Effective atomic numbers for W/Cu alloy for total photon attenuation

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1. Introduction

The study of interaction of photons with matter finds wide application in areas such as industry, medical radiation dosimetry and radiation shielding. Extensive data on experimental photon interaction cross section measurements during the period 1907–1994 is now available in the form of bibliography (Hubbell, 1994). A careful review of these measurements indicates that the studies are exhaustive in respect of pure elements. However, measurements on photon attenuation in alloys are meagre. This is mainly due to the difficulty in procuring targets in suitable form for experimentation. Such studies play a prominent role in selecting alternative shielding materials on the cost-effective basis.

In composite materials, like alloys, the attenuation cannot be represented uniquely across the entire energy region, as in the case of elements, by a single atomic number. Hine (1952) and Murty (1965) suggested theoretical expressions to evaluate 'effective atomic numbers' for the individual partial photon interaction processes. Very few experimental measurements are available on the estimation of these numbers at high energies. Further, discrepancies have been observed (Murty et al., 2000) between the measured effective atomic number values; and the estimated values using Hine's formula in the energy region 60–380 keV. In the present study, attenuation experiments were conducted in the photon energy region 100–1400 keV in W/Cu alloys, with two compositions, W 65%/Cu 35% and W 60%/Cu 40% to explore further the validity of the mixture rule and to see whether any energy dependence of the effective atomic number could be seen.

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2. Theory

In composite materials, like alloys, it is standard to assume that the contribution of each element of the alloy to total photon attenuation is additive which yields the famous 'mixture rule' (Jackson and Hawkes, 1981). In such cases, the mass attenuation coefficient (μ/ρ) of any substance represents the sum of the appropriately weighted proportions of the individual atoms. Thus, $\mu/\rho = \sum_i W_i(\mu/\rho)_i$, where μ/ρ is the photon mass attenuation coefficient for the alloy, $(\mu/\rho)_i$ is the photon mass attenuation coefficient for the individual elements in the alloy, and W_i is the fractional weight of the elements in the alloy. This mixture rule is valid when the effects of molecular binding and the chemical and crystalline environment are negligible. The total photon interaction cross-section in an element is in general given in barns per atom and, for an alloy, it can also be represented in barns per atoms, σ_a, where averaging is carried out over all the atoms of the elements in the alloy. Hence

$$\sigma_a = \frac{(\mu/\rho)_{\text{alloy}}}{N\sum_i W_i/A_i},$$

where N is Avogadro's number and A_i is the atomic weight of the elements in the alloy. Experimentally, the effective atomic number, Z_{eff}, can be obtained by looking at the Z value which corresponds to the total photon cross-section of the alloy.

3. Experimental details

Photon attenuation experiments in a narrow beam collimated geometry, using lead collimator blocks of

apertures of 4 mm diameter, were conducted at photon energies 121.8, 244.7, 344.3, 778.9, 867.4, 964, 1085.8, 1112.1 and 1408 keV (gamma rays from ^{152}Eu) using a Freolectric cooled HPGe detector of 51 mm length and 52 mm diameter and of energy resolution of 0.9 keV at 122 keV coupled to a System 100 PC-based Canberra Multichannel analyser. Pure thin uniform absorbers of W/Cu alloy of two compositions, obtained from Goodfellow (UK), were used in the present study. The absorbers had varying thicknesses, the larger thicknesses being obtained by stacking the foils together.

4. Results and discussion

The evaluated experimental total photon interaction cross-sections in W/Cu alloy of the two different compositions, along with the theoretical values of Hubbell and Seltzer (1995) evaluated using the mixture rule, are given in Table 1. The present experimental total photon cross-sections are of approximately 2–3% accuracy. This error arises mainly from the counting statistics and peak area determination. It can be seen from the table that general agreement is observed between the present experimental cross-sections and the interpolated data of Hubbell and Seltzer (1995), which confirms the validity of the mixture rule in the present energy region.

The effective atomic numbers, Z_{eff}, evaluated using the total photon interaction cross-section data of Hubbell and Seltzer (1995), are given in Table 1 for each energy and for the two alloy compositions. Since the energy region chosen is well above the shell binding energy of the constituent elements of the alloy, the variation of cross-section with energy is smooth. At a specific energy, the effective atomic number for the total photon interaction can be specified uniquely but its magnitude depends on a number of partial processes and their relative contribution. In the present study, since the energy region covered is large, the individual partial processes contribute differently to the total photon attenuation. Furthermore, Z_{eff} values, evaluated using the expressions suggested by Hine (1952) and Murty (1965), are also shown in the table for the two compositions. It can be seen from the table that the experimentally measured values lie in between the two values estimated using the formulas for the two compositions, i.e. they disagree with those evaluated using both the expressions. Even though the measured Z_{eff} values show a decreasing trend with energy, the energy dependence of the value is not strong in the present energy region. As pointed out in our earlier studies (Murty et al., 2000), both the expressions do not indicate a strong energy dependence of the effective atomic number.

Table 1
Total photon interaction cross-sections (σ_a) and effective atomic numbers (Z_{eff})

Energy	σ_a		Z_{eff} (error ~2%)	
(keV)	$W_{65}Cu_{35}$	$W_{60}Cu_{40}$	$W_{65}Cu_{35}$	$W_{60}Cu_{40}$
121.8				
Expt.	334.9±6.7	296.6±6.0	59.0	56.9
H and S	338.5	299.8		
244.7				
Expt.	66.6±1.9	59.9±1.7	58.1	55.9
H and S	67.2	60.7		
344.3				
Expt.	35.4±0.8	32.3±0.7	56.4	54.1
H and S	36.1	32.9		
778.9				
Expt.	14.0±0.4	13.1±0.3	51.7	49.3
H and S	14.2	13.3		
867.4				
Expt.	12.9±0.4	12.1±0.4	51.1	48.7
H and S	13.0	12.2		
964.0				
Expt.	11.9±0.2	11.1±0.2	50.6	48.0
H and S	12.0	11.3		
1085.8				
Expt.	10.9±0.3	10.3±0.3	50.1	47.7
H and S	11.0	10.4		
1112.1				
Expt.	10.8±0.3	10.2±0.3	50.0	47.6
H and S	10.9	10.2		
1408				
Expt.	9.3±0.2	8.8±0.2	49.4	46.9
H and S	9.4	8.9		
Hine's expression (1952)			65	63.5
Murty's expression (1965)			46.6	44.4

In conclusion, attenuation measurements in the photon energy region 100–1400 keV for the two W/Cu alloy compositions did not show a significant energy dependence of the effective atomic number but the results were significantly different from the models of Hine (1952) and Murty (1965).

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