ENEEP Member: Jožef Stefan Institute

Shortlist of novel education and training activities

February 2024

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1. Cherenkov light intensity measurements as a means of reactor power monitoring

Basic information

Main topic: Radiation Physics
Subtopic: Cherenkov radiation

Level of exercise	☚Basic	☚Advanced	Complex
Level of education	☚BSc	☚MSc	PhD

Keywords: Cherenkov radiation, silicon photomultiplier, reactor pulse operation

1.1. Purpose of experiment

The purpose of the experiment is the measurement of the Cherenkov light intensity originating from the core of an operating nuclear reactor, as a means of on-line reactor power monitoring, during steady state operation at varying power levels and during pulse operation.

1.2. What you will learn

Students will gain familiarity with silicon photomultipliers (SiPM) as light detectors, observe the Cherenkov light intensity as a function of the reactor power and appreciate the applicability of Cherenkov light as a means of reactor power monitoring.

1.3. Pre-knowledge required

Photomultiplier operating principles.

1.4. Facilities and instruments

For performance of the experiment a research reactor with a suitable and accessible experimental location is required.

Required instruments for exercise:

- Dry channel with Cherenkov radiator (e.g. water or quartz),
- SiPM detector and associated data acquisition system (HV bias supply, digitizer and buffer, personal computer).

1.5. Experimental procedure

The exercise is started with the installation of a dry light-tight channel in which the Cherenkov light intensity will be measured into the periphery of the reactor core. A Cherenkov radiator (e.g. water, quartz) is placed at the bottom of the channel at the reactor core level. The SiPM detector is installed in the channel at a fixed height, the top of the channel is carefully closed in order to prevent interference from external sources of light. After the completion of background current (dark current) measurements, the reactor is started up and stabilized at different increasing power levels. The SiPM signal is recorded and averaged at each power level for a duration of the order of one minute. The measured SiPM signal is plotted on the spot as a function of the reactor power level and a calibration is established by performing a linear fit to the measured data (with background subtraction). A new measurement is performed in which the reactor is started up from zero power and stabilized at full power for a period of 5-10 minutes, after which it is shut down by rapid insertion of control rods (SCRAM). The SiPM signal fluctuations are estimated from the measurement at a constant power level, the magnitude of the delayed component of the SiPM signal is estimated from the recorded signal during the SCRAM. A series of reactor pulses is performed with varying inserted reactivity. The SiPM signal is recorded and observed. Quantities of interest for reactor pulse operation, e.g. the peak power achieved during the pulses, the pulse duration (or full width at half maximum – FWHM) and the released energy are computed from the measured signal and the calibration established previously.

1.6. Additional information

1.6..1 Limitations

Difficulties may be encountered in performing light intensity measurements in steady state and pulse operation with the same system settings, on account of the larger range of the reactor power during pulse operation. Repositioning of the SiPM between steady state and pulse mode / use of optical attenuators in pulse mode or signal amplifiers in steady state mode may be required.

2. Nuclear fusion using fusor device

Basic information

Main topic: Nuclear fusion
Subtopic: Plasma physics

Level of exercise	Basic	Advanced	Complex
Level of education	BSc	MSc	PhD

Keywords: Nuclear fusion, plasma physics, inertial confinement, DC discharge

2.1. Purpose of experiment

The purpose is to achieve nuclear fusion by using a fusor device, where ions reach sufficient energy in the accelerating electric field between two concentric conductive meshes to fuse and release neutrons. The neutron yield will be measured by neutron detectors placed in the vicinity of the device and plotted as a function of various parameters.

2.2. What you will learn

Students will learn the concept of nuclear fusion in inertial confinement devices, with emphasis on the fusor. They will familiarize themselves with the fusor type of plasma discharge and the parameters that influence the neutron yield. The general difficulties of nuclear fusion will be presented.

2.3. Pre-knowledge required

Basics of plasma physics, basics of nuclear fusion.

2.4. Facilities and instruments

For performance of the experiment a internal confinement device (fusor) is required.

Required instruments for exercise:

- pressure gauges,
- gas flow rate monitor,
- current and voltage measurement system,
- high-voltage probe,
- neutron detector,
- high-voltage power supply.

