RF TIMING TECHNIQUE AND ITS POSSIBLE APPLICATIONS

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Abstract Experimental results that demonstrate principles of operation of a new RF timing technique at 500 MHz are presented. Two new devices based on these principles are considered: the radio frequency picosecond phototube and the time-zero fission fragment detector. Possible applications of the technique in high-energy elementary-particle and nuclear physics experiments as well as in applied physics are discussed.

Keywords: Picosecond time measurement; Photodetectors; Cherenkov detectors; Secondary electron detectors; Hypernuclei. PACS number: 06.30.Ft

1. Introduction

At present the photon detection is carried out with solid state devices, vacuum photomultiplier tubes (PMTs) or hybrid photon detectors (HPDs). These instruments also provide fast time information necessary in different fields of science and engineering. In high-energy particle physics and nuclear physics experiments, the time precision limit for the current systems consisting of particle detectors based on, for example, PMTs and common nanosecond electronics (amplifiers, discriminators, and time-to-digital converters) is about 100 ps, FWHM.

However, it is well known that timing systems based on radio frequency (RF) fields can provide precision of about 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 in 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 a 500 MHz RF timing technique which combines advantages of circular scan streak cameras and regular photomultipliers, and provides fast, nanosecond signals for future events by event processing of each photoelectron or secondary electron with better than 20 ps rms resolution by using nanosecond electronics. Two new devices are proposed based on these principles: a radio frequency picosecond phototube (RFPP) and a time-zero fission fragment (FF) detector.

Below, we present experimental results that demonstrated principles of operation of the new RF timing technique. We describe operational principles of the RFPP with point size and large (4 cm in diameter) photocathode and time-zero FF detectors as well. We consider the Cherenkov time-

of-flight (TOF) detector in a "head-on" geometry and the Cherenkov time-of-propagation (TOP) detector based on RFPP. Results of Monte-Carlo simulations are presented.

Study of hypernuclei by pionic decay and by Auger neutron spectroscopy with RF-driven electron beams by using the new RF timing technique and other possible applications of the technique are discussed.

2. New RF timing technique

2.1 RF phototube

The operational principles of a new RF timing technique and an RF phototube with point size photocathode are shown in Fig. 1. The primary photon pulse hits the photocathode (1) and produces photo-electrons (PEs). These electrons are accelerated by a voltage V applied between the photocathode and an electron transparent electrode (2). The electrostatic lens (3) then focuses the electrons onto the screen (7) at the far end of the tube, were the PE detector is placed. The time structure of the produced PE bunch is identical to that of the light pulse. Along the way the electrons are deflected by the circular sweep RF deflection system, consisting of electrodes (4) and a $\lambda/4$ coaxial RF cavity (6), which operates at 500 MHz, and form a circle on the screen, where the time structure of the input photon signal is transferred into a spatial PE image (5) and detected. In this way the timing error sources are minimized, because PEs are timed before the necessary further signal amplification and processing.

Several factors determine the time resolution of such a device:

- 1) Physical time resolution of the photocathode, i.e., the time dispersion or delay of the photoelectrons: a delay and time spread of the photoelectrons $\Delta \tau_p$ is caused by the finite thickness of the photocathode Δl and the energy spread $\Delta \epsilon$ of the PEs. For the typical thickness of the semitransparent bialkali photocathode, $\Delta l \approx 20$ nm, and $\Delta \epsilon = 1$ eV, we obtain $\Delta \tau_p \leq 10^{-12}$ s.
- 2) Physical time resolution of the electron tube: the minimal time dispersion is determined by chromatic aberration due to the PEs' initial energy spread, $\Delta\epsilon$. The time spread in the case of a uniform accelerating electric field E near the photocathode is $\Delta\tau_t = 1.7 \times 10^{-8} (\Delta\epsilon)^{1/2}/E$ s, where $\Delta\epsilon$ is in eV, and E is in V/cm. For our case, the applied voltage V = 2.5 keV, Z = 0.25 cm and for $\Delta\epsilon = 1$ eV we obtain $\Delta\tau_t \approx 2 \times 10^{-12}$ s.
- Technical time resolution of the electron tube is determined by the electron transit time dispersion. In a carefully designed system this time dispersion can be minimized to be in the ps range.
- 4) Technical time resolution of the RF deflector is $\Delta \tau_d = d/v$ where d is the size of the electron beam spot or the position resolution of the secondary electron detector (if the electron beam spot is smaller), while $v = 2\pi R/T$ is the scanning speed. Here T is the period of the RF field

and R is the radius of the circular sweep on the position-sensitive detector. For example, if T = 2×10^{-9} s (f = 500 MHz), R = 2 cm, and d = 1.0 mm, we have $v \ge 0.5 \times 10^{10}$ cm/s and $\tau_d \le 20 \times 10^{-12}$ s.



