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† On leave of absence from Roorkee University, Roorkee (U.P.), India.

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Photoneutron Production in Thick Targets*

S. M. Seltzer and M. J. Berger
National Bureau of Standards, Washington, D. C. 20234
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This paper reports new results on the yield of photoneutrons from thick targets bombarded with electron beams. Yields have been calculated for incident electron energies from 20 MeV down to the photonuclear cross section threshold, for tantalum and tungsten targets with thicknesses up to 12.5 $g\,cm^{-2}$. The increased yield from composite tungsten-beryllium targets has been explored.

This note is a sequel to an earlier paper[1] on bremsstrahlung and photoneutron production in thick tungsten targets irradiated by electrons with energies between 12 and 60 MeV. We have now extended our calculations – for tungsten as well as tantalum targets – to lower energies, down to the threshold for the photonuclear cross section. The energy region from 12 to 20 MeV has been covered in more detail than before. Finally, sample calculations have been made of the increase in photoneutron yield at 10 MeV obtainable with a composite tungsten-beryllium target.

As before, our calculations were made for beams of monoenergetic electrons incident perpendicularly on plane-parallel targets finite in one dimension and unbounded in the other two. A Monte Carlo method was used to simulate the resulting electron-photon cascade in the target. The thickest target treated (12.5 $g\,cm^{-2}$) was divided into 50 equal layers, and the bremsstrahlung tracklength distribution (differential in photon energy) was obtained by summing over the appropriate number of sublayers. Finally, the photoneutron yield was calculated by forming the product of the differential tracklength, the photonuclear cross section and the number of atoms per unit volume, and integrating the product over all photon energies down to threshold.

For electron bombarding energies not far above threshold, the photoneutron yield depends rather sensitively on the assumed energy dependence of the photonuclear (γ, n) cross section. The photonuclear threshold energy for $^{181}_{73}Ta$ was determined by Geller, Halpern, and Muirhead[2] to be 7.640 ± 0.025 MeV. More recently, the atomic-mass evaluation of Wapstra and Gove[3] led to nearly the same value, 7.644 ± 0.022 MeV. Using monoener-

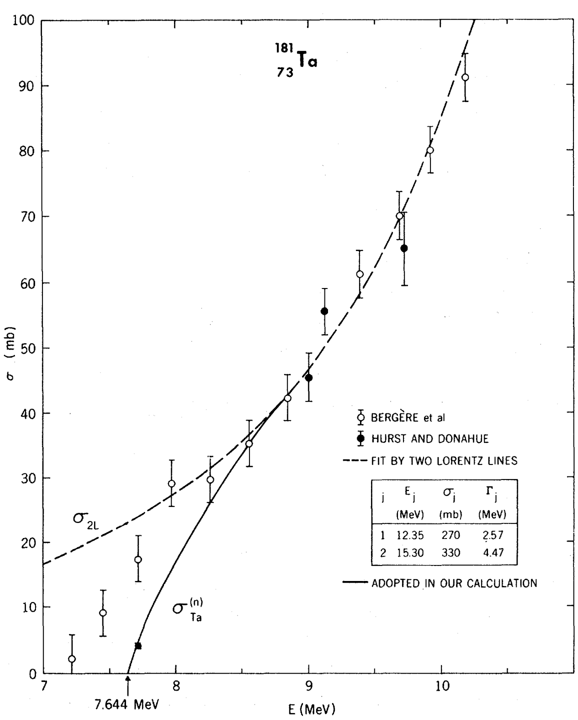


FIG. 1. Photonuclear cross section in tantalum near threshold.

