding of $^{3}_{\Lambda}$H structure is not correct. In other words, the $^{3}_{\Lambda}$H binding energy could not be as small as it is believed.

From the experimental point of view, a clear cut answer to such questions could be obtained by a new dedicated experiment only, possibly relaying on direct time measurement techniques.

As far as the second item of the possible future physics program is concerned, in the last ten years several experiments, that have successfully accomplished their scientific programs,

demonstrated that the systematic study of the Λ-hypernuclei' decay modes is actually a powerful discovery tool [23, 24] and that it makes possible even an indirect spectroscopic study of the observed Λ-hypernucleus [23, 25, 26]. In particular, the FINUDA results put clearly in evidence the modulation effect that the nuclear structure has on the trend as a function of A of the value of the partial decay width of both the mesonic (Γ_{π^-}) [27] and of the non-mesonic channels (Γ_p) [28]. Figures 2 and 3 show the current experimental situation about Γ_{π^-} and, respectively, Γ_p for $A \leq 16$ Λ-hypernuclei. There is an excellent agreement between the existing experimental points and the theoretical calculations presented in Ref. [29]. In addition, they predict a strong difference between the Γ_{π^-} values in case of mirror Λ-hypernuclei pairs, like $^{12}_{\Lambda}$B and $^{12}_{\Lambda}$C (see again Figure 2).
The same effect should be observed for the Γ_p values as well, even though in this case the amplitude of the variation is damped because of the larger momentum transfer involved in the non mesonic decay process with respect to the mesonic one (see again Figure 3).

The stimulating curiosity is that of verifying whether the predictions are correct by producing and by studying the $^{12}_{\Lambda}$B. Since the current experimental value of $\Gamma_p(^{12}_{\Lambda}\mathrm{C})$ is affected by a quite large error, it could be also very useful to measure it again in the same experiment. The advantage is twofold: on the one hand the statistics will be significantly improved, on the other systematic errors will be very well kept under control. This way the comparison between the two measured quantities will be really meaningful.

Of course, the unknown $\tau(^{12}_{\Lambda}\mathrm{B})$ will be measured as well.

2 The experimental setup

In order to produce $^{3}_{\Lambda}$H we plan to exploit, for the first time, the reaction

$$\pi^- + {}^3\mathrm{He} \to K^0 + {}^3_{\Lambda}\mathrm{H} \tag{1}$$

$$\hookrightarrow K^0_S$$

$$\hookrightarrow \pi^+ + \pi^- \tag{2}$$

on a liquid ^{3}He target. As it is experimentally well known [30], the cross section of the charge-exchange reaction (1) is lower by at least a factor $\approx 10^3$ than the one of the $^3\mathrm{He}(K^-,\pi^0)^3_{\Lambda}\mathrm{H}$ process. Nevertheless, we think that this drawback is overcompensated by the fact that when we take into account the decay chain (2), the final state is populated by charged particles only. The second advantage is that we don't need a large and generally very expensive calorimeter in order to detect high-energy γ pairs following π^0 disintegration.

A strongly asymmetric topology of the decay process (2) can be selected. Then, the experimental apparatus should be able to detect π^+ in the forward direction and π^- emitted in an angular range centered around $\theta = 90°$ with respect to the incoming π^- beam axis. Finally, to directly measure $\tau(^3_{\Lambda}\mathrm{H})$ it will be necessary to detect the decay products from the two- and/or the three-body channels:

$$^3_{\Lambda}\mathrm{H} \to {}^3\mathrm{He} + \pi^-, \tag{3}$$

$$^3_{\Lambda}\mathrm{H} \to \mathrm{d} + p + \pi^-. \tag{4}$$

Two facts make the K1.1 line of the J-PARC Experimental Hadron Facility (HEF) the ideal place where to pursue the experimental program outlined in the Sec. 1.

