Applied Radiation and Isotopes 128 (2017) 125–131

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Measurement of large angle Rayleigh scattering cross sections for 39.5, 40.1 and 45.4 keV photons in elements with 26 ≤ Z ≤ 83

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HIGHLIGHTS

- Rayleigh scattering cross sections for the $_{62}$Sm (Kα_2, $K\alpha_1$ & $K\beta_{1,3}$) X-rays at 139° with 26 ≤ Z ≤ 83 are measured.
- The scattering cross sections based on the MFASF are in general higher for up to 7% for the medium- and high-Z elements.
- The S-matrix values exhibit in general good agreement with the measured cross sections.

ARTICLE INFO

Keywords:
X-ray fluorescence (XRF)
Photon scattering
Photon-electron interactions
X-rays
Form factor

ABSTRACT

The present work reports Rayleigh scattering cross section measurements for the 39.5 keV (Sm- $K\alpha_2$), 40.1 keV (Sm-$K\alpha_1$) and 45.4 keV (Sm-$K\beta_{1,3}$) X-ray photons in 35 elements with 26 ≤ Z ≤ 83 at backward angle of 139°. The scattering measurements were performed in reflection mode geometrical set up involving a secondary photon source consisting of Samarium ($_{62}$Sm) target excited by the 59.54 keV γ-rays from the ^{241}Am radioactive source. The scattered photons were detected using a low energy germanium (LEGe) detector. The product of detector efficiency, intensity of incident photons and other geometrical factors were determined by measuring the K X-ray yields from targets with 47 ≤ Z ≤ 59 and knowledge of the respective K X-ray fluorescence cross sections. The measured cross sections are compared with the theoretical cross sections based on the modified form factor (MF) formalisms and the second-order S-matrix approach. The experimental results demonstrate large deviations from the MF values for the elements with K shell binding energy (B_K) in vicinity of the incident photon energy (E_{in}), which smooth out with inclusion of the anomalous scattering factors (ASFs). The S-matrix values, in general, agree with the measured cross sections for all the elements under investigation.

1. Introduction

Rayleigh scattering is one of the predominant modes of photon interaction with atom in the X-ray energy region (< 100 keV). In this process, the photons are scattered by bound electrons mainly in the forward direction and the atom is neither ionized nor excited. Since the recoil is by the entire atom including the nucleus (rather than by an individual atomic electron as in the Compton effect) and photon loses only a negligible fraction of its energy, the Rayleigh scattering is coherent or elastic in nature resulting in interference effects. In case the coherence is spread over an array of atoms (photon wavelength ~ inter atomic distance), the interference becomes the Bragg diffraction, which is of importance in X-ray crystallography, crystal diffraction spectrometry and studies of molecular structures of biological interest.

The theoretical methods used to evaluate the Rayleigh scattering cross sections are based on the form factor formalisms and the S-matrix approach. The form factor was included as a correction factor for scattering by an extended charge distribution in the Thomson formula for the point charge, i.e., $d\sigma_T/d\Omega = (1/2)\, r_o^2(1 + \cos^2\theta)$ weighted by $F^2(x,Z)$, where $F(x,Z)$, is the atomic factor. In the sequential development of form factor formalism, non-relativistic and relativistic individual electron and total atomic wave functions were utilized to derive the electron charge density, and later, the relativistic modified form factor (MF), $g(x,Z)$, $[x = (E/hc)\sin(\theta/2)$, is the momentum transfer] was introduced to include the effect of electron binding energy. Further, anomalous-scattering factors (ASF's), g'(real) and g''(imaginary), were introduced to correct for strong interference of spatial distribution of electrons in the ordered structure at photon

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http://dx.doi.org/10.1016/j.apradiso.2017.07.012
Received 17 May 2017; Received in revised form 5 July 2017; Accepted 7 July 2017
Available online 08 July 2017
0969-8043/

energy in proximity of the electron binding energy. The imaginary part of the ASF's (g'') at forward angle is determined from the photo effect total cross section and the real part (g'), can then be obtained from a dispersion relation (Cromer and Liberman, 1981; Henke et al., 1982; Kissel and Pratt, 1990). All the calculations for photoabsorption cross section done so far consider only the bound-free transitions and neglect the bound-bound transitions, which become significant (~10%) at energies close to threshold (Zhou et al., 1990; Kissel et al., 1995). The ASF's are often considered to be angle-independent, (Karle, 1989), but this assumption can be poor for high-Z inner shells.