getic γ rays from thermal-neutron capture, Hurst and Donahue[4] determined the (γ, n) cross section in $^{181}_{73}$Ta at 7.72, 9.00, 9.72, and 10.83 MeV. Using nearly monoenergetic γ rays from positron annihilation (with an energy spread of ~1%), Bergère, Beil, and Veyssiere[5] measured the (γ, n), $(\gamma, 2n)$, and $(\gamma, 3n)$ cross sections at many values between threshold and 24 MeV. The threshold energy deduced by them from their data was 7.45 ± 0.2 MeV, somewhat lower than the values quoted above; their cross-section values close to threshold are higher than those of Hurst and Donahue. These differences may be due to the fact that no correction was made for the energy spread of the γ-ray beam. We have adopted for our calculation a cross-section curve, indicated in Fig. 1, which is consistent with the experimental results of Hurst and Donahue and of Bergère, Beil, and Veyssiere at energies down to 8.5 MeV, which then passes through the cross-section value of Hurst and Donahue at 7.72 MeV, and goes to the Wapstra-Gove threshold at 7.644 MeV.

Direct experimental information about the photonuclear cross section for tungsten is incomplete. From a perusal of the *Photonuclear Data Index*[6] one finds that even the most extensive set of measurements, due to Berman *et al.*[7] is limited to the isotope $^{186}_{74}$W and to energies above 9.5 MeV. Tungsten and tantalum nuclei are quite similar; they differ by only one unit in atomic number and have about the same amount of deformation, as can be seen for example from the comparison of the values of the intrinsic quadrupole moment Q_0 given by Hayward.[8] We have therefore used the tantalum cross sections for tungsten, but made an allowance for the different threshold energies, using a procedure suggested to us by E. Fuller.

It can be seen in Fig. 1 that the (γ, n) cross section $\sigma^{(n)}_{\rm Ta}$ for $^{181}_{73}$Ta, at energies above 8.8 MeV can be accurately represented by a two-component Lorentz-line fit σ_{2L}, using parameters given by Bergère, Beil, and Veyssiere. The ratio $\sigma^{(n)}_{\rm Ta}/\sigma_{2L}$ can be regarded as a correction factor (depending on the energy above threshold) which can also be

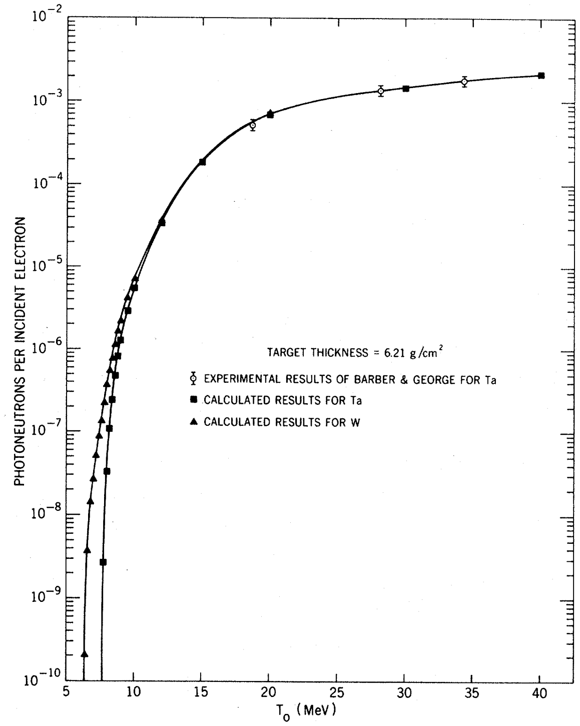


FIG. 2. Photoneutron yields from tantulum and tungsten as functions of the incident electron energy.

