nBHEAM 2025: Neutron Beams at High Energy: Applications and Metrology

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Book of Abstracts

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POSTERS

Aviation, Space and Radiobiology

Neutron radiobiology - The need to bridge experimental gaps for future space missions

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Neutrons are significantly more effective than low linear energy transfer (LET) radiation, such as photons, in inducing biological damage. However, our understanding of neutron radiobiology, particularly at high energies, remains limited and is largely based on legacy data. The majority of experimental insights stem from in vitro and in vivo studies involving low-energy neutrons (50) reported were for low-energy neutron-induced carcinogenesis in animal models, raising concerns about extrapolating such results to high-energy scenarios. This lecture will highlight the current gaps in experimental data, particularly for high-energy neutrons, and discuss how these limitations hinder our ability to accurately model and predict biological outcomes. In order to improve radiation risk assessments for astronauts on future long-duration missions, a renewed effort is needed to conduct radiobiology experiments using well-characterized neutron fields, where detailed knowledge of neutron spectra, fluence, and secondary particle production can be combined with modern radiobiological assays. Cross-disciplinary collaboration between physicists and radiobiologists is essential to reduce uncertainties and improve the scientific basis for neutron risk assessment in the 21st century.

Aviation, Space and Radiobiology

Radiation exposure from neutrons in spaceflight and aviation

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Secondary neutrons produced in the interactions of primary cosmic rays with matter are a relevant component of the radiation field in spaceflight and aviation and play a major role in radiation protection in these fields. On the International Space Station, the ORION spacecraft of the ARTEMIS program or any human-rated vehicle, neutrons are produced in the walls and other structures of the spacecraft. On planetary surfaces or at aviation altitudes, neutrons originate from the soil and regolith and from interactions with the constituents of the atmosphere. Energies of secondary neutrons from cosmic rays span many orders of magnitude from thermal energies up to tens of GeV and are relevant to the exposure in the range from approximately 100 keV to several GeV, depending on the shielding conditions and the primary particle spectra. Models predict that the build-up of the secondary neutron field leads to a maximum in the dose equivalent at altitudes in the Earth's atmosphere of approximately 20 km above ground and an increase in the dose equivalent for aluminum shielding above approximately 10 cm in space, but little experimental validation for these predictions exist. Model calculations and measurements of neutrons and neutron dose in aviation and space flight will be presented.

Accelerator Facilities 1

Towards an ISO-accredited fast neutron beam facility at iThemba LABS

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iThemba Laboratories for Accelerator Based Sciences (LABS) is a national facility and one of business units of the National Research Foundation (NRF) in the Republic of South Africa (RSA). It is a multidisciplinary research facility that is based on the development, operation and use of a number of particle accelerators and related research equipment. The largest accelerator at the facility, a K=200 separated sector cyclotron (SSC) powered by two solid-pole injector cyclotrons (SPCs) could accelerate protons to energies of up to 200 MeV and heavier particles to much higher energies.
Over the years, the iThemba LABS fast neutron beam facility has been developed to a unique status with respect to the production of nearly monoenergetic ns-pulsed neutron beams ranging between 30 MeV and 200 MeV. Other available neutron beam facilities with energy range similar to this facility are described in detail by the EURADOS (European Radiation Dosimetry) Report [1]. With protons beams available from the SSC, quasi-monoenergetic neutron beams at iThemba LABS can be covered almost continuously via (p,n) reactions using ^{7}Li and ^{9}Be targets of varying thicknesses [2]. We are presently upgrading the facility with the aim of achieving ISO-accreditation as a fast neutron beam reference facility. This came about as a result of the facility being designated by the National Metrology Institute of South Africa (NMISA) as an entity responsible for providing traceability for the medium and high-energy neutron measurements in South Africa. The project of upgrading the facility is ongoing and is currently being realized by a formal collaboration between iThemba LABS, University of Cape Town (UCT), together with international partners Institut de Radioprotection et de Sûreté Nucléaire (IRSN in France), National Physical Laboratory (NPL in UK) and Physikalisch- Technische Bundesanstalt (PTB in Germany). As part of the project, the iThemba LABS fast neutron beam facility has been redeveloped in an attempt to overcome some of the identified shortcomings, particularly associated with low energy neutron backgrounds and the stability of the proton beam on target. Once the upgrade and development project of the facility is completed, traceability of measurements shall be ensured by setting up a primary standard for neutron measurements in the energy range from 30 MeV to 200 MeV or by using a transfer device which is traceable to one of the primary standards. The ISO-accreditation status will also provide the facility with the ability to participate in international key-comparison studies in the area of neutron metrology for medium to high-energy neutrons. The upgraded facility is set to practically accommodate irradiations of a phantom of up to 30 x 30 cm^{2} of beam size. For this contribution, we aim to discuss plans and activities using the fast neutron beam facility at iThemba LABS [3].

Accelerator Facilities 1

Characterization of high-energy neutron standard fields and study of calibration methods

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The National Metrology Institute of Japan (NMIJ) has developed a 45-MeV quasi-monoenergetic high- energy neutron standard field using the cyclotron of the Takasaki Ion Accelerators for Advanced Radiation Application (TIARA) facility of the Takasaki Institute for Advanced Quantum Science (TIAQ), National Institutes for Quantum Science and Technology (QST). The quasi-monoenergetic neutron field generated by the 7Li(p,n) reaction consists of a high-energy monoenergetic peak and continuum neutrons down to the low energy. Neutron fluence of the high-energy peak neutrons, which is essentially used for the detector calibration, was evaluated by a recoil proton telescope consisting of a polyethylene radiator and an organic liquid scintillator (E) with a Si(Li) detector (dE). The spectral fluence of the continuum neutrons at the calibration position, which are usually contaminants for the detector calibration, was evaluated by time-of-flight measurements using an organic liquid scintillator and a lithium glass scintillator, and the Bonner unfolding method. This information can be used for correction during the detector calibration.
We also studied the applicability of the two-angle differential method for detector calibration using 100-400 MeV quasi-monoenergetic neutrons generated by the 7Li(p,n) reaction at the cyclotron facility of the Research Center for Nuclear Physics (RCNP), Osaka University. In this facility, the neutrons generated in the target can be extracted at any angle by using a target swinger and a mov- able collimator wall. In this study, measurements were performed for quasi-monoenergetic neutrons generated in front of the target, i.e., in the 0 degree direction, and for continuum neutrons without the high-energy peak, generated diagonally forward, 25 degrees or 30 degrees, and the difference between them was used to attempt calibration only for the virtual high-energy peak neutrons. This method was tried out for multiple Bonner sphere detectors, which have various energy response characteristics depending on the spherical diameter and material of the moderator, and the applicability of the method was discussed.
We also introduce shielding experiments for quasi-monoenergetic neutrons at RCNP and white neutrons at CHARM of CERN that were conducted as application experiments for high-energy neutrons.

Accelerator Facilities 1

High-energy mono-energetic and white neutron sources in RCNP, University of Osaka

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High-energy (above ~100 MeV) neutron beams offer unique opportunities to perform experiments in the fields from fundamental physics such as nuclear physics and particle physics to applied science such as studying performances of detectors and shielding materials for high-energy neutrons, soft errors of semiconductor devices, and space engineering. Research Center for Nuclear Physics (RCNP) in University of Osaka provides two types of high-energy pulsed neutron beams, one is produced via the 7Li(p,n)7Be reaction and another generated via the spallation reaction with a tungsten target, both are driven by the primary proton beams provided by the K=400 RCNP ring- cyclotron. The monoenergetic neutron beam covers the energy range from ~5 MeV up to 390 MeV, and thanks to TOF (time-of-flight) tunnel with a 100 m-long flight path, the energy resolution is as good as 2.9MeV (FWHM) at the neutron energy of 387 MeV. The neutron intensity of the monoenergetic component is typically ~1010 neutrons/sr/[gC at 387 MeV [1]. The white neutron source has an energy distribution very similar to that of atmospheric neutrons produced by cosmic-rays [2] and is useful to test soft errors of semiconductor devices or highly integrated electric circuits due to cosmic neutrons. In this paper the specifications of those neutron sources and previous works with use of them will be presented. The recent results of the operation and information for users will be also mentioned.