Fig. 1. The schematic layout of the RF phototube with point-size photocathode. (1) – photo-cathode, (2) – electron transparent electrode, (3) – electrostatic lens, (4) – RF deflector, (5) – image of photo electrons, (6) – $\lambda/4$ coaxial RF cavity, (7) – SE detector.

To scan circularly 2.5 keV electrons a dedicated RF deflecting system at a frequency of f = 500 MHz has been developed. The sensitivity of this new and compact RF deflector is about 1 mm/V or 0.1 rad/W^{1/2} and is an order of magnitude higher than the sensitivities of the RF deflectors used previously. About 1 W (on 50 Ω) RF power at 500 MHz has been used to scan the beam circularly and to reach 2 cm radius or 20 ps resolution for 2.5 keV electrons.

The detection of the PEs is accomplished with a position-sensitive detector based on a dual, chevron type micro-channel plates (MCPs). Position determination can be performed in two basic architectures:

- Direct readout: array of small (~ 1 mm²) pixels, with one readout channel per pixel. Position
 resolution in this case is about or better than the size of the readout cell.
- 2. Interpolating readout: the position sensor is designed in such a way that measurement of several signals (amplitudes or/and times) on neighboring electrodes defines event position. Position resolution limit for both cases (amplitude or times) is $\Delta x/x \sim 10^{-3}$.

A typical signal from a single secondary electron (SE) induced on the position sensitive resistive anode is displayed in Fig. 2. It consists of two parts: a signal generated in MCP by circularly scanned 2.5 keV electrons, and a signal induced by the RF deflector's 500 MHz RF noise. One can see that the amplitude of the induced 500 MHz RF noise from ~1 W RF power is about an

order of magnitude smaller than the amplitude of single SE signals amplified in the MCP. Thus, signals from such a device can be processed by using common nanosecond-time electronics (amplifiers, discriminators, logic units, analog-to-digital converters, etc.), and time resolution better than 20 ps can be achieved for a single SE.

The RF phototube with direct readout scheme, for example, with 1 mm size pixels, can operate as a 20 GHz optical scope and can be used for digitization of nanosecond or subnanosecond light pulses.

This technique, like streak cameras, can be operated in the "synchroscan" mode and a temporal stability of 200 fs can be reached for a long (more than one hour) time exposure by using proper calibration [2]. The time resolution can be improved, if necessary, by improving characteristics of the electron tube and the SE detector, and/or by using higher frequencies, since it is possible to operate the developed RF deflector and scan circularly keV electrons in the frequency range 500 – 1500 MHz.



Fig. 2. Photo of the oscilloscope screen showing scanned single SE signal from a position-sensitive anode.

A large-size photocathode can be applied as well, without essential distortion of the temporal resolution, by using a "spherical-capacitor" type immersion lens and a transmission dynode [1].

2.1 Time-zero FF detector

The principal scheme of the RF time-zero FF detector is similar to the design of the RFPP (see Fig. 3). The high-energy electron beam passes through the target (1) and produces FFs (2). Each FF exiting the target surface produces SEs (5). These electrons are accelerated by a voltage applied between the target and the electron transparent electrode (3). The electrostatic lens (4) then focuses the electrons onto the screen (7) where the SE detector is placed. Along the way the SEs are deflected by the RF deflector (6) and detected 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 the target surface produces about 100 secondary electrons.



Fig. 3. The schematic layout of the time-zero FF detector. (1) - target, (2) - fission fragments, (3) - electron transparent electrode, (4) - electrostatic lens, (5) - secondary electrons, (6) - RF deflector, (7) - SE detector.

In the next paragraph we will consider Cherenkov time-of-flight (TOF) and time-ofpropagation (TOP) detectors based on the developed technique and will present their expected parameters obtained by means of MC simulation.

