Radiation Physics and Chemistry 96 (2014) 1–4

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

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

Measurements of *K*-shell X-ray production cross-sections and fluorescence yields for Cr, Mn, Fe and Co elements

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HIGHLIGHTS

- K_α and K_β X-ray production cross-sections have been determined for the elements Cr, Mn, Fe and Co at 8.735 keV.
- Fluorescence yields have been determined for the elements Cr, Mn, Fe and Co.
- Results have been compared with results from experimental and theoretical studies.

ARTICLE INFO

Article history:
Received 8 March 2013
Accepted 6 August 2013
Available online 14 August 2013

Keywords:
X-ray
Fluorescence yields
Cross-sections

ABSTRACT

K_α and K_β X-ray production cross-sections have been measured for the elements Cr, Mn, Fe and Co. Measurements have been carried out at 8.735 keV excitation energy by using secondary source. The values of *K*-shell fluorescence yields ω_K have been measured for the same elements. The results obtained for *K* X-ray production cross-sections and fluorescence yields have been compared with theoretically calculated values and other available semi-empirical values.

1. Introduction

K_α and K_β X-ray production cross-sections and fluorescence yields (ω_K) are important in a variety of fields such as atomic physics, molecular physics, space physics, plasma physics, X-ray fluorescence analysis, medical research, environmental protection and industrial processing (Hubbell et al., 1994; Özdemir et al., 2002). In addition, these measurements provide an indirect check on physical parameters, such as *K*-shell fluorescence yields, photoionization cross-sections, jump ratios and *K* X-ray emission rates.

The de-excitation of an atom with an inner-shell *K* vacancy can proceed either by the emission of an X-ray photon or by the ejection of Auger electrons. The de-excitation of an atomic shell is characterized by these fluorescence yields and is defined as the probability that a vacancy in the *K*-shell filled through a radiative transition.

K X-ray production cross-sections and fluorescence yields for different elements have been investigated for many years. Earlier experimental *K* X-ray production cross-sections have been measured using radioisotopes as excitation sources (Garg et al., 1985). Photon-excited *K* X ray production cross-sections have been measured for some light elements in the range 20–60 keV (Rao et al., 1993d). *K* X-ray production cross-sections have been determined theoretically for all of the elements at energies ranging from 10 to 60 keV (Krause et al., 1978). *K*-shell X-ray production cross-sections and fluorescence yields have been measured for some elements (Bhan et al., 1981; Kumar et al., 1987; Durak et al., 1998; Durak and Özdemir, 2001; Şimşek et al., 2002; Budak et al., 1999; Özdemir et al., 2002). However, limited investigations in the case of cross-sections of intermediate-Z elements have been made at different excitation energies (Singh et al., 1990; Casnati et al., 1991).

K-shell fluorescence yields for different elements have been investigated for many years. Bambynek et al., (1972) in a review article have fitted their collection of selected experimental values in the $13 \le Z \le 92$ range. Krause (1979) compiled ω_K adopted values for elements $5 \le Z \le 110$. Hubbell et al. (1994) have compiled more recent experimental values. Theoretical values of ω_K were obtained in the region $4 \le Z \le 54$ by McGuire (1970a,b) and Walters and Bhalla (1971) using the Hartree–Fock–Slater model. Kostroun et al. (1971) presents computations for elements in the range $10 \le Z \le 70$ by combining Scofield's (1969) radiative widths with radiationless transition probabilities calculated from non-relativistic hydrogenic wave functions (Durak and Özdemir, 2001).

In the present study, the *K* X-production cross-sections for the elements Cr, Mn, Fe and Co have been measured at 8.735 keV.

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http://dx.doi.org/10.1016/j.radphyschem.2013.08.004

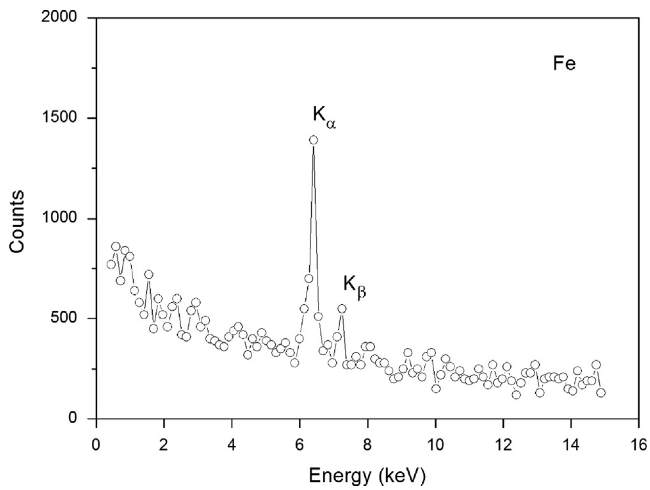

Fig. 1. *K* X-ray spectrum of Fe.

K-shell fluorescence yields were deduced from the measured cross-sections by using the theoretical photoionization cross-sections, and fractional X-ray emission rates. The results obtained for *K* X-ray production cross-sections and fluorescence yields are compared with the theoretically calculated values and other available semi-empirical values.