References:

[1] Y. Iwamoto et al., Nuclear Instruments and Methods in Physics Research, A629, 43-49 (2011).

[2] Y. Iwamoto et al., Nuclear Technology, Vol.173, pp.210-217 (2011).

Accelerator Facilities 1

The neutron Time-Of-Flight facility, n_TOF at CERN: Status and perspectives

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Co-authors: Alberto Mengoni ; Paolo Maria Milazzo

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n_TOF, at CERN, is the neutron time-of-flight facility dedicated to the study of neutron-induced reactions for fundamental and applied nuclear research. With high-precision neutron cross-section data, n_TOF plays a crucial role in addressing key questions in nuclear astrophysics and for innovation in advanced nuclear technologies. In nuclear astrophysics, experiments performed at n_TOF provide essential insights on the nucleosynthesis processes, such as the s-process responsible for the formation of chemical elements in stars. In nuclear technology, n_TOF contributes to the study of isotopes relevant for reactor design, nuclear waste transmutation, and radiation shielding. Furthermore, the facility investigates aspects linked to medical and space applications, including neutron therapy and radiation effects on electronics.

Established in 2001, n_TOF utilizes a high-intensity, pulsed neutron beam produced by spallation reactions, where 20 GeV/c protons from the CERN Proton Synchrotron (PS) impact on a lead target. The resulting neutron flux spans a wide energy spectrum, from thermal to GeV energies, enabling measurements with high accuracy and resolution over an extensive range. n_TOF is the only facility in which measurements from thermal up to few GeV are possible.

The facility features two areas suitable for time-of-flight measurements. EAR1, with a 185-meter flightpath, is optimized for high-resolution measurements. EAR2, with the 20-meter beamline, is designed for high-flux applications, fundamental for low mass and short-lived radioactive samples or reactions with low cross sections. These complementary stations allow for different experimental conditions optimized for specific measurements, such as neutron capture, neutron-induced fission, elastic, inelastic and charged-particle emission reactions. NEAR is the novel experimental area, placed at about 3 meters from the spallation target, designed for spectral-averaged cross section measurements via activation, when a time-of-flight measurements are not possible. Recent developments at n_TOF include upgrades of the spallation target to enhance neutron pro- duction efficiency, improvements in experimental techniques, and expanded research programs ad- dressing emerging scientific challenges. In this contribution, an overview of the status of the facility, the ongoing experimental activities and the planning of future projects will be presented with a focus on the activities induced by high energy neutrons. In this contribution, an overview of the status of the facility, the ongoing physics program and the planning of future projects will be presented. The experimental activities at high energy will be the focus of this talk.

Accelerator Facilities 1

70MeV~100 MeV Quasi-monoenergetic neutron reference fields in China

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Based on the 100 MeV proton cyclotron at the China Institute of Atomic Energy (CIAE), we have established and investigated quasi-monoenergetic neutron reference radiation fields in the (70-100) MeV energy range. Quasi-monoenergetic neutrons were generated through proton bombardment on metallic Li targets with thicknesses of 3, 4, and 5 mm, followed by deflection magnets and a 3-meter- long collimator system. The neutron energy spectra were measured using the double-scintillator time-of-flight (TOF) method, while neutron fluence was determined through U-8 fission ionization chambers and recoil proton telescopes.
Over the past two years, systematic facility upgrades have been implemented:

1. Comprehensive concrete shielding was installed to fully enclose the neutron target chamber, effectively reducing scattered neutron background.
2. A beam-limiting aperture was added at the beam extraction port to confine the beam spot size to a minimum of 1×1 mm^2, ensuring complete proton bombardment on Li targets while minimizing parasitic neutron production from peripheral materials.
3. A pair of quadrupole lenses was incorporated upstream of the target chamber to enhance beam regulation and control capabilities.
4. Preliminary modifications for pulsed beam operation have been attempted at the cyclotron's extraction port, with this ongoing research currently underway.

Accelerator Facilities 2

NEPIR (NEutron and Proton Irradiation) facility at INFN-LNL

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The NEPIR (NEutron and Proton Irradiation) facility at the SPES (Selective Production of Exotic Species) project at LNL-INFN (Italy), is designed to serve as a unique fast neutron irradiation facility in Italy and a reference point for applied and basic science as well as industrial applications. Driven by the SPES cyclotron, which delivers 35-70 MeV protons at maximum currents of 500 μA, NEPIR will be developed in phases. Phase 0 will produce continuous energy (white spectrum) neutron beams with the possibility to mimic quasi monoenergetic neutron beams (we call it pseudo monochromatic). Phase 1 will provide not only a white spectrum but also true Quasi Mono-energetic Neutron (QMN) beams with controllable energy peaks in the 20-70 MeV range and a almost perfectly shaped atmospheric neutron spectra up to 70 MeV.
NEPIR represents a significant step toward addressing the growing demand for accessible, cost-effective neutron sources, filling the gap left by the declining availability of reactor-based neutron facilities, with the aim to advance the frontiers of neutron science by enabling the production of high-intensity neutron beams. It will support a wide range of scientific and industrial applications, from radiation shielding studies to developing advanced detectors and medical technologies. Even NEPIR phase zero, will allow studies like Single Event Effects (SEE) in electronics, relevant to numerous fields including nuclear energy, space, aviation, and automotive industries.
The modular approach of NEPIR and the strategic integration within the SPES infrastructure emphasizes cost-to-benefit efficiency establishing it as a crucial milestone in the advancement of Compact Accelerator-driven Neutron Sources (CANS) technology.
This talk will outline the overall details of the phases of NEPIR project and highlight the innovative features of the of the facility: the CoolGal target system and the ANEM (Atmospheric Neutron Emulator) presenting the results of the design as well as the advances in the prototype construction.

Accelerator Facilities 2

Introduction of a new test area for neutron detection instruments with a dominant high energy neutron component at PSI

Author: Sabine Mayer[1]

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Neutron radiation fields around high-energy particle accelerator facilities or at high altitudes often have a broad energy distribution with significant component of neutrons with energies greater than 20 MeV. Reference fields with comparable conditions are desirable for the calibration of monitoring instruments and dosemeters to be used in these environments. In the present study, a suitable area for this purpose is investigated.
The PSI High Intensity Proton Accelerator facility (HIPA) is a cascade of three accelerators that de- livers a proton beam with a final energy of 590 MeV and, at present, a maximal current of 2.2 mA. The beam passes through two graphite targets, and it is used to produce intense beams of secondary particles feeding experimental areas for research in multiple disciplines. A collimation system en- sures a reproducible position of the beam spot on the targets.
The experimental areas are heavily shielded by layers of concrete and iron. This setup outside the shielding above the targets provides a steady neutron field with a broad spectral neutron distribution and dominant high-energy component, which can be used as test area for survey instruments and dosimeters. The area is accessible from May to December with mean availability of 95%, considering normal operation of HIPA.
The neutron spectral distribution of this area is characterized at two positions by measurements with an extended range Bonner Sphere spectrometer (ERBSS). The results are compared to Monte Carlo simulations using the multi-purpose particle transport code FLUKA. Three commercially avail- able extended range survey instruments sensitive to neutron radiation constantly monitor the field intensity in addition to a proton current monitor positioned upstream the target. Long term investigations of the reading of these instruments in addition to measurements of the intensity gradient of the neutron field showed that it can be considered as a reference workplace field with a dominant high-energy neutron component.

