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Experimental Investigation of Filtered Epithermal Photoneutron Beams for BNCT

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The Idaho National Engineering Laboratory (INEL) has been investigating the feasibility of a concept for an accelerator-based source of epithermal neutrons for BNCT that is based on the use of a two-stage photoneutron production process driven by an electron accelerator. In this concept [1,2], relativistic electron beams impinge upon heavily-shielded tungsten targets located at the outer radius of a small cylindrical tank of circulating heavy water (D_2O). A fraction of the energy of the electrons is converted in the tungsten targets into radially-inward-directed bremsstrahlung radiation. Neutrons subsequently generated by photodisintegration of deuterons in the D_2O within the tank are directed to the patient through a suitable beam tailoring system. Initial proof-of-principal tests using a low-current benchtop prototype of this concept have been conducted. Testing has included extensive measurements of the unfiltered photoneutron source [2] as well as initial measurements of filtered epithermal-neutron spectra produced using two different advanced neutron filtering assemblies, as described here.

A tunable electron linear accelerator manufactured by the Varian Corporation was used to drive the experimental apparatus shown in Figure 1. The electron beam energy was established at a nominal average value of 6 MeV with an approximately gaussian distribution in energy with an estimated spread of plus or minus roughly 2 MeV (2 sigma) about this value. The foreward-peaked bremstrahlung radiation from the tungsten accelerator target was collimated by a cylindrical tungsten shield and was subsequently directed into a sealed cylindrical lucite container of D_2O where a well-characterized source of photoneutrons [2] is produced. Neutron filtering and moderating structures were placed downstream of the heavy water photoneutron source region. This arrangement would not be typical of an actual clinical device, where the axis of the neutron beam would be at right angles to that of the electron beam to reduce photon contamination at the patient irradiation point. For these experiments however, it was desired to have a simple geometry that could be easily modeled in theoretical calculations.

The first neutron filtering and moderating assembly of interest was constructed of a composite material (69% AlF_3, 30% Al, and 1% natural LiF), developed [3] by the Technical Research Center of Finland (VTT-Finland) and provided for this work to the INEL by VTT under a research agreement. The dimensions of the filter region were 30x30x40 cm. The filter thickness along the beam axis was 30 cm. The measured density of the VTT filtering material was 3.01 g/cm^3. The entire filter was surrounded by 2.54 cm of borated polyethylene to provide a degree of isolation from room return of neutrons.

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The second filtering and moderating assembly was composed of laminated 0.635-cm Teflon™ (CF_2) and aluminum sheets. Teflon™ is an inexpensive, readily available, chemically-stable material with good radiation resistance which, in combination with aluminum, was postulated to be an effective neutron filtering material, provided that there is not an unacceptable level of spectral degradation by elastic scattering from carbon. The Teflon™/Aluminum filtering region had a cubic configuration, 30.5 cm on a side and the entire filter region was again surrounded by borated polyethylene.

Neutron intensity and spectral measurements using standard resonance and threshold activation foil techniques were made at two locations in the experimental apparatus: 1) on the electron beam axis, between the D_2O photoneutron source region and the filter region (the "upstream" side of the filter) and, 2) on the opposite, "downstream", side of the filter, again on the beam axis. In the experiments involving the VTT filtering material, indium, gold, and copper foils were placed at azimuthally-symmetric locations about the beam axis on the downstream side of the filter. Only indium foils were used on the upstream side of the filter. This provided three linearly-independent foil response functions on the upstream side of the filter: neutron capture in indium with and without cadmium, and inelastic scatter in indium, which was experimentally corrected for photon activation of the 336 keV indium-115 isomer by repeating all measurements using light water rather than heavy water in the photoneutron production region. Five response functions were available on the downstream side (the same three indium response functions along with neutron capture in the gold and copper foils).

Effective coarse-group-average response functions for each foil, required for the direct spectral unfolding process that was employed, were computed using a 27-group DORT [4] model of the entire apparatus, with input cross section data generated by the COMBINE [5] code. The coarse-group data (one coarse group per foil response function) were prepared by averaging the 27-group detailed foil cross sections over the calculated a-priori 27-group neutron fluxes within each coarse group at each foil location.