applied to tungsten. We thus set

$$\sigma^{(n)}_{\rm W}(E) = \sigma_{2L}(E)\frac{\sigma^{(n)}_{\rm Ta}(E - E^{(n)}_{\rm W})}{\sigma_{2L}(E - E^{(n)}_{\rm W})}, \quad (1)$$

where $\sigma^{(n)}_{\rm W}(E)$ is the (γ, n) cross section for the tungsten isotope with threshold energy $E^{(n)}_{\rm W}$, and E is the photon energy. The correction near the threshold for the $(\gamma, 2n)$ cross section was made by assuming that

$$\frac{\sigma^{(2n)}_{\rm W}(E - E^{(2n)}_{\rm W})}{\sigma^{(n)}_{\rm W}(E - E^{(n)}_{\rm W})} = \frac{\sigma^{(2n)}_{\rm Ta}(E - E^{(2n)}_{\rm Ta})}{\sigma^{(n)}_{\rm Ta}(E - E^{(n)}_{\rm Ta})}, \quad (2)$$

where $E^{(2n)}_{\rm W}$ and $E^{(2n)}_{\rm Ta}$ are the threshold energies for the $(\gamma, 2n)$ cross sections in tungsten and tantalum.

Equations (1) and (2) were applied to the various tungsten isotopes, assuming the following abundances and threshold energies[3]:

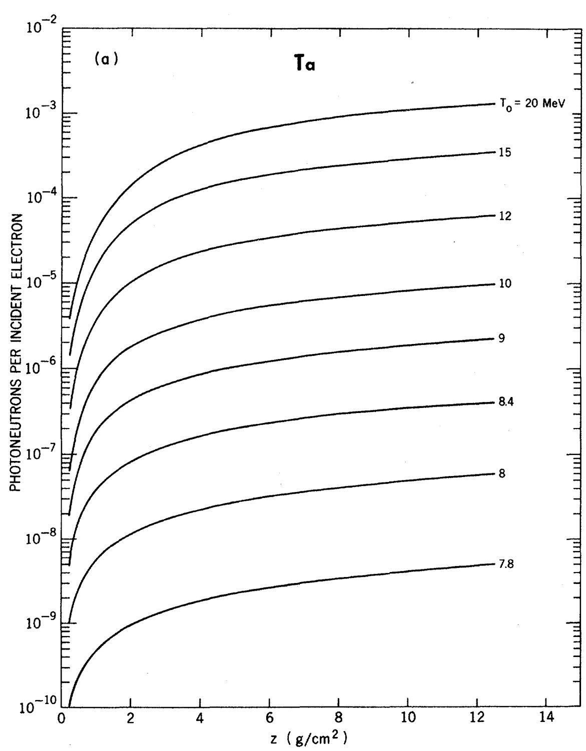
Isotope	$^{180}_{74}$W	$^{182}_{74}$W	$^{183}_{74}$W	$^{184}_{74}$W	$^{186}_{74}$W	$^{181}_{73}$Ta
Percentage by weight	0.14	26.41	14.40	30.64	28.41	100.00
$E^{(n)}$, threshold energy (MeV)	8.490	8.054	6.191	7.411	7.202	7.644
$E^{(2n)}$, threshold energy (MeV)	15.370	4.700	14.246	13.602	12.952	14.224

The possibility of direct photoproduction by electrons has been disregarded in the calculation, but this effect is very small. It is known theoretically as well as experimentally[9] that the cross section for direct electron-neutron production has a magnitude of the order of α (=1/137) times the photonuclear cross section.

Figure 2 shows the calculated photoneutron yield as a function of the electron energy, for a tantalum target and a tungsten target, each with a thickness of 6.21 g cm^{-2} (approximately one radiation length). The uncertainty of the calculated yields arises principally from three sources: (a) uncertainty of the photonuclear cross sections, (b) uncertainty of the bremsstrahlung cross section, and (c) statistical and systematic errors of the Monte Carlo transport calculation. It is estimated that these three errors are approximately 20, 15, and 5%, respectively, for electron energies between threshold and 10 MeV; 10, 10, and 5%, respectively, for energies between 10 and 20 MeV; 5, 10, and 5%, respectively, for energies between 20 and 40 MeV. If one were to calculate the square of the over-all error by summing the squares of the individual errors, the over-all errors would be 20, 15, and 12% in the three energy regions. The errors for the tungsten yields at energies near threshold are probably somewhat larger, due to the extrapolation from tantalum to tungsten photonuclear cross sections.

