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On the measured lifetime of light hypernuclei $^3_\Lambda$H and $^4_\Lambda$H

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ABSTRACT

A statistical combination of the experimental lifetime estimations available in the literatures is performed for $^3_\Lambda$H and $^4_\Lambda$H, including several recent measurements. The combined average values of the lifetime for $^3_\Lambda$H and $^4_\Lambda$H are respectively 216^{+19}_{-16} ps and 192^{+20}_{-18} ps with a reduced χ^2 of 0.89 and 0.48. A new insight into the lifetime estimation of the HypHI Phase 0 experiment by a Bayesian approach is also presented. In this approach, several different prior distributions including the combination of previous lifetime data and a Jeffrey prior are used. The principal mode and the smallest credible interval at 68% of the posterior distribution, given by the prior belief of the previous measurements, are 217^{+19}_{-16} ps and 194^{+20}_{-18} ps respectively for $^3_\Lambda$H and $^4_\Lambda$H. The two employed approaches have revealed that the lifetime of hypernuclei $^3_\Lambda$H and $^4_\Lambda$H can be shorter than the Λ–hyperon lifetime.

1. Introduction

The study of the lifetime of heavier baryons than the nucleons can reveal the nature of the weak interaction being responsible for the flavor conversion and the strong interaction which governs the structure of the quarks and gluons within the baryons. The lightest one of such baryons is the Λ–hyperon which consists of up-, down- and strange-quarks. The lifetime of the Λ–hyperon has been measured very accurately over the years to be 263 ± 2 ps [1].

Thanks to the long lifetime of Λ in comparison with the typical lifetime of resonance states decaying via the strong interaction, the study of the nucleon–Λ interactions has been possible by studying a Λ–hypernucleus, a bound state of nucleons and the Λ–hyperon, though it has not been practical to study these interactions by means of scattering experiments. Additionally the study of the deviation of the lifetime of Λ–hypernuclei from the lifetime value of the free Λ–hyperon could exhibit the modification of the Λ wave-function in the nuclear medium. It would especially strike new insight on their fundamental structures, though some light Λ–hypernuclei are considered to have a Λ–hyperon weakly bound to their core nucleus. Full understanding of light Λ–hypernuclei has to be intended, and theoretical models should be able to describe simultaneously the binding energy, the dynamics of the weak decay, the value of the lifetime, and the decay modes.

Several experiments estimated the lifetime of the light hypernuclei, $^3_\Lambda$H [2–9] and $^4_\Lambda$H [2,4,9–13]. At first, the lifetime values were deduced mainly by experiments with emulsion techniques and bubble chambers [2–7,10,11]. Then few more counter experiments were performed improving the interval estimation of the lifetime [8,9,12,13]. Yet, the dispersion of the different estimation to each other did not allow to draw a clear conclusion on the lifetime of those hypernuclei. It was considered that the lifetime of the light hypernuclei should be close to the lifetime of the Λ–hyperon, especially for $^3_\Lambda$H since it is weakly bound. Theoretical calculations do not either provide a clear picture because of

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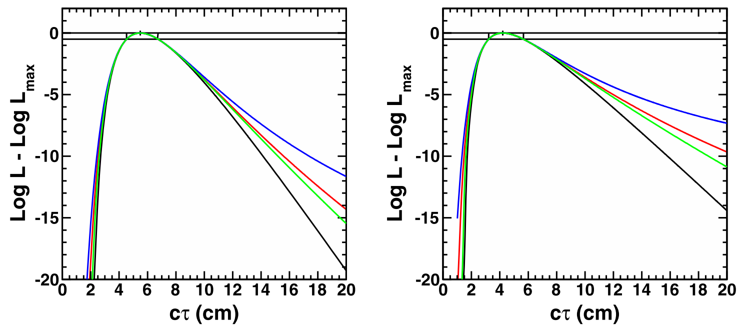

Fig. 1. (Color online.) The likelihood function of the data set shown in [9] with the different extrapolations based on Gaussian function of $^3_\Lambda$H and of $^4_\Lambda$H in left and right panel respectively. The red curves correspond to the real likelihood function obtained from the dataset. The blue and black curves correspond to the Gaussian function with linear standard deviation and with linear variance respectively. The green curve is the average combination of the two curves.

scattered predicted lifetime values [14–22]. However, Outa et al. measured the lifetime of $^4_\Lambda$H by observing the non-mesonic weak decay mode [13], which revealed that the lifetime of $^4_\Lambda$H should be significantly shorter than Λ. Recently, the lifetime of $^3_\Lambda$H, and anti-hypertriton, $^3_{\bar{\Lambda}}\bar{\text{H}}$ was measured at RHIC [8]. The lifetime values of $^3_\Lambda$H and $^4_\Lambda$H were also measured very recently by the HypHI Collaboration [9], indicating that the lifetime of these hypernuclei is shorter than Λ.

