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Gamma ray Compton profiles of dysprosium and holmium

Thomas Varghese*, K M Balakrishna[1] and K Siddappa[1]
Department of Physics, Nirmala College, Muvattupuzha-686 661, Kerala, India
[1]Department of Studies in Physics, Mangalore University, Mangalagangotri-574 199, Mangalore, India

E-mail : surajthomas@sancharnet.in

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Abstract : The electron momentum distribution and Compton profiles of rare earth elements dysprosium (Dy) and holmium (Ho) were measured using HPGe detector. The measurements were carried out on a high purity thin elemental foil using 59.54 keV gamma rays from Am-241. The data was recorded and analyzed using a 4 K multichannel analyzer. The experimental data was corrected for instrumental resolution effects, sample absorption, energy dependence of the differential Compton cross section and double scattering. The results are presented along with theoretical free atom values. The present experimental Compton profiles of Dy constitute the first measurement.

Keywords : Compton scattering, Compton profile, electron momentum density, impulse approximation.

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1. Introduction

Compton scattering is one of the interactions between an incident radiation and electron in the target atom. It is predominant in the incident energy range from 0.1 to 1 MeV. When photon is Compton-scattered, the wavelength of the emerging beam is increased depending upon the angle of scattering but independent of the material. The emerging beam is Doppler-broadened due to the motion of the target electrons. The momentum distribution of electrons is investigated by measuring the energy spectrum of Compton-scattered photons. The Compton profile can be considered as the Doppler broadening of the Compton-shifted line. The spectral analysis of the scattered radiation reveals the line shape. The interpretation of Compton line shape, the Compton profile, are based upon impulse approximation. In this approximation, the double differential cross section, with respect to both scattering angle and the energy of the scattered photon, is proportional to the Compton profile which is the projection of the electron momentum density along the direction of the scattering vector. The implication of this approximation is that the bound electron can be treated as free with the same momentum distribution [1–4].

When the impulse approximation is valid, the relativistic Compton cross section is given by [5] :

$$[d^2\sigma/d\Omega d\omega] = [\{r_0^2 mc\omega_2(1 - \omega_1/mc^2)B\}/\{A_1(\omega_1 + \omega_2)^2(1 + \omega/mc^2)\}]J(q), \quad (1)$$

where r_0 = classical electron radius, $m = 1$, $c = 137.036$ (atomic unit a.u.), ω_1 = energy of the incident photon in a.u., ω_2 = energy of the photon after scattering in a.u.

$$B = [\omega_1 A_1/\omega_2 A_2] + [\omega_2 A_2/\omega_1 A_1] - [4/A_1 A_2] + [4/A_1^2 A_2^2]. \quad (2)$$

$$A_1 = 1 + q/mc. \quad (3)$$

$$A_2 = 1 - q/mc. \quad (4)$$

$$\omega = \omega_1 - \omega_2. \quad (5)$$

$$k = k_1 - k_2. \quad (6)$$

$$J(q) = \iint n(P_0) dp_x dp_y \quad (7)$$

The relationship between the energy of the scattered photon and q (in atomic units) is given by :

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*Corresponding Author

$$q = -137\{\omega_1 - \omega_2 - \omega_1\omega_2(1 - \cos\theta)/mc^2\}/\{\omega_1^2 + \omega_2^2 - 2\omega_1\omega_2\cos\theta\}^{1/2}. \quad (8)$$

In this paper, a systematic study of the Compton profiles of rare earth elements dysprosium and holmium has been reported.

2. Geometry and experimental setup

Compton profiles of Dy and Ho were measured using 59.54 keV gamma rays from 300 mCi Am-241 point source capsule obtained from M/s. Amersham Inc., U.K. Although the resolution of experiment with Am-241 is lower than for synchrotron radiation, the reporting of a measurement with this source is still important where no experimental data are available in the literature. The reflection geometry setup is employed in the present work to reduce the angular spread over a wide range [6]. Using sufficiently thick lead as shielding material with graded shielding arrangement, compact geometry is obtained by properly optimizing the source to target and target to detector distance.

The geometry and shielding arrangement of the experimental setup employed for the present study has been described elsewhere [7]. A well-collimated beam of photons from the source is made to fall on the target scatterer mounted on a target holder. The optimum distance between the source and the target is chosen to be 20 cm and that between the target to the detector 25 cm. These scattered photons are made to fall on the detector, which is shielded properly with lead and graded shielding to minimize the background radiation. The gamma rays scattered at a mean angle 165°(±2°), were detected by the HPGe detector. The momentum resolution of the detector which depends on detector properties and beam divergence (±2°), was about 0.51 a.u. of momentum [8]. The source S is kept in a lead source holder H having a cylindrical hole 1 cm in length and 0.5 cm in diameter. A collimator C made from lead in the form of a disc having cylindrical hole of diameters 1.0 cm is placed suitably in front of the source. The source is properly shielded with lead so that the detector sees only the scattered gamma rays from the scatterer. The alignment of source, target and detector is done with the help of laser beam. The entire setup constitutes a low background and high-resolution gamma ray spectrometer.

