Short-pulse Photoneutron Production on Beryllium Using the Mercury Pulsed Power X-ray Source

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INTRODUCTION

An x-ray beam can produce neutrons using beryllium as a photoneutron converter because of the relatively low ^{9}Be(ɣ,n) reaction energy threshold. Previous photoneutron production simulations have focused on using a linear accelerator and heavy water to generate photoneutrons for potential medical therapies [1,2]. This experimental work focused on creating a short, intense neutron pulse using the Mercury pulsed power machine at the U.S. Naval Research Laboratory, which fired a Bremsstrahlung photon beam with an energy endpoint of 4.8 MeV [3]. Several independent detector systems were included in the experiment to measure both the characteristics of the x-ray pulse and resulting photoneutrons. We discovered the neutron pulse follows the time history of the x-ray pulse, enabling neutron pulses as short as 30 ns with less than 10% shot-to-shot variation. The approach offers a high-flux of neutrons with a higher end-point energy than using a heavy water converter. Previous experiments at Mercury have generated fission neutrons using a higher x-ray endpoint and ^{238}U(n,f) [4].

We conclude that a significant quantity of neutrons, consistent with our early estimates and simulations, were produced. Initial measurements from activation yield detectors are on the order of (3±1)x10^{9} neutrons per pulse with time-of-flight to the time-resolved detectors being as expected. Very few neutrons over 2.5 MeV were produced, and the vast majority had energies under 1.0 MeV, peaking around 300 keV. Data and simulations supporting these observations are presented here. Mercury fired slightly more than 100 shots, including those needed for machine configuration and to explore various systematic effects in the detectors that measured x-ray pulse timing and neutron flux. Results indicate that with an optimized diode and beryllium converter target design, neutron production could be further increased.

RESULTS

Neutron Production Method

The Mercury inductive voltage adder (IVA) facility at the Naval Research Laboratory (NRL) is a versatile accelerator presently used to support x-ray radiography development. A diagram of the Mercury accelerator is shown Fig. 1. Mercury's operating envelope extends from -8 to +6 MV with matched peak currents of 200 kA [5].

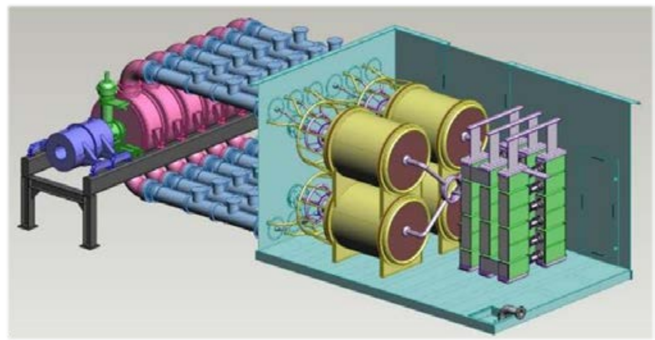

Fig. 1. A cutaway of the Mercury IVA machine at the Naval Research Laboratory

Mercury fired an electron pulse that impinged on a tantalum large area diode (LAD), and generated a Bremsstrahlung photon spectrum with endpoint energy of approximately 4.8 MeV. A beryllium sphere of 112 mm diameter and 1.33 kg was placed approximately 1.5 m from the LAD, and is show in Fig 2. An uncollimated beam of x-rays was fired approximately five times daily. The characteristics of the x-rays were simulated and measured using a suite of x-ray diagnostics that are described later in this document.

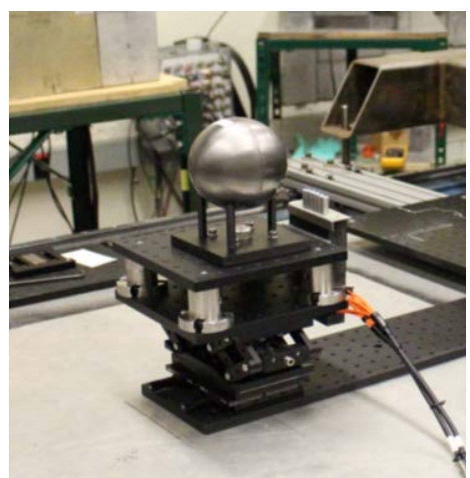

Fig. 2. The beryllium ball shown in-situ at Mercury.

