Detection of Neutron at Low and High Energies

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Neutron detection, either as free particles from fission reactions or from proton-electron collisions at high energies, depends on the neutrons interaction with the detection media. In this paper, the detection of neutron in wide energy ranges, i.e. from a few eV in fission reaction to a few GeV in high energy physics is discussed.

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I. INTRODUCTION

Neutron, as a sub-component of the nuclide and a family of baryon, is composed three quarks – one up (u) and two downs (dd) (see Fig. 1). With a mass of 0.9396 GeV and mean life \( \tau = 886 \) s [1], free neutrons outside of a nucleus would decay via a weak nuclear force into \( n \rightarrow p + e^- + \bar{\nu}_e \). Within the nucleus, hadrons (i.e. proton and neutrons) are bounded by strong nuclear forces through an exchange of meson particles. In case of uranium-235, these nuclear forces are broken by an absorption of a thermal neutron resulting in the fission of the nucleus to release 198 MeV of energy, plus two fission fragments and an average of 2 fission neutrons with energy of \( \sim 2 \) MeV in low energy reactor [6]. In high energy physics experiment at HERA, the neutrons in the range of GeV produced during the electron-proton collision were detected using hadronic calorimeters. In the following sections, neutrons detection of in both experimental low and high energies is discussed.

II. NEUTRONS DETECTION AT LOW ENERGY

In a nuclear research reactor, there were three main neutron groups in a thermal research reactor (a) thermal (0–1 eV) with Maxwellian distribution, (b) resonance (1 eV–10 keV) with \( 1/E \) distribution \( (E \equiv \text{neutron energy}) \) and (c) fast (10 keV–10 MeV) in the fission region. The neutron detection at low energy was carried out based on its respond region of the material of the detector used. Certain materials have higher response towards neutrons in the thermal region than others. In the activation foil method, the energy responses of different type of nuclides towards neutrons in various energy ranges were used.

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to measure neutron flux spectrum using \((n, \gamma)\) reaction rates of \(27\text{Al}, 115\text{In}, 75\text{A}, 98\text{Mo}, 187\text{Re}, 59\text{Co}\) to measure neutron fluxes in thermal, resonance and fast regions [3].

For \(^{197}\text{Au}\), 90% of its response region lies the range of 0.015 eV–5.6 eV. Neutrons in this energy range would have cross-sections of \(\sigma_{\gamma} = 99.2\) barns and resonance integral \(I_\gamma = 1550\) barns. The reaction rate is then given by [2]:

\[
R = \int_0^\infty \phi(E)\sigma(E)N_SD(E)dE
\]

\[
= \phi_{thermal}\int_0^{0.55\text{eV}}\sigma(E)\frac{dE}{E} + \phi_{epithermal}\int_{0.55\text{eV}}^{0.2\text{MeV}}\sigma(E)\frac{dE}{E}
\]

\[
= \phi_{thermal}\sigma_{\gamma} + \phi_{epithermal}I_\gamma
\]

The above equation uses cadmium cut-off energy 0.55 eV to differentiate between the thermal and epithermal energy of neutrons. \(\phi(E)\) and \(\sigma(E)\) are the neutron flux and microscopic cross section as a function of neutron energy \(E\) respectively with \(N_S\) as the number of target nuclides.

**III. RESULTS – THERMAL AND EPITHERMAL NEUTRON FLUXES MEASUREMENT USING ACTIVATION METHOD**

Fig. 2 and Fig. 3 show the measured thermal and epithermal neutrons fluxes in the central thimble (CT) of the reactor core and the rotary rack (RR) respectively, of the 1 MW Reactor TRIGA PUSPATI (RTP) using the activation method with \(^{197}\text{Au}(n, \gamma)^{198}\text{Au}\) reaction. The measured thermal and epithermal neutrons were a result from the slowing down process of fission neutrons as it underwent slowing down process through collision with light water moderator in the reactor core. The high thermal neutron distribution in the centre of the core was a result of high fission rate in this region. In Fig. 2, the
high distribution of epithermal neutrons at the top of the core was a result of higher water temperature exiting the reactor core through natural convection, while in Fig. 3, the neutron flux remains more or less constant, with thermal fluxes higher than epithermal fluxes due to moderating properties of the graphite. It also shows that neutron fluxes is lower in the upper part (stacked) of the RR than the lower part.

FIG. 2: (a) Thermal and (b) epithermal neutron fluxes in the central thimble of Reaktor TRIGA PUPATI (RTP) using $^{197}$Au(n, $\gamma$)$^{198}$Au reaction.

FIG. 3: (a) Thermal and epithermal neutron fluxes in the rotary rack (RR) of Reaktor TRIGA PUPATI (RTP) using $^{197}$Au(n, $\gamma$)$^{198}$Au reaction, showing neutron fluxes at the bottom position and the stacked position of RR.
IV. NEUTRONS DETECTION AT HIGH ENERGY

In the former ZEUS detector at HERA, particles produced during the collision of high energy of proton beam (at 920 GeV) with electron beam (at 30 GeV), were detected using the calorimeters surrounding the ZEUS detector. Neutrons in the high energy collision were produced when the electron and proton collided in a deep inelastic scattering (DIS) resulting in the production of a virtual photon $\gamma^*$ being emitted by the decelerated proton. In the quark parton model (QPM), the constituents of the incoming proton i.e. two up quarks ($uu$) and one down quarks ($d$) are assumed to be free and point like, called partons. During the hadronization process, the virtual photon $\gamma^*$ would interact with the partons inside the proton and formed new hadrons, such as $\Lambda$ that fragmented into $\Lambda \rightarrow n\pi^0$, with mean life $\tau = 2.631 \times 10^{-10}$ s. Fig. 4 shows a Feynman diagram that illustrates the interaction between the incoming electron and proton during the collision, with the virtual photon $\gamma^*$ interacting with the quarks within the proton to produce $\Lambda$ that later decay into neutron and $\pi^0$.

