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Abstract. New possibilities of hypernuclear studies at modern electron accelerators based on recently developed radio frequency photomultiplier tubes are discussed.

1. Introduction

The studies of hypernuclear systems are of crucial importance for our understanding of the physics of neutron stars. The very early discussion by Ambartsumyan and Sahakyan [1] based on the model of free (non-interacting) hadron and lepton gases made a very plausible case for the existence of a non-vanishing hyperonic charge in neutron stars. Dense matter in β-equilibrium in the absence of strong interactions starts to populate Σ-hyperons already at $4n_0$, where n_0 is the normal nuclear matter density, whereas the lighter Λ-hyperons appear at $8n_0$. The inclusion of nuclear forces generically reduces these critical densities by substantial amount. Theoretically predicted thresholds for appearance of various hyperons are around $2n_0$ [2]. Because of the importance of interactions, high quality hypernuclear data are essential for the understanding not only the nuclear physics but also the physics of the compact stars (see [3] and references therein).

The binding energies of light hypernuclei provide the most valuable experimental information that constrains various models of YN interaction. Table 1, taken from Ref. [4], lists the results for the Λ separation energies obtained from theoretical ab initio calculations using different YN interactions, along with the existing experimental results [5]. It is seen that the precise experimental measurements of binding energies of light hypernuclei can discriminate various models of YN interactions.

The binding energies of light hypernuclei have been measured in emulsion exclusively from π^--decays [5]. In addition to the quoted statistical errors, they have also systematic errors of about 0.04

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MeV. Monochromatic π^- mesons from weak decays of hypernuclei have been studied by magnetic spectrometers in fragmentation reactions with K^- beams on targets in the range from ^{7}Li to ^{16}O [6]. This group was the first to detect the decayed discrete π^-mesons from ${}^{4}_{\Lambda}H$ hyperfragments as a "*delayed-particle*" in stopped K^- reactions by magnetic spectrometer (see Ref. [7] for details). This result is a clear demonstration for a new "*delayed-*π^-" spectroscopy of nuclear matter.

Table 1. Λ separation energies, B_Λ given in units of MeV, of A = 3-5 Λ hypernuclei for different YN interactions.

YN	$B_\Lambda({}_\Lambda^3\mathrm{H})$	$B_\Lambda({}_\Lambda^4\mathrm{H})$	$B_\Lambda({}_\Lambda^4\mathrm{H}^*)$	$B_\Lambda({}_\Lambda^4\mathrm{He})$	$B_\Lambda({}_\Lambda^4\mathrm{He}^*)$	$B_\Lambda({}_\Lambda^5\mathrm{He})$
SC97d(S)	0.01	1.67	1.20	1.62	1.17	3.17
SC97e(S)	0.10	2.06	0.92	2.02	0.90	2.75
SC97f(S)	0.18	2.16	0.63	2.11	0.62	2.10
SC89(S)	0.37	2.55	Unbound	2.47	Unbound	0.35
Experiment	0.13±0.05	2.04±0.04	1.00±0.04	2.39±0.03	1.24±0.04	3.12±0.02

In 2007 the usage of magnetic spectrometers to measure the momenta of pions from weak two-body decays of electroproduced hyperfragments was proposed for Jefferson Lab [8]. The method is aimed at the determination of ground state masses of light Λ-hypernuclei off the stability line with high precision. Since the hypernuclei are produced from fragments, their nucleon and atomic numbers could be widely distributed, and hyperisotopes, e.g. A = 3-5 Λ hypernuclei, can be studied which are hardly accessible in missing-mass experiments. The proposed investigations are based on the unique time structure of the radio frequency (RF) driven electron accelerators, which provide a few ps electron bunches in every few ns, continuously, and are enabled by (1) the use of kaon spectrometer (HKS), (2) the precise magnetic spectrometer for hypernuclear decayed pions (HπS), and (3) the development of an ultra high resolution timing technique, based on recently developed novel photon detector RF Photo-Multiplier Tube (RF PMT) [9, 10].