2.5. Experimental procedure

A tungsten filament loop is positioned inside a vacuum chamber and connected to the external power supplies for filament heating. Two concentric spherical conductive meshes, used for particle acceleration, are placed in the vacuum chamber. The vacuum chamber is then pumped to very high vacuum. Afterwards the working gas (deuterium) is fed into the chamber with a constant flow rate and a fixed pressure of the neutral gas is set and recorded. We then initiate a background plasma discharge by leading a high electrical current through the tungsten filament loop, which starts emitting electrons. The electrons will be accelerated by the negative voltage applied to the filament and will begin to ionize the surrounding gas – forming plasma. Afterwards, a voltage difference of several kilovolts is applied between the two concentric spherical meshes of the fusor. This voltage accelerates the plasma ions to very high energies, enabling them to overcome the repelling force of the positive nuclei and fuse into heavier elements, i.e. d(d,n)t or d(d,p)3He, with a probability of about 50 % for each reaction. We increase the voltage difference between the two meshes in multiple steps and record the neutron yield measured by the neutron detectors up to the full range of the high-voltage power supply (20 kV). To investigate the properties of the fusor discharge and their influence on the fusion neutron yield, other controllable parameters will be varied: neutral gas pressure, plasma discharge current, accelerating voltage between the cathode and the chamber. The neutron yield is plotted as a function of all varied parameters.

2.6. Additional information

2.6..1 Limitations

Very low neutron yield, high voltage setup (equipment).

3. Gamma spectrometry of irradiated TRIGA Mark II fuel element

Basic information

Main topic: Reactor physics, radiation protection
Subtopic: Spent nuclear fuel characterization

Level of exercise Basic Advanced ☛Complex
Level of education BSc ☛MSc PhD
Keywords: Gamma Spectrometry, irradiated fuel, isotopic composition, delayed gamma radiation

3.1. Purpose of experiment

The main purpose of the experiment is to obtain knowledge regarding isotope composition of a fuel element previously irradiated in a TRIGA Mark II research reactor, enabling the determination of the absolute burnup, and additionally to gain knowledge on the delayed gamma spectrum of irradiated nuclear fuel. The experiment also demonstrates the importance of energy and efficiency calibration of the HPGe (High-Purity Germanium) detector used for the measurements, performed by means of standard calibration sources with known activity.

3.2. What you will learn

With the experiment students will gain knowledge regarding nuclear fuel burnup and its characterization. They will observe different delayed gamma rays that are emitted by specific radioisotopes originating from nuclear fission and observe the axial burnup dependence as a consequence of the neutron flux distribution in the reactor core. Knowledge will be gained on the detector calibration and its use for absolute fuel burnup determination.

3.3. Pre-knowledge required

Knowledge regarding the fission process in a fission reactor, in particular the solutions of the neutron transport equation in simple geometries (cylindrical) is needed to understand the axial dependence. Knowledge is required on the production of fission products, in particular the Bateman equations describing this process. Basic knowledge on gamma transport and gamma spectrometry is required to understand the measurement process.

3.4. Facilities and instruments

For performance of the experiment a ??????????????????? is required.

Required instruments for exercise:

- High Purity Germanium detector ,
- data acquisition system.

3.5. Experimental procedure

For the experiment, a single previously irradiated fuel element stored in the TRIGA reactor pool will be used, with a lower gross activity than the fuel elements located in the reactor core. The experimental setup will consist of a steel table, a remotely operated fuel element positioning system gamma shielding (lead and concrete), a gamma collimator and a HPGe detector and associated data acquisition system. Initially, the HPGe will be calibrated in-situ using standard calibration sources. Following the calibration, the fuel element used in the experiment will be moved from the reactor pool, contained within a standard TRIGA fuel element transport cask, to the experimental area in the reactor hall. Dose rates around the experimental setup will be measured to determine the radiation field which is of high importance from the radiation protection standpoint. In the main part of the experiment, the fuel element will be moved using the positioning system in multiple vertical steps (about 10) and measurements of the gamma spectrum will be performed at each step. Additionally, by rotation of the fuel element about its axis and a suitable collimator setup, the angular burnup dependence could be measured. On conclusion of the measurements, the fuel element will be repositioned into the transport cask and returned to the reactor pool. A determination of the axial dependence of the absolute burnup of the fuel element will be made on the basis of the detector calibration information, measured delayed gamma spectra, the fuel element irradiation history and the relevant nuclear data. The determined burnup distribution will be compared to results obtained by means of detailed Monte Carlo burnup calculations provided in advance.

4. Assessment of neutron diffusion around a point neutron source

Basic information

Main topic: Radiation Physics
Subtopic: Neutron diffusion

Level of exercise	Basic	☛Advanced	☛Complex
Level of education	☛BSc	☛MSc	☛PhD

Keywords: Neutron diffusion, neutron scattering, neutron source, neutron detectors

4.1. Purpose of experiment

The purpose of the experiment is the qualitative and quantitative assessment of the macroscopic phenomenon, which can be roughly characterised as neutron “diffusion”, as a result of neutron scattering on microscopic scale, for different types of neutron moderators, by measuring the count rate from a detector, sensitive to thermal neutrons, as a function of distance from a “point” source of predominantly fast neutrons.

4.2. What you will learn

Students will gain familiarity with the attenuation of the thermal neutron flux around a point source within different moderator materials. They will qualitatively understand the concept of neutron diffusion.

