EXPERIMENTAL MEASUREMENTS OF TOTAL MASS ATTENUATION COEFFICIENTS IN LIQUID GALLIUM

Dr. B. Vasundhara  
Assistant Professor,  
Department of Nuclear Physics,  
GITAM UNIVERSITY  
Gandhi Nagar, Rushikonda,  
Visakhapatnam-530 045  
Andhra Pradesh, India

Abstract

K-shell mass attenuation coefficient measurements in Gallium liquid in the low energy region have been presented. The experiments are performed using a Gallium liquid film and an extended range HpGe-Detector. The results are in agreement with the theoretical estimates. No evidence could, however be gained in favor of the microscopic theories such as RRS and EXAFS in so far as there are no energy points available within a range of 100 eV on either side of the K-edge.

Key Words: K-shell, Mass attenuation coefficient, K-edge, Liquid Gallium, & Scattering
1. Introduction:

Energy dependence of K-shell mass attenuation coefficient in the element Gallium in the low energy region of 5 to 17 has not been measured so far. It covers the K-edge of Gallium located at 10.367. This data is important because it provides not only the much needed experimental values but also it enables one to understand the anomalous X-ray scattering near the K-edge of the element that has not been adequately studied till now. For this study it may be essential to do such an investigation, it is of primary importance to have some experimental data which is close to the K-edge in regular intervals of small magnitude. It may not be possible to realize this through using the radioactive sources as is normally done. Therefore, in the present study the characteristic X-rays are produced by the secondary excitation in the suitable neighboring elements, namely Cr, Mn, Fe, Co, Ni, Cu, Zn, Ge, Se, Br, Sr, and Y. [B.W. Betterman, D.R. Chipman and J.J. Demarco 1961; Wang Dachun, et.al. 1992; Y. Ménesguen, M.C. Lépy 2010; Leif Singman 1974] have used for measurement of total mass attenuation coefficients.

2. Experimentation:

The experimental arrangement is illustrated in Figure-1. The primary source is R, which is a strong Pu$^{238}$ point source of 10 mc; is properly shielded to allow the X-rays to fall onto the selected scatterers, S [Sharanabasappa et.al. 2010]. The characteristic X-rays from the scatterers pass through a Compton shielded circular slit and then through the absorber film of Gallium and two more circular slits to reach the detector kept in a lead box, which shields the detector from unwanted radiation of any other origin.

Figure 1: Geometrical Set up Showing Detector, Absorber, Exciter, and Primary Source with Various Graded Slits.
The detector used is an extended range HpGe detector with a low energy cut-off of 3 and has an energy range up to 1000. It is fitted with a 5 Mil Beryllium window. The energy resolution of the detector is 200 eV at 5.9.

The absorber foils of Gallium, which are made in the usual way of evaporating on a thin Mylar foil are found to be very brittle and are invariably breaking during the experimentation. In the present experimentation, therefore, the absorbers that are made of liquid Gallium are used successfully. The preparation and use of the absorbers in the experimental set-up is detailed below.

2.1 **The Liquid absorbers:** Two identical Mylar rings of 2cms outer diameter with 1cm central circular hole and thickness of the 3 mm are taken in very thin cello plane film is attached to one surface of each of these Mylar rings. A similar third Mylar ring is taken with thicknesses of 1 mm and 2 mm and a central hole of 1cm and outer diameter of 2 cm as in case of the other two rings. This third ring is carefully attached to one of the former two rings on the cello plane side and the liquid Gallium is dropped into the central 1 cm diameter hollow keeping it perfectly horizontal. Then the liquid Gallium hole is sealed off using the cello plane side of the other Mylar ring. After the Gallium absorbers thus made ready, it is found that even in vertical position the Gallium liquid absorber does not loose its uniformity. In spite of this, the experiment has been conducted with the whole equipmental arrangement changed into vertical position, the Hp-Ge detector looking down from the above and the absorber kept in a perfect horizontal position, the liquid film in the absorber is found to be undisturbed and uniform throughout the experiment because of its surface tension and its thinness.

3. **Results and Discussion:**

The mass attenuation coefficient \( \mu / \rho \) is obtained from the formula.

\[
\frac{\mu}{\rho} = \ln \frac{I_0}{I}
\]

Where \( I_0 \) is the initial intensity, \( I \) is the transmitted intensity and \( x \) is the thickness obtained from the mass ‘m’ and area ‘a’ of the liquid film as \( x = \frac{m}{a} \).

The experimental mass attenuation coefficients of Gallium metal in liquid form are measured at eighteen energies. Out of these, nine energies fall below the K-edge which is 10.367. The mass attenuation coefficients of Gallium with the associated experimental errors at eighteen energies are given in Table-1.

Column 3 in the above table gives the theoretical estimates of mass attenuation coefficients derived from the total photon attenuation cross-sections obtained by combining the photo electric cross-sections of Saloman [Saloman E. B., Hubbell J. H., Scofield J. H. 1988] and the coherent and incoherent scattering cross – sections of Hubbell [Hubbell J.H 1982] and Hubbell & Overbo [Hubbell, J.H.and Overbo, I., 1979] respectively.

