The Application of Fission Fragments Chamber in Direct Measurement of Heavy Λ Hypernucear Lifetime*

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Abstract In this paper a new method to measure the lifetime of heavy hypernuclei is introduced, and the main device used in the measurement — fission fragment chamber (FFC) — is tested by a ^{252}Cf spontaneous source at Thomas Jefferson National Accelerator Facility (JLab). The chamber has a single-module timing resolution of ∼163ps. Based on the timing resolution tested, our computer simulation predicts that the error of the measured lifetime is about 9.6ps.

Key words hypernuclei lifetime, FFC, computer simulation

1 Introduction

In recent years, hyperons as a probe to study the hadron-hadron interaction have become a focus in particle physics field[1—3]. The measurement of hyperons lifetime is one of the topics. In contrast to the other hyperons (Σ, Ξ, Ω), Λ has a longer lifetime, because it decays only by weak interaction eventually. Though the free Λ decay is purely mesonic ($\Lambda \longrightarrow \mathrm{N}+\pi$+38MeV), the mesonic branches are strongly suppressed for hypernuclei case. Instead the nonmesonic bayon-bayon weak interaction progress ($\Lambda+\mathrm{N} \longrightarrow \mathrm{N}+\mathrm{N}$+176MeV) becomes dominant even in light hypernuclei like $^{12}_{\Lambda}$C[4], and the mesonic decay branches are negligible in heavy hypernuclus due to the Pauli blocking. This kind of ΔS=1 nonmesonic decay is a unique tool to study hadronic weak interaction. As an observable in the decay, the lifetime τ_Λ of many kinds of Λ hypernuclei has been measured by the scientists at BNL[4, 5], COSY[6], CERN[7] and KEK[8—11] et al. The lifetime of light hypernuclei can be given by direct measurements. However, for very heavy hypernuclei the application of direct timing methods — as used for light hypernuclei — is not feasible due to the large background of light particles. Fortunately, nonmesonic decay releases enough energy (∼176MeV) to cause fission. So the recoil shadow method suggested by Ref. [12] has become a popular way to measure the lifetime of very heavy hypernuclei indirectly[6, 7]. The experimental results for light or even medium-heavy hypernuclei (e.g. $^{11}_{\Lambda}$B, $^{12}_{\Lambda}$C, $^{28}_{\Lambda}$Si, $_{\Lambda}$Fe[11]) show a drop of lifetime in comparison with that of free Λ but no obvious mass dependence within the error limits. The lifetimes of heavy hypernuclei (e.g. Au[13], Bi[14] and U[15]) do not indicate a mass dependence for the large error either. On the other hand the lifetime of heavy hypernuclei is sensitive to the ratio $\Gamma_\mathrm{n}/\Gamma_\mathrm{p}$ of the neutron induced to proton induced Λ nonmesonic decays, which concerns the violation of ΔI=1/2 rule[16, 17]. So, precise measurement of heavy hypernuclei lifetime is critically needed.

The high-power and high-precision continuous wave (CW) electron beam with 1.67ps pulse width

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and 2ns pulse separation at JLab makes this possible. In our experiment (E02-017 at JLab) the hypernuclei are produced by the reaction ^{209}Bi(e, e'K$^+$)$^{209}_{\Lambda}$Pb. The fission fragment chamber (FFC) (Fig. 1) based on low pressure multi-wire proportional chamber (MWPC) technique[18] is used to detect the fission fragments produced by the nonmesonic decay and to reconstruct the decay time $t_{\rm d}$. And the newly designed high resolution kaon spectrometer (HKS) installed in Hall C is used to select K^{+}[19] and reconstruct the Λ produced time $t_{\rm p}$. So that the hypernuclei lifetime $t_{\rm life}=t_{\rm d}-t_{\rm p}$ can be calculated directly. In the experiment the unambiguous K$^+$ particle identification is a specialty that other measuring methods don't have. It ensures each fission event corresponding to a Λ produced event.

The work of this paper is mainly to test the FFC at JLab and give some prediction for the experiment (E02-017) by our computer simulation. In the following FFC configuration and test are described in Section 2. In Section 3 some concerning simulation and prediction on the experiment are presented. And Section 4 gives a summary.

