A new D-T neutron facility at UCT

T. Hutton, A. Buffler

Department of Physics, University of Cape Town, Cape Town, 7701, South Africa

E-mail: `tanya.hutton@uct.ac.za`

Abstract. The Department of Physics at the University of Cape Town has recently installed a new fast neutron facility featuring a Sealed Tube Neutron Generator (STNG) to be used for applied nuclear physics research and education. The MP-320 neutron generator utilises a 90 kV accelerated deuteron beam impinging upon a tritium target, producing approximately 14 MeV neutrons via the $t(d, n)\alpha$ reaction. The long term aim of this facility will be to offer fully characterised neutron energy spectra, yield, and calibrated reference detectors. The potential use for such a facility is wide ranging, from nuclear data measurements to elemental analyses to detector development and calibration. This paper presents the design, building, and commissioning of this facility and proposes future uses. Radiation dosimetry and shielding data is presented for this facility, and initial beam characterisation using a calibrated scintillation detector.

1. Introduction

The MP-320 sealed tube neutron generator (STNG) from Thermo Fisher Scientific [1] produces neutrons of approximately 14 MeV via the deuterium-tritium fusion reaction. Deuterons are accelerated towards a solid target of titanium embedded with tritium. The MP-320 operates in pulsed or steady state mode, with variable beam current and accelerator voltage. The maximum production rate is 10^8 neutrons per second into 4π steradians at 60 μA and 80 kV [2]. Devices such as this are typically used in industrial settings for mining and oil logging, but here the STNG is used as part of the applied nuclear physics teaching and research program at the University of Cape Town (UCT). The STNG was purchased in 2010 and was relocated from iThemba LABS to the nuclear physics research laboratories within the UCT Physics department at the start of 2017.

This facility will complement the existing neutron facilities in South Africa increasing the footprint the fields of neutron physics and nuclear data measurements. One example is iThemba LABS, offering quasi-mono energetic neutrons from 30 MeV to 200 MeV in the D-line vault [3]. The use of this beamline is shared between many international research groups, and availability is limited. The smaller scale fast neutron facility at UCT aims to offer flexibility, availability and access to world-class expertise and equipment, offering neutron energies of 14 MeV and below.

2. Facility Overview

The STNG is installed in close proximity to accessible areas of the building, with the general layout shown in figure 1. The generator is well shielded in the neutron vault, with a beamline extending into the experimental area where neutron detectors and other experimental components are mounted upon an optics table. The STNG and detectors are all managed from the control area, where experimental data is recorded, processed and analysed.

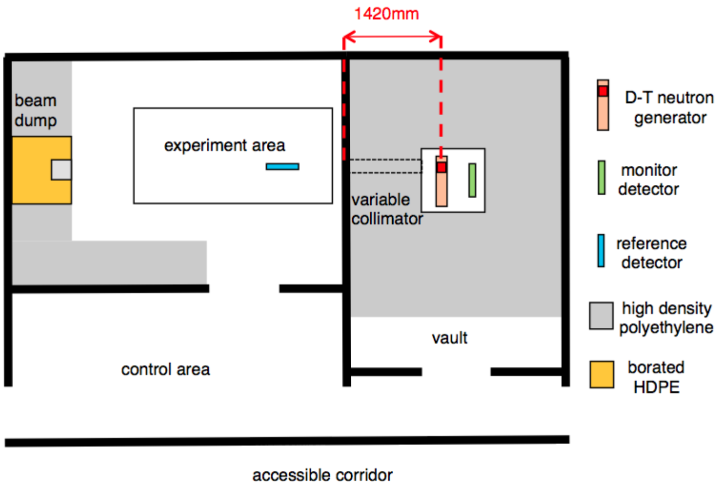

Figure 1. Layout of the fast neutron facility at UCT. The generator is installed within the vault, surrounded by HDPE shielding. Neutrons enter the experimental area via the variable collimator. Detector and generator controls are located in the control area. All areas are access controlled unless explicitly labelled.

The $t(d,n)\alpha$ fusion reaction requires an incident deuteron energy between 100 keV and 400 keV [4], and as such no neutrons will be produced when the device is switched off, or power is interrupted due to a fault. However, the fast neutrons produced during operation, and secondary radiation, can be extremely damaging when interacting with matter. Computational simulations were used as a design aid to ensure appropriate levels of radiation shielding for safe operation.