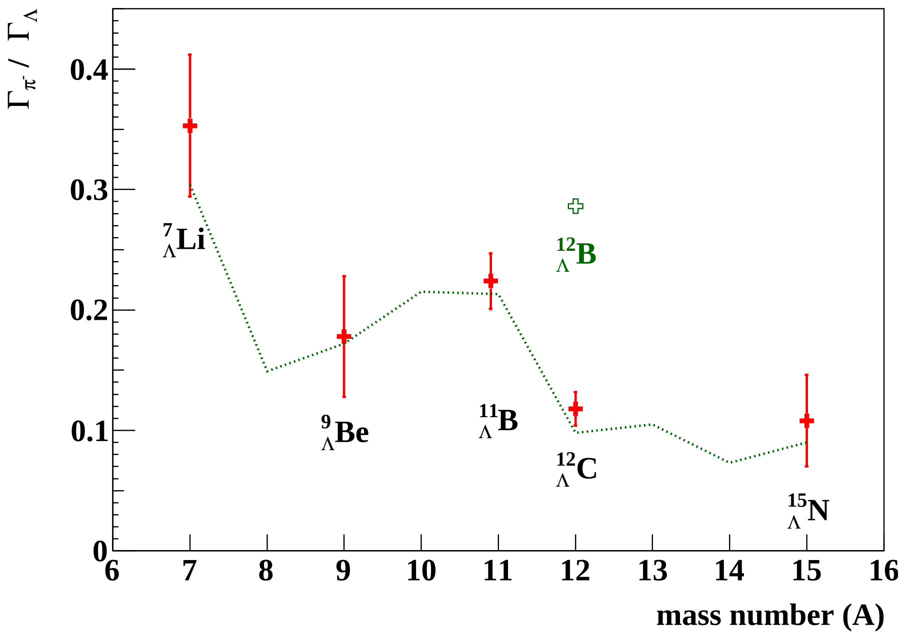

Figure 2: World average of the experimental $\Gamma_{\pi^-}/\Gamma_\Lambda$ values (red crosses) for different p-shell Λ-hypernuclei (adapted from Ref. [23]). The green dotted line and open cross represent the theoretical prediction of $\Gamma_{\pi^-}/\Gamma_\Lambda$ [29] for the already studied Λ-hypernuclei and, respectively, for the still unmeasured $^{12}_{\Lambda}$B.

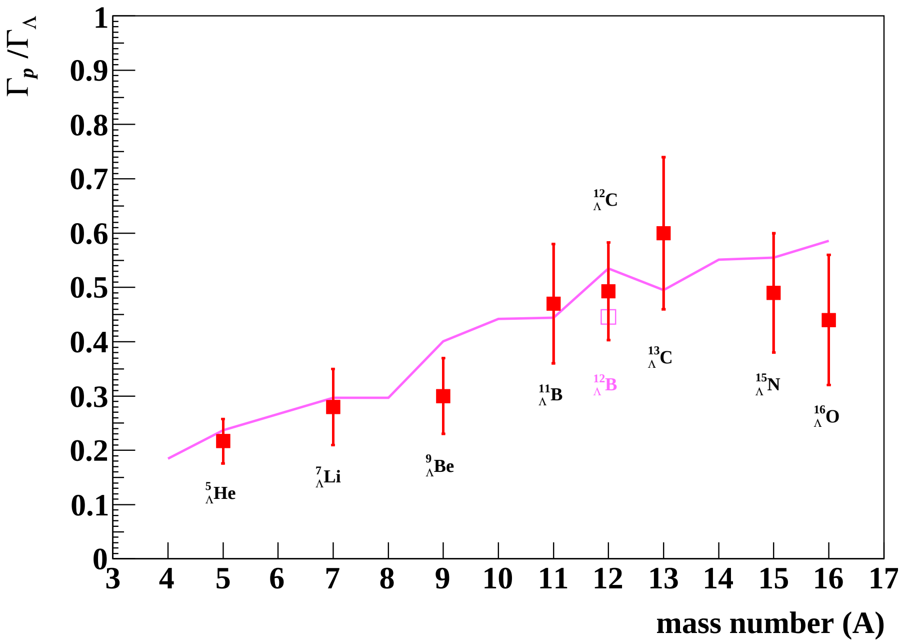

Figure 3: World average of the experimental Γ_p/Γ_Λ values (red squares) for different p-shell Λ-hypernuclei (adapted from Ref. [23]). The magenta line and open square represent the theoretical prediction of Γ_p/Γ_Λ [29] for the already studied Λ-hypernuclei and, respectively, for the still unmeasured $^{12}_{\Lambda}$B.

First, this new beam line will provide π^- beam of excellent quality and intensity, suitable for the experimental needs.
Second, the Superconducting Kaon Spectrometer (SKS) complex was recently moved to the HEF K1.1 experimental area to carry on the already approved physics program on γ-spectroscopy of Λ-hypernuclei.