Accelerator Facilities 2

n_ACT@BDF: A high intensity & high energy neutron activation station at the CERN Beam Dump Facility

Authors: Alberto Mengoni[1]; Alice Manna[1]; Claudia Lederer-Woods[1]; Frank Gunsing[2]; Marco Calviani[1]; Michael Bacak[1]; Nikolaos Patronis[3]; Paolo Maria Milazzo[1]

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The Beam Dump Facility (BDF) at CERN is a new, general-purpose intensity-frontier experimental facility operating in beam-dump mode at the CERN SPS accelerator. It is designed to search for feebly interacting GeV-scale particles and to perform measurements in neutrino physics, serving the Search for Hidden Particles (SHiP) experiment (SPSC-P-369).

The high-energy (400 GeV/c), high-intensity (350 kW) proton beam from the SPS, impacting BDF's tungsten production target, generates a unique particle spectrum, fluences, and radiation dose in the region surrounding the target. This presents an opportunity to create synergies to exploit the target complex for additional purposes, without perturbing the main physics goals of BDF and SHiP.

A Letter of Intent has been submitted by the n_TOF Collaboration for a parasitic Neutron Activation Station (n_ACT, CERN-SPSC-2024-027) to utilize the copious neutrons produced in the spallation target. Due to the high-energy and intensity proton beam, a wide-energy neutron spectrum is generated, including a large quantity of high-energy neutrons, extending up to few GeVs, which could be exploited for physics research.

This contribution will detail the scientific case, feasibility considerations, as well as the plan for a complete scientific and technical proposal by the end of 2025, aiming for a staged start-up from 2031, with full implementation by 2035.

Materials and Instrumentation

Evaluation of spectrum and fluxes of the ChipIr facility for atmospheric neutron testing of electronics

Authors: Carlo Cazzaniga[1]; Christopher Frost[1]; Maria Kastriotou[1]; Nahid Bhuiyan[1]; Steven Lilley[1]

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The ChipIr beamline at the Rutherford Appleton Laboratory, UK, is a facility dedicated to fast neutron testing, particularly aimed at evaluating single-event effects (SEEs) on microelectronics. SEEs, induced by energetic particles such as high-energy atmospheric neutrons, pose significant reliability threats to electronic devices utilized in safety-critical applications including avionics, automotive, aerospace, and medical applications. With advancements in microelectronic miniaturization and complexity, rigorous SEE testing has become increasingly critical, demanding precise neutron environments that accurately reflect atmospheric energy distribution. ChipIr extracts fast neutrons from an 800 MeV proton beam impinging on a tungsten target. This specialized setup includes filters and collimators enabling flexible configuration options for researchers. To comprehensively characterize ChipIr's neutron beam, two principal measurement techniques have
been employed: activation foil with threshold reactions and silicon diode detectors. Activation foils, composed of diverse materials including gold, bismuth, and cobalt, serve as a passive method enabling determination of neutron flux across a broad energy spectrum. (n,xn) reactions are identified as an important tool for high-energy neutron measurements. Post-irradiation, gamma-ray spectroscopy with high-purity germanium detectors quantifies the activation rates, from which neutron flux spectra are derived through Bayesian unfolding methods. Results indicate that the ChipIr neutron spectrum, spanning from thermal energies up to 800 MeV, mimics the terrestrial atmospheric neutron spectrum, with a flux (E > 10 MeV) of 5.9E6 s-1 cm-2. Active measurement approaches utilize silicon detectors, enabling real-time monitoring and map- ping of beam profiles. Such detectors are sensitive to neutrons with energies greater than 10 MeV, aligning with the established standards for SEE evaluation. Extensive spatial profiling across multiple beam configurations has demonstrated excellent beam uniformity for smaller beam apertures, essential for precise device-level testing, and a defined gradient suitable for larger system-level evaluations. Furthermore, the facility provides a flux reduction capability via steel and polyethylene attenuators, maintaining spectral integrity sufficiently close to atmospheric conditions, albeit with slight hardening of the neutron spectrum. The results detailed in this characterization highlight ChipIr's suitability for industry and academic users needing to test the susceptibility of electronics to SEEs in a field that replicate terrestrial conditions.

Materials and Instrumentation

Detector response functions for in situ high energy neutron spectrometry

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[1] *University of Cape Town*

Fast and high energy neutron fields are produced through the interaction of energetic charged particles with matter, which is a concern for aviation, space exploration, radiotherapy and accelerator environments. To improve radiation risk models for exposed individuals it is necessary to fully characterize the different components of the mixed radiation fields at the point of exposure. In situ measurements of neutron fluence spectra can be achieved through spectrum unfolding, where the incident neutron energy distribution is deconvolved from the measured signature(s) using a library of energy-dependent response functions and mathematical or computational techniques. The detector response functions must span the full energy range for the application and account for non- linearities associated with the whole system, including the detector, electronics and acquisition. For neutrons with energies below 20 MeV, detector response functions can reliably be simulated subject to appropriate scaling to experimental data. However, for neutrons with energies above 20 MeV the availability and quality of reaction cross section data and models are insufficient for the simulation of detector response functions, requiring direct measurement at high energy neutron facilities providing ns-pulsed beams.

The experimental and analytical procedures to derive detector response functions for unfolding are presented for the example of organic scintillators. Detector response functions are simulated with Geant4 between 1-20 MeV and validated against measurements at fast neutron reference facilities AMANDE (Autorité de Sûreté Nucléaire et de Radioprotection, France), and PIAF (Physikalisch-Technische Bundesanstalt, Germany). For applications where neutrons exceeding 20 MeV are ex- pected, nearly mono-energetic detector response functions are measured at the iThemba LABS (South Africa) neutron facility using time-of-flight techniques. The spectroscopic capabilities of modern (EJ- 276) and traditional (BC-501A) detector systems are demonstrated through the unfolding of known neutron fields with MAXED, using simulated and measured detector response functions.

Materials and Instrumentation

Development of a portable monitor for cosmic ray neutron observations

Authors: Andrea Cirillo[1]; Andy Buffler[1]; Marco Caresana[2]; Massimiliano Clemenza[3]

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Measurements of high-energy cosmic-ray neutrons are typically carried out using neutron monitors located around the world. These measurements have a wide range of applications, including space weather observation, solar cycle analysis, and radiation protection at flight altitudes. The flux of cosmic-ray neutrons is also responsible for inelastic reactions that produce isotopes such as ^{26}Al in rocks—used to date the age of rocks and minerals that have been exposed to these neutrons over extended periods.
However, several aspects of cosmic-ray neutron measurements remain under investigation, including the spatial heterogeneity of the particle flux across the Earth and its relationship with other secondary cosmic-ray particles, such as muons. On the one hand, studies in this field would greatly benefit from widespread measurements of secondary cosmic rays at the Earth's surface; on the other hand, neutron monitors are generally heavy, non-portable systems. Additionally, environmental fac- tors such as snow cover can significantly affect neutron flux intensity at ground level, especially for low-energy neutrons (below 10 MeV). As a result, cosmic-ray observations typically achieve high sensitivity only for neutron energies above 20 MeV.
For these reasons, Politecnico di Milano and INFN are developing a portable neutron monitor for ground-level cosmic-ray neutron measurements. The system is based on a commercial thermal neutron counter with high sensitivity, housed within a modular moderator made of polyethylene and lead. This work presents the characterization of the neutron detector in a mixed neutron/gamma radiation field and the Monte Carlo simulations used to determine the optimal moderator dimensions. These efforts are preparatory steps toward the device's calibration in quasi-monoenergetic neutron fields at iThemba LABS.
Calibration of moderator-based detectors is typically performed using the shadow-cone technique in monoenergetic fields to suppress the background from scattered neutrons. According to ISO 8529, this technique is a standard for neutron energies up to 20 MeV; however, its application becomes more complex at higher neutron energies. That said, the low sensitivity of neutron monitors to neutrons below 10 MeV may allow for a relaxation of the stringent requirements for background suppression. This work includes Monte Carlo simulations evaluating the effectiveness of the shadow-cone technique for high-energy neutron measurements.