The project was defined with two types of experiments as follows:

- Experimental studies based on simultaneous detection of kaons and decay pions by using HKS and HπS. In this case produced kaons are detected in coincidence with decayed π^- and used as a positive tag for strangeness production [11]. Similar experimental program was started at MAMI, Mainz [12, 13].
- Experimental studies which use HπS and ultra high resolution timing technique.

In this paper we are discussing perspectives of the decayed pion spectroscopy at RF driven accelerators by using HπS and ultra high resolution timing technique based on RF PMTs.

2. Delayed π^- spectroscopy

In the first type of experiments the produced kaons and decay pions were detected simultaneously by using two magnetic spectrometers, HKS and HπS (Fig. 1). The detection probability $R_{K^+}(HKS)$ of produced K$^+$ in the momentum acceptance $P_0 \pm \Delta P$ of the HKS magnetic spectrometer is: $R_{K^+}(HKS) = [\Delta\Omega/(4\pi)] \times \varepsilon_s^K \times \varepsilon_{ef} \approx 10^{-3}$, were $\Delta\Omega = 20-30$ msr is the acceptance of HKS, $\varepsilon_s^K \cong 0.5$ is the survival probability of K$^+$, $\varepsilon_{ef} \cong 0.5$ is the detection efficiency of the detector package, $\Delta P \cong 100$ MeV. Similar figure we have for the detection probability of decayed pions:

$R_{\pi^-}(H\pi S)\approx 10^{-3}$. These two events are correlated in time but not in space, consequently their simultaneous detection probability is: $R_{K^+\&\pi^-} = R_{K^+}(HKS)\times R(\pi^-)\times R_{\pi^-}(H\pi S)$, where $R(\pi^-)\leq 10^{-2}$ is the probability of decay pion formation for each produced K^+ [8]. Therefore, for the first type of experiment the useful event probability for each produced K^+ is $R_{K^+\&\pi^-}\approx 10^{-8}/K^+$.

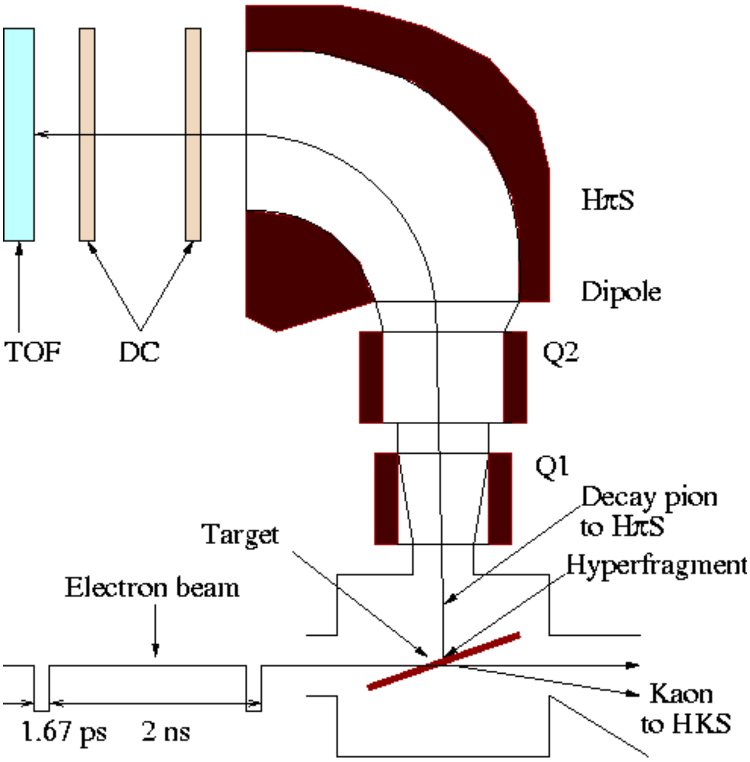

Figure 1. The scheme of the decayed pion experiment.