Several separate neutron detector systems were also deployed to Mercury to measure the total yield and time-of-flight of the photoneutrons. All diagnostics observed a substantial difference in signal during beryllium "target-in" shots throughout the data-taking run when compared with "target-out", or background shots. A difference in the energy endpoint of the neutron spectrum were observed when a 1 L cylindrical container (88 mm diameter) of heavy water was used in place of the beryllium. An aluminum sphere of 75 mm diameter and 0.56 kg was inserted to measure x-ray scatter backgrounds on a small number of shots.

The photoneutron spectrum was modeled using a Monte Carlo n-particle code, MCNP, with a bremsstrahlung x-ray spectrum from an independent simulation as an input [6]. The photoneutron spectrum is shown in Fig. 3. Few neutrons above 2 MeV are produced, and the majority have energy of a few hundred keV. This simulation predicted on the order of 3×10^9 neutrons leaving the ball for each Mercury shot. The simulated spectrum shows a substantial modification from the as-born (flux×cross section) spectrum which consists of a few spectral lines indicating the interactions of the neutrons within the beryllium target cannot be ignored - the "thick" target limit. The angular dependence of neutrons off the ball was investigated in simulation but found not to be substantial for the purposes of our experiments.

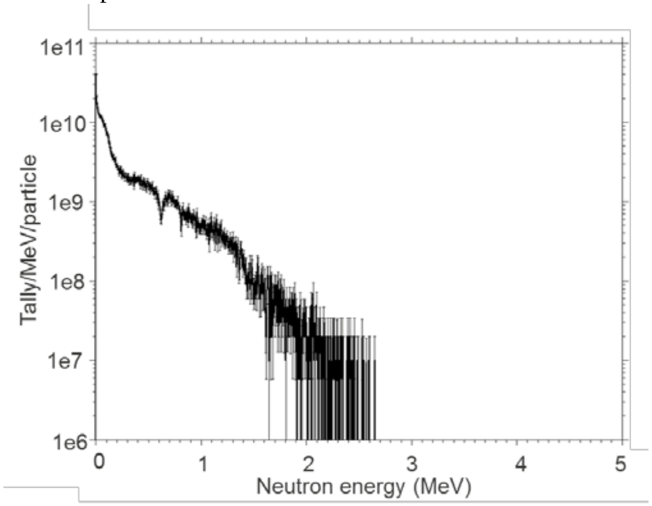

Fig. 3. The MCNP model of the number of photoneutrons produced at Mercury.

X-Ray Spectrum Measurements

To verify Mercury was producing a consistent x-ray spectrum for each shot, the dose and timing were monitored. TLD's placed throughout the room for each shot measured the x-ray dose. The Compton spectrometer and ACD/C (an Aerogel Cherenkov Detector for Cygnus) were fielded to measure the spectrum and shot-to-shot variation of the x-ray pulse.

A Compton spectrometer was used to measure the energy spectrum of the x-ray source. Its primary operating principle is conversion of incident x-rays into Compton electrons. The collimated electrons are deflected in magnetic fields and sweep out a pattern according to their energies onto a sensitive detection plate, and the energy distribution can be determined. This was the first measurement performed on a distributed x-ray source; all previous measurements were taken at machines producing a point source, including Mercury in a previous configuration [7].

At Mercury, the Compton spectrometer was fielded close (~ 1 m) to the beam exit and in-line to a portion of the beam produced by the LAD. A lead shield was built around the spectrometer to reduce the x-ray background. Background data were taken by introducing a sweeper magnet downstream of the converter foil on select shots. A 6 mm beryllium Compton converter target was used to produce the measured electrons. The data showed that the energy spectrum off the LAD had an endpoint of around 4.8 MeV with most photon production occurring between 0.5 and 2 MeV, as seen in Fig. 4.