3. Cherenkov timing technique based on the RFPP

When a charged particle passes through the radiator bar, Cherenkov photons are emitted in a conical direction defined by the Cherenkov angle θ_c , where $\cos\theta_c = 1/n\beta$, n is the refractive index.

The flash duration of the Cherenkov radiation is ≤ 1 ps [3]. The paths of the Cherenkov photons in the radiators are determined by the Cherenkov photon emission angle, θ_c , i.e. by the particle velocity β and azimuthal angle Φ_c [4]. These characteristics of the Cherenkov radiation in combination with a picosecond photon detector can result in relatively simple particle identification devices [5-7]. Here we will consider Cherenkov TOF and TOP detectors based on the RFPP and quartz radiator. The following dominant factors have been taken into account in the MC simulations [8]:

- The time spread of Cherenkov radiation along the particle trajectory over the thickness of radiator: Cherenkov photons are emitted uniformly along the path of particle passage through the radiator.
- 2) The transit time spread of Cherenkov photons due to different trajectories: trajectories of the individual photons determined according to θ_c and Φ_c .
- 3) The chromatic effect of the Cherenkov light: for the numerical calculations we take $n = 1.47 \pm 0.008$. The Gaussian distribution for *n* has been used.
- 4) The timing accuracy of the photon detector.

3.1. Cherenkov TOF detector in a "head-on" geometry

The Cherenkov TOF detector in a "head-on" geometry is schematically shown in Fig. 4. The incident particle produces Cherenkov photons in the radiator. These photons produce PEs on the photocathode (1) which are accelerated in the "spherical-capacitor" region formed by the photocathode (1) and electron transparent electrode (2) and focused on the crossover where they pass through the transmission dynode (3), producing SEs on both sides of the dynode. Low-energy SEs produced on the rear side of the transmission dynode are accelerated with the help of the electron transparent electrode (4) and enter into the electron tube which is the same as in the case of the point-size photocathode (see Fig. 1).

The expected time distribution of single PEs as well as 155 PEs for the normally incident 5000 MeV/*c* pions and for the quartz radiator, n = 1.47 and L = 1.0 cm, and for the photon detector with 20 ps time resolution, are displayed in Fig. 5. These simulations have demonstrated that such a Cherenkov detector can provide time resolution better than 5 ps FWHM.



Fig. 4. The schematic layout of the Cherenkov TOF detector with RF phototube in a "head-on" geometry. (1) – photocathode, (2) – electron transparent electrode, (3) – transmission dynode, (4) – accelerating electrode, (5) – electrostatic lens, (6) – RF deflection electrodes, (7) – image of PEs, (8) – $\lambda/4$ RF coaxial cavity, (9) – SE detector.



Fig. 5. Time distribution of single PEs for tracks of p = 5000 MeV/c pions (a), and mean time distribution of N₀ = 155 PEs (b).

3.2. Cherenkov TOP detector

The schematic of the Cherenkov TOP detector [5] is shown in Fig. 6. Similar to the DIRC (Detection of Internally Reflected Cherenkov) light [4], the Cherenkov TOP couples a radiator bar with a picosecond photon detector that times the photoelectrons seen at the end of the bar. In so doing, a TOP utilizes the optical material of the radiator as a Cherenkov radiator, and as a light pipe for the Cherenkov photons trapped in the radiator by total internal reflection. The source length of the emitting region is the particle trajectory length in the radiation material. The angles, positions, momentum and start time of the incident particle are provided by other detectors. The photon propagates a length (L_p) in a time of propagation (TOP) (t_p) down a bar length of (L) as is given by $t_p = L_p n(\lambda)/c = Ln(\lambda)/cq_z$, where $n(\lambda)$ is the refractive index of the radiator at wavelength λ , c is the light velocity in vacuum, and q_z is the directional z-component of the photon emission. The technique uses the correlation between photon path-length, L_p and Cherenkov production angle, θ_c to infer this angle by measuring the time taken for the totally reflected Cherenkov photons to "bounce" to the end of the radiator. Figure 6 also demonstrates the difference in flight path for light emitted by π 's (thick line) and K's (thin line). Due to this difference the TOP is inversely proportional to the z (quartz-axis direction) component of the light velocity, which produces TOP differences of, for instance, about 100 ps or more for normal incident 4 GeV/c π and K at 2 m long propagation.