In the Teflon™/aluminum filter experiments a single cadmium-covered indium foil was placed on the upstream side of the filter for normalization and five indium foils, followed by one copper foil, were stacked in a single cadmium-covered package that was placed on the beam axis on the downstream side of the filter. The center indium foil in the downstream package was thus shielded from resonance neutrons, forcing it to have a linearly-independent spectral response relative to that of the first indium foil in the stack. Also, the copper foil was heavily-shielded from neutrons below about 100 eV by the intervening indium foils, forcing its spectral response toward the energy range of the primary resonance for this particular foil material. Four spectral response functions having a useful degree of linear independence were thus available from the downstream foil package. Effective coarse-group-average response functions used in the spectral unfolding process were computed in this case using an MCNP [6] model of the filter and foil package, since the COMBINE resonance model is not appropriate for stacked foils.

The results of the on-axis filtered photoneutron experiments are shown in Figures 2 and 3. A-priori calculated neutron spectra for the upstream and downstream measurement locations are shown along with the measured neutron flux data, unfolded from the foil activation rates using a direct inversion of

the matrix equation describing the relationship between the foil activation rates and the corresponding neutron fluxes in each coarse energy group over the range of interest. In these figures, the spectral data are plotted at the lethargy (logarithmic) midpoint of each coarse energy group defined in the direct unfolding process. The calculated spectra are normalized to the actual measured electron beam current in each case using the measured activation rates of the upstream indium foils which, as demonstrated by the unfiltered neutron source experiments [2], have a well-characterized relationship to the electron beam current and the photoneutron priduction rate.

Both the VTT filtering material and the Teflon™/Aluminum filter produced neutron spectra that, within the unavoidably large experimental uncertainty characteristic of the apparatus used, were generally as expected, with the VTT material being somewhat more effective in reducing the fast neutron component of the spectrum for a given filter thickness. It thus appears that on the basis of neutronic performance, the proposed photoneutron device could offer a promising alternate approach to the production of epithermal neutrons for BNCT. Future work on this concept will be focused on construction of a new experimental prototype using a much higher-power L-band electron accelerator, with a system geometry having the irradiation point on an axis at right angles to the electron beam axis. This will reduce the uncertainties and will permit a more realistic measurement of the photon content of the neutron source at the irradiation point. Control of photon contamination to acceptable levels at the irradiation point is crucial to the success of the overall concept. In addition, experimental optimization studies leading to the design of a full-scale device will also be greatly facilitated by the next prototype.

Acknowledgement

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References

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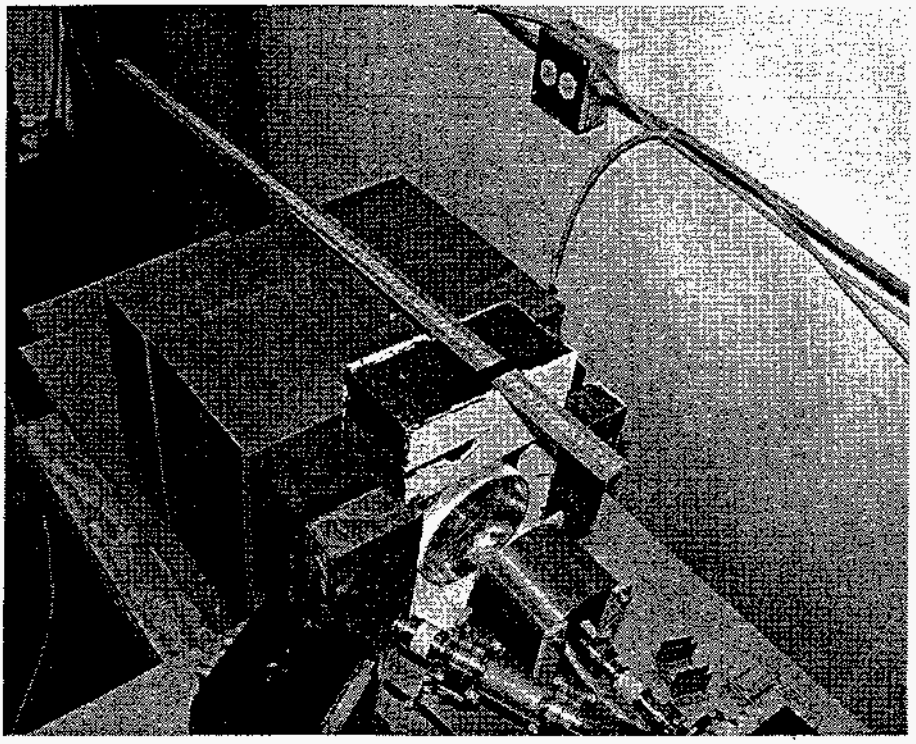

