$K\beta$-to-$K\alpha$ x-ray intensity ratios after ionization by γ rays

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(Received 13 October 1988; revised manuscript received 25 April 1989)

The $K\beta$-to-$K\alpha$ x-ray intensity ratio was measured for the following elements: Mn, Cu, Zn, Ag, Cd, In, and Sn. The vacancies in the K shell were created by 59.54-keV γ rays from an ^{241}Am source and the x rays were measured using a hyperpure germanium detector. Our results agree with previous published experimental results.

I. INTRODUCTION

Several recent publications[1–10] point to the continued interest in the precise measurement of the $K\beta$-to-$K\alpha$ yield ratio. In these measurements the K-shell vacancies were created either by internal conversion[1–3] or by several types of projectiles—photons,[4–6] electrons,[7] protons,[8–10] or heavier ions[11,12]—and filled by outer electrons, leading to the emission of K x rays. The $K\beta$-to-$K\alpha$ yield ratio is related essentially to the atomic potential but also carries information on the kind of excitation and the chemical state of the target. Its measurement is also important for applications ranging from multielemental analysis[13] to sub-barrier nuclear fusion.[14]

Although this parameter seems to be easily measurable, the experimental data from individual experiments still present a relatively large spread and even the average experimental data, presented by the two more complete compilations of these data,[15,16] differ by as much as 3%. Several factors contribute to this spread, such as the above-mentioned dependences on the vacancy origin and on the target chemical state. Other possible relevant sources of error are the eventual use of low-resolution detectors, the uncertainty of the detector efficiency measurement, and the procedure to obtain the areas under the peaks.

Theoretical calculations were made by Scofield[17] using relativistic Hartree-Slater single-particle wave functions. Although reproducing the major features of the experimental data compilations,[15,16] these calculations underestimated the averaged experimental data by values ranging from 4% to 10%. That could be attributed to the exchange correction arising from the overlap of the inner shell wave functions, as pointed out by Scofield in a subsequent paper.[18] His newer results[18], corrected for this nonzero overlap, fitted the experimental values much better. For atoms with Z smaller than 40 again the agreement was not so good, this time overestimating experiment by a maximum of 4%. Although small, these disagreements were larger than the claimed experimental uncertainties.

The measurements reported here were made in the medium Z region using a germanium detector and obtaining more precisely the areas under the peaks. The $K\beta$-to-$K\alpha$ intensity ratios were measured for Mn, Cu, Zn, Ag, Cd, In, and Sn, the K-shell vacancies being created by 59.54-keV γ rays, emitted by an ^{241}Am source.

II. EXPERIMENTAL ARRANGEMENT

A commercial radioactive ^{241}Am source was used, with an activity of 100 mCi. It was sealed in a welded stainless-steel annular capsule, with 38 mm outer diameter, blocking the α particles and the Np L-shell x rays and allowing only the emission of 59.54-keV γ rays. The targets were placed at 5 cm from the source, their x rays going through the hollow center of the source assembly and also through a graded-Z collimator placed in front of the detector (Fig. 1).

A hyperpure germanium detector, with a volume of 40 cm^3, was used for the detection of the x rays. Its absolute efficiency was determined using International Atomic Energy Agency (IAEA) calibration sources.

III. DATA ANALYSIS

The measured x-ray emission rate N_i is given by

$$N_i = \left[\frac{A\omega_1\omega_2}{16\pi^2} \right] \beta_i T_i \epsilon_i \sigma_i t n \ , \tag{1}$$

where A is the source activity, ω_1 and ω_2 are the target-source and the target-detector solid angles, respectively, i specifies the x ray ($K\alpha$ or $K\beta$), σ_i is the emission cross section, β_i is the target absorption correction factor, T_i is the air transmission coefficient, ϵ_i is the detector efficiency, t is the target thickness, and n its mass density.

The target absorption correction β_i is given by

$$\beta_i = \frac{1-\exp\{-t[(\mu_0/\cos\theta_1)+(\mu_i/\cos\theta_2)]\}}{t[(\mu_0/\cos\theta_1)+(\mu_i/\cos\theta_2)]} \ , \tag{2}$$