Fig. 6. Schematic of the Cherenkov correlated timing technique.

We have carried out a simulation study of the proposed technique. The expected total number of photoelectrons N_{p.e.} detected in the device is: N_{p.e.} = N_c× Δ l×(Δ Φ_c/360), where N_c = 155 photoelectrons/cm is the Cherenkov quality factor [6], Δ l is the thickness of the radiator, and Δ Φ_c is the azimuthal angular interval of the detected Cherenkov photons. The size of the radiator bar is 10 mm thick (in *y*), 20 mm wide (in *x*), and 100 cm long (in *z*). One end of the Cherenkov radiator is connected to the photon detector, and the opposite end assumed blackened to avoid reflection. So we are considering only forward (FW) going photons. The time of propagation distribution of single and FW going photons for tracks of p = 2 GeV/*c* pions, $\theta_{inc} = 90$, with $|\Phi_c| \le 45^\circ$ (a), and the average time distribution of detected photons with $|\Phi_c| \le 15^\circ$ (b) or with propagation times less than $t \le 6950$ ps (c), obtained as a result of Monte-Carlo simulation, is shown in Fig. 7a,b,c. As follows from Fig.7b,c restriction of azimuthal angles $\Delta \Phi_c$ or arrival times of Cherenkov photons are equivalent and result in the same average time distribution. Therefore by using a direct readout scheme, the RFPP can be used to digitize the Cherenkov photon pulse, i.e. to detect each Cherenkov photon and measure its arrival time. This information, in combination with particle trajectory ant start time, results in a Cherenkov angle θ_c .



Fig. 7. Time of propagation distribution of single and FW going photons for tracks of p = 2 GeV/c pions, $\theta_{\text{inc}} = 90^\circ$, with $|\Phi_c| \le 45^\circ$ (a), and mean time distribution of all detected photons for the cases with $|\Phi_c| \le 15^\circ$ (b) and $t \le 6950 \text{ ps}$ (c).

These simulations have demonstrated that such a simple and compact TOP Cherenkov counter can be used for π and *K* separation in the 1–3 GeV/*c* momentum range. The differences of TOF between π and K are 231 and 37 ps at 10 m time-of-flight distance and for p = 4 and 10 GeV/*c*, respectively, and by using the TOF Cherenkov detector based on the RFPP with 20 ps

resolution, about 120 σ and 19 σ π/K separation can be reached for p = 4 and 10 GeV/*c*, respectively. Therefore both techniques can find applications in Jefferson Lab 12 GeV experiments as relatively simple and effective particle identification devices.

Operation of the RF timing technique at RF-driven accelerators, synchronously with a master oscillator, results in a 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 the RF timing technique with Jefferson Lab CW electron beams (1.67 ps duration bunches each 2 ns) allows promptly produced events to localize on the same point of the scanned circle, but delayed events are distributed on the whole circle according to the lifetime of the 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 Jefferson Lab by using Cherenkov detectors based on RFPP and RF time-zero FF detectors are discussed in sections 4 and 5 consequently.

4. Study of hypernuclei by pionic decay at Jefferson Lab

The binding energies B_{Λ} have been measured in emulsion for a wide range of light ($3 \le A \le 15$) hypernuclei [9]. The emulsion data on B_{Λ} values of about 24 from 43 observed hypernuclei include 4042 uniquely identified events, culled from some 36000 π^{-} mesonic decaying hypernuclei produced by stopping K⁻ mesons [9, 10]. The hypernuclear decayed discrete π^{-} spectra can be measured by using a magnetic spectrometer as well, but in conventional fixed target experiments employing kaon beams, the need to use thick targets introduces major limitations on the achievable resolution. The momentum resolution of the Tokyo group's magnetic spectrometer, for example, was ~1 MeV/c [11]. However, the Tokyo group was first to detect the decayed discrete π^{-} mesons from ${}^{4}_{\Lambda}$ H hypernuclei by using a magnetic spectrometer.

