PRAMANA
— journal of
physics

Vol. 65, No. 1
July 2005
pp. 137–145

Performance of 20 Ci ^{137}Cs γ-ray Compton spectrometer for the study of momentum densities

B L AHUJA* and M SHARMA
Department of Physics, College of Science Campus, M.L. Sukhadia University, Udaipur 313 001, India
*Corresponding Author.
E-mail: blahuja@yahoo.com

MS received 16 August 2004; revised 3 January 2005; accepted 28 February 2005

Abstract. In this paper, we present the design and construction of a 20 Ci γ-ray Compton spectrometer that employs a ^{137}Cs source with a strong line at 661.65 keV. The total resolution of the spectrometer in momentum scale is 0.40 a.u., which is much better than the conventional ^{241}Am Compton spectrometers. The in-house ^{137}Cs spectrometer is very useful for the measurement of momentum densities of heavy materials. The performance of the machine is assessed using aluminum, terbium and mercury samples and the experimental data from comparable apparatus.

Keywords. Compton scattering; electron momentum density; band structure calculation; γ-ray scattering.

PACS Nos 13.60.F; 78.70.ck; 78.70.-g

1. Introduction

The Compton experiment can be treated as a principal method of obtaining an experimental measure of the momentum distribution of electrons in materials [1,2] from energy distribution of inelastically scattered photons, leading to the Compton profile (CP).

The Compton profile, $J(p_z)$, is defined as

$$J(p_z) = \int_{p_x} \int_{p_y} \rho(\vec{p}) \mathrm{d}p_x \mathrm{d}p_y, \tag{1}$$

where $\rho(\vec{p})$ is the momentum distribution of the electronic system before scattering and p_z is the component of the electron momentum along the scattering vector (chosen as the z-axis). Besides ^{241}Am, a number of γ-ray sources like ^{123m}Te, ^{197}Au, ^{51}Cr, ^{137}Cs have been used in such measurements [1,2]. In Compton experiments, the critical limiting parameters are resolution, half-life of the source and

Compton count rate. Typically, with a ^{197}Au source (which has very small half-life ∼2.7 days) or a ^{137}Cs source (half-life ∼30.1 years), one can obtain a resolution (Gaussian FWHM) of about 0.4 a.u. (1 a.u. of momentum = 1.993×10^{-24} kg ms^{-1}) while with a ^{241}Am source (half-life ∼432.2 years) the resolution comes out to be about 0.6 a.u. Most of the earlier γ-ray Compton scattering studies were based on ^{241}Am source [1–3]. To minimize the geometrical broadening, Compton scattering experiment requires collimation of incident and scattered radiations, which helps in getting the best possible resolution of the experiment. Recently, synchrotron radiation facilities (which are very expensive) have also been used for charge and magnetic Compton experiments [4] but due to limitations of beam time at these facilities, indoor Compton experiments with intermediate momentum resolution (0.35 a.u. $\leq \Delta p_z \leq$ 0.45 a.u.) are very helpful to study the electronic structure of heavy materials. ^{137}Cs Compton spectrometers that are currently in use are mainly based on very high-intensity sources, viz. 85 and 95 Ci [5,6]. There are some additional advantages in γ-ray Compton spectroscopy if photons with high energy (>200 keV) are used. This is particularly true in the case of heavy elements or their alloys/compounds in which binding energies of electrons from inner shells are of the order of 50 keV and therefore cannot be treated in impulse approximation (IA), when a low incident energy is used. It is important to emphasize that there is no fundamental barrier in improving the resolution in CP measurements. We have therefore decided to concentrate on developing a new design of widely used high intensity ^{137}Cs-based Compton spectrometers [5,6], which can give a comparable count rate and similar resolution, even with relatively low-intensity sources, viz. 5–20 Ci. Probably due to problems of biological shielding during the transportation and installation of high-intensity ^{137}Cs source, only a limited number of groups have come up in this field. In this paper, a design with optimum choice of experimental parameters for India's first 20 Ci ^{137}Cs γ-ray Compton spectrometer is presented. We discuss our results on Al, Tb and Hg, and compare the performance with other ^{137}Cs Compton spectrometers that are in use.