where μ_0 and μ_i are the target absorption coefficients for

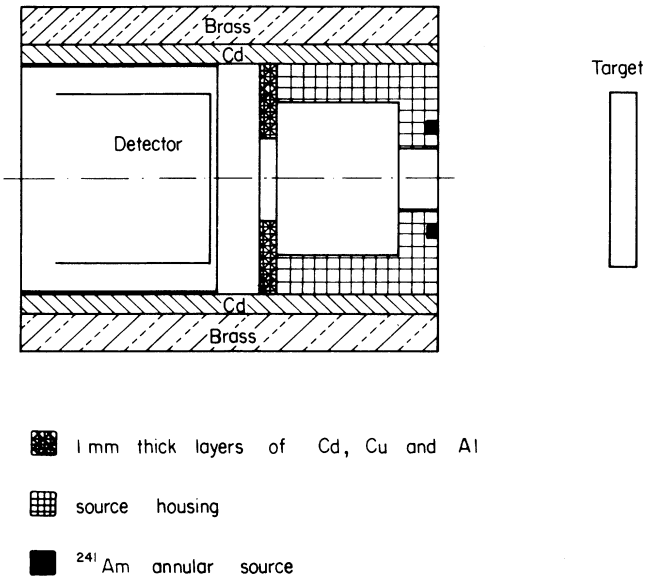

FIG. 1. Experimental arrangement.

the incident γ rays and the emitted x rays and θ_1 and θ_2 are the incidence and the emission angles with respect to the target normal.

Equation (1) yields the ratio of the σ_β and the σ_α cross sections

$$\frac{\sigma_\beta}{\sigma_\alpha}=\frac{N_\beta\epsilon_\alpha\beta_\alpha T_\alpha}{N_\alpha\epsilon_\beta\beta_\beta T_\beta}\ . \tag{3}$$

In this experiment the angles θ_1 and θ_2 were equal, as the directions of incidence and emission were nearly normal to the target. Also the target thickness was much larger than the mean penetration depths for the x rays. This simplifies Eq. (2) and then Eq. (3) becomes

$$\frac{\sigma_\beta}{\sigma_\alpha}=\frac{N_\beta\epsilon_\alpha(\mu_0+\mu_\beta)T_\alpha}{N_\alpha\epsilon_\beta(\mu_0+\mu_\alpha)T_\beta}\ . \tag{4}$$

The above simplification avoids the errors introduced in the measured $\sigma_\beta/\sigma_\alpha$ ratio due to normalization errors in the absorption coefficients and to the target thickness determination. Nevertheless still contributing to the uncertainty of the yield ratio are the several factors on the right-hand side of Eq. (4), as discussed next.

The β_α/β_β ratios are now a quotient of absorption coefficients, as Eq. (4) shows. The values calculated using the Veigele[19] absorption coefficients were 1% lower than the ones obtained using the Storm and Israel values.[20] We averaged both sets of data and set this error equal to 1%, which is certainly an overestimation. The T_α/T_β ratios were calculated using the absorption coefficients for air given by Hubbell.[21] As these ratios are nearly equal to unity, the uncertainty in the absorption coefficients is negligible.

The N_α and N_β areas were typically in the range 10^4-10^5, leading to a statistical error equal to 1% in their ratio. The areas for the Mn, Cu, and Zn cases, where there was a strong superposition of the $K\alpha$ and $K\beta$, were obtained by the doublet graphical separation. The areas on the other cases (Ag, Cd, In, and Sn) were obtained directly from the spectra, as the peaks were well separated, but also checked against the results of the graphical analysis, with excellent agreement.

The standard peak shape used in this separation was obtained from a composition of low- and the high-energy tails of the $K\alpha$ and the $K\beta$ peaks. As an example, the separation of our worst case of superposition, the manganese spectrum, is shown in Fig. 2. The area determination error, mainly due to the peak tails, is much smaller than 1%. The $K\alpha$ and $K\beta$ are complex peaks but, for the small Z targets, the $K\beta$ main components coincide within 1 eV. The $K\alpha$ components, differing by less than 20 eV, make the $K\alpha$ peak only 1% wider than the detector standard response to a monoenergetic radiation, as the contributions to resolution add up quadratically.

A simpler alternative way to obtain the N_β/N_α ratio is to neglect the superposition of the peaks at their maxima and, after the subtraction of the background, to divide the peak heights one by the other. The values obtained were identical to the ones given by the graphical analysis.

Another way to obtain the area ratio would be the computational decomposition of the spectra, as done by