Materials and Instrumentation

Challenges and requirements for neutron dosimetry at laser-driven accelerators

Authors: Anna Cimmino[1]; Benoit Lefebvre[1]; Dávid Horváth[1]; Roberto Versaci[1]; Roman Truneček[1]; Veronika Olšovcová[1]

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Over the past 40 years, laser wakefield acceleration (LWFA) has been developing at a dramatic rate, from a conceptual notion into a concrete reality. Many petawatt (PW) and multi-PW facilities are operating or under-construction worldwide presenting a novel and exiting alternative to conventional accelerators. In fact, with current technology, the expected particle energies are up to 100 GeV for electrons and at the GeV order for protons. While beam intensities can be as high as 10^{9} - 10^{10} electrons and 10^{10} - 10^{12} protons per laser shot. In these conditions, fast and high-energy neutrons are generated as secondary particles. Furthermore, by optimizing experimental setups, laser-driven neutron sources are subsequently produced. Neutron dose measurements at laser-driven accelerators are pivotal and concurrently arduous. In- deed, the generated primary and secondary radiation fields are mixed and non-monochromatic. They exhibit a challenging time structure as they follow the laser pulses which are typically in the sub- picosecond regime. This poses severe limitation on any measurement device and complicates the correct interpretation of the collected data. Additionally, there is a lack of well-established reference standards and procedures for metrology and dosimetry of neutrons at laser facilities. In this contribution, we present the difficulties associated with neutron dose measurements at laser- driven accelerators. We, as well, highlight the needs both for adequate detection systems as well as for traceability to internationally recognized reference standards. We present the use case of multi-PW laser-driven ELI Beamlines facility as a concrete example.

Materials and Instrumentation

A new GEANT4 fission physics model for simulation of high energy neutron detection and measurements

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Nuclear fission is a subatomic physical phenomenon in which a nucleus divides into two parts, emit- ting several light particles and releasing substantial energy. It may occur spontaneously or be induced by incident particles, such as photons and neutrons. Neutrons in a wide energy range can be detected by exploiting nuclear fission, as neutrons may induce fission for neutron energies from thermal to high-energy regions above 20 MeV, depending on nuclides. A fission counter for neutron detection, commonly made of gas ionization counters embedded with fissile nuclides, detects incident neutrons by counting energetic fission fragments. Therefore, considering the dynamics of fission fragments and secondary particles is important in characterizing a fission counter, as the secondary particles may affect the overall detector performance. GEANT4, a simulation toolkit for the passage of particles through matter, has physics models for nuclear fission; however, none of them provides fission observables as detailed as FREYA (Fission Reaction Event Yield Algorithm) or GEF (General description of Fission process) code can describe. A new fission physics model has been developed based on the high-precision particle physics model, and it invokes evaluated nuclear data files (ENDF) and some GEF calculation results for modeling nuclear fission for fissionable and fissile nuclides under the GEANT4 framework. This presentation will introduce the newly developed GEANT4 fission model in detail.

Nuclear Data

Experiment for double-differential cross section measurement with the emission of light charged particles from high energy neu- trons on carbon at n_TOF

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In hadron therapy for cancer treatment, secondary neutrons with energies up to about 200 MeV are produced by beam interaction with tumor cells and other surrounding materials. The risk assessment of secondary tumors induced by these neutrons requires double-differential cross sections (DDX) data for the emission of light charged particles (p, d, t, 3He and α). Experimental DDX data for tissue constituents are still rather scarce for neutron energies above 20 MeV and mostly measured for discrete neutron energies at mono-energetic neutron beam facilities. There are only very few DDX data available for discrete neutron energies close to and above 100 MeV for carbon. Therefore, a proof-of-principle measurement of DDX on carbon at continuous neutron energies from 20 MeV to 250 MeV was carried out between September and October 2024 at the neutron time-of- flight facility n_TOF at CERN. This facility offers a white neutron spectrum up to several GeV which is unique in Europe. Two carbon targets were irradiated inside a new dedicated vacuum chamber, and the ΔE-E technique was used to identify secondary particles emitted at several measurement angles with combinations of silicon transmission detector (ΔE) and organic/inorganic scintillators as stop detector (E). Furthermore, the time-of-flight technique was exploited for the determination of the neutron incident energy on the target. Preliminary results have shown our valid experimental approach for some combinations of ΔE-E telescopes. Some experimental inconsistencies with theoretical expectations still emerged and have provided useful insights for optimisations of the experimental setup. An analysis of the overall performance including first results will be presented. In the end, DDX data with uncertainties com- parable to data from mono-energetic neutron sources are expected for the final validation of this proof-of-principle experiment with continuous energy coverage, which can then be extended in future experiments to tissue elements beyond carbon.

Nuclear Data

Measurement of high energy neutrons penetrating shields from GeV protons on a thick copper target

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Secondary neutrons are a significant concern in high-energy and high-intensity hadron accelerator facilities (e.g., J-PARC, CERN, SNS, ESS). The neutrons with energies from thermal to maximum energy contribute to external doses behind the shields and activate materials around the beamlines. For neutrons below 20 MeV, several techniques to measure their energy spectra and its reference field has been established. For neutrons above 20 MeV, only a few techniques and fields are available [1]. Thus, Monte Carlo codes (e.g., PHITS, FLUKA, MCNP) employing nuclear physics models and cross-section data are mainly used to obtain the energy spectra through particle production and transport. However, discrepancies among calculated results have been observed across different codes, particularly as the primary beam energy above GeV. Therefore, technique to measure neutron energy spectra above 20 MeV at facilities with incident energy exceeding 1 GeV is desired to obtain experimental data that enable us to validate the calculated results.

To obtain neutron spectrum above 20 MeV, a few detection techniques can be used behind the shields, including NE213 liquid scintillator, Bonner spheres, and activation foils. Recently, shielding experiments have been conducted employing these techniques for neutrons generated by 24 GeV/c protons and 50 cm long copper target at the CERN High-energy Accelerator Mixed-field (CHARM) facility in the East Hall of the CERN Proton Synchrotron (PS) [1-7]. Using an unfolding method with data obtained from NE213 scintillator, neutron energy spectra were derived. The spectra indicated high- energy neutron components (>100 MeV) [1]. The NE213 scintillator, however, has limited sensitivity to neutrons above 100 MeV, and thus, the shape of the neutron response matrix is less dependent on its energy, which may lead to uncertainty in the unfolding process. To address this limitation, alternative detection methods are being studied. CsI(Tl) scintillator, known for its pulse shape discrimination (PSD) capability and high light yield, is one of the candidates for extending the measurable neutron energy range beyond 100 MeV [8-10]. However, several challenges, such as determining detector response characterization, energy calibration, and back- ground suppression, must be overcome before actual application in the high-energy neutron field vicinity of high energy accelerator. Thus, this study aims to investigate the feasibility of using CsI(Tl) scintillators. In this presentation, we will introduce (1) the results of neutron energy spectra measurement using the NE213 scintillator at CHRAM facility and (2) the test results obtained with the CsI(Tl) scintillators under the same condition as that of the NE213 scintillator. For (2), we acquired waveforms for PSD to distinguish neutron events from gamma-rays and obtained cosmic-ray muon events for energy calibration. We will discuss how these measurements improve neutron detection above 100 MeV.