3. Neutron Vault Design

The Monte-Carlo radiation transport code, MCNP5 [5], was used to estimate the average behaviour of neutrons, and secondary photons, throughout the facility. From these simulations the effective dose was determined at key points and used to estimate safe operating parameters for the STNG and optimise the shielding design.

The simulations assume an isotropic point neutron source of 14 MeV at the centre of the tritium target and simulated the worst-case scenario, i.e. maximum neutron production rate. In reality the STNG will often be run at lower beam current and accelerator voltages, producing fewer than 10^8 neutrons per second. The shielding design was adapted until safe radiation levels were estimated in accessible areas for a run time of 100 hours per year. The device has a total usable lifetime of 1200 hours [1] at maximum production rates before refurbishment is required. A compromise was made between device longevity and useful research hours, allocating 100 hours of run time per year. Given the previous light use of the STNG, this gives an estimated accelerator lifetime of 11 years.

The ICRP (International Commission on Radiological Protection) dose limit for dose to members of the public is 1 mSv per above natural background levels per annum [6]. The ALARP (As Low As Reasonably Practicable) principle of shielding design was used to reduce dose levels below this level in controlled and accessible areas.

The estimated combined neutron and photon dose throughout the room, as calculated with MCNP5, can be seen in Figure 2. Plots ai) to aiii) are associated with an unshielded generator. The doses were calculated from the average particle behaviour, and multiplied by the ICRP-116 dose weighting factors [7].

The highest risk area for human accessibility was determined to be within the doorway to the neutron generator room (as indicated by the dashed lines in Figure 2), within the controlled area.

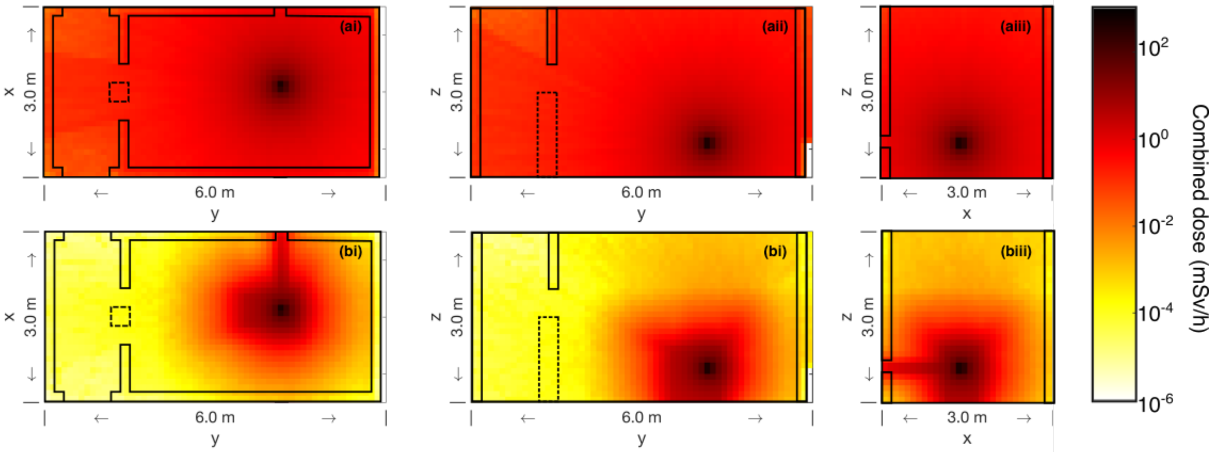

Figure 2. Combined neutron and photon dose maps for the (a) unshielded and (b) shielded geometries, as centred on the generator, i.e. the highest dose regions. The x-y plane is parallel to the floor and the z-axis is in the vertical direction. Solid lines indicate concrete walls, and the dashed region in (ai), (aii) and (bi), (bii) relates to the highest risk accessible area. Any regions with doses above 10^{-2} mSv per hour are considered unsafe for 100 operating hours per year.

The energy dependent doses for this region can be seen in figure 3 for both neutrons and photons. The neutron dose rate is peaked at 14 MeV, where uncollided neutrons pass through. The lower energy contributions are scattered from the surrounding walls. The estimated dose rate for the unshielded generator in this region is 17.7 ± 0.6 mSv per year, excluding any background contributions. If a member of the public were to occupy the doorway, annual dose limits would be exceeded within 5.5 ± 0.5 hours. This scenario is considered unsafe for the expected 100 operating hours per year. An additional 10% uncertainty has been included in the quoted estimates to compensate for additional nuclear data, model and geometry uncertainties[9]. These results confirm that even without shielding, it is safe to run the generator for long enough for a dosimetry survey to take place.