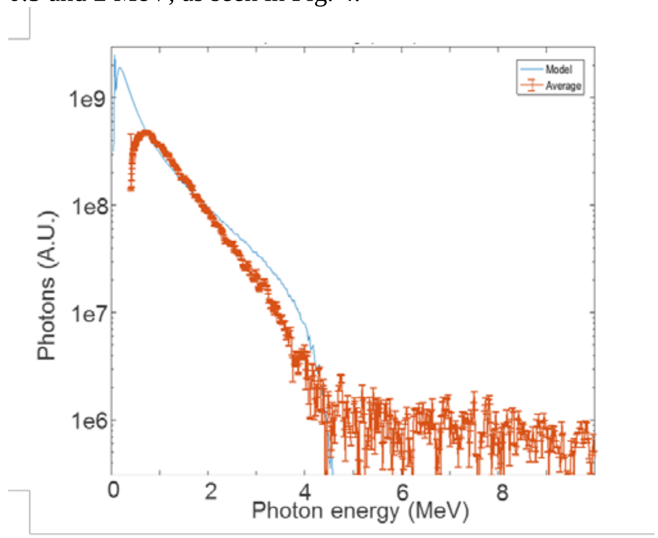

Fig 4. The CS measured spectrums averaged over four shots (red) shown with the model (blue).

The ACD/C is a time-dependent, x-ray spectral detector [8]. Incoming photons have a Compton interaction with an aluminum converter and create relativistic electrons that produce Cherenkov light in an aerogel or glass medium when the speed of the electrons is faster than the speed of light in the medium. Compared to gases and liquids, aerogels have the appropriate index of refraction (n = 1.02 – 1.07) to span the 1.1 – 2.3 MeV photon energies for a Cygnus and Mercury endpoint. The Cherenkov light is then coupled through two off-axis-parabolic mirrors to a photomultiplier tube (PMT - Hamamatsu R5946 series) which is located out of the incoming photon beam. For the first three weeks, a dual module ACD/C observed a collimated Mercury spectrum in-beam behind the Compton spectrometer. For the last three weeks, a four module ACD/C remained in the same location with an uncollimated beam. Despite high radiation and electromagnetic interference background, ACD/C was able to overcome them due to 4 inches of lead shielding.

For each Mercury shot, ACD/C measured a time resolved signal on each channel. The primary pulse and the secondary ringing ~90 ns later were observed with the glass medium. ACD/C observed a narrower pulse for higher aerogel thresholds. Data from shot #2069 in Fig. 5 shows the machine pulse had a Full Width Half Maximum (FWHM) of 30 ns, the glass signal (above 0.3 MeV) had a FWHM of 25 ns and the 1.5 MeV threshold aerogel had a FWHM of 21 ns. The narrower pulse for higher energy thresholds is an observation of the rising edge and falling edge of the machine voltage pulse on the LAD – indicating that it takes more time to ramp up to the highest photon energies and that the highest energies fall off faster once the pulse is complete. The observed variance of the FWHM of pulses reached at most around 17%, but the standard deviation was only 7% [9].

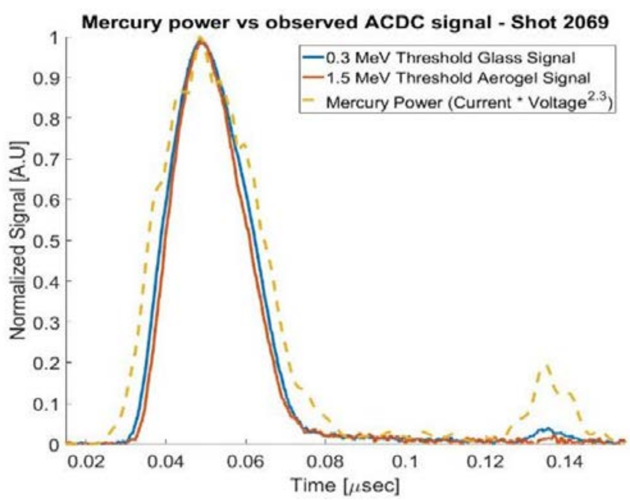

Fig. 5. The Signal traces of shot 2069 (solid) with the recorded power from collimated Mercury (dashed).

Photoneutron Measurements

Several detector systems were deployed to Mercury to measure total neutron yield or time-of-flight information. The types of neutron detectors fielded during this measurement can be broken into two main categories: yield determination through activation and measurements and time-of-flight information through high-sensitivity time-resolved measurements.