We proposed a new experiment for precise measurement of binding energies, B_{Λ} , for light $(A \le 15)$ hypernuclei at JLab, by using again π^- mesonic decays [12, 13]. The proposed experiment will provide binding energies, B_{Λ} , with a resolution of about or better than 100 keV, which is 5–10 times better than in the case of emulsion. Average values of the B_{Λ} will be determined within an error of about 10 keV or better. These investigations are enabled by the use of: (1) HKS in Hall C [14], (2) high-resolution magnetic spectrometer for hypernuclear decayed pions, $H\pi S$ and (3) Cherenkov detectors based on RFPP [8]. Two configurations for such an experiment have been proposed.

4.1 Decay π^- spectroscopy in coincidence with HKS

The schematic layout of the hypernuclei π^{-} decay spectroscopy is shown in Fig.8.

The incident electron beam hits the target and produces a hypernucleus (Fig. 8). The hypernucleus is stopped in the target and decays after some 200 ps inside the target. The decay pion exits the target and is detected by the $H\pi S$ located at large (>90 degree) angles relative to the incident beam. The forward produced K⁺ meson is detected by the HKS and used as a trigger for hypernucleus production [15].



Fig. 8. Plan view for the decay pion spectroscopy experiment.

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 using MC code. The momentum spread of 100 MeV/*c* monochromatic pions in a 24 mg/cm² 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 [12]. The forward produced kaons are a good trigger for hypernuclei production: about 3% of them are associated with

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"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 hypernuclear decay pion "daily" yields detected in $H\pi S$ in the case of 150 Hz K^+ rate in HKS for ¹²C target are listed in the accompanying table. The relative yields for hyperfragments, π^- -decay widths and decay π^- momentums are listed as well. The relative yields were evaluated by taking into account the emulsion data. The decays of all hyperfragments are considered as two-body decay. In the case of three-body decays, e.g., in the cases of decays of ${}^5_{\Lambda}$ He and ${}^9_{\Lambda}$ Be, the momentum distribution of decayed pions has a long tale at the lower momentum side and the values listed in the table correspond to the maximum value of the distribution for these hyperfragments.

Hypernuclei	Relative	π -decay width	Decay π^- "daily" yield	π ⁻ mom.
	yield	Γ_{π}/Γ_{A}	detected in $H\pi S$	(MeV/c)
q. f.	0.77	0.64	$5.6 10^3$	spread
⁹ Be	0.015	0.17	29	95.96
⁸ Be	0.01	0.15	17	97.17
⁵ He	0.09	0.34	349	99.14
¹¹ B	0.01	0.21	24	105.9
⁷ Li	0.015	0.30	51	107.9
³ H	0.01	0.30	34	114.3
¹² B - direct	0.03	0.29	100	115.8
production	0.05	0.29	100	115.0
⁸ Li	0.04	0.37	169	124.1
⁴ H	0.01	0.50	57	132.9

Table. Hypernuclei (ground states only) and decay pion "daily" yields for ¹²C target ($t_{eff} = 50 \text{ mg/cm}^2$) with 150 Hz K^+ rate in HKS (beam current 45 μA).

The simulated spectrum including background with total of 10^5 pions produced in the 25 mg/cm² carbon target (with energy loss) and measured in the $H\pi S$ with resolution $\sigma = 4.9 \times 10^{-4}$ is shown in Fig. 9. It demonstrates that monochromatic pion spectra are clearly seen even with a huge amount of quasi-free background.



Fig. 9. Simulated spectrum of the decayed pions (87% from quasi-free produced Λ particles and 13% from different hyperfragments with their relative weights). Target thickness is 25 mg/cm²; momentum resolution of $H\pi S$ is $\sigma = 4.9 \times 10^{-4}$; total number of events is 10^{5} .

4.2 Delayed π spectroscopy

The experimental setup in this case is basically different than in the former case. It consists only of 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. With Jefferson Lab 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 $\sim 70\%$ 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 using 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 310⁵ detected hyperfragment "daily" yield [12]. For comparison let us note that the total emulsion data on π -mesonic decays amount to 3.6×10⁴ events.

From the precise binding energy *B* of hypernuclear ground states and detailed low lying structure, we can establish the ΛN spin-dependent (spin-spin, spin-orbit, and tensor forces) interaction strengths, investigate ΣN - ΛN coupling force, and study charge symmetry breaking. Experimental information on these characteristics of the ΛN interaction plays an essential role to discriminate and improve baryon-baryon interaction models, not only those based on the meson-exchange picture but also those including quark-gluon degrees of freedom, toward unified understanding of the baryon-baryon interactions. In addition, understanding of the *YN* and *YY* interactions is necessary to describe high-density nuclear matter containing hyperons [16].

