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PHOTONEUTRON SOURCE BASED ON A COMPACT 10 MeV BETATRON*

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Abstract

Accelerator-based photoneutron sources have enjoyed wide use and offer the advantages of long term stability, ease of control and absence of radioactive materials. We report here measurements of the yield of photoneutrons from a neutron generator using a compact betatron (466 kg total weight, 900 by 560 by 350 mm betatron dimensions) at the Institute of Introscopy of the Tomsk Polytechnic University. Electrons were accelerated to energies up to 10 MeV and produced a bremsstrahlung beam with a dose rate of 0.16 Gy/min (at 10 MeV, 1 meter from the bremsstrahlung target) to irradiate LiD, Be, depleted U, and Pb neutron-producing targets. The angular distributions of photoneutrons produced by bremsstrahlung beams were measured with a "long" counter and integrated to determine neutron yield. In addition, neutron time of flight spectra were recorded from all targets using a 15 meter flight path perpendicular to the photon beam. The maximum observed yields were 5.2×10^4 n/rad/gram target obtained with LiD, 1.7×10^4 n/rad/gram from Be, 3.3×10^3 n/rad/gram from U, and 7.5×10^2 n/rad/gram from Pb. Optimization of target dimensions, shape, and positioning is expected to increase the yield from the LiD target by a factor of 35. With the increased yield, this compact betatron-based system could find application in the interrogation of waste containers for fissile material.

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Introduction

Measurements of neutron yields induced by bremsstrahlung radiation have been performed since the 1950s. In early papers[1] the aim was to investigate interactions between photon radiation and atomic nuclei, but later great attention has been given to the application of photoneutrons in various fields: activation analysis[2], fissile element content determination[3,4], radiation physics, chemistry, and the production of radionuclides for medicine. In addition, neutron irradiation has been used in waste management applications in which it is important to ascertain that a container destined for burial in a landfill contains fissile material in amounts below regulatory limits. It was a goal of this work to investigate an alternative neutron source for this last application.

Devices for waste drum interrogation based on D-T generators have been built[5]. Since these devices generate 14 MeV neutrons, and significant amounts of moderator are required to thermalize these neutrons, and this moderator captures a portion of the neutrons, it may be possible to increase the efficiency of the machines by generating neutrons whose initial average energy was much lower than 14 MeV. By starting with a cooler spectrum, less moderator would be needed, and fewer losses to the moderator would be sustained. Thus it is possible that a source not as luminous as a D-T generator could still produce a net yield of thermalized neutrons comparable to that of a D-T generator.

The accelerator-based bremsstrahlung photoneutron source was a logical choice for three main reasons: First, in contrast to a radioactive source (such as Sb-Be or actinide-Be) the accelerator-based source can be switched off without moving any part of it into a heavy shield. Second, an accelerator-based source is inherently more luminous than a conveniently achievable radioactive source. Third, a bremsstrahlung photoneutron source offers the possibility of adding x-ray interrogation (DxT or CT) of the waste drum as an aid in interpreting the results of neutron interrogation.

Experimental Procedure

A bremsstrahlung beam was produced with a KRAB betatron fabricated at the Institute of Introscopy of the Tomsk (Russia) Polytechnic University. This betatron is a compact unit weighing 275 kg (magnet and vacuum chamber) with dimensions 960 mm by 560 mm by 350 mm, which is comparable in size to a desktop personal computer, and uses 4 kW to operate. It is capable of accelerating electrons to energies from 3 MeV to 10 MeV (continuously variable), and can operate continuously at 50 pulses per second or with a 67% duty cycle (1 hour on, 30 minutes off) at 100 pulses per second. X-ray pulse width (full width at 10% maximum) can be as low as 250 ns. The radiation dose rate at 1 meter from the bremsstrahlung target is 8 R/min at 50 Hz and 16 R/min at 100 Hz.