Three separate neutron activation diagnostics, sensitive to different neutron energies, measured the total number of neutrons produced per pulse. Two 2 in diameter rhodium foils and one 5 in diameter rhodium foil were moderated with polyethylene and shielded with cadmium [10]. Indium pucks of 1 in diameter were fielded near (6 in or less) from the beryllium sphere photoneutron converter [11]. The rhodium foils were coupled to scintillators and PMT’s which were measured directly after the pulse. Indium pucks were placed into a HPGe detector minutes after the run when experimental personnel were allowed to enter the radiation cell to retrieve the puck, following the method in [12]. The preliminary yield results are shown with simulation estimates in figure 6.

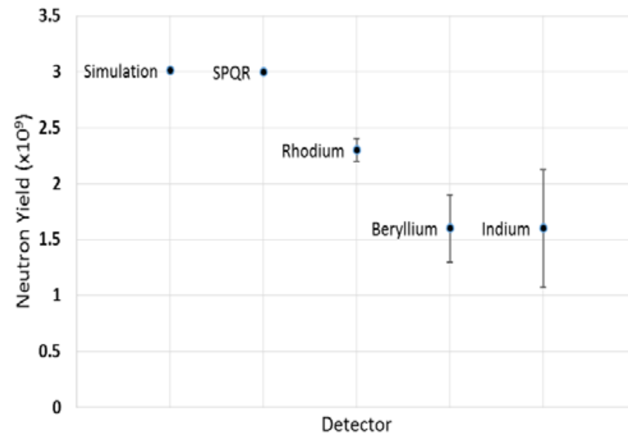

Fig. 6 Preliminary data for independent neutron yield measurements are all within the same order of magnitude

The SPQR (Sapphire Plastic Quartz Radiator) Detector measured information about the photoneutron energy spectrum. The selection of the sapphire, plastic (BC-408) and quartz (fused silica) detector materials were chosen to show photoneutron production because of their varying sensitivities to neutrons and x-rays. Plastic scintillators are sensitive to both x-rays and neutrons. Fused silica and sapphire radiators are overwhelmingly sensitive to x-rays as these detectors utilize the Cherenkov radiation mechanism for the signal creation. Elastic collisions of neutrons with the large nuclei in the radiator materials are unable to recoil particles above the threshold for Cherenkov radiation, leaving these materials largely insensitive to neutrons.

A bare plastic scintillator was coupled to an Electron Tubes D454 PMT attenuated with a neutral density OD2 filter, and the sapphire to a high-gain ET9202 PMT. The scintillators, PMT’s, and 1.6 cm line-of-sight tungsten collimators were all encased in lead and polyethylene shielding to reduce background, partially shown in Fig. 7. The PMTs’ signal and high voltage cables ran to a digitizer and power supply housed in an RF-shielded box nearby on the floor of the radiation cell. The digitizer and high voltage power supply were connected to the data acquisition laptop in the counting house using an optical fiber USB extender system to allow communication between the two rooms. The data acquisition was triggered by an optical fiber array located on the fixture holding beryllium sphere.

SPQR measured a background subtracted preliminary time-of-flight measurement that showed clear separation between the gamma flash from the main Mercury x-ray pulse and the arrival of the beryllium photoneutrons. The later arrival time of lower energy neutrons (due to the higher Q-value of the deuterium photoneutron reaction) for the shots with heavy water was also clearly distinguishable.

Fig. 7. The three detectors in SPQR are shown with some shielding removed.

CONCLUSION

A successful series of measurements were made at NRL's Mercury machine, which was configured to produce an x-ray photon spectrum that was suitable to induce photoneutron production on beryllium. The spectrum was carefully measured to confirm it was operating with the expected energy endpoint. Many diagnostics clearly detected photoneutrons; and preliminary yield estimates indicate about $(3\pm1)\times10^9$ neutrons were produced. The time-resolved measurements indicate the produced neutron spectrum is consistent with our initial simulation results. The pulse width is on the order of 30 ns. We continue to refine our simulations and reduce the uncertainties in our measurements. The success achieved so far demonstrates the feasibility of configuring pulsed power sources to become an intense, short-pulse neutron source.

Acknowledgments

The experiment could not have been completed without the help and technical expertise of Joseph Engelbrecht, Anthony Culver, and Brian Sobocinski.

This work was supported by the US Department of Energy through Los Alamos National Laboratory. Los Alamos National Laboratory is operated by Los Alamos National Security, LLC, for the National Nuclear Security Administration of U.S. Department of Energy (Contract DEAC52-06NA25396). LA-UR-2018-xxxxx

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