The useful event rate can be increased by several orders of magnitude by using the oncept of "*delayed-*π^-" spectroscopy [14]. The experimental setup in this case consists only of the decay pion spectrometer, HπS (see Fig. 1). The tracking detector package of HπS is the same as before, but as a timing technique, we propose to use RF PMT based Cherenkov detectors [15]. The expected time resolution of such detectors is better than 10 ps, FWHM. The expected reconstructed transit-time spread of pions in HπS is about or less than 20 ps, FWHM, and consequently the expected total time resolution is about or less than 30 ps, FWHM. With CEBAF at Jefferson Lab and MAMI at Mainz RF driven electron beams, the production time is about a few ps in every few ns. By using such a high resolution timing technique the decay pions can be separated from the huge amount of promptly produced background by using the time information only, i.e. without detecting K^+ mesons as a positive tag of strangeness production. Indeed, the probability to find promptly produced pions in the region with times larger than 100 ps is less than 10^{-5}, and ~70% of decay pions from Λ or hyperfragments (lifetime 260 ps) are delayed more than 100 ps. Therefore, the HπS with the RF PMT based Cherenkov detectors at RF driven electron beams, allows to carry out "delayed π^- spectroscopy", similar to "delayed γ-ray spectroscopy". The useful decay pion event probability in the "delayed π^-spectroscopy" experiment is: $R_{\pi^-} = 0.7 \times R_S \times R(\pi^-) \times R_{\pi^-}(H\pi S)$, where R_S is the probability of strangeness production. In this case, all two-body reactions, in which photons produce strangeness contributed. These reactions are: 1: $\gamma + p \rightarrow \Lambda + K^+$; 2: $\gamma + p \rightarrow \Sigma^0 + K^+$; 3: $\gamma + p \rightarrow \Sigma^+ + K^0$; 4: $\gamma + n \rightarrow \Lambda + K^0$; 5: $\gamma + n \rightarrow \Sigma^- + K^+$; 6: $\gamma + n \rightarrow \Sigma^0 + K^0$. In addition all useful virtual photon spectra take part, unlike the first type of experiment, were only K^+ production reactions, and a part of virtual photons, that produce K^+ mesons with momentum laying in HKS momentum acceptance ($\Delta P \cong 100$ MeV), contributed. Due to this $R_{\pi^-} \geq 10^3 \times R_{K^+\&\pi^-}$, i.e. the expected rates of useful events in case of "delayed π^-spectroscopy" is 10^3 times higher than rates expected in the first type of experiments.

3. Absolute calibration of the HπS

The key point of the proposed experimental program is determination of the binding energies of light hypernuclei by decay π^- momentum measurement. These moments are in the range around 100 MeV/c and could be measured precisely by using high resolution magnetic spectrometer $H\pi S$. However, method of absolute calibration of the magnetic spectrometer within 10^{-4} precision remains still open. Absolute calibration of the HπS can be realized by time-of-flight (TOF) measurement of promptly produced pions and electrons. We propose to use the high resolution and highly stable TOF system with RF PMT based Cherenkov detectors located on the focal plane of $H\pi S$ [16]. Indeed, the TOF of particle with mass m and momentum p and a flight path L is:

$$t_\pi = \frac{L}{\beta_\pi c} = \frac{L}{c}\left(1 + \frac{m_\pi^2 c^2}{p^2}\right)^{1/2} \qquad (1)$$

$$t_e = \frac{L}{\beta_e c} = \frac{L}{c}\left(1 + \frac{m_e^2 c^2}{p^2}\right)^{1/2} \qquad (2)$$

where c is the speed of light, $\beta = v/c$. From these equations we have:

$$\frac{L}{c} = \left(\frac{t_e m_\pi^2 - t_\pi m_e^2}{m_\pi^2 - m_e^2}\right)^{1/2} \qquad (3)$$

$$p_\pi = \frac{L}{c}\frac{m_\pi c}{[t_\pi^2 - (L/c)^2]^{1/2}} \qquad (4)$$

Therefore absolute calibration of the HπS can be performed by measuring flight times of pions, t_π and electrons, t_e, and determining L/c and p_π by using equations (3) and (4). The Monte Carlo simulations demonstrated that precision better than 10 keV can be achieved. This method of absolute calibration can be used continuously during experiment. It is assumed that for a fixed configuration of the system, the flight path length L and the magnetic rigidity of the spectrometer stay stable with in relative precision better than 10^{-4}. Similar technique is established for precise measurements of masses of exotic nuclei (see e.g. [17]).