2. Experimental set-up and data correction

The practical consideration of intensity, resolution and background guides the geometry of a Compton spectrometer. One should have as high a scattering angle as possible with adequate shielding around the source, and scattering volume which contains only the sample. To accommodate sufficient shielding of the source, the scattering angle has to be reduced from 180°. In the present 20 Ci ^{137}Cs Compton spectrometer (energy 661.65 keV), this has led to a choice of scattering angle of about 160°, source to sample (s-s) distance 380 mm and sample to detector (s-d) distance 548 mm. These distances are smaller than those chosen by Andrejczuk *et al* [5] (s-s: 422 mm, s-d: 666 mm) for their 85 Ci ^{137}Cs source and also by Chang *et al* [6] (s-s: 590 mm; s-d: 960 mm) for their 95 Ci ^{137}Cs source. The scaling down of distances has helped us to enhance the Compton intensity and therefore, while maintaining the resolution, we got a comparable count rate for Al as reported by Andrejczuk *et al* [5]. The layout of the Compton spectrometer designed, fabricated and commissioned by us is shown in figure 1. The spectrometer is a parallelopiped

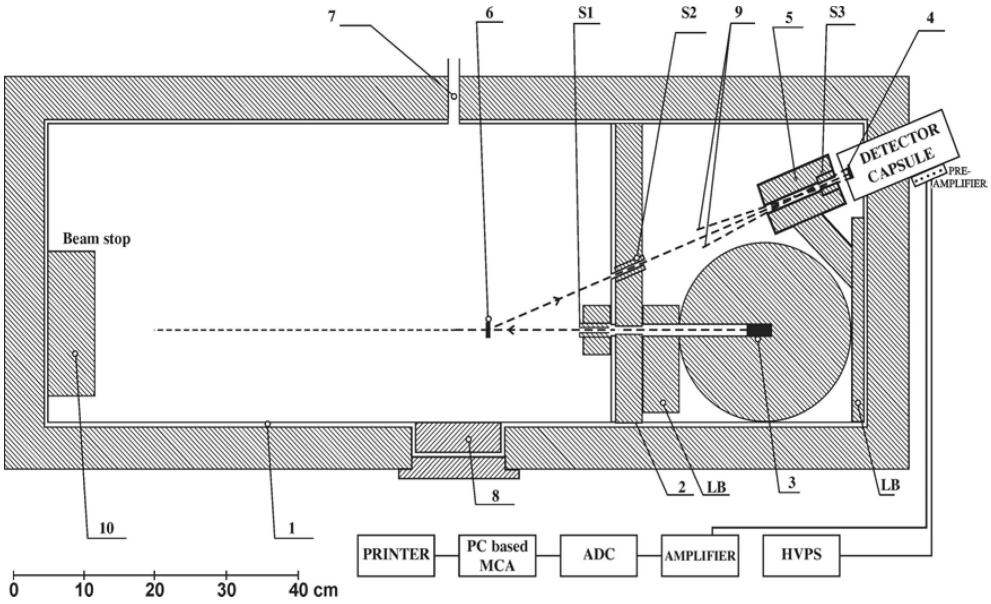

Figure 1. Layout of 20 Ci ^{137}Cs Compton spectrometer. Shown here are: Steel chamber of dimension 1150 × 350 × 400 mm^3 divided into two parts, namely, sample chamber in the left-hand side and source chamber in the right–hand side (1), lead partition to separate source housing and scattering chamber (2), ^{137}Cs source (3), HPGe detector crystal (4), detector collimation (5), sample (6), port for evacuation (7), additional window for 90° scattering, viz. for Compton scanning (8), volume seen by detector (9), beam stop (10), collimating slits (S1 to S3) and lead bricks (LB). Other shaded region also shows the lead shielding. The lead shielding (5–7 cm) all around the steel chamber is shown by lined area. The associated standard electronics (Canberra, USA) is also shown.

of dimensions 1150 × 350 × 400 mm^3 made of 6 mm thick steel sheet. The right-hand side of the parallelopiped (figure 1) consists of a source container, which is a cylindrical block made of lead with a diameter of 220 mm and height 220 mm. The source container as shown in figure 2 can also be used for transportation purposes. Two vertical holes (7 and 6 in figure 2) in the cylindrical block contain a source holder and a rotatable cylindrical shutter with an exit channel for the beam. The vertical hole (6 in figure 2) serves as a beam port if aligned with horizontal hole in the shield and as a shutter if rotated perpendicularly. As can be seen in figure 1, the γ-rays coming out from the beam port are collimated using a lead collimator (S1) having internal diameter 8.0 mm and length 41 mm. The diameter of beam spot on the scatterer (kept vertically) at a distance 122 mm from the collimator S1 was found to be 15 mm. The scattered radiations were collimated at two stages (S2 and S3) and were energy analyzed using high-purity germanium (HPGe) detector (Canberra, Model GL0210P). The germanium wafer in the detector has a diameter of 16 mm and 10 mm thickness. Analogue signal pulses from γ-ray detector were