2. Experimental method

The experimental arrangement used in the present study has been described elsewhere (Yılmaz, 2012). The targets were excited by the *K* X-rays of the secondary source excited at 59.5 keV γ-rays from a ^{241}Am point source. Fluorescent X-rays spectra from targets were recorded by a colimated Si(Li) X-ray spectrometer (FWHM = 160 eV at 5.96 keV, active area = 12.5 mm^2, sensitivity depth = 3.5 cm, Be window thickness = 12.5 μm) coupled to a nuclear data MCA system (ND66B) consisting of a 4096 channel analyzer, an ADC and spectroscopy amplifier. The net peak areas of the *K* X-rays of each target were determined after background subtraction, talling and escape-peak corrections (Öz, 2006). The secondary excitation source was pure Zn (99.99%). The excitation energy was taken as average of K_α and K_β X-ray energies. For Zn, weighted averages K_α, K_β, $K_{\alpha\beta}$ energies are 8.631, 9.532 and 8.735 keV, respectively (Storm and Israel, 1970).

The experimental *K* X-ray production cross-sections were evaluated using the relation

$$\sigma_{Ki} = \frac{N_{Ki}}{I_0 G \varepsilon_{Ki} t \beta} \tag{1}$$

where N_{Ki} (($i = \alpha, \beta$) is the net number of counts per unit time under the corresponding photopeak, the product I_0G is the intensity of exciting radiation falling on the area of target foil visible to the detector, ε_{Ki} is the detector efficiency for the K_i X-rays, t is the mass thickness of sample in g/cm^2, and β is the self-absorption correction factor for the incident photons and emitted *K* X-ray photons. β is calculated by using the relation.

$$\beta = \frac{1 - \exp[-(\mu_1/\sin\theta + \mu_2/\sin\theta)t]}{(\mu_1/\sin\theta + \mu_2/\sin\theta)t} \tag{2}$$

where μ_1 and μ_2 are the total mass absorption coefficients of target material at the incident photon energy and the emitted average K_α and K_β X-ray energy (Storm and Israel, 1970). θ is the angle of incident photon and emitted X-rays with respect to the normal at the surface of the sample. θ is 45^0 for the present set-up.

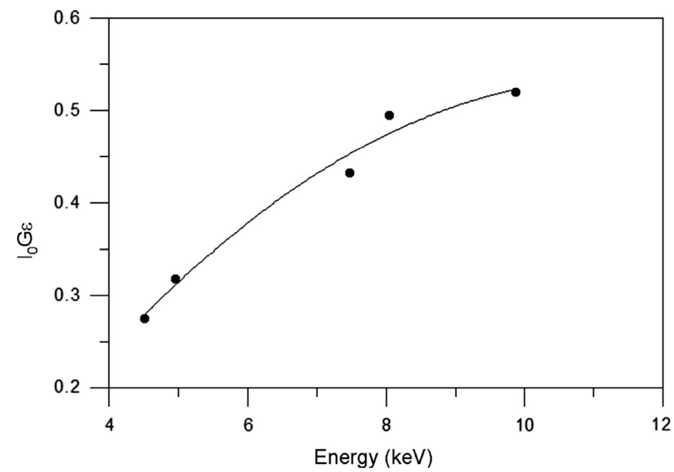

Fig. 2. $I_0G\varepsilon$ values versus *K* X-ray energy for Cr, Mn, Fe and Co elements.

Table 1
Experimental and theoretical K_α X-ray cross-sections(barns/atom).

Element	Excitation energy (keV)	Present work	Theoretical predictions (from Eq. (4))
Cr	8.735	3640 ± 260	3738.892
Mn	8.735	4831 ± 362	4778.448
Fe	8.735	5861 ± 448	5981.217
Co	8.735	7480 ± 517	7359.525

In the present work, as shown in Fig. 2, the values of the factors, $I_0G\varepsilon$, which contain terms related to the incident photon flux, geometrical factor and the efficiency of the X-ray detector, were determined by collecting the *K* X-ray spectra of thin samples of Ti, V, Ni, Cu and Ga, in the same geometry in which the *K* X-ray fluorescence cross-sections were measured and using the equation

$$I_0 G \varepsilon_{K_\alpha} = \frac{N_{K_\alpha}}{\sigma_{K_\alpha} \beta t} \tag{3}$$

where N_{K_α} is the net number of counts under the corresponding photopeak, ε_{K_α} is the detector efficiency for K_α X-rays and β is the self-absorption correction factor for the incident photons and emitted K_α X-ray photons. A typical *K* X-ray spectrum for Fe is shown in Fig. 1.

3. Theoretical method

The theoretical values of *K* X-ray production cross-sections $\sigma_{K\alpha}$ and $\sigma_{K\beta}$have been calculated using the relation (Durak et al., 1998),

$$\sigma_{K\alpha} = \sigma_K(E)\omega_K f_{K\alpha} \tag{4}$$

$$\sigma_{K\beta} = \sigma_K(E)\omega_K f_{K\beta} \tag{5}$$

where $\sigma_K^P(E)$ is the *K*-shell photoionization cross-section for the given element at excitation energy E, ω_K is the *K*-shell fluorescence yield. $f_{K\alpha}$ and $f_{K\beta}$ are fractional X-ray emission rates for K_α and K_β X-rays that are defined as,

$$f_{K\alpha} = (1 + I_{K\beta}/I_{K\alpha})^{-1} \tag{6}$$

$$f_{K\beta} = (1 + I_{K\alpha}/I_{K\beta})^{-1} \tag{7}$$

where $I_{K\beta}/I_{K\alpha}$ is the K_β to K_α X-ray intensity ratio. In the present calculations, the values of $\sigma_K^P(E)$ were taken from Scofield (1973a)