The first point is of course a mandatory requisite for the proposed measurement. The second circumstance permits, in principle, to design an experimental setup fulfilling the following important requirements:

- reinforcement of the synergic cooperation between non-Japanese researchers and J-PARC based Collaborations;
- mechanical integration of a new set of detectors with a preexisting hardware in order to reduce the cost and the completion time;
- modularity, in order to cope with the needs of different physics programs and to eventually permit a staged approach to the final detector configuration;
- optimization of the beam time allocation.

The liquid ^{3}He target, placed in the K1.1 line final focus, will have a radius of 2–3 cm and a length of 7–8 cm, that is ≈ 1 g/cm^2. It will be surrounded by a set of fast plastic scintillator slabs, arranged like the staves of a barrel. This detector, featuring a time resolution of less then 100 ps FWHM, will provide the stop time of the $^3_\Lambda$H decay products, while the start signal will be given by a beam scintillator or by a small hodoscope in case of high beam intensity. The trajectories of the charged particles following both the K^0_S ((2)) and the $^3_\Lambda$H ((3) or (4)) decays will be precisely determined thanks to four pairs of low-mass drift chambers, installed immediately outside the scintillator barrel and placed in front of four modules of a fine layered range detector. The chambers will permit to measure the particle direction with a precision of the order of ≈ 100 mrad, thanks to their design spatial resolution better than 300 μm FWHM. The range detector, possibly made of about one hundred 1 mm thick scintillator layers, will measure the energy of such particles and it will allow to identify them. The final goal is to achieve an energy resolution better than 2 MeV FWHM on the missing mass of the produced Λ-hypernucleus.

All this sub-detectors will cover a solid angle of $\approx 2\pi$ sr and will be placed around the target, upstream the SKS complex in its present configuration which will detect the forward emitted π^+ from K^0_S decay (2). Figure 4 shows a schematic view of the outlined experimental setup.

The modular architecture will eventually permit a staged approach to the construction of the described apparatus. This way, it will be possible to cope with eventual mechanical clashes or with reduced budget problems by installing the detectors quadrant by quadrant (two at the minimum, either in the top-bottom or in the left-right configuration (see Table 1)). More details can be found in Ref. [20].

In order to carry on the second part of the proposed physics program, it will be sufficient to replace the liquid ^{3}He target system only with a series of solid targets. $^{12}_\Lambda$B will be produced via the ^{12}C(π^-,K^0)$^{12}_\Lambda$B on graphite, machined in thin tiles of a typical thickness of ≈ 4 mm, that is ≈ 1 g/cm^2. It will be possible to install up to 4 of them along the π^- beam axis and at an angle of 15–20 degrees with respect to it, as usually done in the past. Figure 5 shows

