RF picosecond timing technique and new possibilities for hypernuclear studies

A. Margaryan[a]

Yerevan Physics Institute, 2 Alikhanian Brothers Str., Yerevan-36, 375036, Armenia

Abstract. Two types of RF picosecond timing technique: Cherenkov detector based on the radio frequency picosecond phototube and time-zero fission fragment detector are proposed. Study of hypernuclei by pionic decay and Auger neutron spectroscopy of hypernuclei at CW RF driven electron beams by using new RF picosecond timing technique are discussed.

PACS. 21.80.+a Hypernuclei – 21.10.Dr Binding energies and masses – 21.10.Gv Mass and neutron distributions – 25.30.Rw Electroproduction reactions

1 Introduction

It is well known that timing systems based on radio frequency (RF) fields can provide precision of the order of 1 ps or better (see [1] and references therein). Streak cameras, based on similar principles, are used routinely for precise measurements in the picosecond range. With a streak camera operating in the "synchroscan" mode, a typical temporal resolution of 2 ps can be reached for a long (more than one hour) time exposure. Nevertheless, the RF timing technique as well as the streak cameras did not find wide application in the past, including the elementary particle physics and nuclear physics experiments. This is mainly connected to the fact that commercially available streak cameras provide slow or averaged time information.

Recently we have developed 500 MHz RF timing technique which combines advantages of circular scan streak cameras and regular photomultipliers, and provides fast, nanosecond signals for future event by event processing of each photoelectron or secondary electron with better than 20 ps r.m.s. resolution. We propose two types of detectors based on the developed technique: Cherenkov detector based on the RF picosecond phototube (RFPP), and RF time-zero fission fragment (FF) detector.

The operational principles of the proposed RFPP are described in the Ref.[1] and can be summarized as follows. The primary photon pulse hits the photocathode and produces photo-electrons (PEs), the time structure of which is identical to that of the light pulse. These electrons are accelerated by a voltage V applied between the photocathode and an electron transparent electrode. The electrostatic lens then focuses the electrons onto the screen at the far end of the tube, were secondary electron (SE) detector is placed. Along the way, the electrons are deflected by the circular sweep RF deflection system and form a circle on the screen, where the time structure of the input photon signal is transferred into spatial one and detected. By this way the timing error sources are minimized, because PEs is timed before the necessary further signal amplification and processing. The detection of the RF analyzed PEs is accomplished with position sensitive detector based on multichannel plates that provide fast nanosecond signals.

Timing characteristics of the Cherenkov detector with a 40 mm diameter RFPP in a "head-on" geometry was investigated by means of Monte Carlo (MC) simulation and it has been demonstrated that about 20 ps (FWHM) resolution can be achieved for 100 MeV/c pions [2]. The Cherenkov radiator should have $(40 \times 40) mm^2$ size, 2 mm thickness and refractive index $n = 1.82$.

The principal scheme of the RF time-zero FF detectors are similar to the design of RFPP. The high energy electron beam passes through target and produces FFs. Each FF exiting target surface produces secondary electrons. These electrons are accelerated, RF analyzed and detected like PEs in the case of RFPP with time resolution better than 20 ps. The expected time resolution for FF is about or better than 5 ps (FWHM), because each FF exiting target surface produces about 100 secondary electrons.

Operation of RF timing technique at RF driven accelerators, synchronously with muster oscillator, results high precision and highly stable timing system. In this case SEs or PEs from different time intervals are separated in space, but from periodic events are located on the same place at the scanned circle. Therefore, synchronous operation of RF timing technique at JLab CW electron beams (1.67 ps duration bunches each 2 ns) allows promptly produced

[a] e-mail: mat@mail.yerphi.am

events localize on the some point of the scanned circle, but delayed events are distributed on the whole circle according to the lifetime of delayed process. This feature can be used to separate delayed events, e.g. hypernuclei decay products (lifetime 200 ps) from promptly produced ones.

Study of hypernuclei by pionic decay and Auger neutron spectroscopy of hypernuclei at JLab by using Cherenkov detectors based on RFPP and RF time-zero FF detectors are discussed in paragraph 2 and 3 consequently.

