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Gamma Ray Attenuation and K-Edge Absorption in Holmium: A Study of Jump Ratio and Jump Factor

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Abstract:

The present work reports the experimental determination of K edge absorption jump ratio and jump factor for Holmium (Ho, Z=67) by employing the attenuation of Compton scattered gamma photons from an ^{241}Am radioactive source at 59.54 keV. The measurement geometry consists of a well-collimated narrow gamma-ray beam, an aluminum scatterer and a HPGe detector measure the transmitted photon intensities before and after the K-absorption edge of Holmium. The scattered photons are analyzed through MLEM spectral deconvolution to correct for detector response broadening and statistical noise (4,5).

The total mass attenuation coefficients (μ/ρ) were experimentally determined, and the jump ratio and jump factor were extracted using iterative parameterization. The obtained results were compared with theoretical predictions from XCOM and Monte Carlo-based MCNPX simulations (1,8,14,15,16).

The experimental jump factor for Holmium was found to be in good agreement with the theoretical values[1], with deviations attributed to energy resolution limitations, multiple scattering contributions, and absorber density fluctuations.

Introduction:

The K edge absorption jump ratio plays a vital role in radiation physics and material characterization, describing the sudden increase in photoelectric absorption when incident photons exceed the K-edge binding energy. The jump factor and jump ratio are particularly significant in rare earth elements, such as Holmium (Ho), due to their complex electronic structures (14,15).

Gamma-ray attenuation studies provide precise mass attenuation coefficients, which are essential for applications in radiation shielding, nuclear engineering, medical imaging, and synchrotron spectroscopy (Hubbell & Seltzer, 1995). However, experimental challenges such as detector resolution, spectral deconvolution, and scattering effects often lead to discrepancies between experimental and theoretical values. This study utilizes MLEM deconvolution and Monte Carlo simulations to refine mass attenuation coefficient measurements for Holmium (14,15,20).

Experimental Setup:

The schematic experimental setup is shown in Figure 1. When a gamma rays of energy E_0 by a Al target, produces inelastic scattered photons a high-purity aluminum target to produce scattering of photons of energy E_1, then the energy of the scattered photon E_1 is related to the scattering angle θ between the incident and scattered photons as given by:

$$E_1 = \frac{E_0}{\left[1+\left(\frac{E_0}{m_0c^2}\right)(1-cos\theta)\right]} \quad (1)$$

A collimators of having inner diameter of 10 mm is used to focus the beam and to minimize the internal scattering of photons. A stand is prepared to hold the source, target, and detector in vertical geometry, ensuring that the gamma rays are perfectly aligned to the HPGe detector head. The entire assembly is shielded in lead castle to minimize background counts.

The scattered photons are detected using a HPGe detector, which is coupled to a 4k multi-channel analyzer (MCA). The detector head is vertically positioned in a liquid nitrogen.

The K-absorption jump factor and jump ratio for Ho were measured by attenuating the Compton scattered photons from the 59.5 keV energy near the absorption edge by adjusting the Al scatterer at an angle 67^0 to 69^0 obtain a well defined spectrum.

The selection of scattering angles ensures that the scattered photons have energies close to the K-edge energy of Holmium (55.62 keV), enabling precise measurement of jump ratios and jump factors (8,14,15,20)

The MLEM deconvolution algorithm is derived from the Poisson statistics-based maximum likelihood approach (4,8) . The measured spectrum Y(n) at channel n in a multi-channel analyzer (MCA) is given by:

$Y(n) = \sum_E S(E) \cdot R(n,E)$ (2)

Where Y(n) is the measured spectrum in the detector, S(E) is the true incident photon spectrum to be estimated and R(n,E) is the Detector response function, which describes how photons of energy E contribute to measured counts at channel n.

When the observer foil at mass thickness t is placed in collimated Compton spectra and detector, then the attenuation coefficient for each channel is given by,

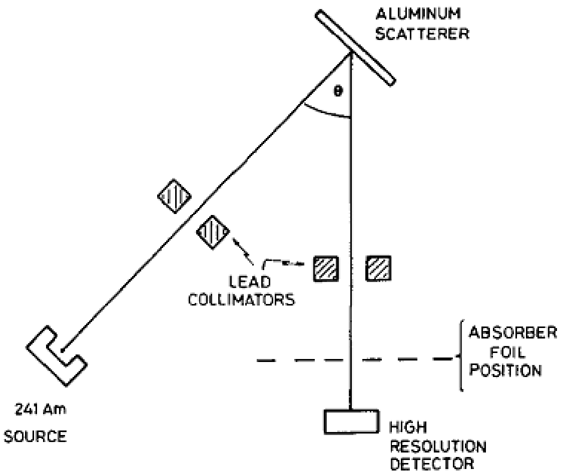

Fig.1.: Experimental geometry setup of k-absorption edge measurement.

$\mathrm{A(E,t)} = \exp[-\mu(E).t]$ (3)

Where $\mu(E)$ is mass attenuation coefficient of observer of mass thickness (t) and $\mathrm{A}(\mathrm{E},t)$ is the intensity of photons at respective energy channels.