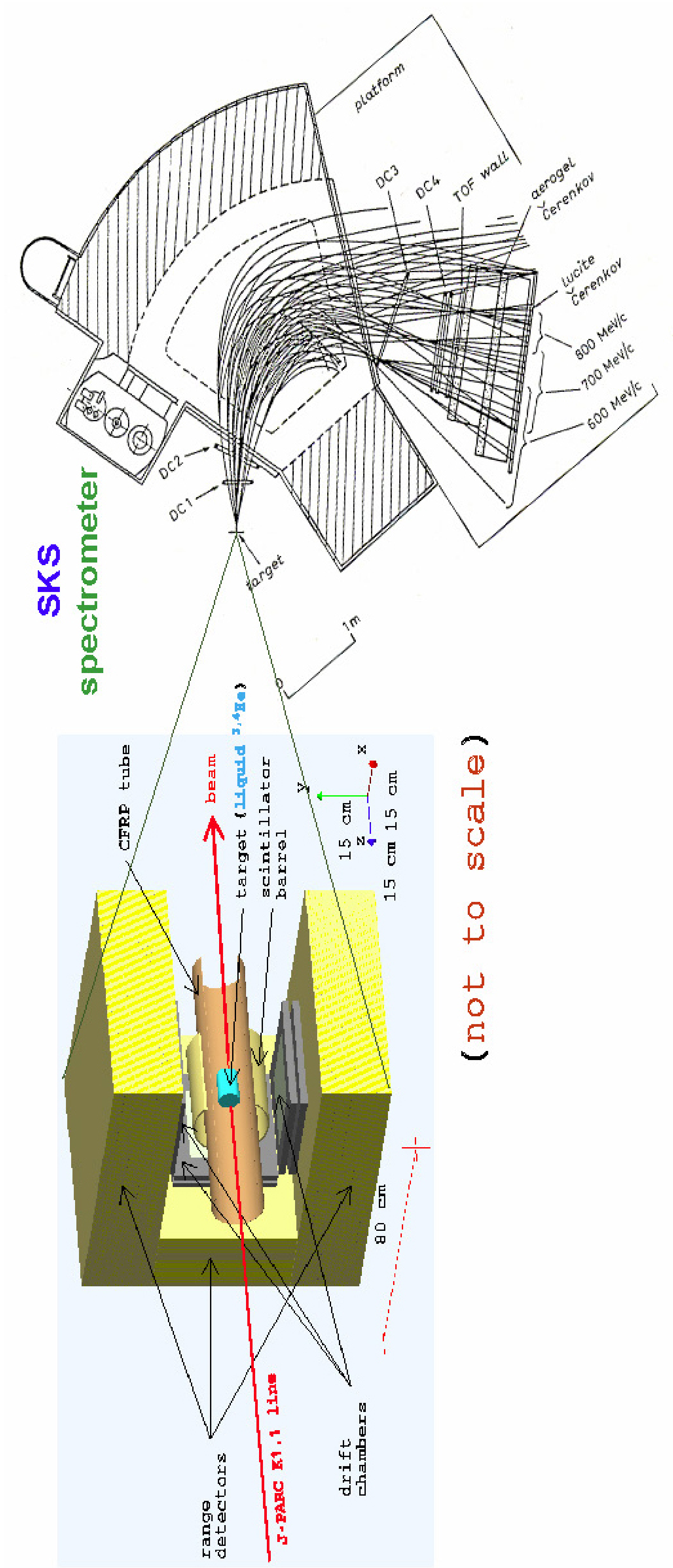

Figure 4: Schematic view of the proposed setup for the ${}^{3}_{\Lambda}$H lifetime measurement. One of the quadrant of the apparatus has been removed to permit to see the interior details.

how the above described experimental setup will be modified to perform measurement on solid targets. Also in this case, more details can be found in Ref. [20].

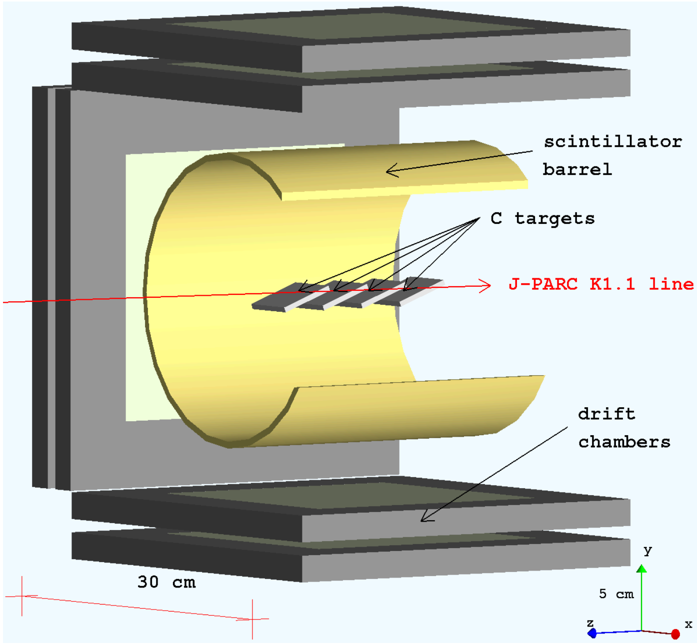

Figure 5: Magnified schematic view of the target layout for the decay measurement on p-shell Λ with the (π^-,K^0) reaction. One of the quadrant of the apparatus has been removed to permit to see the interior details.

3 Expected event rates and beam time requests

The main problem in evaluating the expected ${}^3_\Lambda$H yield is the fact that the cross section for process (1) is actually unknown. In order to get a plausible estimate of its value, one can remind that a prediction based on a DWIA calculation was done for the cross section of the ^{4}He$(\pi^+,K^+){}^4_\Lambda$He reaction [31], which is the isospin symmetric of the ^{4}He$(\pi^-,K^0){}^4_\Lambda$H process. It reaches the quite large value of ≈ 10 μb/sr for incident π^- momentum ranging between 1.0 and 1.1 GeV/c. Then a reasonable guess for the cross section of reaction (1) could be ≈ 5 μb/sr.