2 Study of hypernuclei by pionic decay

The binding energies of light hypernuclei are the most valuable experimental information for checking different models of YN interaction. They have been measured in emulsion by pionic decay with $\sigma \leq 500$ keV [3,4], and their average values have been determined with a statistical error laying in the range 50−100 keV and systematic error of about 40 keV. Recent ab initio calculations demonstrated that more precise data of binding energies are needed in order to check different models of YN interaction [5].

We propose a new experiment for precise measurement of binding energies, B_Λ, for a light ($A \leq 15$) hypernuclei at JLab, by using again π^- mesonic decays [2]. The expected results will provide binding energies, B_Λ, with $\sigma \leq 100$ keV. Average values of the B_Λ will be determined within an error of about 10 keV which is 5-10 times better than in the case of emulsion. These investigations are enabled by the use of: (1) HKS in Hall C [6], (2) high resolution magnetic spectrometer for hypernuclear decayed pions ($H\pi S$), and (3) time of flight (TOF) wall consisting of about 100 Cherenkov detectors based on RFPP. The combination of precise RF timing technique and high resolution magnetic spectrometer with RF driven electrom beam can be used also for investigations of exotic hypernuclei toward to neutron and proton drip-lines, for study of impurity nuclear physics and the medium effect of baryons [2]. We propose two configurations for the experiment.

2.1 Decay π^- specroscopy in coincidence with HKS

The incident electron beam hits the target and produces a hypernucleus. The hypernucleus is stopped in the target and decays after some 200 ps inside the target. Decay pion exits the target and is detected by $H\pi S$ located at large ($\geq$ 90 degree)angles relative to the incident beam. The forward produced K^+ meson is detected by HKS and used as a trigger for hypernucleus production. Two factors contribute to the total resolution of the experiment: the momentum resolution of the $H\pi S$ spectrometer and momentum losses of pions in the target. The expected momentum resolution of $H\pi S$ is about $\sigma = 3 \times 10^{-4}$, solid angle $\Delta\Omega = 30$ msr, flight path length ≤ 4 m. The influence of the ionization energy losses, (dE/dx), has been calculated by using MC code. The momentum spread of monochromatic pions from ${}^{12}_{\Lambda}B \rightarrow {}^{12}C + \pi^-$ decays ($p = 115.8$ MeV/c) in a 24 mg/cm^2 carbon target is about $\sigma = 70$ keV/c due to dE/dx. For the total error we have $\sigma = 75$ keV/c.

Taking into account "direct" and "indirect" production mechanisms we can estimate hyperfragment yields [2]. We will consider a 30 μA electron beam, typical for HKS experiments and a ${}^{12}C$ target with an effective thickness of 100 mg/cm^2 (24 mg/cm^2 foil, tilted by about 10 degrees relative to the incident beam). The forward produced kaons are a good trigger for hypernuclei production: about 3% of them are associated with "direct" and 10% with "indirect" production of hypernuclei. The remaining 87% of kaons are associated with "quasi-free" produced Λ particles, 64% of which decay through the $\Lambda \rightarrow \pi^- +$p channel. The K^+ rate in HKS in these conditions is ≃150 kaon/s and the expected rate of the pions detected in the $H\pi S$ from ${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^-$; ${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^-$ and ${}^{12}_{\Lambda}B \rightarrow {}^{12}C + \pi^-$ decays in coincidence with HKS are equal to 23, 31 and 134 events/day respectively [2]. For the ${}^{7}Li$ target, 3 times higher rate is expected for ${}^{4}_{\Lambda}H$ hyperfragments. The expected π^- rate in $H\pi S$ is about $1.4 \times 10^3/sec$. The Cherenkov TOF wall consists of about 100 modules, therefore the rate of each module will be about 14/sec which can be easely processed by using nanosecond electronics.

We have three sources of background: the promptly produced pions (will be excluded by using coincidence with produced kaons); the decay pions from "quasi-free" produced Λ particles (in the 100 keV/c momentum bite in which the discrete pions are localized, this rate will be about 8.6 event/day as follows from MC simulations, and can be suppressed additionally by using a "vertex cut", which requires the reaction point and the decay point to be in coincidence at a three-dimensional point); accidentals (are expected to be negligible).