In the present Letter, we report on the combined analysis of the world data of the lifetime of $^3_\Lambda$H and $^4_\Lambda$H in order to deduce the combined interval estimation of their lifetime values. We also revisit the lifetime values of the HypHI experiment by means of the Bayesian analysis. The results of these two independent analyses infer that the lifetime of $^3_\Lambda$H and $^4_\Lambda$H could be shorter than that of the Λ–hyperon.

2. Combinations of the lifetime world data

In order to summarize the lifetime values of $^3_\Lambda$H and $^4_\Lambda$H deduced in the different experiments, a good practice would be to construct the combination of the estimations [1]. Generally the statistical combination of measurements is to combine the likelihood functions used to estimate the lifetime values that were reported by the experiments.

The lifetime values are usually reported as the inferred mean value, the asymmetric errors corresponding to one standard deviation and occasionally including the systematic uncertainties. In the introduction section of the PDG review [1], the procedure to produce the combined averages and fitting is explained for reported estimations with symmetric errors.

The situation is not as convenient when a parameter estimation is reported with asymmetric errors. One reasonable procedure is to use directly likelihood functions used for the lifetime estimation and then to combine them. However, publications on the lifetime measurements usually do not include deduced likelihood functions, therefore, one has to parametrize the likelihood functions from the deduced mean values and their asymmetric errors. A way to extrapolate expressions of the likelihood function from the reported measurements with asymmetric errors was discussed in [23], and it has been applied for the lifetime observables except for the values reported by the HypHI Collaboration. For the lifetime estimations by the HypHI Collaboration, the likelihood functions were provided and used for the combination. In the following, the procedures to extrapolate the likelihood functions are discussed. The validity of the method is also examined based on the data and deduced likelihood functions by the HypHI Collaboration. The procedures to combine the world data and results are then presented.

2.1. Extrapolation of likelihood functions

First, the method to extrapolate the likelihood function was tested with the data by the HypHI Collaboration [9] since likelihood functions were available. The form of the extrapolated likelihood function was built by applying the methods discussed in [23] and then was compared to the known real likelihood function of interest. Several functions were applied for better or worse extrapolations in the case study presented in [23].

In the following the extrapolation form which was adopted is the *variable Gaussian* form (*Forms 6 and 7* in [23]). Those forms are equivalent to a Gaussian function in which the variance or the standard deviation is a linear function of the parameter of interest. Let us write the extrapolated functions for a likelihood function depending on the parameter of interest x, having its maximum at $\hat{x}$ and with the one standard deviation errors, σ_+ and σ_- obtained by the likelihood ratio $\triangle \ln \mathcal{L} = -1/2$, where the $+$ and $-$ subscripts indicate the upper and lower asymmetric errors, respectively.

For the Gaussian function with a variable variance the extrapolation of the likelihood function is:

$$\ln \mathcal{L} = -1/2 \frac{(\hat{x} - x)^2}{V + V'(x - \hat{x})} \tag{1}$$

in which $V = \sigma_- \sigma_+$ and $V' = \sigma_+ - \sigma_-$. When the Gaussian function has instead a linear variance, the extrapolation function is written as:

$$\ln \mathcal{L} = -1/2 \left(\frac{(\hat{x} - x)}{s + s'(x - \hat{x})} \right)^2 \tag{2}$$

with $s = 2\sigma_- \sigma_+ / (\sigma_+ + \sigma_-)$ and $s' = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$. By applying this method, the approximation of the likelihood functions of the HypHI data was calculated and is shown in Fig. 1 with the real likelihood function (in red line) of the $^3_\Lambda$H proper decay time $c\tau$ in the left panel and of $^4_\Lambda$H in the right panel. The two forms Eqs. (1) and (2) of a variable Gaussian function are represented in black and blue lines, respectively. The third extrapolation form, which is the arithmetic average of the two forms Eqs. (1) and (2), was also investigated and is represented by the green line in Fig. 1.

A fair agreement between the extrapolations defined by Eqs. (1) and (2) and the real likelihood functions (in red line) is observed at the small $\triangle \ln \mathcal{L}$ values, however, beyond 3 standard deviation ($\triangle \ln \mathcal{L} = -4.5$), the extrapolation forms deviate from the real likelihood function. On the other hand, the arithmetic average of the two forms agrees better with the real likelihood function up to 5 standard deviation ($\triangle \ln \mathcal{L} = -12.5$) as shown in Fig. 1. For the further combination studies, the employed extrapolation form is the arithmetic average of the forms Eqs. (1) and (2).