Further theoretical effort toward improved values of the Rayleigh scattering cross sections is focused on use of the second-order relativistic S-matrix approach (Kissel et al., 1980, 1995; Pratt et al., 1994). This formalism is capable of revealing anomalous scattering, particularly, in vicinity of the absorption edge energies. The effect of binding in the intermediate state, which was neglected in the form-factor calculations, has been taken into account analytically in the S-matrix calculations. The calculations were performed in the independent particle approximation (IPA), which assumes that the independent electrons interact electrostatically with a central potential resulting from charge distribution of the nucleus and electrons.

Most of the Rayleigh scattering measurements have been performed using photons emitted from the radioactive sources, viz., the Np L X-rays and the 59.54 keV γ-rays using the ^{241}Am source (Varier and Unnikrishnan, 1989; Casnati et al., 1990; Elyaseery et al., 1998, 2000; Shahi et al., 1998; Kumar et al., 2009), the Ag K X-rays and the 88.03 keV γ-rays using the ^{109}Cd source (Basavaraju et al., 1995; Kumar et al., 2001, 2007), the 279.2 keV and 661.6 keV γ-rays using ^{203}Hg and ^{137}Cs sources (Bradley and Ghose, 1986). The primary photon beams directly available from the radioisotopes and X-ray tube have limitation of the fixed incident photon energies. A few measurements were also performed using secondary target excited using photons from the ^{241}Am radioisotope (Singh et al., 2004, 2006) and X-ray tube (Tirsell et al., 1975; Garg et al., 1993; Rao et al., 1994, 1995, 1998). These measurements (Tirsell et al., 1975; Garg et al., 1993; Rao et al., 1994, 1995, 1998) lack proper corrections related to determination of the incident photon intensity and geometrical factors. Others (Varier and Unnikrishnan, 1989; Casnati et al., 1990; Elyaseery et al., 1998, 2000) used theoretical values of angle-dependent scattering cross sections in the low-Z elements for deducing these parameters. Intensive differential Rayleigh scattering cross sections at the 59.54 keV photon energy covering the atomic region $22 \le Z \le 92$ and over a wide angular range 10–160°, have been reported by Kumar et al. (2009). The measured values are found to be in general lower than those based on the MF including ASF's values by ~10% at forward angles and ~20% at backward angles for the medium and high Z-elements, which are indicative of possible angular dependence of ASF's. The ASF's contributions to the MF cross sections become significant at large angle and for elements having electrons with binding energy close to the incident photon energy. In the present work the Rayleigh scattering cross sections for 39.5, 40.1 and 45.4 keV K X rays obtained from Samarium ($_{62}$Sm) secondary photon source have been measured at an angle 139° for 35 elements in the atomic range $26 \le Z \le 83$. The measured Rayleigh scattering cross sections have been compared with those based on the modified form factor (MF) and ASF corrected MF (MFASF) formalisms and the S-matrix (SM) approach.

2. Experimental details

2.1. Experiment procedure

The differential Rayleigh scattering cross sections measurements were performed in reflection mode geometrical set-up shown in Fig. 1(a). It involved a secondary photon source consisting of $_{62}$Sm annular foil (inner diameter = 27 mm and width = 4 mm) excited by the 59.54 keV γ-ray photons from the ^{241}Am (300 mCi, DUPONT, US).