Tagged-Weak π-Method

Hypernuclear investigations provide unique information on many-body hadronic systems by utilizing new “strangeness” degrees of freedom. A hyperon added to a nuclear system does not feel the Pauli exclusion. It also experiences nuclear forces that are different from those among nucleons in a nucleus. Therefore, a hyperon introduced in a nucleus may give rise to various changes of the nuclear structure. It may affect the size and the shape of a nucleus, change its cluster structure, lead to emergence of new symmetries, change the collective motions, etc. An example of how one can modify a nucleus by adding to it a distinguishable baryon is given by the experiment on γ-spectroscopy of ${}^{7}_{\Lambda}$Li [18]. When a Λ in 1s orbit is added to a loosely bound nucleus such as ^{6}Li, the nucleus is expected to shrink into a more compact system due to the attractive force between Λ and nucleons (“glue-like” role of the Λ). This effect can be verified from the E2 transition probability B(E2), which contains information of the nuclear size. Experimentally B(E2) is derived from the lifetime of the $5/2^+$ state. The expected lifetime ($\sim 10^{-11}$ sec) is of the same order as the stopping time of the recoil ${}^{7}_{\Lambda}$Li in lithium in the case of the (π^+, K^+) reaction at 1.05 GeV/*c*. It was determined to be $5.8^{+0.9}_{-0.7} \pm 0.7$ ps with the Doppler Shift Attenuation Method (DSAM). B(E2) was then derived to be 3.6 ± 0.5 e^{2}fm^4. This result, compared with the B(E2) = 10.9 ± 0.9 e^{2}fm^4 of the core nucleus ^{6}Li ($3^+ \rightarrow 1^+$), indicates about 20% shrinkage of the ${}^{7}_{\Lambda}$Li size vs. ^{6}Li. The DSAM can be applied to measure lifetimes in the range of $10^{-12} - 10^{-11}$ s. For the E2 transition with energy around ~1 MeV the expected lifetimes will be too long ($\sim 10^{-10}$ s) for DSAM and the γ transition competes with weak decay. For this case a new “γ-weak coincidence method” has been proposed [19] for the future J-PARC experiment.

Recently a new "tagged-weak π-method" has been proposed for measurements of electromagnetic rates of hypernuclear states with lifetimes of $\sim 10^{-10}$ s, tagged by weak decayed pions [20]. By using "tagged-weak π-method" and RF PMT based Cherenkov detectors, the electromagnetic rates of hypernuclear states with lifetimes down to 10^{-11} s could be measured. It is worthy to mention that unlike DSAM, “tagged-weak π-method” can be used for hyperfragments as well.

4. Conclusions

The recently developed high resolution RF PMTs opens new opportunities for hypernuclear studies. The RF PMT based Cherenkov detectors allow the realization of a new type nuclear spectroscopy, the “*delayed-*π^-” spectroscopy at modern electron accelerators. By using “*delayed-*π^-” spectroscopy, binding energies of hypernuclear ground and low lying states can be measured with precision of about 10 keV. In addition by measuring lifetimes of the low lying states and by applying "tagged-weak π-method", electromagnetic rates of hypernuclear states with lifetimes down to 10^{-11}s could be investigated. The experimental information on these characteristics of the ΛN interaction is essential for the discrimination and improvement of baryon-baryon interaction models, which are needed for a unified, comprehensive understanding of the strong force that determines the properties of the high-density nuclear matter with hyperons.

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