2.2 Delayed π^- specroscopy

The experimental setup in this case is basically different than in the former case. It consists only with the decay pion spectrometer $H\pi S$. The tracking detector package of $H\pi S$ is the same as before, but as a timing technique, we propose to use Cherenkov detectors based on RFPP. The expected time resolution of the new Cherenkov timing technique is about 20 ps FWHM. The expected reconstructed transit time precision for pions in $H\pi S$ is about 20 ps FWHM, and consequently the expected total time resolution is about or less than 30 ps FWHM. In this case decay pions are separated from the huge amount of promptly produced background by using time information only. At the JLab electron beams the production time is about 2 ps each 2 ns and as follows from MC simulations the probability to find promptly produced pions in the region with times larger than 100 ps is less than 10^{-5} and that $\sim 70\%$ of decay pions from Λ or hyperfragments (lifetime 260 ps), have times larger than 100 ps. Therefore, the $H\pi S$ with the new Cherenkov detectors at the JLab electron beam allows to carry out "delayed π^- spectroscopy", similar to "delayed γ-ray spectroscopy" in nuclear spectroscopy. This will be the most precise and sensitive experiment for the detecting of hypernuclei decay pions, with about 3.2×10^5 detected hyperfragment "daily" yield [2]. For comparison let us note that the total emulsion data on π^--mesonic decays amount to some 3.6×10^4 events.

3 Auger neutron spectroscopy of hypernuclei

The Λ binding energies are usually much larger than those for a nucleon, and hypernuclear states in which a Λ hyperon is bound in an orbit above the p shell are often nucleon unbound and decay by emitting nucleons, mainly neutrons because of the Coulomb barrier. Such a deexcitation is known as the nuclear Auger effect [7]. The widths for Λ hypernuclear states are expected to be much smaller than the energy spacing between the Λ major shells in contrast to the case for an ordinary nucleus and, consequently, Λ hypernuclear states should be observable as reasonably narrow peaks. The probability for the Auger emission is many orders of magnitude larger than for the gamma emission and the observation of Auger neutrons, emitted during the deexcitation of the hypernucleus after the initial creation of a Λ in an excited state is a promising alternative for spectroscopy in medium and heavy mass hypernuclei [8]. The energy spectrum of the emitted Auger neutrons reflects the Λ single particle level structure, but folded with the neutron single-particle spectrum. Due to this, the spectral distribution of the emitted Auger neutrons in heavy mass ($A \simeq 200$) hypernuclei is extremely complex [9]. For this reason a very detailed reconstruction of each event will have to be done in experimental measurements, e.g. by focusing on initial states of the produced Λ . But this will decrease rates of the detected Auger neutrons, making experiments with electromagnetic probe practically impossible.

The energies of monochromatic Auger neutrons can be measured by using the time-of-flight technique, and neutron detectors e.g. based on liquid scintillators [10]. For such a neutron detectors with thickness of ΔL = 1.25 cm and flight path $L = 200$ cm, the expected time resolution will be about ΔT = 0.5 ns FWHM. The total (geometrical and detection) efficiency of about 130 such modules located at 200 cm from target is $\sim$1% for (1-10) MeV neutrons. The expected energy resolution e.g. for 3 MeV neutrons from A = 50 mass hypernuclei is $\sigma = 50$ keV (time resolution, flight path spread and kinematical broadening taken into account).

However, in order to find out the optimal conditions for Auger neutron spectroscopy with electron beams, we need to carry out test studies of neutron detectors and developed RF time-zero FF detectors in the real experimental environment as well as additional results of theoretical investigations to find out proper hypernucleus with simple and interpretable Auger neutron spectral distribution.

4 Conclusions

An interesting hypernuclear physics program is conceivable at JLab, based on the recently developed 500 MHz RF timing technique. It includes precision decay pion spectroscopy, production of neutron reach hypernuclei, and Auger neutron spectroscopy. Decay pion spectroscopy of hyperfragments produced in electromagnetic interactions is also possible. The expected count rates are of the same order of those expected at DAΦNE2 and J-PARC [11], but the proposed experiments are not duplicated by any in the currently approved or planned experimental program.

The discussions on the realization of experimental program are actually going on, as well as the R&D for developing, manufacturing and testing of real prototypes of the RF timing technique.

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