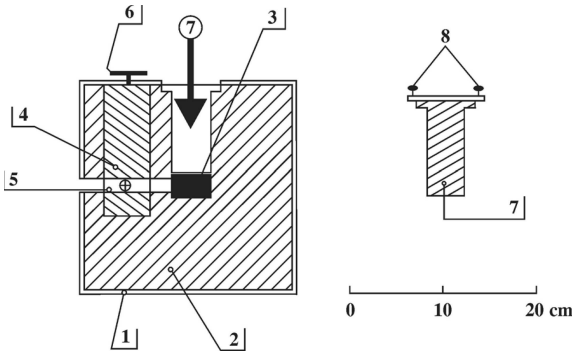

Figure 2. Schematic arrangement of the source container: Steel container of thickness 8.5 mm (1), cylindrical lead block (220 mm height × 220 mm diameter) mounted on the steel base and fits into a steel container (2), 20 Ci ^{137}Cs source of 23 mm diameter and 36 mm length as procured from Board of Radiation and Isotope Technology, Department of Atomic Energy, Mumbai, India (3), rotatable collimator-cum-beam shutter (diameter is 5 cm and length 14 cm) (4), hole in rotatable cylindrical collimator (5). The 90° rotation of this collimator is used to close/open the beam exiting from the hole, handle to rotate the cylindrical beam shutter (rotatable collimator) (6), lead T-shaped plug to cover and fix the ^{137}Cs source (7). The lower dimensions of T-shaped plug is 7.0 cm in height and 3.8 cm in width and the upper dimension is 2.6 cm in height and 4.8 cm in width. Screws are used to fix the T-shaped lead plug to avoid opening of source (8). An extra plug to stop the γ-ray beam while transporting the source container can be inserted in hole (5). Lined area represents the lead.

amplified, shaped and sorted in a 4096-channel analyzer (Canberra Accuspec B with Genie 2000) using the associated electronics as shown in figure 1. For the present set-up, one channel of MCA was equal to 62 eV (= 0.0352 a.u.). The stability of the detection system was checked several times during the course of measurement. To get a true Compton profile, the measured background was subtracted from the raw Compton spectrum channel-wise after scaling it to the measurement time of raw data. As required in such experiments, the resulting spectrum was corrected for instrumental resolution, sample absorption, Compton cross-section, detector efficiency, multiple scattering etc. [2,7] by using the computer code of Warwick University [7]. The instrumental resolution was limited to stripping off the low-energy tail in the measured data. In addition to these usual corrections, the data are also corrected for bremsstrahlung background correction which is due to continuous spectrum of bremsstrahlung (BS) emitted by photo and Compton electrons. A detailed, first ever, calculation for quantitative determination of BS background correction in high-energy Compton experiments is being reported separately by us [8] while the initial BS calculations for Hg sample along with the detailed analysis of the experimental profile are reported in [9]. The detector response function at Compton peak energy (188.5 keV) was reconstructed using 122.04 keV ^{57}Co line as suggested by Andrejczuk *et al* [5]. Relevant experimental parameters for Al, Tb and Hg samples are given in table 1.

Table 1. Experimental parameters of Al, Tb and Hg samples. The beam size at the sample position is 15 mm (dia). The effect of multiple scattering is determined using a Monte-Carlo simulation [7].

Sample	Dimensions of the sample	Exposure time (h)	Integrated counts in Compton region (million)	Normalization of profiles in 0–7 a.u. region	Multiple scattering (0–10 a.u.)
Aluminium (foil)	$30 \times 20 \times 2$ mm^3	84.2	6.46	6.15 e$^-$	5.8%
Terbium (foil)	$12 \times 12 \times 0.4$ mm^3	319	15.00	24.65 e$^-$	4.2%
Mercury (liquid)	Ampoule, thickness 3 mm, diameter 17 mm	321	20.60	28.73 e$^-$	10.9%