Also shown in Fig. 2 are experimental yields for tantalum at 18.7, 28.3, and 34.3 MeV which were measured by Barber and George.[10] These are in close agreement with the calculated curve. Reference 10 also gives the yield at 10.2 MeV, as 8×10^{-5} neutrons per electron, a value which is 11 times larger than the calculated value. According to a private communication from Professor Barber, the reliability of the experimental value at 10.2 MeV is in doubt, and it has therefore not been shown in Fig. 2.

Figures 3(a) and 3(b) show the calculated photoneutron yields from tantalum and tungsten as functions of the target thickness, for various electron bombarding energies between threshold and 20 MeV. The estimated errors of the results are the same as those for the results in Fig. 2. These data allow one to estimate the neutron background in many applications involving the use of electron



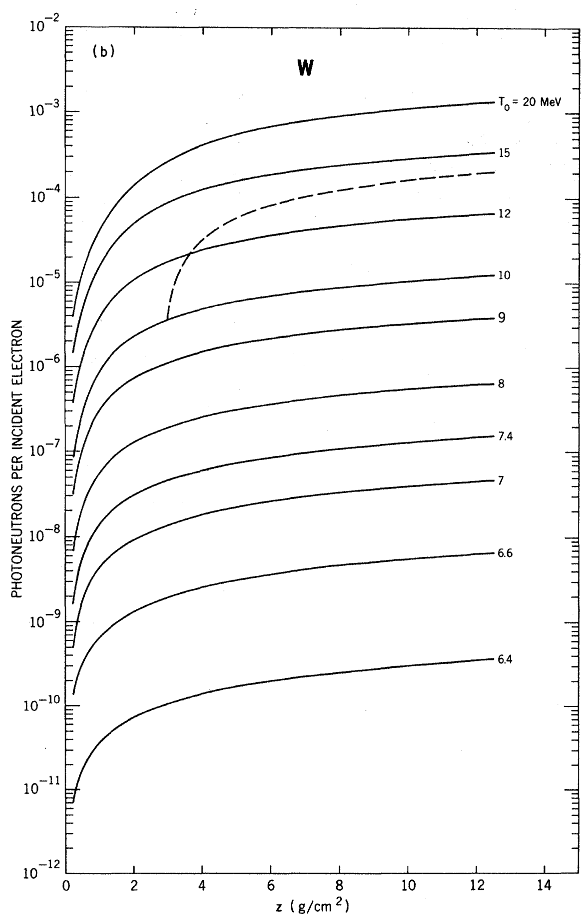


FIG. 3. Photoneutron yield as a function of target thickness. (a) Tantalum targets. (b) Tungsten targets. Dashed curve is for composite target of 3.0 g cm^{-2} of tungsten followed by beryllium.

beams for thick-target bremsstrahlung production. They are especially pertinent to the accelerators now coming into use that produce enormously intense electron beams with broad spectra extending up to 10–12 MeV. For example, one machine (Hermes II) has been described[11] which puts out a current of 9×10^4 A over a 100-nsec pulse, and another machine (Aurora) is nearing completion that is designed to deliver a current of 1.0 to 1.5 $\times10^6$ A over a 100-nsec pulse.[12]

Targets irradiated by these intense electron beams constitute strong pulsed neutron sources. The neutron source strength can further be boosted by using a composite target consisting of a layer of tungsten (an efficient radiator) followed by a layer of beryllium (with a low photonuclear threshold of only 1.7 MeV). We have carried out a sample calculation for a composite target, assuming 10-MeV electrons to be incident on 3.0 g cm^{-2} of tungsten followed by various thicknesses of beryllium. The needed photonuclear cross section for beryllium was pieced together from a large number of experimental data listed in the *Photonuclear Data Index*.[6] As shown in Fig. 3(b) (dashed curve) the use of a composite target increases the yield by a factor of more than 10 compared to the yield from a pure tungsten target.

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