The shielding was constrained by the availability of materials and the room dimensions. A total volume of 5 m^3 High Density Polyethylene (HDPE) blocks was used to build the central component of the shielding. This was combined with close to 16 m^3 of recycled HDPE beads, which is 40% less dense than the blocks, to form the main body of the radiation shield. A central void was left for the generator and neutron monitor detector. The estimated doses associated with the final design can be seen in figures 2(bi) to (biii). The energy dependent dose rates in this region are shown in figure 3(b). The neutron component has reduced over all energy ranges, but most notably at 14 MeV. The high energy photon component has also diminished to zero, and the capture and inelastic scattering peaks from the shielding materials have become more apparent. The total dose rate in the doorway was reduced to 0.112 ± 0.008 mSv per year. In this case, the safe operating time was estimated to be 810 ± 80 hours per year, far exceeding the predicted runtime of 100 hours. By erring on the side of caution, model assumptions, errors or real-world differences in dose rates can be safely accommodated. The construction of the shielding was completed in April 2017, and a series of photos can be seen in figure 4.

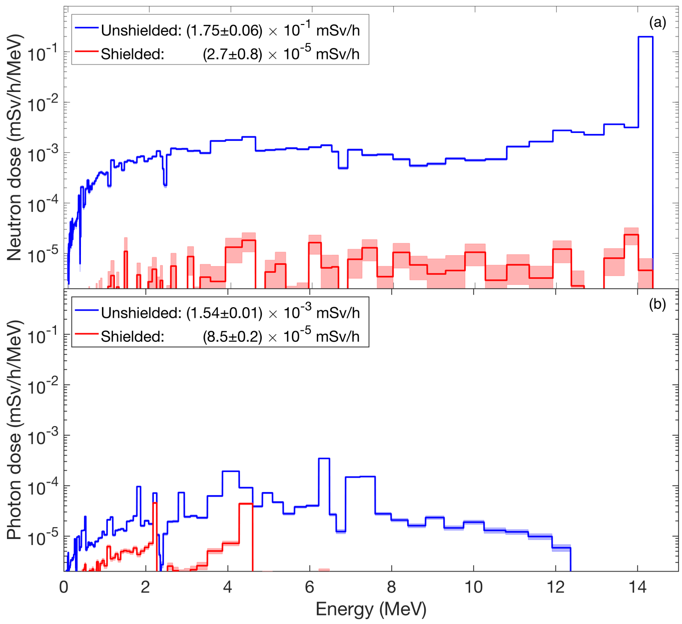

Figure 3. Energy dependent (a) neutron and (b) photon dose rates in the doorway as indicated by the dashed lines in figure 2. Blue lines relate to the unshielded simulation, and red lines relate to the shielded simulation. Statistical uncertainties are represented by the shaded bars, and integrated dose rates are given in the legend. Peaks at 2.2 MeV and 4.4 MeV in the photon spectrum are due to the radiative capture of thermal neutrons on hydrogen, and inelastic scattering of fast neutrons off carbon.