2.1 *Momentum resolution*

In Compton scattering experiments, the electron momentum p_z is given by

$$\frac{p_z}{m_0 c} = \frac{\{E' - E + EE'((1-\cos\theta)/m_0c^2)\}}{(E^2 + E'^2 - 2EE'\cos\theta)^{1/2}}, \tag{2}$$

where E and E' are the energies of primary and scattered radiations, θ is the scattering angle and m_0c^2 is the rest mass energy of an electron. The overall momentum resolution is given by

$$\Delta p_z = \left[\left(\frac{\delta p_z}{\delta E'}\Delta E'\right)^2 + \left(\frac{\delta p_z}{\delta \theta}\Delta\theta\right)^2\right]^{1/2}, \tag{3}$$

where $\Delta E'$ is the resolution of the detector and $\Delta\theta$ is the resultant angular divergence of the incident and scattered beams. The position of the Compton peak depends on the scattering angle, so a range of scattering angles (due to divergence) will produce a different spread in the peak position and hence an additional broadening of the Compton profile. In fact, the design of the present experimental set-up was decided after a careful estimation of the minimum possible spread ($\Delta\theta$) in the scattering angle using a Monte-Carlo simulation [7], which simulates the path of the incident and scattered photons through the spectrometer. Our result of simulation for 99,999 photons as applicable to a sample size of 12 mm diameter and a source collimator size of 8.0 mm diameter shows a Gaussian shape with a FWHM of 1.25°. Hence incorporating this angular spread and $\Delta E'$ (resolution of detector as 640 eV at Compton peak energy), the overall momentum resolution (Gaussian FWHM) of the spectrometer comes out to be 0.40 a.u., which can be called as an intermediate resolution. Andrejczuk *et al* [5] have reported a similar resolution for their 85 Ci ^{137}Cs spectrometer while Chang *et al* [6] have quoted Δp_z as ±0.34 a.u.

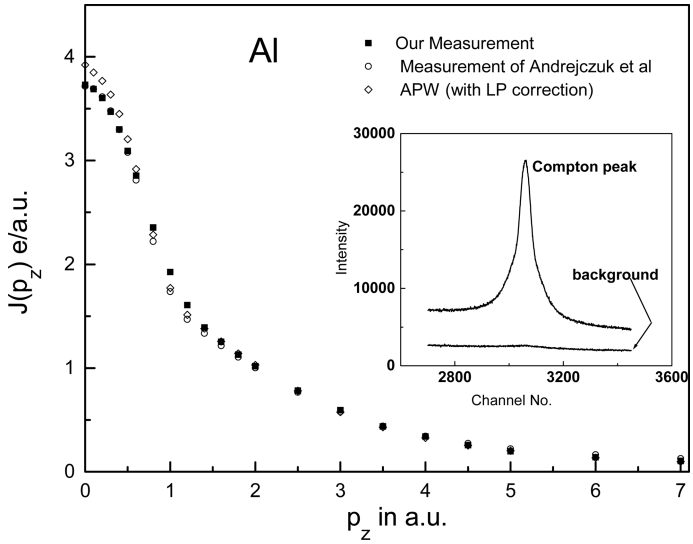

Figure 3. Duly corrected Compton profile data of Al sample along with measurements undertaken by Andrejczuk *et al* [5]. The APW Compton profile (with e^-–e^- correction) [12] is shown after convolution with a Gaussian instrumental function of FWHM 0.4 a.u. In the inset, our raw Compton profile data for 2 mm thick Al and the spectrum of background intensity (almost linear) recorded with the sample removed is also shown. Errors in the experimental Compton profiles are of the size of the symbols.

2.2 *Compton count rate*

The count rate under Compton profile can be given by source strength, number density of scatterers, Compton scattering cross-section, detection efficiency, attenuation coefficients for incident and scattered photons, thickness of the sample, solid angles subtended by the source and detector at the sample and the shape of the collimating tubes. For the present ^{137}Cs spectrometer, with approximately 50% detector (HPGe) efficiency at the Compton peak energy (188.5 keV), the measured counting rate for Al sample (2 mm thick) and Hg sample (3 mm thick) comes out to be 0.09 and 0.06 counts/62 eV channel width/s at the Compton peak. It is comparable to 0.17 counts/ 50 eV channel width/s at the Compton peak of Al reported by Andrejczuk *et al* [5] who have used 85 Ci ^{137}Cs source.

The figures of merit, namely, momentum resolution and count rate, which have been achieved in the present Compton spectrometer, are adequate to probe the momentum densities of heavy materials and study their Fermi surface topologies.