2 FFC in JLab

The FFC (Fig. 1) is a cylinder vacuum chamber with two windows (one for incoming beam and the other for outgoing particles). The four MWPC modules are placed symmetrically forming the top arm and the bottom arm. The inner modules have an active area of 149mm×149mm and the active area of outer ones is 209mm×209mm. The distances between different modules are: L_{12}=77.1mm (distance between $T1$ and $T2$), L_{23}=73.5mm (distance between $T2$ and $T3$) and L_{34}=76.8mm (distance between $T3$ and $T4$). The technique of low pressure MWPC had been talked in detail by Ref. [18]. In the following we will turn to the test of the FFC. During the test, the chamber volume (connected to a reservoir of liquid heptane) was filled with about 267Pa of heptane vapor. The target was not mounted instead a ^{252}Cf spontaneous fission source was placed in a source holder with a collimator at a distance of 137.3mm from $T1$ (Fig. 1). The fission fragments emitted from ^{252}Cf crossed the modules one by one, and presented a double-peak mass distribution[20]. So we got the double-peak timing TDCs spectrum except $T1$ (Fig. 2), which had a single peak because it was the trigger module in the test work. Assuming the four

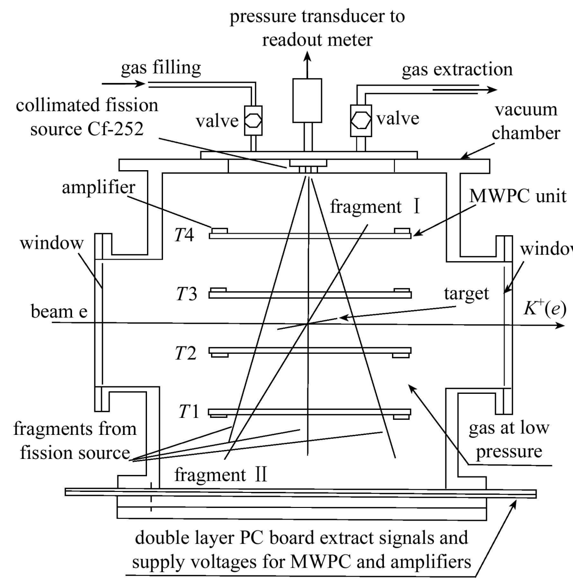

Fig. 1. A schematic diagram of the fission fragments chamber based on LPMWPC technique. The four LPMWPC modules are labeled with $T1$, $T2$, $T3$ and $T4$ from the bottom to the top.

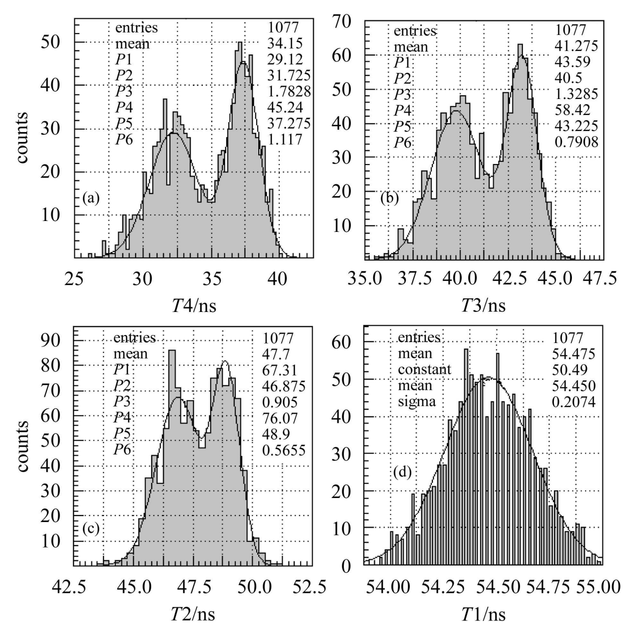

Fig. 2. The timing TDCs of the four modules in the FFC. In the legend $P1$, $P2$ and $P3$ are the parameters (constant, mean value and sigma of Gaussian fitting) of the left peak; $P4$, $P5$ and $P6$ is the corresponding fitted parameters for the right peak.

modules have the same timing resolution, the timing resolution of single module R_t can be given by spectrum (Fig. 3) of

$$(T1-T2)-\frac{L_{12}}{L_{13}}(T1-T3) \tag{1}$$

event by event, where $L_{13}=L_{12}+L_{23}$ is the distance between $T1$ and $T3$. Using a Gaussian fit we got the timing resolution of single module R_t=163.1ps. The background in Fig. 3 was caused by electrical noise, e.g. the sparkling between cathode and anode with high voltage.

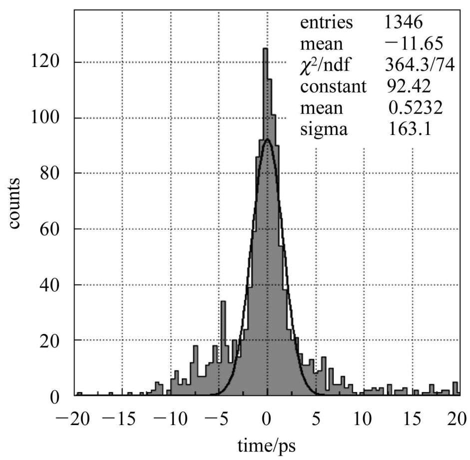

Fig. 3. The spectrum of $(T1-T2)-(L_{12}/L_{13})$ $(T3-T1)$. Fitted with Gaussian function, it gives the sigma value 163.1ns.

