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Measurement of total M shell photoionization cross sections for Au, Pb, Th and U in the energy region 6–12 keV

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Abstract. The total M shell relative photoionization cross-sections for Au, Pb, Th and U have been measured in the energy region 6–12 keV. External conversion K X-rays of suitable elements has been employed as incident photons to photo ionize the total M shell of elements under investigation. The method provides relative cross-sections therefore does not make use of theoretically calculated average M shell fluorescence yields which involve uncertainties of the order of 20%. No evidence of deviation from calculated values of cross-sections have been observed within experimental errors for all incident photon energies.

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1 Introduction

Our earlier experimental study [1,2] of energy dependence of K as well as L shell photoionization (PI) cross sections by measuring the intensity of emitted fluorescent X-rays, have been extended to M shell since no such measurement has been reported so far. Methodology of measurements already developed [2], which eliminates the use of fluorescence yield and absolute efficiency of detector, has been applied in present measurements. Moreover, small variations in fluorescence yield due to chemical, solid state and multiple ionization effects [3] are automatically cancelled in present work. Elimination of average M shell fluorescence yield (ϖ_M) alone improves the reliability of measured cross sections to greater extent as scarcely available values [4] of ϖ_M of high Z elements differ from each other by ~20%. Method needs only ratios of counting rates, absorption in target and efficiency of detector to measure intensity of incident photons falling on target under investigation. Due to limited resolution of presently available Si(Li) detector, various M shell X-ray lines are not well resolved, only total M shell PI cross sections have been measured in Au, Pb, Th and U for incident photons of weighted mean [5] energies 6.47, 7.558, 8.136, 8.735, 10.005 and 11.372 keV and results are reported in this paper. Elements under investigation and energy range of incident K X-ray photons have been so chosen so as photoionization of only all M sub shells takes place.

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2 Experimental set-ups, methodology and analyzing procedures

Experimental arrangement used in present measurements is different from earlier one [2] and is described elsewhere [6]. Present geometry uses annular gamma ray source instead of point source to enhance intensity of incident photons which, in turn, produce measurable intensity of M X-rays of elements under study with uncertainties in the range ~1–3%. Briefly, primary targets [PT] of Fe, Ni, Cu, Zn, Ge and Se, were irradiated with 59.57 keV gamma rays emitted from one-curie annular ^{241}Am source. Photons emitted from each of PT were allowed to fall on secondary targets [ST] of Au, Pb, Th and U. Each target was of 4 cm in diameter. Photons emitted from ST were counted by Si(Li) detector purchased from EG&G ORTEC, USA. Si(Li) detector having active diameter 10 mm, sensitive depth 4.6 mm of crystal and Be window of thickness 0.0254 mm, was coupled to ND-600 MCA. The resolution of X-ray spectrometer was found to be ~170 eV at 5.9 keV. Self-supporting and spectroscopically pure targets of Fe, Ni, Cu, Au, Pb, Th and U were procured from Reactor Experiments Inc. USA while targets of Zn, Ge and Se were made from their spectroscopically pure powder by the technique explained earlier [7]. The distance between PT and ST was kept 6 cm and it has been found that change in weighted mean energy of incident K X-rays is very small of the order of ~0.04% due to absorption in air and such a small change has been neglected.

Table 1. Measured values of relative total M shell PI cross-sections $\sigma(E)/\sigma(E_{ref})$ of Au, Pb, Th and U, compared with theoretical calculations of Scofield [9]. E and E_{ref} are weighted mean [5] energies of incident K X-rays. The E_{ref} for all target elements is 8.735 keV.