Four photoneutron targets (LiD, Be, depleted U, and natural Pb) were irradiated with bremsstrahlung beams with endpoint energies above photoneutron threshold and in the range of the betatron. The 1 kg LiD target was cylindrical, 150 mm in diameter, 135 mm long, and irradiated through its base. The rectangular metallic Be target weighed 3340 grams, was 139 by 139 by 99 mm, had a 40 mm diameter hole through the square faces and was irradiated through a rectangular face. The hole was not drilled through the target for this experiment, rather it was a legacy from the sample's previous service. The Pb target was 10.7 kg cylinder 155 mm in diameter and 50 mm long irradiated through the base. The 1438 g depleted U target was irregularly shaped with rough dimensions of 90 mm by 85 mm by 45. This target was rounded, contained voids, and had been used previously in other experiments at Tomsk. All targets were centered 580 mm from the betatron bremsstrahlung target.

The bremsstrahlung dose was measured with an ionization chamber placed 490 mm from the betatron target (90 mm in front of the photoneutron targets) and displaced 26 mm from the beam axis. The chamber was calibrated against a commercial dosimeter resulting in an estimated error in dose of no more than 5%.

Neutron yield (neutrons/rad/gram target, integrated over neutron energy) was measured using a

"long" counter of the variety suggested by Hanson and McKibben[6]. The neutron detector was a 97% $^4\text{He}/3\%$ Ar gas counter 35.5 cm long, 1.8 cm in diameter, with a 0.9 mg/cm^2 B_2O_3 , enriched to 85% in ^{10}B , coating on the inside walls. The dimensions and response of the detector were essentially those shown by Knoll[7]. It was found that the relative sensitivity of the detector was flattest when the end of the gas counter was positioned 3.5 cm forward of the end of the center moderator cup. In this position, the relative sensitivity of the detector varied by no more than 15% over the neutron energy range 1 - 5 MeV as measured with radioactive neutron sources and the average absolute efficiency was measured with a calibrated ^{252}Cf source to be 0.39%.

The yield integrated over neutron energy was obtained by detecting photoneutrons at -90° , -60° , -30° , 0° , and 30° with respect to the photon beam in the horizontal plane, and at points directly above and below the target (at $\pm 90^\circ$ with respect to the photon beam in the vertical plane), and numerically integrating these differential values over 4π . The detector face was positioned 810 mm from the photoneutron target. The fraction of neutrons scattered from the room and reaching the detector was estimated by interposing an 80 mm diameter by 215 mm long shadow bar between the detector and the photoneutron source.

Time of flight (TOF) spectra were accumulated with a 60 mm diameter by 60 mm thick stilbene crystal scintillator, with detection threshold at 0.18 MeV, sited at the end of a 15.5 m flight path in air. Losses in the air were small (estimated to be 12% at 1 MeV) and ignored. The crystal was shielded by 50 mm of lead which reduced the effects of the gamma flash to less than 0.1 per pulse. The start signal for the TOF electronics was generated by a NaI scintillation detector situated near the photoneutron target. The contribution to the TOF spectrum from scattered neutrons was estimated by accumulating TOF spectra with the shadow bar described above placed at the photoneutron target between the stilbene crystal and the target.

Results

The time distribution of events in the long counter were well described by a model in which incident neutrons are first thermalized by the moderating material and subsequently captured according to an exponential law in the gas tube. For the counter used in this work, the thermalization time was $10 \pm 4 \mu\text{s}$ and the time constant of the exponential was $8050 \pm 90 \text{ s}^{-1}$, corresponding to a mean lifetime of $124 \pm 1.4 \mu\text{s}$ for thermal neutrons in the counter. After each burst from the betatron, counts from the long counter were accumulated for 32 ms ensuring complete collection of neutrons.