It can be seen from the above table that the errors which are associated with the present experimental attenuation coefficients are less than 2 %. These errors include statistical error of 0.5 % at the maximum and sometimes of the 1 % due to other effects such as the dead time correction, error in estimation of mass of the absorber and error due to the impurity of the element. The Gallium liquid metal is obtained M/s Fluker, Chemica-Bio Chemica, Switzerland and its purity is 99.9 %.
The energy point immediately below the K-edge i.e., 9.87 eV is 497 eV away from the K-edge. Even though the energy point lies within 500 eV from the K-edge, the percentage deviation in the experimental mass attenuation coefficient is quite small (1.8 %) and does not support the theoretical predictions, due to Resonance Raman Scattering (RRS) which require a deviation of about 10 % and is expected to show-up at closer energies from the K-edge. The energy point at 10.986 eV above the K-edge of Gallium and the measured mass attenuation coefficient at this energy is not expected to show the predictions of EXAFS because this point is quite far-off from the k-edge, exceeding 500 eV although within 1 range. The measured value seems to be quite in agreement with the theoretical value with a 1.9 % deviation which is similar to that of the experimental error. This deviation is calculated from the mean value of the attenuation coefficient without considering the errors.

In order to test these theoretical predictions of RRS and EXAFS, the energy points need to be much closer to the K-edge on either side in the range of hundred eV. Even then, only one energy point on either side may not serve to test these microscopic effects. Because at this point an accidental coincidence with the normal value, on the predicted oscillatory pattern of the mass attenuation coefficients vs. energy curve is quite likely to create wrong inferences. One cannot, therefore, draw any conclusions regarding their validity or otherwise of the above microscopic theories relying on the present experimental output.

In addition to these two energy points, there are sixteen more energy points in the energy region of 5 to 17 eV. Where photon mass attenuation coefficients are measured accurately in the present work and compared with the theoretical total photon mass attenuation coefficients, and one computed depending on the accurate photo – electric cross-sections of Scofield and the coherent and incoherent are cross-sections of Hubbell and Hubbell and Overbo. In Table-1 column 2 and 3 these theoretical values and their percentage deviations respectively are given. There is, in general a reasonably good agreement between the experimental and theoretical values. This gives further support to these theories even in the low energy region. The data reported in this paper is new and no other measurements are available in this energy region.

The present experimental values are further compared with the available semi empirical predictions as given in column – 4 through 7 of table – 1 along with their percentage deviations. It can be seen from these columns that none of the semi – empirical predictions is consistently good. The values due to Victoreen et.al, however, fit the experimental results well at higher energies and fail at lower energies in the present energy range, where as the values due to Orlic et.al, are better fits at lower energies and fail at higher energies. The trend of the predictions due to the “Power Law” follows, in general, that due to ORLIC. Gerward’s [L. Gerward, 1983] version of the power law where the exponents are functions of Z and E is supposed to be an improved version and should fit the experimental results better. However, this assumption is not true with respect to the results in Gallium, because the percentage deviations with the measured values appear to be better with the Victoreen’s simple relation rather than with that of Gerward.

The above semi-empirical results are also given pictorially in four different plots in order to avoid clumsiness and also to see clearly the order of agreement of the semi-empirical predictions which are provided in each graph.
<table>
<thead>
<tr>
<th>Energy</th>
<th>Experimental values</th>
<th>Theoretical values of Scofield + Hubble + Hubble &amp; Overbo</th>
<th>Victoreen et al., Deviation (%)</th>
<th>Power Law Deviation (%)</th>
<th>Oric. et Al. Deviation (%)</th>
<th>L. Gerward et al. Deviation (%)</th>
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<tr>
<td></td>
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<td>Deviation</td>
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</table>
Figure – 1(b) shows experimental values compared with the theoretical values alone. Figure-1(c) gives Victoreen’s values in comparison with the theoretical and the experimental mass attenuation coefficients of Gallium. Figure-1(d) shows a comparison of the theoretical, the experimental and the values due to power law. The values due to Orlic et.al are plotted in Figure-1(e) along with the theoretical values and the experimental values. The values due to the improved power law of Gerward are plotted in Figure-1(f) and compared with the theoretical values.

There are no earlier experimental measurements on the photon attenuation coefficients in this element in the present energy range or even outside this range.

Fig – 1 (b): Comparison of Theoretical and Experimental Mass Attenuation Coefficient of Gallium

Fig – 1 (c): Comparison of theoretical and experimental mass attenuation coefficient of Gallium with Victoreen’s values
Fig - 1 (d): Comparison of theoretical and experimental mass attenuation coefficient of Gallium with Orlic’s values.

Fig – 1(c): Comparison of theoretical and experimental mass attenuation coefficient of Gallium with the Orlic’s values.
Fig – 1 (f): Comparison of theoretical and experimental mass attenuation coefficient of Gallium with Gerward’s values

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References:


Saloman E. B., Hubbell J. H., Scofield J. H., (1988) X-ray attenuation cross sections for energies 100 eV to 100 and elements \( Z = 1 \) to \( Z = 92 \) Atomic Data and Nuclear Data Tables (1988) 38 pp. 1-196


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