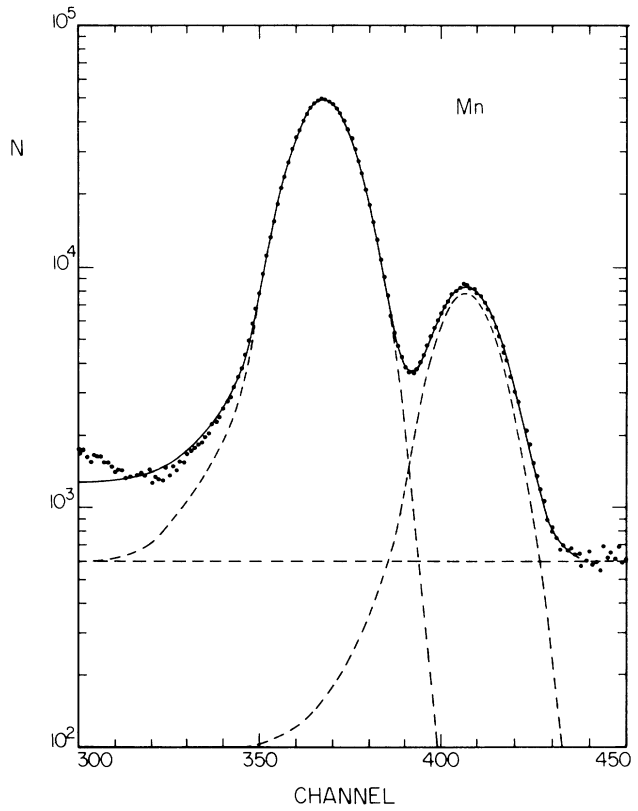

FIG. 2. Graphical analysis of the experimental Mn K x-ray spectrum. The dashed lines represent the background and the two peaks and the solid line shows the sum of these three components.

TABLE I. $K\beta$-to-$K\alpha$ intensity ratios. Our values are compared to most probable experimental values (Refs. 15 and 16) and to Scofield's theoretical results (Ref. 18).

Element	Mn	Cu	Zn	Ag	Cd	In	Sn
Z	25	29	30	47	48	49	50
Our values	0.129	0.133	0.134	0.203	0.210	0.217	0.215
Khan and Karimi (Ref. 15)	0.134	0.137	0.139	0.212	0.216	0.218	0.222
Salem *et al.* (Ref. 16)	0.135	0.136	0.138	0.211	0.213	0.216	0.220
Scofield (Ref. 18)	0.138	0.138	0.141	0.213	0.216	0.220	0.223

Campbell *et al.*[3] Their peak standards were obtained using monoenergetic photons from an x-ray tube, adjusting these peaks to an analytical shape and interpolating these parameters. The data of Campbell *et al.* for the electron-capture-produced $K\beta$-to-$K\alpha$ ratio present two problems: they show relatively large χ^2 values and there is also a discrepancy as large as 4% between data taken using two different detectors. These fitting problems were probably due to the differences between the monoenergetic standards obtained with an x-ray tube and the ones for monoenergetic photons emitted by a target (with another geometry). They point to the main problem of computational analysis at these low energies: to have reliable experimental standards yielding areas with errors smaller than 1% or even 5% (as shown, for instance, in a recent publication[22]).

The last and largest source of error is due to the quotient of the efficiencies $\epsilon_\alpha/\epsilon_\beta$. In fact the x rays studied lie near to the discontinuity in the efficiency curve at 11 keV caused by the escape of the Ge K x rays, where the energy dependence of the efficiency is large. Also contributing to the uncertainties in the efficiency curve is the large absorption of radiation by the calibration sources envelope. The error in the quotient is estimated equal to 2%.

Adding these sources of error, the total experimental relative error is 2.5%.

IV. RESULTS AND CONCLUSIONS

The results are shown in Table I, together with calculations of most probable experimental results[15,16] and Scofield theoretical values. For the elements studied here these most probable results differ by nearly 0.5% and their average is about 1% smaller than the most reliable Scofield calculations.[18] Our values are, on average, 2.5% smaller than the results[16] of Salem *et al.* and 3.0% smaller than that of Khan and Karimi.[15] As our experimental error is 2.5% there is a reasonable agreement with these compilations of experimental data.

Our results however lie systematically lower than theory[18] being, on average, 4% smaller. There are several possible reasons for these findings. They may either be seen as confirming the slight overestimation of the experimental values by theory or they may be due to some methodological effect. Three types of effects were investigated: scattering of x rays either (a) in the target or (b) in the surrounding detector shield and (c) systematic errors in the determination of the areas under the peaks. The method used here to eliminate (a) was studied by Casnati *et al.* for thick targets and found to be reliable.[5] The other two possible sources of systematic errors were experimentally checked by changing the shielding and the methods to obtain the peak areas ratio. No significant changes could be observed. The overestimation of the experimental values by theory, also found in a recent paper,[23] 5% for photoelectric produced K vacancies in Cu, needs further experimental work. In order to reach a more definite conclusion about this small discrepancy between experiment and theory, we plan to extend these measurements for larger values of Z and also to reduce the error bars by the use of thinner targets.

ACKNOWLEDGMENTS

This work was partially supported by Financiadora de Estudos e Projetos (Brazil) and by Volkswagen Foundation (Federal Republic of Germany).

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