Figure 1. Experimental apparatus for the filtered epithermal photoneutron experiments, showing the AlF_3/Al/LiF filtering region.

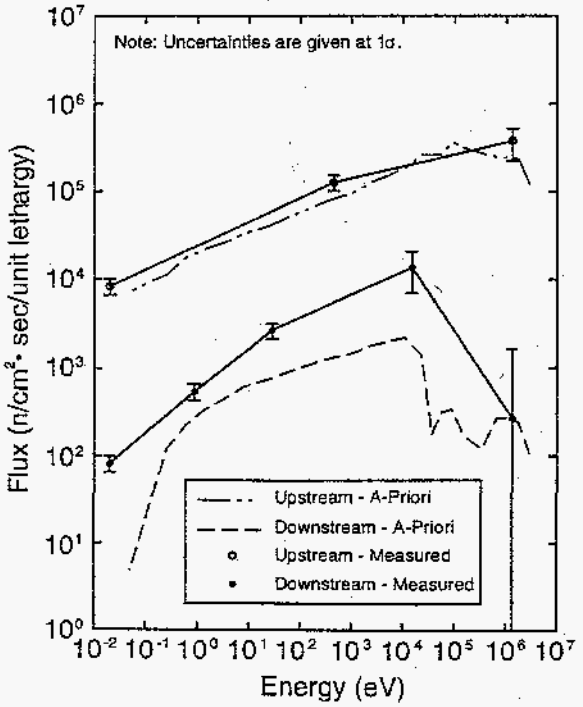

Figure 2. A-priori and measured photoneutron spectra for the 30-cm aluminum-aluminum fluoride lithium fluoride filtering assembly. (Electron current = 3.7 microamperes)

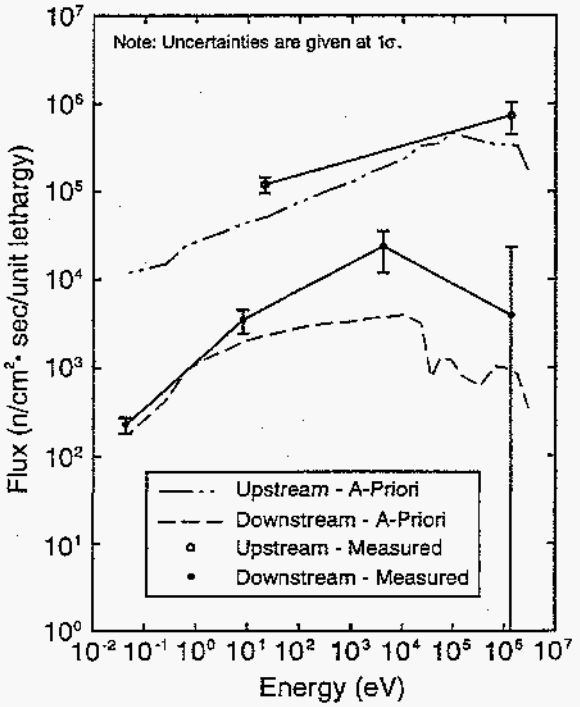

Figure 3. A-priori and measured photoneutron spectra for the 30-cm aluminum-Teflon filtering assembly. (Electron current = 6.2 microamperes)

Figure Legends

1. Experimental Apparatus for the filtered epithermal photoneutron experiments, showing the AlF_3/AL/LiF filtering region.

2. A-priori and measured photoneutron spectra for the 30-cm aluminum-aluminum fluoride-lithium fluoride filtering assembly. (Electron current = 3.7 microamperes)

3. A-priori and measured photoneutron spectra for the 30-cm aluminum-Teflon™ filtering assembly. (ELectron current = 6.2 microamperes)