[1] E. Lee, et al., NIMA 998:165189 (2021).
[2] E. Iliopoulou, et al., NIMA 855: 79–85 (2018).
[3] N. Nakao, et al., JNST 57 (9) 1022–1034 (2020).
[4] N. Nakao, et al., JNST 61 (4) 429–447 (2024).
[5] T. Kajimoto, et al., NIMB 429:27–33 (2018).
[6] T. Kajimoto, et al., NIMA 906:141–149 (2018).
[7] T. Matsumoto, et al., JNST 61(1) 98–110 (2024).
[8] C.M. Bartle, et al., NIMA 422:54–58 (1999).
[9] Y. Ashida, et al., Prog. Theor. Exp. Phys., 043H01 (2018).
[10] S. Longo, et al., JINST 13, P03018 (2018).

Nuclear Data

EURADOS task on improving the description of nuclear reactions between nucleons and light nuclei, notably ^{12}C, ^{14}N and ^{16}O

Author: Michaël PETIT[1]

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[4] *Politecnico di Milano*

The European Radiation Dosimetry Group (EURADOS) has identified a weakness in nuclear models describing the interactions between nucleons with energies from 20 to 200 MeV and light nuclei, mainly carbon, nitrogen and oxygen. This type of interaction is fundamental to a proper description of radiation transport for nucleons in the environment and in the human body.
This contribution will present the actions underway within EURADOS, the nuclear data community with the JEFF meeting and within the High Priority Request List (HPRL) of the Nuclear Energy Agency (NEA).

Neutron Metrology: Why and how?

Neutron metrology: Why and how?

Author: Neil Roberts[1]

[1] *NPL*

This talk will give an overview of the importance of neutron metrology to a range of sectors such as nuclear power, defense, healthcare and aviation. The current framework of National Metrology Institutes, key comparison exercises and transfer standards that underpins traceable neutron measurements worldwide up to neutron energies of 20 MeV will be discussed.

HE Neutron Fields: Broad Energy, Workplace, etc.

Challenges and developments in neutron metrology for high energy workplace radiation fields

Author: Fabio Pozzi[1]

[1] *CERN*

Neutron spectra found in typical workplace environments, especially in the high-energy (>20 MeV) domain, of particle accelerators, accelerator-driven spallation sources, and at cruising altitudes on- board aircraft, often differ significantly from those produced by standard radioactive sources defined in the ISO 8529 series. This discrepancy poses a substantial challenge in neutron metrology, as the energy-dependent response of dosimeters and survey instruments can lead to inaccurate measurements if they are calibrated using reference fields that do not reflect actual workplace conditions. In addition, above 20 MeV, neutron interaction cross-sections are derived from theoretical models with limited experimental verification. This introduces significant uncertainties and complicates the validation of detector response functions in high-energy fields. ISO 12789 highlights the need for well-characterized and application-specific radiation fields to ensure meaningful calibration and performance evaluation of radiation protection instruments.

This presentation will provide an overview of representative workplace radiation fields and their critical role in advancing neutron metrology, particularly for radiation protection applications. It will illustrate the unique challenges involved in establishing and characterizing reference workplace fields in the high-energy radiation environments. These include the need to replicate complex, mixed radiation fields with broad energy spectra, and the difficulty in accurately modeling and measuring neutron fluence and energy distributions.

An emerging aspect with significant implications is the introduction of the new operational quantities –ambient dose and personal dose –as recommended by the ICRU and the ICRP. These quantities are intended to provide a more meaningful link to protection quantities across a broader energy range, particularly at high energies where traditional quantities such as H*(10) and Hp(10) may not remain conservative. Their adoption will likely require the redefinition of reference fields and re- calibration procedures, particularly for workplace environments, to ensure consistent and accurate dose assessments.

To progress in this respect, several essential advancements are required: the development of standards how to characterise different high-energy reference fields, improved physics models that are benchmarked against experimental data, advanced spectrometric techniques for real-time field characterization, and internationally coordinated efforts to update and expand the ISO framework (including ISO 12789). These efforts seem essential to improve the traceability and reliability, and relevance of neutron measurements in the complex radiation environments.

HE Neutron Fields: Quasi-monoenergetic

Quasi-monoenergetic high energy neutron fields: present status and future prospects

Author: Andy Buffler[1]

[1] *University of Cape Town*

I provide a review of the status and features of facilities presently offering quasi-monoenergetic neutron fields above 20 MeV, and discuss the physical and technological challenges associated with providing such fields to a metrological standard. I present perspectives on facilities which might mature or emerge in the next few years.

Reference Standards: Instrumentation

Instruments for the characterization of high energy neutron beams

Author: Ralf Nolte[1]

[1] *PTB (retired)*

Despite the increasing importance of simulation tools for the development of detectors and dosemeters for high-energy neutron radiation, measurements in neutron reference beams are still indispensable for the verification of calculated detector responses. Beams with a continuous energy distribution can be used if the instrument under test allows the selection of the neutron energy using the time-of-flight technique, but quasi-monoenergetic beams are required for dosemeters integrated over the neutron energy distribution. Thus, the characterization of these reference beams must basically cover the energy range from thermal neutrons to the maximum energy, which can be several hundred MeV. In most cases, this task can only be accomplished by combining measurements with several different reference detectors traceable to the primary standards of the neutron fluence. The talk will give an overview of the most important types of reference detectors for the fluence of high- energy neutrons. In addition, detectors for measuring the spatial neutron fluence distribution, i.e. the beam profile, and monitor detectors for correlating measurements at different fluence rate levels will be discussed.

Reference Standards: Cross sections

Nuclear reference data for high energy applications

Author: Roberto Mario Capote Noy[1]

[1] *IAEA NAPC-NDS*

High-quality nuclear data is the most fundamental underpinning for all neutron metrology applications. A review of recommended evaluated nuclear data for high-energy dosimetry applications will be presented, focusing on IAEA Neutron Data Standards (nds.iaea.org/standards) and the International Reactor Dosimetry and Fusion File (IRDFF-II). Neutron data standards include evaluated fission cross sections on H, U-235, and U-238 targets that extend up to at least 150 MeV. Reference neutron spectra, like the Cf-252(sf) spectrum, are also included, serving for the validation of evaluated dosimetry cross-section data as well as to define the efficiency of multiple neutron detectors. The International Reactor Dosimetry and Fusion File (IRDFF-II) contains a consistent set of nuclear data for fission and fusion neutron metrology applications up to 60 MeV neutron energy. The IRDFF-II library includes 119 metrology reactions and five metrology metrics used by the neutron dosimetry community. The recommended decay data, particle emission energies, and probabilities for 68 activation products are also listed, together with 29 neutron benchmark fields (including some high-energy fields) for the validation of the library contents. The IRDFF-II library and comprehensive documentation are available online at nds.iaea.org/IRDFF/.

Reference Standards: Cross sections /

Uncertainties of MC calculations

Author: Jason Hirtz[1]

[1] *CEA*

The accuracy (the bias) and precision (the uncertainties) of high-energy spallation models is a key issue for the design and development of new applications and experiments. In the case of the combination of the IntraNuclear Cascade model of Liège (INCL) [1, 2] and the Ablation model (ABLA) [3, 4], we address the problem through two orthogonal approaches, both based on a Bayesian framework. In the framework of the joined project NURBS, shared between the Swiss National Science Foundation (SNF) and the French National Agency for Research (ANR), we developed an approach to optimise the internal parameter of the model [5] and, on the other hand, we developed a method to estimate the bias of the model [6]. The first approach improves the accuracy and the second quantifies the accuracy and the precision of model combination. This will be used to study observable ranging from the double differential neutron production to the hypernuclei fission cross section.