![Feynman diagram](image)

**FIG. 4:** The Feynman diagram for a deep inelastic scattering (DIS), - neutron $n$ was produced through virtual $\gamma$, $Z^0$ exchange [4]; $e$ is the incoming electron, $e'$ is the scattered electron, $p$ is the incoming electron, while $X$ is $\Lambda$ that was formed during hadronization process during DIS.

In the former ZEUS detector, the particles produced during the electron-proton collision were detected using the calorimeters build around the interaction point. Fig. 5A shows a schematic diagram of the calorimeter in the ZEUS detector. The calorimeter of the ZEUS detector was designed for high energy resolution, uniformity, stability and fast response with ability to handle up to 10.4 MHz of HERA bunch crossing rate. The hadronic energy resolution of the calorimeter was $\sigma(E)/E = 35%/\sqrt{E}$, while electromagnetic energy resolution was $\sigma(E)/E = 18%/\sqrt{E}$.

In each module of the calorimeter, uranium-scintillator (SCSN-38) plates were sandwiched together to provide signals to the photomultiplier tube (see Fig. 5B). The SCSN-38 scintillator produced the photons that interacted with wavelength shifter WLS (Y-7 in PMMA) into visible light before being transmitted to the photomultiplier tube (PMT) as signal energy of the particles deposited in the calorimeter.

Uranium, as passive material, produced slow neutrons through fission reaction that helped in compensating losses in the hadronic shower. It also acts as absorber of elec-
tromagnetic particle generated in the electromagnetic part of the hadronic shower, thus enhancing the compensation mechanism [4].

Due to its long mean life of $\tau = (885.7 \pm 0.8)$ s, neutrons could travel across the detector in a straight path to the hadronic calorimeter (HAC) in the outer part of the detector, without experiencing any magnetic deflection throughout its trajectory in the ZEUS detector. In the hadronic calorimeter, neutrons deposited more than 70% of its energy, as compared with electromagnetic shower that deposited more than 90% of its energy in the electromagnetic calorimeter (EMC) in the inner region of the detector (in Fig. 5A).

V. RESULTS – HIGH ENERGY NEUTRON MEASUREMENT USING CALORIMETER

During the electron-proton collision, the energy of the photons collected by each PMT in the calorimeter were kept in a recorded and kept in a data storage system. The data would be retrieved and analysed to select appropriate neutron candidates by using the ORANGE software and PAW subroutines. The neutron candidates should have more than 70% of its energy deposited in the hadronic part of the calorimeter [5]. After eliminating the background contamination, the four momentum that comprised energy and the x, y, z components of the momentum were plotted as given in Fig. 6.

VI. DISCUSSION

In the ZEUS detector, neutrons were produced through the interaction of virtual photon emitted by the de-accelerated electrons and the incoming protons at femto-scale. Neutrons traveled in a straight trajectory to the hadronic calorimeter (HAC) in the outer part of the detector, and interacted with the scintillator material to produced photons that were later transmitted to photomultiplier tubes (PMTs) via wavelength shifters [4]. Signals from these PMTs were then transmitted to a data storage system where neutron candidates were later selected for momentum reconstruction and analysis. The neutron energy resolution of the calorimeter depended on the neutron energy and is given by $\sigma(E)/E = 35%/\sqrt{E}$.

In low energy i.e. 0–12 MeV in thermal reactor, neutrons were detected when they interacted with the detector medium to produce radioactive nuclides that later decayed to emit radiations such as gamma, beta, alpha, etc. In case of foil activation method, neutrons energy range was integrated over the response region of the target nuclei used. For $^{197}$Au, the integral neutron flux over the response region 0.015 eV–5.6 eV. Here, the resonance integral and the absolute cross-sections in $(n, \gamma)$ reaction of $^{197}$Au were used, with the reaction occurring in the scale of barns ($1 \times 10^{-24} cm^2$). The standard deviation for these randomly radioactive decays are given by $\sqrt{N}$ or the fractional statistical uncertainty as $1/\sqrt{N}$ (which ideally should be less than 5%), with $N$ as the total number of radioactive decays recorded during count.
FIG. 5A: ZEUS detector viewed from the top. Proton beam at 920 GeV collided with electron beam at 30 GeV – hadrons such as neutrons deposited its energy in the hadronic calorimeters (HACs) while electromagnetic shower deposited >90% of its energy in the electromagnetic calorimeters (EMCs) surrounding the interaction point.

FIG. 5B: SCSN-38 + $^9$n $\rightarrow$ visible light $\rightarrow$ WSL. WSL: SCSN-38: scintillator WSL: wavelength shifter. Light with shifted wavelength were transmitted to photomultiplier tube (PMT) as energy deposited by particles in the calorimeter.

VII. CONCLUSION

The interaction of neutron with matter provides a convenient way to measure the presence of neutrons in the system under study. In low energy range, neutron direct interaction with the target nuclei provides a useful tool to probe the atomic and molecular structure of the target nuclei. For most nuclear research reactor applications, thermal neutrons are used to probe the structure of the matter, whether at nanoscale or bulk level.

At high energy range, detection neutrons, needs higher resolution method. Neutron
interaction with the active material in the detector, such as SCSN-38 and wavelength shifter (WSL) that provide visible photon signals to the photomultiplier tubes (PMT), provides a mechanism to measure its energy, with uranium used to reduced background signal and increase the resolution of the detector.

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