Incident	Au		Pb		Th		U	
energy	Expt	Calc	Expt	Calc	Expt	Calc	Expt	Calc
6.47	2.29 ± 0.16	2.16	2.20 ± 0.16	2.15	2.05 ± 0.11	2.12	2.18 ± 0.10	2.12
7.558	1.51 ± 0.12	1.45	1.41 ± 0.11	1.45	1.50 ± 0.08	1.44	1.40 ± 0.08	1.44
8.136	1.14 ± 0.09	1.20	1.28 ± 0.10	1.20	1.15 ± 0.06	1.20	1.15 ± 0.06	1.20
8.735	1.00 ± 0.00	1.00	1.00 ± 0.00	1.00	1.00 ± 0.00	1.00	1.00 ± 0.00	1.00
10.005	0.685 ± 0.055	0.703	0.715 ± 0.055	0.705	0.726 ± 0.050	0.709	0.685 ± 0.045	0.710
11.372	0.525 ± 0.040	0.503	0.521 ± 0.040	0.505	0.490 ± 0.035	0.509	0.529 ± 0.035	0.511

The relative M shell PI cross section is given by the relation [2]:

$$\frac{\sigma_M(E)}{\sigma_M(E_{ref})} = \frac{N_S(P)}{N_S(P_{ref})} \frac{\beta(E_{ref})}{\beta(E)} \frac{N_K(P_{ref})}{N_K(P)} \frac{\varepsilon(E)}{\varepsilon(E_{ref})} \quad (1)$$

where P and P_{ref} are the two primary targets giving external conversion K X-rays of weighted mean energy E and E_{ref} respectively. $N_S(P)$ and $N_S(P_{ref})$ are the counting rates under the photo peaks of the spectra of secondary target M X-rays when secondary target is irradiated with primary K X-rays from P and P_{ref} respectively. $\beta(E)$ and $\beta(E_{ref})$ are the correction factors of secondary target which take account of the absorption of incident K X-rays and emitted M X-rays. $N_K(P)$ and $N_K(P_{ref})$ are the counting rates under photo peaks of incident K X-rays of primary targets P and P_{ref} when primary target is irradiated with 59.57 keV gamma rays from ^{241}Am source. $\varepsilon(E)$ and $\varepsilon(E_{ref})$ are the effective efficiencies of the detector to detect primary target K X-rays of energy E and E_{ref} respectively. The ratio $N_S(P)/N_S(P_{ref})$ was evaluated by measuring the ratio of the areas under the composite M X-ray peak observed in the spectra of radiation emitted from secondary target on irradiation with K X-rays from P and P_{ref} targets respectively. A sufficient number of sets of area under M X-ray peak were taken for time interval ranging from 30 000 to 80 000 s to reduce the statistical error in area evaluation to $\sim$1–2%. The ratio $\beta(E_{ref})/\beta(E)$ was calculated in a similar way as explained in our earlier communication [6] using values of absorption coefficients obtained from standard database Berger et al. [8]. The ratio $N_K(P_{ref})/N_K(P)$ was determined in separate experimental set-up, which consists of ($Xe + CO_2$) filled proportional counter manufactured by Reuter Stokes USA, placed at the position of target emitting M X-rays and further details have been described earlier [2]. Measured counts of K X-rays involve uncertainties of the order of <1%. From known physical parameters of ($Xe + CO_2$) proportional counter as supplied by manufacturer such as thickness of Be window, gas pressure, composition of gas, physical dimensions of gas chamber etc., the ratio $\varepsilon(E)/\varepsilon(E_{ref})$ was calculated using absorption coefficients of Berger et al. [8].

Radiation emitted from PT, which in turn falls on ST, consists of characteristic K and higher shell X-rays of PT and 59.57 keV scattered gamma ray photons. Contribution of unwanted M X-rays produced due to the interaction of scattered gamma ray photons, has been measured by using equivalent aluminum as PT as detailed in earlier communication [6].

3 Results and discussion

The values of $\sigma(E)/\sigma(E_{ref})$ for Au, Pb, Th and U as determined experimentally are listed in Table 1. As no other experimental data are available, the results have been compared with theoretical values interpolated from the values calculated by Scofield [9]. The weighted mean [5] energy of Zn K X-rays is taken as reference energy (E_{ref}). There is a fairly good agreement between experimental and calculated values. The overall error in results is of the order of $\pm$5–8% which has been evaluated by properly propagating errors in various measured/computed parameters given in equation (1). It is to be noted here that the calculated values of cross sections, which are based upon relativistic mechanics and Hartree Slater potential carry errors as low as <1% and therefore for precision testing of theory one needs minimum possible error in experimental values of the order of <1%.

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