3 Simulation and prediction of the experiment

In our simulation, the coordinates are set up as the following: the beam direction is z direction, y axis points upwards in Fig. 2, and the intersection of the beam line and the target is the origin, ignoring the thickness of target because the target is too thin to influence the simulation result. The ^{209}Bi target foil with a thickness of 2mg/cm^2 is placed in a small tilt angle of 10 degrees with respect to the beam direction in order to increase the beam-target interaction thickness for better yield. To avoid the thin target being molten by the high energy focused beam, a 0.4cm×0.4cm raster is located in front of the target to smear the beam on xoy plane obeying uniform distribution. In the mentioned reaction ^{209}Bi (e, e'K$^+$) $^{209}_{\Lambda}$Pb, a proton in the target nucleus is converted to a Λ by absorbing a virtual photon, with the momentum transfer about 300MeV/c. To use this reaction the beam energy of 1.8GeV has been chosen, sufficiently high to optimize the virtual photon flux and assure the value of momentum transfer, but low enough to avoid opening other channels for K$^+$ production. In case of a bound hypernucleus with a large mass, its velocity is so low ($\beta\approx$0.0016) and its lifetime is so short (∼200ps), that we assume the decay position is the same as the production position. The nonmesonic decay released energy 176MeV is high enough to cause the fission of the rest nucleus when the two produced nuclei escape from it. So the lifetime is determined by the nonmesonic decay time, while the nonmesonic decay can be identified by detection of fragments from time delayed fission. The fission fragment mass distribution is a Gaussian-like distribution with width (FWHM) depending on the excitation energy E^*[21]. According to the experiment data[21] the FWHM is set to be 42 atomic mass units in our simulation. The atomic number Z of the fragments approximately obeys the following distribution[20]:

$$p(Z)=K\exp[-(Z-\overline{Z})^2/c](1+\delta), \tag{2}$$

where K is the unitary coefficient, the average value of c is 0.80±0.14 and δ=0 in our case. For heavy one of the two fragments

$$\overline{Z}_{\rm h}=\frac{Z_{\rm f}}{A_{\rm f}}A_{\rm h}-\Delta Z\ , \tag{3}$$

where $Z_{\rm f}$ and $A_{\rm f}$ are the atomic number and mass number of the fissioning nucleus, $A_{\rm h}$ is the mass number of the heavy fragment, and ΔZ is usually in the range (−0.5, 0). For light fragment

$$\overline{Z_{\rm l}}=Z_{\rm f}-\overline{Z_{\rm h}}\ . \tag{4}$$

The average total kinetic energy released from ^{209}Bi fission is about 155MeV[21] having nothing to do with the excitation energy. The hypernucleus momentum is so small in comparison with that of the fragment gained from the fission. So we assume the two fragments fly back to back. When the fragments fly in the low pressure gas we don't think the interaction between the fragments and the gas molecule in quite detail but calculate the nuclear and electronic energy loss of the fragments with SRIM and make them move in suitable step. At last the 'detected' time is written to data files as output.

Before the reconstruction of the lifetime, we must note that when the Λ comes into being, the hypernucleus may stay in exited states ('hot'). So there is a probability that the hypernucleus fissions promptly before the decay of the Λ. This kind of fission fragments called prompt events can also be detected in the experiment. Only the survived 'hot' hyperculei and 'cold' hypernuclei (stay in low exited states or ground state) have the chance of delayed fission caused by Λ decay and give the lifetime. The prompt events don't include Λ lifetime information; however they play a very important role to reconstruct the lifetime. In the simulation we generated the two kinds of events.

With the simulation data, we used the following formula to reconstruct the decay time t_{d}

$$
\begin{aligned}
t_{\mathrm{d}}^{\mathrm{bottom}} &= T2-\frac{T1-T2}{L_{12}}\ L_{23}/2\ , \\
t_{\mathrm{d}}^{\mathrm{top}} &= T3-\frac{T4-T3}{L_{34}}\ L_{23}/2\ , \\
t_{\mathrm{d}} &= (t_{\mathrm{d}}^{\mathrm{bottom}}+t_{\mathrm{d}}^{\mathrm{top}})/2\ ,
\end{aligned} \tag{5}
$$