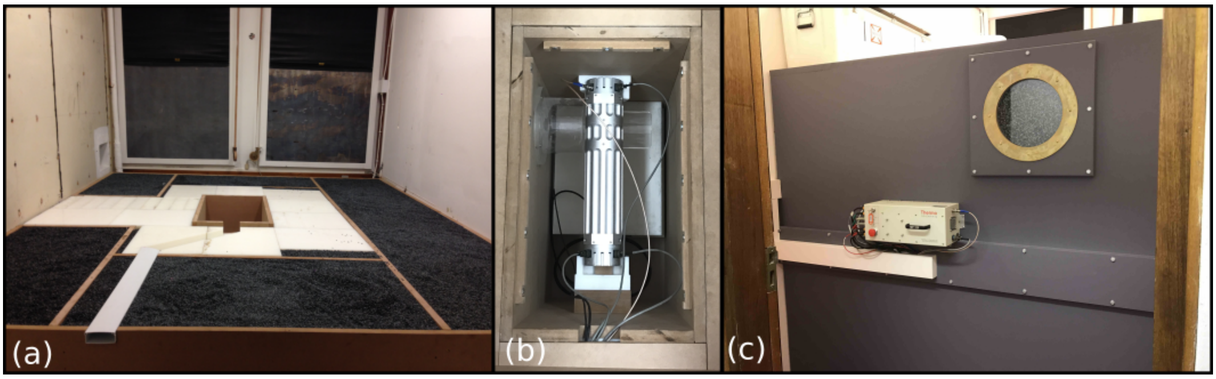

Figure 4. Photos of the neutron shielding (a) during and (c) after construction. The core component of the shielding are white blocks of HDPE, surrounded by the black HDPE beads. The neutron generator is situated in the central void as shown in photo (b). A neutron and gamma-ray sensitive monitor detector is installed underneath the STNG. The electronics have been separated from the generator and are installed outside the shielding as shown in photo (c). All generator and detector cables are routed into the control area. Note that the porthole visible in photo (c) serves no scientific function.

4. Experimental capabilities

Experiments can be run in two different modes, activation and narrow beam, by changing the variable collimator. Samples up to 17 cm diameter can be activated within the central cave. These samples can then be transported to the neighbouring low background HPGe detector facility for high precision gamma-ray measurements. Alternatively, narrow beam of nearly mono-energetic 14 MeV neutrons can be delivered to the experimental area using an 8 mm diameter HDPE collimator (with external dimensions of 17 cm diameter and 100 cm length). At the time of writing this paper, the RP survey process was ongoing, necessitating a conservative beam diameter, with the view to broaden this in the future. Further optimisation is expected in terms of beam divergence, and management of scattered neutrons entering the beam. Any un-collided neutrons will be incident upon a beam dump at the far end of the experimental room, where they will be thermalised and captured. This is composed of borated HDPE (5% by mass), with a maximum thickness of 1.0 m.

Several neutron and gamma-ray sensitive detectors have been set-up within the experimental area. Of note is the organic liquid scintillator EJ-301 from Scionix, which is used as the reference detector for fast neutron detection. The excellent pulse shape discrimination properties of this scintillator is used to isolate the neutron events for further analysis [10]. Analogue and digital data acquisition systems are in place, both of which have pulse shape discrimination capabilities. The digital DAQ uses an open source software package, QtDAQ [11], with a Vx1761 CAEN digitiser [12].

Preliminary results are shown in figure 5 for neutron and gamma-ray pulse height spectra as recorded with the EJ-301 reference detector and digital DAQ. The gamma-ray pulse height spectra shows the two Compton edges associated with 2.2 MeV and 4.4 MeV gamma-rays from the shielding. The neutron pulse height spectra behaves as expected for a nearly mono-energetic beam of 14 MeV neutrons. The neutron energy spectra can be unfolded from the pulse height spectra with the GRAVEL and MAXED unfolding codes as part of the UMG package [13] provided the detector response is known. The facility includes a suite of additional detectors, sensitive to fast or thermal neutrons and/or gamma-rays.