The yield of neutrons from each of the four targets was obtained at several angles, numerically integrated over 4π , corrected for detector efficiency and in-scattered neutrons. The results are shown in Figure 1. Uncertainties are not shown because of the close overlap of the data sets, but they may be taken to be +25% and -15%. These error bars are comprised of counting statistics, uncertainty in the measurement of the efficiency of the long counter and the differences in that efficiency arising from differences between the spectrum from the calibrated ^{252}Cf source and the spectra of neutrons emitted from the targets, the time distribution of the start pulse from the NaI scintillator, and the uncertainty associated with the dosimeter used to normalize measurements with and without the shadow bar.

The Be and LiD targets produced the greatest yields, primarily because of the low thresholds for the (γ, n) reaction. The data from different targets should not be compared directly, however, since there has been no account taken in the figure of the absorbed fraction of the incident photon beam. From the known photon absorption cross sections (which, even though they neglect photonuclear reactions, give a good approximation of the probability of interaction) and the bremsstrahlung distribution above photoneutron threshold, it may be inferred that the LiD target absorbed only 14% of the incident beam, while the Be and Pb targets absorbed 54% and 94% respectively. Consequently, significant improvement in the LiD yield may be realized by lengthening the cylinder or increasing the density of

deuterium in the target.. A factor of three, for example, can be achieved by using liquid or frozen deuterated ammonia. Additional gain would be realized by increasing the size of the target and/or moving it closer to the bremsstrahlung target. Moving the target to the exit window of the betatron will increase the photon flux incident on the target from 50 R/min to 260 R/min and increasing the thickness to 60 g/cm² would result in a neutron yield of 1.6×10^9 n/s, a gain of a factor of 35. On the other hand the maximum gain expected to be achievable with the Be block is only about a factor of 10.

Time of flight data was also accumulated and typical data are shown in Figure 2. These data have not been corrected for dead time. The same data are displayed as neutrons per unit energy per unit time a function of neutron energy and include the width of the corresponding time of flight bin. The broad hump in the distribution is a result of a combination of moderation within the Be block target, the shape of the photoneutron cross section, and the shape of the bremsstrahlung distribution. For all targets except for the LiD, the maximum neutron energy observed closely corresponded to the difference between the bremsstrahlung endpoint energy and the photoneutron threshold energy. In the case of the LiD target, the kinematics of the $D(\gamma,n)p$ reaction limit the maximum energy to 3.9 MeV (with a 9.83 MeV bremsstrahlung beam).

Discussion

The possibility of achieving 10^9 neutrons/sec makes this betatron-based source attractive for use in waste drum assay systems. It is well known that the matrix has a significant effect on the response of neutron interrogation system[8, 9] and it is necessary to either measure correction factors to account for the presence of hydrogenous material in the drum or to estimate the corrections with a Monte Carlo calculation based on the assumed contents. The use of the betatron-based source permits an interrogation of the drum with a high energy x-ray beam either in CT mode or transmission radiography mode to obtain a measurement of the distribution of materials first. Then, using this knowledge, the effects of the matrix on the neutron moderation process may be more accurately treated

In addition to the feature of combining both neutron and x-ray interrogation into a single device, the photoneutron source provides a softer neutron spectrum than does a D-T source. This will translate into less moderator, fewer losses to the moderator, and a slightly shorter thermalization times for neutrons. Assuming neutrons lose approximately half their energy, on average, in a collision with hydrogen, the bulk of the neutrons from a betatron-based source will require 3 fewer collisions to thermalize.

Lastly, although the betatron is larger than a D-T tube, it is still small enough to be incorporated into a drum monitoring system. The accelerating chamber, being only about 1 m by 0.5 m by 0.35 m, does not take up significant space and would require only a slight enlargement of the interrogation chamber.

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Figure 1. Total yield of neutrons as a function of electron beam energy

Figure 2. Normalized time of flight spectrum from Be target irradiated with 9.83 MeV bremsstrahlung beam.

Figure 3. Neutron energy spectrum from Be target irradiated with 9.83 MeV bremsstrahlung beam.