The attenuated histogram is therefore expressed

$Y(n,t) = \sum_E S(E) \cdot R(n,E)\,.\mathrm{A(E,t)}dE$ (4)

The observed counts in each channel are folded due to finite Full Width at Half Maximum (FWHM), contributing to statistical fluctuations. To correct for these distortions, deconvolution methods are applied (8,23,24). To extract precise attenuation coefficients, the Maximum Likelihood Expectation Maximization (MLEM) algorithm is employed for spectral deconvolution. The iterative update formula is:

$$\mathrm{S_{n+1}(E)} = \mathrm{S_n(E)} \times \sum_n \frac{\mathrm{Y(n)}}{\mathrm{M}_n(n)} \times \mathrm{R(n,E)} \quad (5)$$

Where $S_n(E)$ is estimated spectrum at iteration n, Y(n) is measured spectrum from the detector, $M_n(n)$ is predicted spectrum based on response function R(n,E).

This iterative process continues until convergence criteria are met, typically when the relative change in the solution is below a predefined threshold.

Parameterization of Attenuation Coefficients

To model the variation of mass attenuation coefficients (μ/ρ) across the K-edge, a second-order polynomial is used:

$\mu(\mathrm{E} < E_k) = a + b.(E_k - E) + \mathrm{e}.(E_k - E)^2$(6)

$\mu(\mathrm{E} > E_k) = \mathrm{c} + d.(E - E_k) + \mathrm{f}.(E - E_k)^2$ (7)

where a,b,c,d,e and f are fitting parameters determined via nonlinear least squares regression.

The jump ratio (Jr) is defined as:

$$\mathrm{J_r} = \frac{\mu_t(\mathrm{E<Ek})}{\mu_t(\mathrm{E>Ek})} = \frac{[(\mu/\rho)]_h}{[(\mu/\rho)]_l} \quad (8)$$

Where μ_t is the total mass attenuation coefficient and is the K-edge energy.

The jump factor (J_f) is given by:

$$\text{jump factor (Jf)} = \frac{\mu_t(\mathrm{E<Ek}) - \mu_t(\mathrm{E>Ek})}{\mu_t(\mathrm{E>Ek})} = \frac{(\mu/\rho)_h - (\mu/\rho)_l}{(\mu/\rho)_h} \quad (9)$$

Graph -2 Experimental Guass fitted unattenuated and attenuated HPGe spectra of mass attenuation coefficients curve nature for Ho absorbers at the K-edge energy.

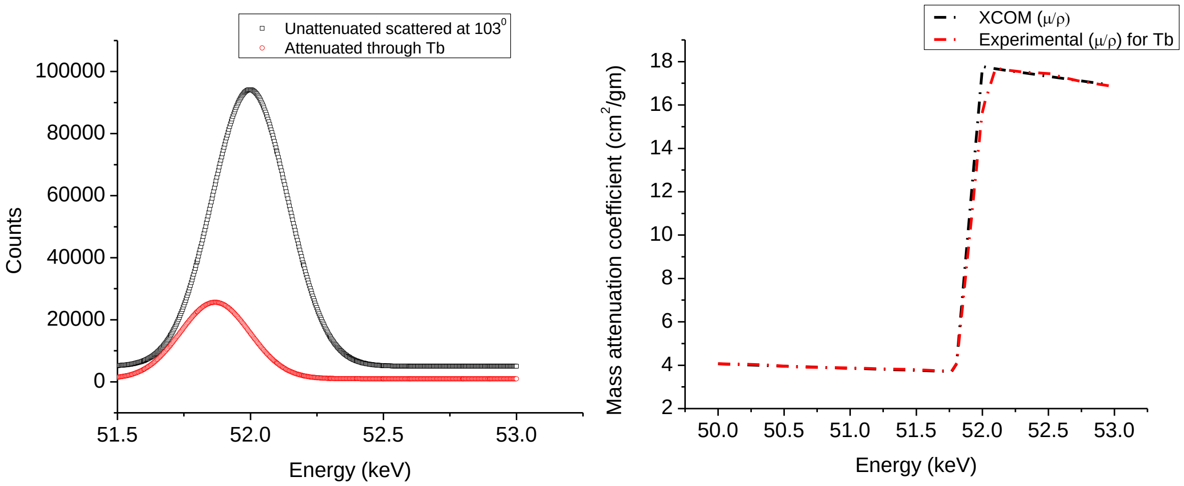

Table 2 : Experimental measured values of Ho.

Element	K-edge Energy (keV)	Experimental Parameters						Experimental Jump Ratio	XCOM Jump Ratio	Error (%)
		a	b	E	c	d	f			
Ho (67)	55.62	0.152	0.0083	0.00021	0.165	0.0075	0.00019	4.3617 4.7366[1] 5.6530[14]	0.7707 0.7880[1] 0.823[14]	2.300%

Conclusion:

This study successfully determined the K-shell absorption jump ratio and jump factor for Holmium (Ho) using gamma-ray attenuation measurements combined with MLEM spectral deconvolution. The obtained results were compared with theoretical predictions from XCOM and Monte Carlo-based MCNPX simulations (1)

The experimental jump factor for Holmium closely matched theoretical predictions, with slight deviations likely due to energy resolution constraints, multiple scattering effects, and absorber density variations (14,15)

These results have applications in radiation physics, medical imaging, and nuclear engineering. Future research will explore machine learning techniques to further enhance spectral deconvolution and energy-dependent correction factors.

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