3. Performance of the apparatus

The duly corrected (except BS) Compton profile of Al along with similar data reported by Andrejczuk *et al* [5] and the spherically averaged convoluted augmented-

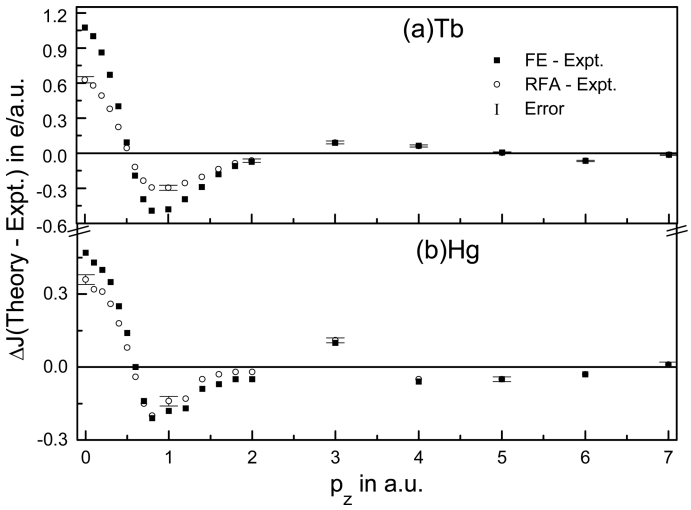

Figure 4. The difference profiles (ΔJ) between the convoluted RFA and free electron profiles and the experiment (with bremsstrahlung background correction) for (**a**) Tb and (**b**) Hg. The statistical error ($\pm\sigma$) is shown at a few points.

plane-wave (APW) calculations (with Lam-Platzmann e^-–e^- corrections) [10] are shown in figure 3. The appearance of raw Compton profile data for Al and representative energy spectrum of the background, measured with the window open but no sample in the position are also shown in the inset of figure 3. A comparison of experimental profiles of Al measured with 85 Ci ^{137}Cs source by Andrejczuk *et al* [5] and us, in figure 3, shows excellent agreement between the two experiments. A good agreement between the experimental and theoretical values in the core contribution region ($p_z \geq 4.0$ a.u.) shows the correctness of our data and its analysis. Both the experiments show disagreement with APW calculation for lower momenta. We cannot assign any particular reason for this but wish to point out that it may be due to some shortcomings (like limited number of reciprocal lattice vectors used) in the APW calculations [10].

To assess the performance of the spectrometer in the case of heavy materials, we have measured the Compton profiles of polycrystalline Tb and liquid Hg. In both the cases the data are corrected for systematic corrections including bremsstrahlung background correction. In the absence of band structure calculations, the experimental Compton profiles of Tb and Hg are compared with the renormalized-free-atom (RFA) model and the free electron (FE) model-based profiles. For the details of RFA calculations and the FE model profiles, we refer to [11–13]. For the present RFA calculations, the HF wave function for the 6s electrons of Hg was taken from the table of Herman and Skillman [14], while for Tb the 6s electron wave function of Fischer [15] was used. These wave functions were truncated to the corresponding Wigner–Seitz radius. Compton profiles due to valence 6s electrons of Tb and Hg were computed using 25 shortest reciprocal lattice vectors. For the contribution of the core electrons, free atom Compton profiles of Biggs *et al* [16] were used.

Figure 4 depicts that our experimental data for both the samples, namely, Tb and Hg give a reasonable agreement with the RFA model calculations, as seen in our earlier ^{241}Am-based studies on transition metals [3,12,13]. Our simple RFA calculations overestimate the momentum densities in the vicinity of Compton peak. In the high-momentum region ($\geq$4 a.u.), the experimental values are closer to the theoretical ones that ensure the correctness of our experiment and the data analysis. The agreement in the high-momentum side ($\geq$4 a.u.) is as per expectations since the core contribution, which dominates in this region was same in both the cases and inner core electrons are reasonably described by the free-atom profiles. In fact a systematic difference between the experiment and the theory (not shown here) in the high-momentum region was found, for both the samples, before the application of BS background correction. Therefore, we have corrected our experimental CPs for the background correction due to BS. It was seen that the effect of BS correction was to increase the experimental profiles in the vicinity of $p_z = 0$ and decrease these values for $p_z \geq 4$ a.u. which led to an overall better agreement between the theory and the experiment. Furthermore, using the feasibility of 90° scattering angle (as shown in figure 1), the spectrometer can also be used for the purpose of Compton scanning which will be helpful for 2D non-destructive examination like detection of voids, cracks etc. in industrial components.