Since the beginning of the J-PARC operation, the performance of the accelerator complex steadily increased. In particular the quality and, moreover, the intensity of π secondary beams delivered to the different HEF experimental areas are approaching the design values. For this reason we prefer to evaluate the ${}^3_\Lambda$H and the ${}^{12}_\Lambda$B yields as a function of the number of available π^-. This way, the rate of the further beam improvement will determine the actual time necessary for a significant measurement.

The number of produced (detected) ${}^3_\Lambda$H in the apparatus acceptance is given by

$$\mathrm{yield}({}^3_\Lambda\mathrm{H}) = N_{\pi^-} \times \frac{T_{\mathrm{tar}}}{A} \times N_A \times \frac{d\sigma}{d\Omega} \times \Omega_{\mathrm{spe}} \times \varepsilon_{\mathrm{spe}} \times \varepsilon_{\mathrm{rec}} \approx 1 \times 10^4, \qquad (5)$$

where

- $N_{\pi^-} = 5 \times 10^{13}$,

- $T_{\rm tar} \equiv$ liquid ^{3}He target thickness $= 1$ g/cm^2,

- $A \equiv {}^3$He atomic weight $= 3$,

- $N_A \equiv$ Avogadro constant,

- $\frac{d\sigma}{d\Omega} = 5$ μb/sr,

- $\Omega_{\rm spe} \equiv$ spectrometer solid angle coverage (range detector + SKS) ≈ 0.05 sr,

- $\varepsilon_{\rm spe} \equiv {\rm BR}(K^0 \to K^0_S) \times {\rm BR}(K^0_S \to \pi^-\pi^+) \times (\pi^-\pi^+)$ pair detection probability ≈ 0.01,

- $\varepsilon_{\rm rec} \equiv$ reconstruction algorithm efficiency ≈ 0.5.

By taking into account the branching ratios values for ${}^3_\Lambda$H decay channels (3) and (4) it is possible to estimate the number of useful events for the $\tau({}^3_\Lambda{\rm H})$ measurement. The decay products from two- and three-body will be detected by the range counters only, then the number of observed ${}^3_\Lambda$H is

$$\text{yield(decaying } {}^3_\Lambda\text{H}) = \text{yield}({}^3_\Lambda\text{H}) \times \text{BR}({}^3_\Lambda\text{H} \to \text{2-b/3-b}) \times \Omega_{\pi^-} \times \varepsilon_{\pi^-} \times \varepsilon_{\rm rec} \approx 1 \times 10^3, \qquad (6)$$

where

- ${\rm BR}({}^3_\Lambda{\rm H} \to$ 2-b/3-b$) \equiv$ two- or three-body branching ratios ≈ 0.25 [5] or ≈ 0.40 [5],

- $\Omega_{\pi^-} \equiv$ range detector solid angle coverage for $\pi^- \approx 0.5$,

- $\varepsilon_{\pi^-} \equiv \pi^-$ detection efficiency ≈ 1,

- $\varepsilon_{\rm rec} \equiv$ reconstruction algorithm efficiency ≈ 0.4.

Then, for both two- and three-body decay events we expect to have $\approx 1 \times 10^3$ entries in the corresponding time delay spectra, enough to get $\tau({}^3_\Lambda{\rm H})$ with a statistical error of few percent.

In order to get the same number of detected ${}^{12}_\Lambda$B hypernuclei a lower number of incoming π^- will be necessary. Actually, by using in (5) the measured cross section value of 15 μb/sr [32] for the reaction ^{12}C(π^+,K^+)${}^{12}_\Lambda$C we got yield(${}^{12}_\Lambda$B) $\approx 1 \times 10^4$ with "only" 2×10^{13} initial π^- (see the third row of Table 1). Starting from this data sample and by resorting to the theoretical predictions available in literature for $\Gamma_{\pi^-}({}^{12}_\Lambda{\rm B})$ (0.29 [33]) and for $\Gamma_p({}^{12}_\Lambda{\rm B})$ (0.45 [29]) we estimated that we will collect $\approx 1.5 \times 10^3$ and $\approx 3.0 \times 10^3$ events which will permit to determine the mesonic and, respectively, the non-mesonic decay partial widths with a statistical error of few percent. The same statistical precision will be achieved on the measurement of $\tau({}^{12}_\Lambda{\rm B})$ as well.

If on the one side the described physics program is very appealing, on the other it is very challenging. First of all it must be reminded that such an experimental approach has never attempted before. Then some aspects, first among all the cross section for reaction (1), are completely unknown and they could represent important factors of uncertainty. Moreover, the measurements are very demanding on both the human and the economic levels. Actually, they requires long data taking campaign and, just as an example, an expensive liquid ^{3}He target.