4.3. Pre-knowledge required

Neutron transport and diffusion theory.

4.4. Facilities and instruments

For performance of the experiment an external neutron source is required.

Required instruments for exercise:

- water tank,
- graphite,
- polyethene and optionally lead blocks,
- fission chambers,
- BF3 detectors,

- associated data acquisition system (HV bias supply, digitizer and buffer, personal computer).

4.5. Experimental procedure

Each part of the exercise is started with the placement of the neutron source in the water tank, graphite, polyethylene or lead block. As the neutron source intensity is relatively low, the detectors can be run in pulse mode with gamma-ray discrimination throughout the exercise. The detectors sensitive to thermal neutrons (either fission chambers or BF3 counters) are first used to perform a background measurement. They are then placed within the experimental setup. For the H2O case, a single detector is sufficient as it can be moved to any distance from the neutron source within the water tank. For the other cases, it is convenient to place several detectors in different slots within the blocks of the moderator material to enable a simultaneous measurement of the thermal neutron induced reaction rates at different distances from the neutron source and thereby accelerate the experimental procedure. Please note that the relevant distances of the detector from the source strongly depend on the type of material. After the subtraction of the background, the number of counts, averaged over a sufficiently long time intervals to achieve a negligible uncertainty originating from the counting statistics, is plotted vs. distance from the neutron detector for each moderator material. An attempt is made to separate the diffusion effect from the geometric spread of radiation in 3D (i.e. $1/r^2$) and the neutron spectral effects in close proximity of the neutron source.

5. PET calibration and measurement

basic information

Main topic: Nuclear Medicine Applications
Subtopic: Positron emission tomography

Level of exercise	☛Basic	☛Advanced	Complex
Level of education	☛BSc	☛MSc	PhD

Keywords: Positron emission tomography, Bismuth Germanate Oxide (BGO), coincidence measurement

5.1. Purpose of experiment

Implementation of PET with stress on physicist’s point of view. The students meet with PET detection technology, perform calibration procedure of modules, synchronize modules for proper coincidence detection and investigate spatial resolution properties of the setup.

5.2. What you will learn

Students gain understanding of PET operation and meet with technology of sensors, associated electronics, data processing, image reconstruction and interplay between detector properties and image quality.

5.3. Pre-knowledge required

Understanding of photon detection. Rudimentary knowledge of electronics. Laboratory skills - oscilloscope usage, processing modules, multi-meter usage. Image reconstruction methods -filter back-projection and maximum likelihood expectation maximization.

5.4. Facilities and instruments

For performance of the experiment a radiation controlled environment with registration to use calibration radioactive sources is required.

Required instruments for exercise:

- optical table,
- power supplies,
- detector modules,
- electronics (NIM, VME),
- oscilloscope.

5.5. Experimental procedure

Two BGO modules with 5x5 cm2 face size are placed 25 cm away from a point Na-22 positron emitting source. Supply voltages for modules and electronics are switched and parameters (current) are measured. The setup is switched to OR mode to collect non-synchronized data from both modules. The data is recorded and analysed to determine separation of interactions to crystals within modules. Separation map is stored.

The setup is switched to AND mode. Timing signals from both modules are inspected on the oscilloscope and their synchronicity is adjusted using delay and window electronics module. Coincidence data is recorded for rotating source at two to four positions. Data is processed and images are reconstructed. Based on the reconstructed images, image resolution is derived.

5.6. Additional information

5.6..1 Limitations

Rudimentary detector module is not suitable for imaging of extended sources or complex phantom arrangements. Due to low activity of sources driven by safety of participants, the data collection is lengthy.

6. Prompt gamma neutron activation analysis

Basic information

Main topic: Radiation Physics
Subtopic: Prompt gamma neutron activation analysis

Level of exercise Basic [✓ Advanced] Complex
Level of education BSc [✓ MSc] PhD

Keywords: Prompt gamma neutron activation analysis, TRIGA reactor, gamma spectrometer

6.1. Purpose of experiment

The purpose of the experiment is to demonstrate prompt gamma neutron activation analysis and its performance on samples with known and unknown elemental compositions.

6.2. What you will learn

Students will gain familiarity with the neutron activation analysis (NAA) technique. The difference between standard NAA and prompt NAA will be explained and demonstrated.

6.3. Pre-knowledge required

Basic principles on nuclear reactions.

6.4. Facilities and instruments

For performance of the experiment a reactor with a neutron beam port is required.

Required instruments for exercise:

- collimated neutron beam (e.g. Cd collimator inserted into the thermal column),
- sample holder/changer,
- beam catcher,
- collimator for gamma radiation and HPGe gamma spectrometer.