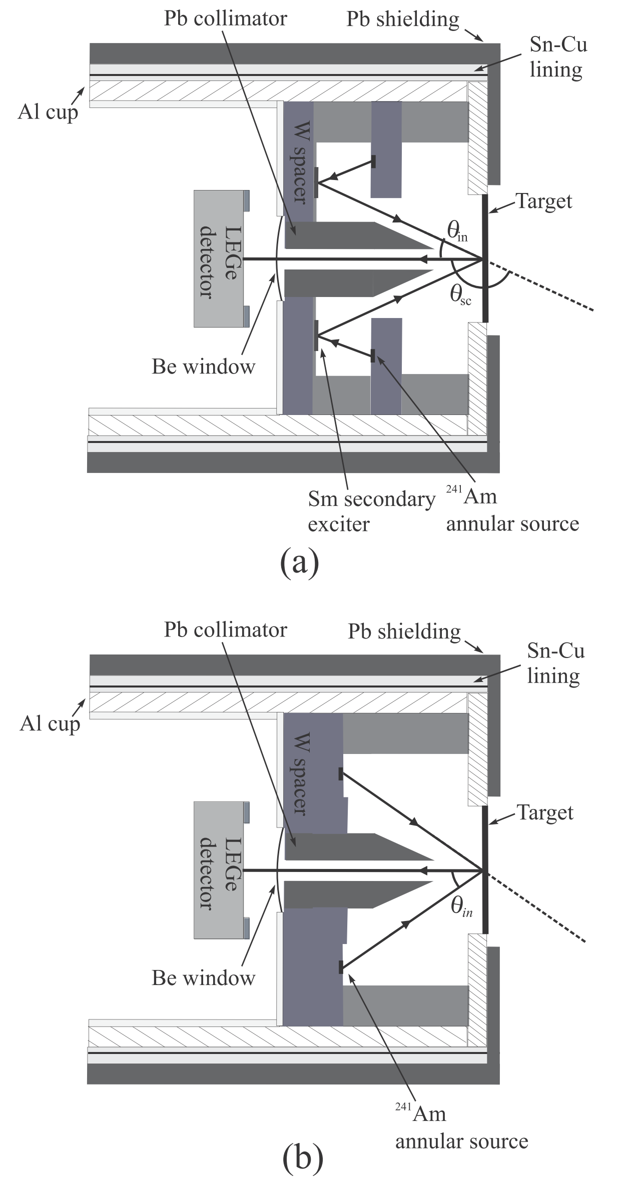

Fig. 1. Geometrical set up involving (a) secondary photon source consisting of the $_{62}$Sm annular foil excited by the ^{241}Am radioactive annular source, and (b) the ^{241}Am radioactive source covered with Cu-Al graded absorber as a direct photon source.

The Sm-$K\alpha_2$, $K\alpha_1$ and $K\beta_{1,3}$ X-ray photons from the $_{62}$Sm annular foil (secondary photon source) were made to scatter from the target and the scattered photons were detected using a low-energy germanium (LEGe) detector (100 mm^2 x 10 mm, 8-μm Be window, Canberra, US). The LEGe detector (full width at half maxima = 300 eV at 59.5 keV) was coupled to PC-based multichannel analyzer (Canberra, Model S-100) to collect the X-ray spectra. The source and target geometrical arrangement was housed inside the Pb-Sn-Cu graded shield. The target-to-detector distance was precisely adjusted to obtain maximum count rate from the target. The reproducibility of the geometrical arrangement was checked. The measurement were performed using spectroscopically pure foils of $_{26}$Fe, $_{27}$Co, $_{30}$Zn, $_{41}$Nb, $_{42}$Mo, $_{46}$Pd, $_{47}$Ag, $_{48}$Cd, $_{49}$In, $_{50}$Sn, $_{51}$Sb, $_{64}$Gd, $_{65}$Tb, $_{67}$Ho, $_{68}$Er, $_{69}$Tm, $_{70}$Yb, $_{72}$Hf, $_{73}$Ta, $_{74}$W, $_{75}$Re, $_{77}$Ir, $_{78}$Pt, $_{79}$Au, $_{82}$Pb and $_{83}$Bi having thickness ranging 2–800 mg cm^{-2}. Thick pelletized targets of the $_{33}$As, $_{34}$Se and $_{52}$Te elements were prepared using their pure elemental powder form, and those of the $_{37}$Rb, $_{38}$Sr, $_{56}$Ba, $_{57}$La, and $_{71}$Lu elements using the $RbNO_3$, $SrCO_3$, $Ba(NO_3)_2$, La_2O_3, and Lu_2O_3 compounds, respectively. Pellets of 1 in. diameter were prepared by pressing the elemental/chemical compound powder using the pelletizer machine (Paul-Otto-Weber Co., Germany). The $_{80}$Hg