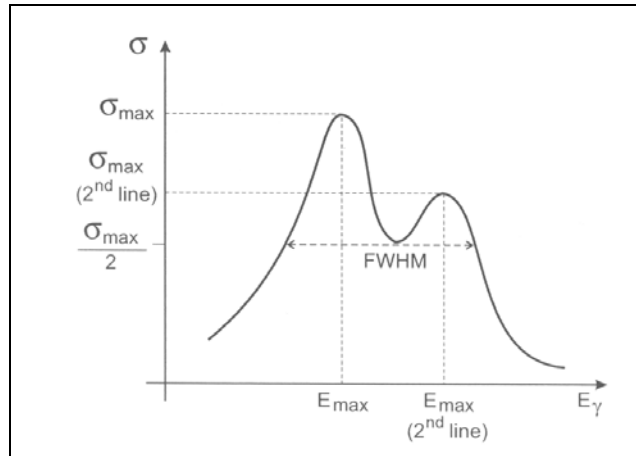


Q5906: How do you calculate the energy of the photoneutrons produced through the interaction with 7.5 MeV bremsstrahlung from a linac? The target is general commercial products in trucks.

ANSWER: A photon is a quantum of electromagnetic energy that takes the form of a wave. The interaction of a photon with a nucleus can cause the nucleus to be excited and, subsequently, emit a neutron if the minimum separation energy is exceeded. The minimum energy required to liberate a neutron ranges from 6 to 16 MeV for most stable nuclei heavier than carbon, although materials such as lead, uranium, and plutonium have thresholds for photoneutron and photofission near 6 MeV. The probability that a photon will undergo a photonuclear interaction is about seven percent of the total photon interaction probability (White 2000).

When the incident photon energy exceeds the threshold energy, or separation energy, the cross section for neutron production increases with photon energy. The neutron production cross section reaches a maximum value and subsequently decreases as the incident photon energy continues to increase. This maximum is referred to as the giant dipole resonance (GDR) and stems from the electric dipole absorption of the photon. The cross section in the vicinity of the GDR is shown in the figure below.



Photonuclear Interaction Cross Section in the Vicinity of the Giant Dipole Resonance

Since photoneutrons are produced from the interaction of bremsstrahlung beams with materials, the analytical approach that could be performed in a spreadsheet is to divide the target into thin regions and numerically integrate the reaction rate in each of the thin regions. The photoneutron source strength, S_v , can be calculated from the energy distribution of the photon flux, $\Phi_\gamma(E)$, using the relationship

$$S_v = \int_{E_t}^{E_{max}} dE \mu_{\gamma,n}(E) \Phi_\gamma(E) \quad (1)$$

where E_{max} is the maximum photon energy, E_t is the photoneutron production threshold and $\mu_{\gamma,n}$ is the (γ, n) interaction coefficient (Chilton et al. 1984). The photoneutron energy can be found from the relationship:

$$E_n = \frac{A-1}{A} \left[E_\gamma + Q - \frac{E_\gamma^2}{1862(A-1)} \right] + E_\gamma \left[\frac{2(A-1)(E_\gamma + Q)}{931A^3} \right]^{1/2} \cos \theta \quad (2)$$

where Q is the Q value for the reaction, A is the ratio of the target nucleus mass to the neutron mass, and θ is the angle between the incident photon and recoiling neutron directions (Chilton et al. 1984). Except for very small A and photon energies near the threshold, the neutron energy varies only a few percent with angle. Q values are tabulated for a variety of nuclides are found in NCRP [Report No. 79](#) (NCRP 1984); although the report almost entirely addresses neutrons produced by bremsstrahlung created using electron beams greater than or equal to 10 MeV in energy.

There are photoneutron cross-section data that can be used in the Monte Carlo N-Particle code or other Monte Carlo codes to couple photon transport with neutron production and transport. The photoneutron cross-section compilation done by White at Los Alamos National Laboratory (White 2000) in the early part of this decade and the [International Atomic Energy Agency](#) photoneutron cross-section compilations are good places to find data for such Monte Carlo simulations. An example of the use of coupled photon-photoneutron transport in the Monte Carlo simulation of cargo containers can be found in the work of Hertel, Shannon, and Naessens (Hertel et al. 2005).

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