References

[1] A. Boudard et al., Phys. Rev. C 87, 014606 (2013). https://link.aps.org/doi/10.1103/PhysRevC.87.014606

[2] D. Mancusi et al., Phys. Rev. C 90, 054602 (2014). https://link.aps.org/doi/10.1103/PhysRevC.90.054602

[3] J. L. Rodríguez-Sánchez et al., Phys. Rev. C 105, 014623 (2022). https://doi.org/10.1103/PhysRevC.105.014623

[4] J. L. Rodríguez-Sánchez et al., Phys. Rev. Lett. 130, 132501 (2023). https://doi.org/10.1103/PhysRevLett.130.132501

[5] J. Hirtz et al., EPJ A 60, 149 (2024). https://doi.org/10.1140/epja/s10050-024-01370-y

[6] G. Schnabel, EPJ Nuclear Sci. Technol. 4, 33 (2018). https://doi.org/10.1051/epjn/2018013

POSTERS

Neutron Metrology at the Frascati Neutron Generator

Authors: Andrea Colangeli[1]; Antonino Pietropaolo[1]; Fabrizio Andreoli[1]; Guglielmo Pagano[1]; Nicola Fonnesu[1]; Stefano Loreti[1]

Co-authors: Alberto Previti [1]; Davide Flammini [1]; Fabio Moro [1]; Marta Damiano [2]; Michele Lungaroni [1]; Paola Batistoni [1]; Rosaria Villari [1]; Simone Noce [1]

[1] *ENEA*

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The Frascati Neutron Generator (FNG) is a 14 MeV neutron source with a maximum neutron strength of 1x1011 s-1, designed and built within the ENEA Frascati research centre, in operation since 1992. FNG is a linear electrostatic accelerator, in which a deuterium ion beam of up to 1 mA is accelerated up to 300 keV onto a tritiated titanium target, enabling the production of 14 MeV neutrons via the D(T, n)α nuclear reaction. The machine can also produce 2.45 MeV, through D(D, n)^{3}He fusion reactions by replacing the tritiated target with a deuterated one. The machine relies on a duoplasmatron ion source, and the deuterium gas is injected into the plasma chamber, in which a hot cathode filament made of tungsten emits electrons thus inducing ionizing collisions with the gas molecules, up to induce an arc plasma discharge with the anode electrode. The extracted ions pass through an Einzellens to counteract space charge and then through a 90-degree deflecting magnet to filter out diatomic and triatomic ions. The D+ beam is then accelerated through the uniform gradient accelerator tube and focused using a quadrupole triplet against the target.

The Frascati Neutron Generator (FNG) was originally conceived to support fusion neutronics by performing benchmark experiments aimed at validating the nuclear analysis of fusion reactors. Several fusion-relevant experiments have been conducted, significantly contributing to key benchmark nu- clear data databases such as SINBAD, as well as nuclear data libraries including JEFF and FENDL. Further experimental activities are undertaken across various research domains, including nuclear physics, medical radioisotope production studies, material testing, the assessment of radiation ef- fects on electronic components, and detector development.

Metrology is fundamental in ensuring accurate measurements of the neutron emission rate, since the precise characterization of the neutron radiation field is essential to design experiments and assess their feasibility. To this purpose, the main neutron monitor of FNG, i.e. a SSD (Silicon Surface barrier Detector), which detects the alpha particles emitted together with 14-MeV neutrons, is complemented by a Fission chamber (FC), and a NE-213 organic scintillator. Two additional detectors, a Li-6 glass scintillator (GS20) and an innovative detector based on optical Fiber, are being calibrated to monitor the neutron emission rate. The calibration of the SSD as the main neutron monitor of FNG is ISO9001-compliant and periodically checked through a set of proper activation foils (mostly Nb) as well as the FC and NE-213.

The activity of such foils is, then, measured in a well-type HPGe (High Purity Germanium) detector, located next to the experimental hall, calibrated with standard point sources provided by three Institutes of Ionizing Radiation Metrology (ENEA-INMRI, Eckert&Ziegler and NPL), ensuring a 1-sigma uncertainty on the neutron strength of 3.1%.

The objective of this work is to provide a comprehensive overview of the machine, neutron monitors, and detection systems, detailing the reference metrological chain, the calibration process, and the ongoing efforts to enhance the metrology system to ensure an ever-increasing quality of the experiments.

Fast Neutrons Time of flight for hazardous materials detection

Author: Ihab Abdel-Latif[1]
Co-author: Shaban Hussein [1]

[1] *Egyptian Atomic Energy Authority*

This paper will explain the use of the fast neutron time-of-flight method in detecting hazardous materials. This method, known for its high accuracy, is particularly effective in determining the presence of dangerous materials in shipments and parcels at airports, a crucial aspect of airport security, as these materials often contain nitrogen in their composition.
We will design a system that precisely manipulates the neutron beam from a fast neutron source. The rotating chopper, a key component, will allow the passage of neutron pulses that fly specific paths. The flight time of these neutrons can be calculated. When exposing different materials, we study the neutron spectrum and determine the elements of these materials from it.

Implementation of Neutron Field Calibration Based on ISO 8529 in the Moroccan Gamma and X Calibration Laboratory: Modeling and Feasibility Study

Author: Abdellatif Talbi[1]

Co-authors: Abdelali Mekkioui [1]; Abderrahim Allach [1]; Abdessamad Didi [1]; Mohamed Zaryah [1]; Noureddine Amenzou [1]; Taibi Zidouz [1]

[1] *National Centre for Nuclear Energy, Science and Technology*

This study explores the development and implementation of a neutron field calibration system com- pliant with ISO 8529 standards, addressing the critical need for accurate neutron dosimetry in industries such as nuclear energy and research. Using a combined approach of experimental measurements and Monte Carlo simulations with MCNP6.1, the research investigates the feasibility of utilizing an Am-Be neutron source for calibration tasks. Experimental data on dose rates, measured at varying distances using radiometers and dosimeters, closely matched the simulation results, validating the approach. The findings demonstrate the practicality of employing existing resources to establish a reliable neutron reference field, especially where dedicated facilities are not feasible. Key challenges, including traceability to international standards, minimizing neutron scattering, and ensuring operator safety, are highlighted, with recommendations provided to address these issues. This work establishes a framework for advancing neutron calibration and enhancing radiological safety practices.

Evaluation of fractional Scatter uncertainty component for Ambient Dose Equivalent Rate meters calibrations at National Metrology Institute of South Africa.

Author: Refuoe Pepenene[1]

Co-author: Sibusiso Jozela [1]

[1] *National Metrology Institute of South Africa*

The quantification of room scatter contribution, and correction depends on several factors, i.e., neutron source type, detector type, calibration distance and configuration of the calibration room. Several methods are recommended by the International Standard ISO 8529 to separate the direct and scattered neutron components from the total neutron flux, i.e., Semi-Empirical Method (SEM), Reduced- Fitting method (RFM), and a Shadow Cone Method (SCM) and the Generalized-Fit Method (GFM), technique. These methods are applied to the analysis of measurement data to obtain the free-field response. Free-field response is the response of the instrument coming directly from the neutron source, without any scatter. In this paper, the uncertainty contribution of fractional scatter contribution was investigated using three methods i.e., Semi-Empirical Method, Reduced-Fitting and Shadow Cone method was investigated. Three neutron monitors from different manufacturers were used to quantify the fractional scatter component of the neutrons in the calibration room. The obtained values of fractional room-scatter contribution from each monitor were used to calculate the percentage experimental standard deviation mean (% ESDM) which was then used as relative uncertainty com- ponent of the scatter contribution. The results shown that the uncertainty estimate was within 5 %, which was lower than the ISO 8529 recommended value of 10% in case the fractional scatter component has not been characterised. With reduction of uncertainty contribution for determination of the scatter correction, the overall uncertainty (k=1) of neutron monitors calibration decreases from 7,5% to 4%. at coverage factor of k=1.
Keywords: Percentage Experimental Standard deviation, Uncertainty of measurements, Semi-Empirical Method (SEM), Reduced-Fitting method (RFM), Shadow Cone Method (SCM) and the Generalized-Fit Method (GFM), technique.