4. Conclusions

The use of relatively low intense ^{137}Cs γ-ray source in our Compton spectrometer shows that the experiments with 5–20 Ci ^{137}Cs source are practicable if one carefully scales down the distances between source–sample and sample–detector and slits the incident and scattered radiations. The resolution of the present Compton spectrometer (0.40 a.u., Gaussian FWHM) and count rate are sufficient to probe the momentum densities and hence the electronic structure of high Z materials. The suggested design may be regarded as a guideline for the use of relatively low-intensity ^{137}Cs source in the high-energy γ-ray Compton spectrometers.

Acknowledgement

We are thankful to DST, New Delhi for financial support to undertake fabrication of India's first 20 Ci ^{137}Cs γ-ray Compton spectrometer through a research project (SP/S2/M-03/99). BLA is grateful to DST, New Delhi for a BOYSCAST fellowship to work in UK for a period of one year in the field of Compton spectroscopy. We are grateful to B K Godwal, S P Agarwal, E Zukowski, A Andrejczuk, M J Cooper and B K Sharma, for their help in setting up the spectrometer. We are thankful to BRIT, Department of Atomic Energy, India for the supply of 20 Ci ^{137}Cs source. Technical assistance of A Khan of our University Workshop is also acknowledged.

References

[1] M J Cooper, *Rep. Prog. Phys.* **48**, 415 (1985) and references therein
[2] B Williams (ed.), *Compton scattering* (McGraw-Hill, London, 1977)

[3] B K Sharma and B L Ahuja, *Phys. Rev.* **B38**, 3148 (1988)
B L Ahuja, M D Sharma, B K Sharma, S Hamouda and M J Cooper, *Phys. Scr.* **50**, 301 (1994)
K B Joshi, Rajesh Jain, R K Pandya, B L Ahuja and B K Sharma, *J. Chem. Phys.* **111**, 163 (1999)
[4] B K Sharma, B L Ahuja, R Jain, A Shukla, P Suortti, J A Duffy and M J Cooper, *J. Phys. Chem. Solids* **62**, 2233 (2001)
B L Ahuja, T Ramesh, B K Sharma, P Chaddah, S B Roy, Y Kakutani, A Koizumi, N Hiraoka, M Toutani and N Sakai, *Phys. Rev.* **B66**, 12411 (2002) and references therein
[5] A Andrejczuk, E Zukowski, L Dobrzynski and M J Cooper, *Nucl. Instrum. Methods* **A337**, 133 (1993)
A Bansil, S Kaprzyk, A Andrejczuk, L Dobrzynski, J Kwiatkowska, F Maniawski and E Zukowski, *Phys. Rev.* **B57**, 314 (1998)
[6] C N Chang, S B Lee and C C Chen, *J. Phys. Soc. Jpn.* **60**, 4253 (1991)
[7] D N Timms, Ph.D. Thesis (University of Warwick, England, 1989) (unpublished)
J Felstenier, P Pattison and M J Cooper, *Philos. Mag.* **30**, 537 (1974)
[8] S Mathur and B L Ahuja, *Phys. Lett.* **A335**, 245 (2005)
[9] B L Ahuja, M Sharma and S Mathur, *Z. Naturforsch.* **A59**, 543 (2004)
[10] N I Papanicolaou, N C Bacalis and D A Papaconstantopoulos, *Handbook of calculated electron momentum distributions, Compton profiles and X-ray form factors of elemental solids* (CRC Press, London, 1991)
[11] K F Berggren, *Phys. Rev.* **B6**, 2156 (1972)
[12] B L Ahuja, B K Sharma and O Aikala, *Pramana – J. Phys.* **29**, 313 (1987)
[13] Usha Mittal, B K Sharma, F M Mohammad and B L Ahuja, *Phys. Rev.* **B38**, 12208 (1988)
[14] F Herman and S Skillman, *Atomic structure calculation* (Prentice Hall Inc., Englewood Cliff, NJ, 1963)
[15] C F Fischer, *Atomic Data* **4**, 301 (1972)
[16] F Biggs, L B Mendelsohn and J B Mann, *At. Data Nucl. Data Tables* **16**, 201 (1975)