The HPGe photon detector used in this study, has dimensions of 5.05 cm of active diameter and an active volume of 90 cc. The operating bias voltage of the detector is +2500 V. The detector was maintained at liquid nitrogen temperature with a cryostat of 30 L capacity. Thin elemental foils of Dy and Ho, having dimensions of 2.5 × 2.5 cm and thickness of 0.0258 gm/cm^2 and 0.0735 gm/cm^2, respectively, were used as targets. The purity of the foils was greater than 99.9%.

The linearity of the spectrometer was studied by using standard gamma ray sources and was found that it possesses very good linearity. The stability was also tested and it was observed that the shift in the peak channel was less than a channel over a period of 3 days. The data were collected and analyzed using a PC based 4 K MCA. A separate measurement was made without the sample to obtain background contribution that was scaled to the measurement time of the foil and then subtracted point by point from the measured data. The signal to noise ratio was found to be 50 : 1. About 10^4 counts were collected at the Compton peak. The spectrum recorded for 59.54 keV gamma rays scattered at 165° is presented in Figure 1. The raw data were corrected for background, absorption in the sample, instrumental resolution and differential scattering cross section [9,10]. The elastic and inelastic-double scattering (DS) contribution was removed by using Monte Carlo simulation technique [11]. The data were then converted to momentum scale to obtain the Compton profile.

The conventional system of atomic units (a.u.) is used for the evaluation of Compton profiles. In this system,

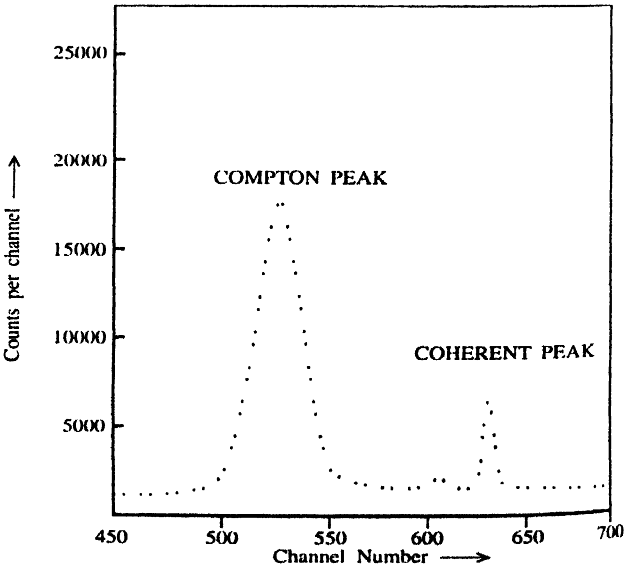

Figure 1. The spectrum recorded for 59.54 keV gamma rays scattered at 165°.

$h/2\pi = 1$, $m = 1$ and $c = 137.036$. Also, 1 a.u. of momentum = 1.9929×10^{-24} kg m s^{-1}, 1 a.u. of energy = 27.212 eV and 1 a.u. of length = 5.2918×10^{-11}m.

The uncertainty in setting the target foil angle was about 2%, which contributes a negligible error in the measured Compton profile. The statistical error due to count rate were reduced and kept within 2% by counting the data for a long time. The counts under the peak were determined accurately after subtracting the background counts and applying Guassian fitting. The error due to the uncertainty in evaluating the solid angles was less than 1%. The estimated error in the determination of photopeak efficiency of the detector using the standard weak sources, was about 2%. The errors associated in evaluating the source strength was estimated to be about 3%. All the errors were compounded according to the well-known rules of propagation of errors and the resultant error was quoted on the measured Compton profiles. The binding energy of K-shell is greater than the recoil energy. Hence, the experimental Compton profiles (high energy side) are normalized to the area of corresponding free-atom profile in the momentum range of 0 to 7.0 a.u. excluding the contribution of 1s electrons. The normalizations used for Dy and Ho are 24.93 and 25.22, respectively.

Table 1. Comparison of Compton profiles of Dy and Ho with theory.