Neutron activation cross-section measurements for ^{92}Mo(n,p)^{92m}Nb and ^{175}Lu(n,xn) (x=2-4) reactions for 15 to 20 MeV incident neutron energies

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Neutron-induced activations are important for fusion and fission technologies as well as for high-energy accelerators where neutrons are produced as secondary radiation resulting from interaction of the primary particles with the shielding and other materials. The improvement of the activation unfolding method used for the determination of flux density spectra requires more precise cross section evaluated data for the relevant dosimetry reactions. Accurate cross sections are essential for improvement and validation of evaluated data. For this reason 92Mo(n,p)92mNb and 175Lu(n,xn) (x=2-4) reactions are listed in the NEA Nuclear Data High Priority Request List [1].
Neutron-induced cross sections for the 92Mo(n,p)92mNb and 175Lu(n,xn) (x=2-4) reactions have been measured at the, Geel by activation method. Quasi-mono-energetic neutrons with energies between 15 and 20 MeV were produced via 3H(d,n)4He reaction (Ed=1,2,3, and 4 MeV). All reaction cross sections measured are referenced to the 27Al(n,α)24Na standard reaction cross sections. Standard gamma-ray spectrometry was employed for measurement of radioactivity using lead-shielded HPGe detectors.
The new results were compared with the experimental data from EXFOR database and evaluations.

Development of a 3D-Printed Range Modulator for Animal Irradiation with Carbon Ion Beam Irradiation

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The FLASH effect is an effect of reducing normal tissue damage while destroying tumor cells through ultra-high-dose-rate (uHDR) irradiation, and has been mostly achieved with electron and proton beams. On the other hand, there are very few data on carbon beams, and then irradiation for animal is required to investigate the details of the carbon ion beams Flash effect. However, the conventional scanning irradiation method uses multiple irradiations to irradiate the entire target, so the dose rate is different at each location on the target. A hybrid delivery approach using 3D printed 3D range- modulator (3D RM) has attracted a lot a research interest recently and can irradiate a whole target in single scan, which can reduce the difference in dose rate at each target location. Therefore, the purpose of this study was to develop a 3D RM for animal irradiation with carbon irradiation.

In this study, 3D RM was developed for an ellipse target volume with a diameter of 30 mm, and a maximum height of 20 mm using 3D printer. The 3D RM was evaluated measuring at different heights of the target. In the depth dose measurements, 7 points in target were measured and compared with the simulation (PHITS) to evaluate whether the dose distribution encompassing the target was formed at each position of the target.

The 3DRM we devised for animal irradiation was shown to be able to form a sufficiently comprehensive dose distribution in the Lateral and Deep directions of the target shape. However, it was also confirmed that the depth dose distribution was distorted in the region where the height of the PIN ridge filter changed abruptly.

The major limitation in this study is that the experimental system does not consider the effects on normal tissues. In this experiment, the irradiation field was set larger than the target. The major issue for future work is to optimize the beam weight map so that only the target is irradiated.

Neutron Metrology at the Neutron Calibration Laboratory in Jordan: current and planned capabilities

Author: Bilal Amro[1]

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The neutron calibration laboratory was recently established to provide neutron metrology services in Jordan. The laboratory provides calibration services of neutron survey meters, neutron EPD, and is used in the irradiation of neutron personal dose monitors for the local community. This laboratory is the first of its kind in the country and is one of a few similar laboratories in the region. The laboratory was accredited with ISO 17025: 2017 in January 2023. The laboratory implements a 252Cf neutron source to generate neutrons, which is traceable to the Czech Metrology Institute (CMI). The laboratory has recently been designated nationally to be the national reference for neutron metrology. The laboratory is seeking to join regional and international metrology institutes.

This laboratory was established to meet the growing demand for neutron calibration services in Jordan. This demand comes after the recent establishment of multiple nuclear facilities in Jordan, such as the Jordan Research and Training Reactor (JRTR), the Jordan Subcritical Assembly (JSA), and the Synchrotron Light for Experimental Science and Applications in the Middle East (SESAME). The implemented 252Cf neutron source is satisfactory for the neutron survey meters used in many facilities, such as the JRTR, JSA, and it is also adequate for irradiating the neutron personal dose monitors (TLDs), but some improvements are needed for the SESAME purposes.

In SESAME, high-energy neutrons are produced by the photonuclear reaction of the high-energy photons with the nuclei of the storage ring and supporting material. The bremsstrahlung radiation results from changing the direction of the electron beam in the storage ring by the bending magnets. Multiple devices are used to monitor the neutron dose around the accelerator in the facility. These monitors are regularly calibrated to ensure proper operation. The laboratory is considering other methods, such as D-T neutron generators, which produce 14.2 MeV neutrons, that provide a better neutron field to calibrate area monitors used in SESAE. In this work, the current neutron calibration capabilities of the neutron laboratory in Jordan will be presented. Then, the proposed higher-energy neutron generator will be discussed. Participation in this event will help the neutron laboratory team in Jordan to build a relationship with regional and international metrology scientists, which will help the laboratory to improve its current and future capabilities and recognition.

Assessment of Neutron Activation Components from an 18 MV Cyclotron

Author: Samuel Wotorchi-Gordon[1]

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High-energy medical cyclotrons used for FDG synthesis, particularly at 18 MV, generate significant secondary neutron fields that can induce activation in surrounding components. This study presents a detailed assessment of neutron-induced activation within the FDG production workflow, focusing on the irradiation target, synthesis modules, and hot cell infrastructure. Using historical nuclear data and manufacturer projected activated components, operational exposure logs, and Monte Carlo simulations, we quantified activation products arising in materials such as Havar® (target foils), stainless steel (tubing and hot cell walls), and copper (beamline and cooling systems). Detected radionuclides include 58Co, 60Co, 54Mn and 65Zn, with activity levels correlated to neutron flux distribution and component proximity to the target. The activation patterns inform critical safety considerations, including maintenance scheduling, component handling, and decay storage. Our findings highlight the need for optimized material selection and shielding strategies in hot cells and cyclotron vaults to manage long-lived radionuclide buildup and enhance radiation protection compliance in FDG pro- duction facilities. Results highlight the importance of accurate neutron field characterization and material selection to minimize activation and optimize radiation safety protocols in high-energy cyclotron facilities. These findings contribute to enhanced safety planning, regulatory compliance, and informed decommissioning strategies.

DD/DT Neutron Generators at Purnima Laboratories and their application for various departmental programs

Author: P.S. Sarkar[1]

[1] *BARC*

Neutron sources are in a great demand in many areas like research, nuclear waste management, Industrial process control, medical and security. In comparison to reactor and isotopic sources, accelerator-based neutron sources have numerous plus points including compact size, pulsed / continuous operation with the possibility to switch on/off at will, maneuverability etc. Particle accelerators based on different types of neutron generators have been developed around the world. Among these deuteron accelerator-based D-D & D-T neutron generators are widely used as they produce mono-energetic fast neutrons. In this direction we have developed two neutron generators. One is named as Purnima neutron generator (PNG). It is a 300 kV electrostatic DC deuteron accelerator installed in Purnima Hall, BARC, Mumbai. This can produce neutrons strength up to 5 x 1010 n/s neutron yield which can be operated in both continuous as well as pulse mode (repetition rate 0.1 Hz to 10 kHz and variable duty cycle). Inductively coupled radiofrequency ion source is used to produce deuteron beam up to 1 mA. A silicone surface barrier detector installed inside the vacuum chamber measures neutron yield in online mode via neutron associated alpha particle measurement. Two HDPe moderated He-3 detectors have also been incorporated for neutron yield measurement and redundancy in safety interlock system. PNG has been the test bed for various experiments such as neutron radiography (fast as well as thermal), ADS experiments, response of CR39 foils, testing of Tissue Equivalent Proportional Counter, Human blood irradiation, neutron damage studies on low voltage power supplies for critical use, cross-section measurements, neutron detector performance testing and shielding evaluation. Another neutron generator named as Trolley Mounted Generator (TMG) has been developed which is a 150 kV DC accelerator capable of producing neuron yield up to 109 n/s. This has specifically designed for Associated Particle Imaging (API) technology for carrying out illicit material characterization studies in bulk. We are also working on the development of proton induced neutron source development using a 30 MeV proton cyclotron and suitable target. This source will be suitable for development of Boron Neutron Capture Therapy research in the country and also open up other domains of neutron induced experiments towards nuclear physics and material research.