6.5. Experimental procedure

Following an initial detailed explanation of the PGNAA technique, the experimental setup is examined and configured. In the next step, samples are prepared. Students can prepare e.g. several samples of aqueous solution of NaCl of varying concentrations from 0 to several %. Each sample is exposed to the neutron beam and the prompt gamma spectrum is measured using the HPGe detector. As a last sample, a realistic sample of soil is taken and prompt gamma spectrum is measured. Students then analyse the recorded gamma spectra, identify the prompt gamma peaks and observe the difference in peak count rates for different samples. Students compute the concentrations of different chemical elements on the basis of the sample mass and the HPGe detection efficiency curve.

6.6. Additional information

6.6..1 Limitations

It is not immediately clear whether a PGNAA setup as proposed would enable adequate performance for education activities. Very probably some modifications to the proposed experimental location are required, i.e. the installation of a cold neutron source.

7. Neutron detection with SiC semiconductor detectors

Basic information

Main topic: Radiation Physics
Subtopic: Neutron detectors

Level of exercise Basic ☚Advanced ☚Complex
Level of education ☚BSc ☚MSc PhD
Keywords: SiC, semiconductor detector, neutron to charged particle converter

7.1. Purpose of experiment

The purpose of the experiment are experimental tests of the response of silicon carbide (SiC) semiconductor detectors to charged particles (alpha radiation), thermal neutrons, with the use of suitable neutron to charged particle converters, based on the B-10 and Li-6 isotopes, and fast neutrons, using hydrogen-rich converters.

7.2. What you will learn

Students will gain familiarity the operating principle of semiconductor detectors and the use of neutron converting materials for enhanced neutron detection.

7.3. Pre-knowledge required

Photomultiplier operating principles.

7.4. Facilities and instruments

For performance of the experiment a reactor with a neutron irradiation location suitable for detector testing (e.g. with feedthrough capability) is required.

Required instruments for exercise:

- SiC detectors,
- HV bias supply preamplifier,
- MCA,
- neutron converters,
- alpha source (e.g. Am-241),
- neutron source (e.g. AmBe).

7.5. Experimental procedure

The exercise is started with a detailed explanation of the operating principles of semiconductor radiation detectors and neutron detection through “conversion” reactions. These are most commonly B-10(n,a) and Li-6(n,t), sensitive predominantly to thermal neutrons, which upon neutron capture give rise to energetic charged particles (alphas and recoil Li-7 nuclei in the first case and tritons and alphas in the second case), or proton recoil reactions in hydrogen-rich materials, predominantly sensitive to fast neutrons. SiC detectors and the associated acquisition system are set up and tested with an alpha particle source (e.g. Am-241). Students observe the recorded spectrum, in which peaks should appear corresponding to the detection of incident alpha particles. The SiC detectors are equipped with neutron converters and irradiated in a suitable experimental location in the JSI TRIGA reactor (e.g. the Dry Chamber). Charged particle spectra are recorded as a function of the reactor power. The characteristic structure appearing in the spectra is interpreted on the basis of the expected charged particle energies. The spectrum integral (above a pre-defined cut off energy, if necessary) is plotted against the reactor power level to determine the response linearity.

8. Dose rate measurements in water phantom

Basic information

Main topic: Radiation Therapy Applications

Level of exercise ☚Basic ☚Advanced Complex
Level of education ☚BSc ☚MSc PhD

Keywords: Water phantom, gamma radiation, radiation therapy, thimble chamber radiation detector

8.1. Purpose of experiment

Implementation of radiation dosimetry with stress on physicist's point of view. The students meet with radiation detection technology, perform dose measurements in water and gain knowledge of the dose depth curve.

8.2. What you will learn

Students gain understanding of dose depth distribution in media resulting from photon irradiation.

8.3. Pre-knowledge required

Understanding of photon detection. Laboratory skills: electrical measurements.

8.4. Facilities and instruments

For performance of the experiment a radiation controlled environment and registration to use calibration radioactive source is required.

Required instruments for exercise:

- thimble chamber radiation detector
- electrometer,
- water phantom,
- remotely-controlled detector support equipment with 1D position adjustment,
- table.

8.5. Experimental procedure

A water phantom is placed on a table adjacent to a horizontal beam port of the JSI TRIGA reactor. When the beam shutter is open, gamma radiation from the reactor core in shutdown conditions irradiates the phantom. A thimble chamber detector is placed in a water phantom in the path of gamma ray beam, and its position is changed along the beam. The position from the water phantom wall to the detector should be known well, as it corresponds to the path length of the gamma rays in the water before interacting with the detector. The charge on the detector is measured with an electrometer for various water-depths. Electrometer measurements are translated to absorbed dose. In this way, students record depth-dose profile in the water.

8.6. Additional information

8.6..1 Limitations

Due to low activity of the source and relatively low energy, measurements can require a long time to obtain a reasonable signal level.