q a.u	$J(q)^{\mathrm{Expt}}$ Dy	$J(q)^{\mathrm{Theo}[12]}$ Dy	$J(q)^{\mathrm{Expt}}$ Ho	$J(q)^{\mathrm{Theo}[13]}$ Ho
0.0	9.535 ± 0.286	11.9	9.498 ± 0.284	9.63
0.1	9.497 ± 0.284	11.3	9.445 ± 0.283	9.55
0.2	9.431 ± 0.282	9.97	9.389 ± 0.281	9.46
0.3	9.215 ± 0.276	8.77	9.207 ± 0.276	9.14
0.4	8.799 ± 0.263	8.03	8.750 ± 0.262	8.82
0.5	8.434 ± 0.253	7.62	8.416 ± 0.252	8.28
0.6	8.121 ± 0.243	7.35	8.099 ± 0.243	7.79
0.7	7.689 ± 0.230	7.10	7.680 ± 0.230	7.30
0.8	7.305 ± 0.219	6.83	7.324 ± 0.219	6.97
0.9	7.018 ± 0.210	–	7.042 ± 0.211	–
1.0	6.727 ± 0.201	6.23	6.751 ± 0.202	6.36
1.2	6.113 ± 0.183	5.65	6.165 ± 0.184	5.77
1.4	5.625 ± 0.168	5.16	5.673 ± 0.170	5.27
1.6	5.195 ± 0.155	4.77	5.230 ± 0.156	4.85
1.8	4.788 ± 0.143	4.46	4.807 ± 0.144	4.52
2.0	4.430 ± 0.132	4.23	4.413 ± 0.132	4.28
3.0	3.423 ± 0.102	3.33	3.436 ± 0.103	3.39
4.0	2.502 ± 0.075	2.49	2.594 ± 0.077	2.56
5.0	1.866 ± 0.055	1.83	1.905 ± 0.057	1.89
6.0	1.417 ± 0.042	1.39	1.468 ± 0.044	1.43
7.0	1.080 ± 0.032	1.10	1.140 ± 0.034	1.13

3. Results and discussion

The present experimental results for Dy and Ho are compared in Table 1 with the theoretical values calculated from the relativistic Hartree-Fock (HF) wave functions [12] and renormalized free atom (RFA) profiles, respectively [13]. It can be seen that at $q = 0$ a.u., the measured values are smaller (~24% for Dy) than profiles calculated from HF wave function. This deviation is due to the fact that the contribution of inner-core electrons is small in this region [14]. Also, this deviation indicates the neglect of electron correlation beyond the HF parallel spin exchange. A proper inclusion of electron correlation produces an isotropic correction, which reduces the difference between experiment and theory. However, between 0.3 and 4.0 a.u., the present results of Dy are slightly broader than the theory. This broadening may be due to electron correlation which pushes a part of the occupied states below the Fermi momentum to momentum values above the Fermi momentum. In the high momentum transfer region ($q > 4.0$ a.u.), experimental values are very close to the corresponding theoretical data. It is interesting to note that in the high momentum range of 3.0 to 7.0 a.u., the experimental results of Ho are also in good agreement with the theoretical values based on RFA model. This is so because the contribution in the high momentum region, comes mainly from the inner-core electrons and these electrons are reasonably described by the free-atom values [15,16].

It can be seen that in the low momentum transfer region ($0 \leq q \leq 0.2$ a.u.), the theoretical profiles of Ho are slightly greater than the experiment. However, in the region ($0.3 \leq q \leq 2.0$ a.u.), the present results for Ho are slightly broader than RFA values. The present experimental results for Ho compare well with the recent 662 keV results of Ahuja and Sharma [13], indicating reliability of the present data.

4. Conclusion

In this paper, we have reported experimental data on Compton profile of the rare earth elements Dy and Ho. The results are in relatively good agreement with theoretical free atom profiles, particularly in the high momentum transfer region. In order to throw more light on the electron momentum distribution of rare earth elements, improvements in the calculations based on proper models and more extensive and systematic measurements, particularly with synchrotron radiation sources, are needed.

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References

[1] K F Berggren *Phys. Rev.* **B6** 2156 (1972)

[2] B G Williams *Compton Scattering* (London : McGraw-Hill) p11 (1977)

[3] M Cooper *Adv. Phys.* **20** 453 (1971)

[4] M J Cooper *Rep. Prog. Phys.* **48** 415 (1985)

[5] J M Jauch and F Rohrlich *The Theory of Photons and Electrons* (Cambridge : Addison Wesley) p231 (1955)

[6] P P Kane, L Kissel, R H Pratt and S C Roy *Phys. Rep.* **140** 75 (1986)

[7] Thomas Varghese, K M Balakrishna and K Siddupa *Indian J Pure Appl. Phys.* **60** 569 (2003)

[8] S Manninen and T Paakkari *Nucl. Instrum. Meth.* **155** 115 (1978)

[9] R Benedek, R Prasad, S Manninen, B K Sharma, A Bansil and P E Mijnarends *Phys. Rev.* **B32** 7650 (1985)

[10] S Manninen, T Paakkari and K Kajantle *Phil. Mag.* **29** 167 (1974)

[11] V Halonen, B G Williams and T Paakkari *Phys. Fenn.* **10** 107 (1975)

[12] F Biggs, L B Mendelsohn and J B Mann *At. Data Nucl. Data Tables* **16** 201 (1975)

[13] B L Ahuja and M Sharma *Rad. Phys. Chem.* **73** 131 (2005)

[14] Thomas Varghese, K M Balakrishna and K Siddappa *Indian J. Phys* **76B** 657 (2002)

[15] B K Sharma, B L Ahuja, H Singh and F M Mohammad *Pramana-J Phys.* **40** 399 (1993)

[16] C N Chang, S B Lee and C C Chen *J. Phys. Soc. Jpn.* **60** 4523 (1991)