where $t_{\mathrm{d}}^{\mathrm{bottom}}$ and $t_{\mathrm{d}}^{\mathrm{top}}$ are the decay time reconstructed from the bottom pair and the top pair of modules respectively and t_{d} is the average of $t_{\mathrm{d}}^{\mathrm{bottom}}$ and $t_{\mathrm{d}}^{\mathrm{top}}$. Because of the excellent time structure of the CW electron beam at JLab and high timing resolution of HKS, we set the Λ producing time to be a constant t_{p}=0 ignoring the devices resolution. Thus t_{d} spectrum actually is the lifetime spectrum (Fig. 4(b)). To extract the lifetime, t_{d} spectrum is fitted with a convoluted statistical distribution

$$
f_{\mathrm{d}}(t)=\int_0^{+\infty} r(t-t')\exp(-t'/\tau)\mathrm{d}t', \tag{6}
$$

where τ is the lifetime to be fitted and $r(t-t')$ is the resolution function (in this paper Gaussian distribution is used). However the fitted τ is only a relative value, we must find the time origin with the help of prompt events. For prompt events we can also use Formula (5) to calculate a reconstructed time t_0, whose spectrum is as shown in Fig. 4(a). These events are detected in the same way as the delayed events whereas t_0 contains no delay. So after a Gaussian fitting the mean value of t_0 spectrum is the time zero. In other words, the fitted τ subtracted by the t_0 mean value t_0^{mean} is the lifetime of the Λ. At the same time, the t_0 spectrum gives the resolution function $r(t-t')$.

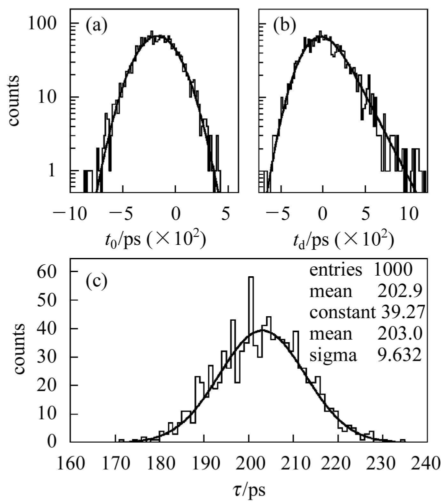

Fig. 4. (a) The prompt events t_0 spectrum; (b) The delayed events t_{d} spectrum; (c) the lifetime (calculated using 2000 events) spectrum of 1000 runs.

In our experiment 2000 events are expected to be taken. So we generated 2000 events to calculate the lifetime. In the simulation Λ lifetime was set to be 200ps and the tested FFC resolution parameters in Section 2 were used. In order to study the measurement precision of our experiment we ran the simulation codes 1000 times and reconstructed the lifetimes respectively. The distribution of the lifetimes was shown in Fig. 4(c), which indicates that the error of measurement is about 9.6ps.

4 Summary

In this paper a method of measuring the heavy hypernuclei lifetime directly is indicated. Compared with the measurements by recoil shadow method, we will get much less yields for the coincidence between fission fragments and K^+, while as compensation we get unambiguous particle identification and good timing resolution. According to our simulation, given 2000 events the error of the measured lifetime can reach the level about 9.6ps with the tested timing resolution of FFC. As was calculated in Ref. [17] (shown in Fig. 5) there is different dependence of Λ lifetime on hypernucleus mass A when the ratio $\Gamma_{\mathrm{n}}/\Gamma_{\mathrm{p}}$ is given different values. Based on the existing experiment data the ratio may verify in a very uncertain range. More precise Λ ifetime measurement can limit Γ_n/Γ_p in a more accurate range, then give the violating of ΔI=1/2 rule an unambiguous answer. Though the direct measuring method has such advantages, E02-017 is the first time to measure the Λ hypernuclei lifetime directly using coincidence between fission fragments and K^+. It's a valuable try, at the same time there are also many unclear problems (e.g. the efficiency of the FFC) needed to be explored by this experiment.

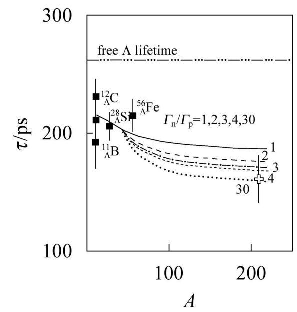

Fig. 5. Calculation of the Λ lifetime as a function of hypernucleus mass A with different Γ_n/Γ_p ratio (Γ_n/Γ_p=1,2,3,4 and 30). The cross mark is the experimental result for Bi target[11].

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裂变碎片靶室在直接测量重Λ超核寿命中的应用*

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摘要 介绍了一种新的直接测量重超核寿命的方法. 并对其中用到的一个重要探测设备——裂变碎片靶室——在托马斯·杰斐逊国家实验室用^{252}Cf放射源进行了测试. 该靶室的单模块时间分辨率为～163ns. 在此分辨率的基础上, 计算机模拟表明用此方法测到的超核寿命误差将在9.6ps左右.

关键词 Λ超核寿命 裂变碎片靶室 计算机模拟

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