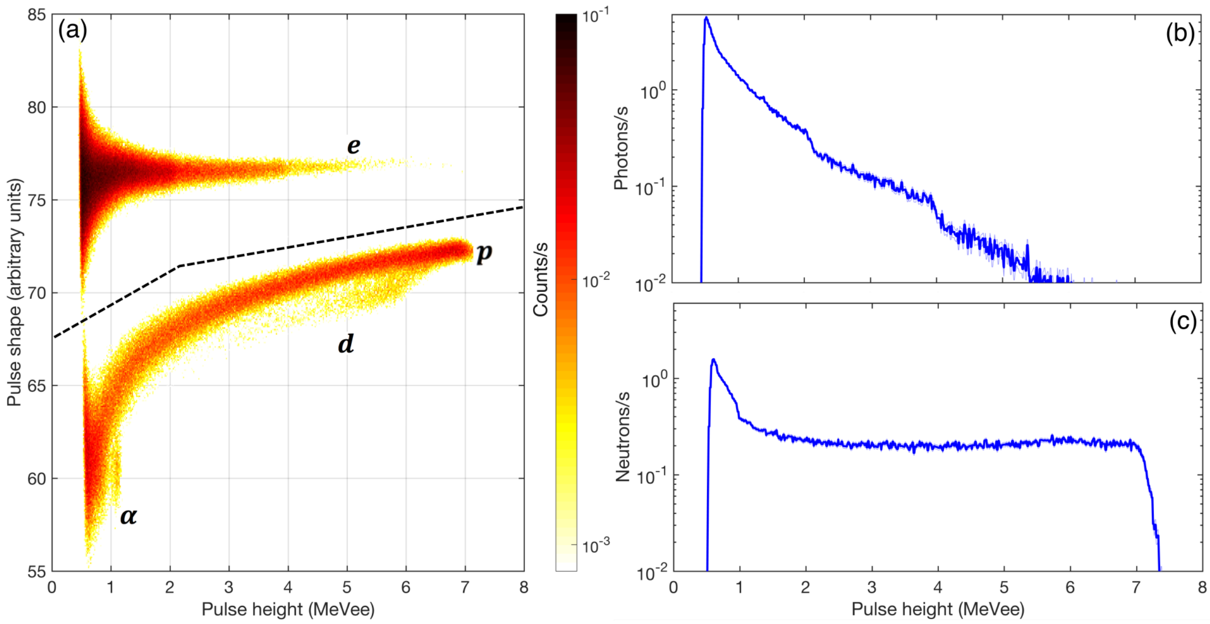

Figure 5. EJ-301 measured neutron and photon pulse height spectra with a narrow beam of 14 MeV neutrons. Figure (a) shows the pulse shape with respect to the detected light output, where the colour scale indicates the number of events per second. The detected light output is proportional to the energy and type of incident radiation. The different recoil particles are indicated, and the cut between gamma-ray induced events and neutron induced events is shown with the dashed line. The (b) gamma-ray and (c) neutron pulse height spectra are determined by integrating the number of events above/below the cut within each light output channel. The Compton edges related to the 2.2 MeV and 4.4 MeV gamma-rays are clearly visible.

5. Commissioning and Current Status

The STNG is operational, with RP measurements ongoing to confirm simulation results. The gamma-ray dose rate was measured to be $0.70 \pm 0.06\,\mu$Sv per hour in the vault doorway areas when running the generator at maximum neutron yield, using the Thermo-Fisher Scientific RadEye B20 survey meter. The measured gamma-ray background dose has been subtracted. Thermal and fast neutron measurements were made in the same location. The thermal neutron rate was measured to be 0.39 ± 0.04 neutrons per second with a BF_3 detector. After efficiency corrections and worst-case dose weightings, the thermal neutron dose rate is estimated to be 0.9 ± 0.1 nSv per hour. The fast neutron rate was measured to be 0.85 ± 0.02 neutrons per second with the reference EJ-301 detector, equivalent to $0.076 \pm 0.002\,\mu$Sv per hour. The total measured dose rate was dominated by gamma-rays, and thermal neutron doses are negligible in comparison. The estimated dose from Monte-Carlo simulations was $0.112 \pm 0.008\,\mu$Sv per year, with measured values estimated at 0.121 ± 0.006 mSv per year. Initial measurements and simulations thus agree within one sigma. Dose rate calculations for the measured neutrons were deliberately conservative, so it is not unreasonable that the final dose rates exceed the simulated values. The measured values are still well within the safe operating limits for 100 hours per year when considering the ICRP guidelines [6]. Further measurements are expected to improve the agreement between simulation and measurement. Several undergraduate student projects are underway to characterise key aspects of the facility; including activation analyses to confirm the neutron production rate, detector characterisation and detector development.

6. Conclusion

The Department of Physics at the University of Cape Town is developing a flexible, fast neutron facility complementary to those currently available, with a focus on training the next generation of nuclear scientists in South Africa. The flexibility afforded by a university-run, in-house facility is key to offering a fast response to applied physics problems. The facility will offer well characterised energy spectra, backgrounds, detector responses, and data handling procedures. The areas of interest to which this facility may be applied includes, but is not limited to, detector calibration, fast neutron activation analysis (both prompt and delayed) and bulk materials analysis (both by activation and fast neutron scattering). Future measurement campaigns will aim to include fusion-relevant cross-section measurements, the development of nuclear data benchmarks and the provision of services to the nuclear engineering communities.

7. Acknowledgements

The authors would like to acknowledge several parties who have contributed to this facility. The STNG was purchased via an NRF grant, and HDPE blocks were donated from the PTB and NECSA. The construction of this facility has relied heavily on the contributions from the UCT mechanical and electrical workshop teams. The authors would also like to thank Dr Tom Leadbeater and Dr Steve Peterson from the University of Cape Town for their contributions.

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