Optimization of OSL Dosimetry for Neutron Radiation: Response Analysis and Correction Factor Evaluation

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In Thailand, Individual Monitoring Services (IMS) primarily utilize optically stimulated luminescence (OSL) dosimeters for personal and workplace radiation monitoring, including beta and photon measurements. However, neutron dosimetry remains challenging due to the wide range of neutron energies encountered in occupational settings. The mainly neutron sources in the country include Am-241/Be and Cf-252, used in industry and research, as well as secondary neutron exposure from research reactors, medical linear accelerators (LINACs), and cyclotrons. With the anticipated expansion of neutron applications, such as Boron Neutron Capture Therapy (BNCT), particle and neutron accelerators for medical purposes, accurate neutron dosimetry across a broad energy spectrum is increasingly critical. This study evaluates the response of an OSL dosimeter (Type LA) to different neutron energy levels using various correction factors in the dose reading algorithm. OSL dosimeters were irradiated at the Korea Research Institute of Standards and Science (KRISS) using moderated Cf-252 (0.57 MeV), bare Cf-252 (2.13 MeV), and Am/Be (4.17 MeV) neutron sources. The neutron dose in terms of Hp(10) ranged from 0 to 2 mSv, with three dosimeters per dose level. The dosimeters were analyzed using an in-house algorithm developed by Landauer, incorporating correction factors provided by the manufacturer (moderated Cf-252 and AmBe defaults) as well as calculated factors according to the manufacturer's formulation (0.722, 3.81, and 6.917). The results indicate that the choice of correction factor significantly impacts neutron dose estimation. The default moderated Cf-252 factor and the calculated factor of 0.722 provided accurate dose readings for moderated Cf- 252 irradiation, while factors of 3.81 and 6.917 yielded better agreement with dose measurements for bare Cf-252 and Am/Be sources, respectively. Notably, the OSL dosimeter exhibited no response for doses below 2 mSv for Am/Be and below 1 mSv for bare Cf-252. These findings emphasize the importance of selecting appropriate correction factors for neutron dose analysis and the need for further investigation into the detection limits of OSL dosimeters for Am/Be and high-energy neutron sources. This research provides critical insights for optimizing neutron dosimetry as neutron applications continue to expand in Thailand.

Indigenous Development of Compensated Ion Chamber Detector for Research Reactor Power Monitoring by Neutron Metrology as Thermal Neutron Flux Measurement.

Author: Arif Ullah[1]

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Indigenous development of Compensated Ion Chamber Detector has been successfully achieved for the neutron metrology as thermal neutron flux measurement in Pakistan Research Reactor-2 (PARR- 2) and Pakistan Research Reactor-1 (PARR-1). Accurate thermal neutron flux measurement is critical for nuclear reactor operation, safety, and research applications. The goal is to enhance the accuracy and reliability of neutron flux measurements, especially with significant gamma radiation backgrounds. The detector body and electrodes are made of reactor grade aluminum (Al1050) to minimize the neutron activation effects. Enriched boron 10B is coated on one electrode of the chamber for thermal neutron detection. The chamber is filled with hydrogen gas at 800 tars, to enhance ionization and provide a conductive medium for current flow. The detector is composed of two con- centric chambers. The outer chamber in the detector is provided positive potential, hence producing positive current on the common signal electrode due to neutron and gamma interaction, while the inner chamber is provided negative potential; hence produce negative current due to gamma rays interaction only. Net current on the common electrode of the detector is from neutron interaction only. The detector is used in out-of-core locations to monitor reactor power levels and neutron flux, providing real-time information for reactor control and safety. Operating voltage of the detector is
+600V and compensation voltage is -100V. The thermal neutron flux is proportional to the reactor power. Hence, the detector is used for the reactor power monitoring. The thermal neutron flux sensitivity of the detector is measured as 2.5fA/nv. The detector development and R&D work has been performed at Pakistan Research Reactor-2, 30 kWth, thermal neutron flux of around 10E12 neutrons/cm2/s. The Voltage/Current (V/I) characteristics and the detector linearity response at higher values of neutron flux in the range of 4x10E3 to 4x10E9 neutrons/cm2/s at PARR-2 has been tested. The output response of radiation in the detector is “current” in the range of 10pA to 10µA, depending on the value of neutron flux at PARR-2. The detector showed a linear response with reactor power. The indigenous developed detector after qualification at PARR-2, tested successfully at Pakistan Re- search Reactor-1 as a reactor power monitoring on experimental basis. PARR-1 is a swimming pool type research reactor of capacity 10 MWth. The detector covers the intermediate power range of PARR-1, where thermal neutron flux range is 5x10E3 to 2x10E10 neutrons/cm2/s and detector responded linearly with output current in the range from 12pA to 50µA.

Intercomparison of Neutron Calibration Laboratories: A New Initiative by EURADOS

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Most neutron calibration laboratories rely on fast neutron reference fields produced by 241Am-Be or 252Cf radionuclide sources to calibrate personal and ambient dose and dose rate meters. While photon calibration laboratories benefit from the IAEA SSDL network [1], no equivalent network exists for neutron calibration. The BIPM network [2] is open to national and designated institutes, but many neutron calibration laboratories remain outside this framework, limiting their opportunities to participate in intercomparisons. To address this gap, EURADOS has launched an initiative to provide intercomparison opportunities for all neutron calibration laboratories. As part of this effort, a survey was conducted to assess the demand for such intercomparisons and to determine the most suitable quantity for comparison. To date, 22 institutes—including national metrology institutes, designated institutes, and secondary standard laboratories—have participated. All respondents expressed interest in joining the inter- comparison, with eleven reporting that they have never had such an opportunity before. Given the significant number of interested laboratories and the fact that all laboratories provide the neutron personal dose equivalent, it is foreseen to use neutron passive dosimetry as an intercom- parison method which would be the first time that this technique will be employed to benchmark neutron calibration laboratories worldwide. In this contribution, we present the results of the EURADOS survey, outline the planned intercom- parison exercise, and discuss key challenges faced by neutron calibration laboratories providing fast neutron reference fields based on radionuclide sources.

1. INTERNATIONAL ATOMIC ENERGY AGENCY, Establishing a Secondary Standards Dosimetry Laboratory, IAEA Human Health Series No. 44, IAEA, Vienna (2023).

2. Olav Werhahn et al, «The CIPM MRA—success and performance», Metrologia 60 042001 (2023).

Neutron Meter: Design, Fabrication, and Verification

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The design of a neutron ambient dose equivalent rate meter (hereafter called as a neutron meter) was proposed using a He3 thermal neutron proportional counter combining with a multi-layer moderator. Monte Carlo simulations using MCNP6 code were conducted to investigate the fluence and the dose responses of the developed neutron meter as functions of incident energies. The configuration of the meter's detector part was selected since its response functions are identical to those of commercial neutron meters. The neutron meter was fabricated and verified following the requirements of the IEC 61005 criteria.