Then, the most advisable strategy would be to start the experiment with the systematic study of the ${}^{12}_\Lambda$B decay process. This way we will have the opportunity to test the validity of the chosen experimental approach and we will gain important know-how to successfully carry on the remaining part of the physics program. In addition, exploiting the above described modularity of the design, we explored the possibility of performing the measurement with a reduced set of new detectors to be coupled to the SKS complex. We checked whether it still makes sense to perform the measurement without installing all the four quadrants of the range detector. Table 1 summarizes the outcome of this exercise, which aimed to demonstrate that it would be possible to carry out a sort of pilot run with still a good physics output. When we consider just one sector of the proposed detector assembly we got the number of detected ${}^{12}_{\Lambda}$B reported in the first row of Table 1. Clearly, it is insufficient in order to perform a significant measurement. As already anticipated at the end of Sec. 2, the minimum possible configuration consists of two modules. In this case, we will be able to measure $\Gamma_{\pi^-}({}^{12}_{\Lambda}\mathrm{B})$ and $\Gamma_p({}^{12}_{\Lambda}\mathrm{B})$ with a satisfactory statistical precision (see the second row of Table 1). Finally, the last row of Table 1 shows the minimum requirement of π^+ beam in order to re-measure the ${}^{12}\mathrm{C}(\pi^+,K^+){}^{12}_{\Lambda}\mathrm{C}$ reaction, as discussed in Sec. 2.

Table 1: Expected Λ-hypernuclei production rates for a given number of π^- (π^+), for different targets and for different experimental configurations. The columns from 6 to 8 indicate the statistical significance of the measurement that can be achieved for the three main observables.

beam request	target	thickness	exp.	n. of detected		statistical significance		
($\times 10^{13}$ π^-)		(g/cm^2)	conf.	${}^{A}_{\Lambda}Z$		$\tau({}^{A}_{\Lambda}Z)$	$\Gamma_{\pi^-}({}^{A}_{\Lambda}Z)$	$\Gamma_p({}^{A}_{\Lambda}Z)$
1	^{12}C	4×1	1/4	1.5×10^3	${}^{12}_{\Lambda}$B	poor	insufficient	poor
1	^{12}C	4×1	1/2	3.0×10^3	${}^{12}_{\Lambda}$B	good	good	good
2	^{12}C	4×1	full	1.0×10^4	${}^{12}_{\Lambda}$B	OK	OK	OK
5	L ^{4}He	1	full	1.5×10^4	${}^{4}_{\Lambda}$H	OK	OK	–
5	L ^{3}He	1	full	1.0×10^4	${}^{3}_{\Lambda}$H	OK	OK	–
($\times 10^{11}$ π^+)								
1	^{12}C	4×1	1/2	3.5×10^3	${}^{12}_{\Lambda}$C	–	–	good

The second step of the staged approach would be the measurement of $\tau({}^{4}_{\Lambda}\mathrm{H})$, which present less critical issues.

Finally, we will face the $\tau({}^{3}_{\Lambda}\mathrm{H})$ determination which, by the way, will hopefully rely on a more and more improved accelerator performance.
Actually, Table 2 shows how the duration of the data taking campaigns will crucially depend on the progress in the intensity of the beam delivered on the target.

4 Conclusions

We focused our attention on some selected arguments of particular interest in the field of hypernuclear physics. In our opinion, they deserve dedicated, well targeted experiments in order to provide a clear cut answer about the real value of the ${}^{3}_{\Lambda}$H lifetime and to definitely

Table 2: Estimated beam time allocation as a function of the beam time intensity.

delivered π ($\times 10^{13}$)	1.0×10^7 π/spill (present)	1.5×10^7 π/spill	1.0×10^8 π/spill	1.0×10^9 π/spill (HIHR)
1	6.9×10 d	4.6×10 d	7 d	< 1 d
2	1.4×10^2 d	9.3×10 d	1.4×10 d	1.4 d
5	3.5×10^2 d	2.3×10^2 d	3.5×10 d	3.5 d

prove the strong effect of the nuclear structure on the size of the Γ_{π^-} and of the Γ_p decay partial widths of some selected neutron-rich Λ-hypernuclei belonging to the p-shell.
We are convinced that the ideal place to perform such an experiment is the K1.1 line of the HEF at J-PARC. To this purpose, we are proposing to build a relatively simple apparatus to be integrated with the existing SKS complex in order to perform such measurements.

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