5. Auger neutron spectroscopy of Λ hypernuclei

The Λ -hyperon 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 [17]. The widths for A-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, A-hypernuclear states should be observable as reasonably narrow peaks [17, 18]. 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 [19]. 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 \approx 200) hypernuclei is extremely complex [20]. 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 an electromagnetic probe practically impossible.

However, the spectral distribution of Auger neutrons is expected to be simple and interpretable for hypernuclei with mass lying in the range A = 50-100. This is due to the fact that in middle heavy hypernuclei, neutron separation and Λ transition energies of comparable magnitude are available for only a few states. Therefore the spectral distribution of the emitted Auger neutrons in A = 50-100 mass hypernuclei can be measured by focusing simply on produced particles (e.g., on forward photoproduced K⁺ mesons detected in the HKS) or weak decays of hypernuclei (e.g., on

delayed fission events detected by means of the RF time-zero FF detector). The schematic view of such an experiment with the HKS or with the time-zero FF detector is shown in Fig. 10.



Fig. 10. Schematic of the hypernuclear Auger neutron spectroscopy experiment.



Fig. 11. The expected Auger neutron spectrum in ${}^{93}{}_{\Lambda}$ Nb: a) the expected spectrum in the c.m. system, b) in the lab system with kinematical broadening, c) in lab with 50% Auger neutron + 50% NM decay background, kinematical broadening and energy resolution included.

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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 [21, 22] with expected time resolution $\Delta T = 0.5$ ns FWHM. The total efficiency of 130 such neutron detectors, with thickness of $\Delta L = 1.25$ cm and flight path L = 200 cm is ~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) [13]. The expected Auger transition strengths in ⁹³_ANb with 50% Auger neutrons and 50% neutrons from non-mesonic, NM decay background are displayed in Fig. 11.

However, in order to find out the optimal conditions to perform a new nuclear spectroscopy, namely Auger neutron spectroscopy with electron beams, one needs to carry out test studies of neutron detectors and RF time-zero FF detectors in the real experimental environment as well as theoretical studies to find out the proper hypernucleus with simple and interpretable Auger neutron spectral distributions.

6. Other possible applications

The developed technique can be used to digitize short, few tens of picosecond duration pulses of charged particles provided by modern accelerators [23]. In this case it operated as a 20 GHz scope for charged particle bunches.

The new photon detector and timing method have a real potential to be used in medicine, namely in Diffuse Optical Tomography (DOT) applications to breast cancer [24]. The clinical potential of optical transillumination has been known for many years, and stems from the fact that the relative attenuation of light in tissue at some near-infrared wavelengths is related to the global concentration of certain metabolites in their oxygenated and deoxygenated states. Thus an optical imaging modality offers the promise of functional as well as structural information. Despite considerable recent interest in the problem, progress towards optical tomography has been inhibited by the lack of suitable instrumentation to acquire sufficient useful data in reasonable times. Among the different approaches considered to produce DOT images, time resolved methods appear to be the most powerful ones in terms of achievable image quality. In these time-resolved instruments, an ultra-short laser pulse is used and temporal distribution of light emerging from the tissue surface known as the temporal point spread function (TPSF) is detected with a high-speed detector. For several centimeters of soft tissue, the TPSF will extend over several nanoseconds. The ideal photon detector for TPSF applications is the one which can sample transmitted photons over any temporal window without contamination by photons arriving outside the window. The proposed new picosecond photon detector is the device which comes nearest to this ideal.

The 500 MHz RF phototube is ideally suited also for time-correlated single photon counting, TCSPC technique applications [25], extending the time domain to the tens of picoseconds ranges.

7. Conclusions

A new 500 MHz RF timing device for the measurement of single photoelectron or secondary electron with 20 ps time dispersion has been developed. The device provides nanosecond signals like regular vacuum phototubes, which can be processed by means of regular nanosecond electronics. The phototubes based on the developed principles can find applications in high-energy elementary-particle and nuclear physics experiments as well as in other fields where a time-correlated single photon counting technique is needed.

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