L-subshell X-ray production cross sections from rare earth elements induced by heavy ions

M. Lugo-Licona and J. Miranda

Instituto de Física, UNAM, Apartado Postal 20-364, 01000 México, D. F., Mexico

ABSTRACT

L-shell X-ray production cross-sections from Ce, Nd, Sm, Eu, Gd, Dy, Ho, and Yb, have been measured for incident 0.5 MeV/amu to 0.75 MeV/amu He, B, C, O, and F ions. Results were compared with experimental data from other authors and with theoretical predictions from the ECPSSR and ECPSSR plus united atom (ECPSSR-UA) models. An evaluation is made of the effect of using several databases for the atomic parameters (fluorescence yields and Coster-Kronig probabilities). It has been found that the ECPSSR-UA approximation describes the experimental results very well.

Keywords: X-ray production cross-sections; Heavy ions; ECPSSR; ECPSSR-UA.

1. INTRODUCTION

Measurement of X-ray production cross-sections is a useful method for studying atomic properties. It has been observed that collisions of heavy ions with atoms have higher cross sections than those of inner-shell vacancy production by light charged particles, such as protons. This observation led to interest in a detailed understanding of the fundamental excitation mechanisms [1,2, and references cited there]. Heavy ion induced X-ray emission has found some applications in environmental, biomedical and industrial problems [3].

Experimental data on L-shell X-ray production cross sections by heavy ion impact is scarce. This is especially true for the case of B ions, with only one published experiment [4,5], where Padhi and coworkers measured cross sections in Au and Bi bombarded by $^10$B$^{3+}$ ions with energies between 4.8 MeV and 8.8 MeV. Large discrepancies with the predictions of the ECPSSR theory of Brandt and Lapicki [6] were found. This theory is based on the Plane Wave Born Approximation (PWBA), modified with the inclusion of the effects of energy loss (E) and Coulomb deflection (C) of the incident ions, as well as the use of perturbed stationary states (PSS) and relativistic (R) effects of the inner-shell electrons. In many cases, the ECPSSR model has been shown to be the best prediction to experimental ionization cross sections [7].

Other attempts to improve the ECPSSR theory have been carried out, such as ECPSSR plus Multiple Ionization (MI) [8], and the ECPSSR plus United Atom (UA) model [9], which considers a correction in the binding energies of the target electrons due to the presence of the projectile. Furthermore, Miranda et al. [10] showed that, at least in the case of protons with energies below 1 MeV, the correct database of atomic parameters (fluorescence yields and Coster-Kronig probabilities) improves agreement with theoretical predictions. Adding to the effects involved in the X-ray emission process, Lapicki et al. [11] proposed a model to correct the fluorescence yields by multiple ionization. The basic assumption of this adjustment is the creation of holes in the outer shells by the incoming projectiles, with an equal probability for each shell. The cross section is calculated using the Binary Encounter Approximation, or BEA [12], avoiding complicated treatments of outer shell ionization by other quantum or semiclassical theories. In the present work, new measurements of L-shell X-ray production cross sections of selected rare earth elements are presented. A comparison with theoretical predictions from the ECPSSR and ECPSSR-MI, and ECPSSR-UA models is given. In addition, an evaluation of the effect of using several
different databases for the atomic parameters involved in L X-ray emission is made, with an attempt to estimate the role of multiple ionization on the fluorescence yields.

2. EXPERIMENTAL

Samples were prepared in the form of thin films of fluorides of rare earth elements (Ce, Nd, Sm, Eu, Gd, Dy) deposited on pyrolytic carbon substrates. The experimental setup is described in detail by Miranda et al. [13]. $^4$He$^{2+}$, $^{10}$B$^{2+}$, $^{12}$C$^{4+}$, $^{16}$O$^{4+}$, and $^{19}$F$^{3+}$ ions were used in the energy range of 0.5 MeV/amu to 0.75 MeV/amu, in 0.125 MeV/amu steps. A Canberra LEGe X-ray detector (resolution 150 eV at 5.9 keV), was used to register the X-rays. The detector efficiency was measured using thin film standards (MicroMatter Co., Deer Harbor, WA, USA) with 42.2 $\mu$g/cm$^2$ average thickness, with $\pm$5% uncertainty. The detector efficiency was determined by measuring the yields of the K X-rays induced from the films by 2.2 MeV protons; the cross sections for proton impact are accurately known[14]. Backscattered ions were recorded with a Canberra PIPS detector to normalize the absolute integrated charge measurements. The thicknesses of the rare earth film targets were measured by Rutherford backscattering with $^4$He$^+$ ions, with seven energies ranging from 2 MeV to 3 MeV. The surface energy approximation was used [15]. Measured thicknesses were in the 30 $\mu$g/cm$^2$ to 200 $\mu$g/cm$^2$ interval; the standard deviation of the measurements was 1.5%.

The uncertainties in the X-ray production cross sections for all the ions were approximately 15%. Contributions from the calculations include uncertainties in the number of backscattered particles, the number of K$\alpha$ X-rays produced in the standard films, the K-shell ionization cross sections, and the number of L$_i$ X-ray photons emitted by the rare earth targets. L$_{\alpha 1,2}$, L$_{\beta 1,3,4}$, L$_{\gamma 1,5}$, and L$_{\delta}$ X-ray intensities were extracted from each X-ray spectrum using the non-linear least-square fitting routine AXIL[16] and the equation:

$$\sigma_{L_i} = \frac{L \Omega \epsilon(E_0) F(E_0, \Delta E_0)}{N_{R} \epsilon(E_{\theta})}$$

Here, $L_i$ is the number of X-ray photons in each peak, where $i = \alpha, \beta, \gamma, \delta$; $\sigma_{R}$ is the Rutherford scattering cross section at an angle of $\theta = 157^\circ$ at energy $E_{\theta}$; $\Omega_{\theta}$ is the solid angle subtended by the particle detector from the target; $\epsilon(E)$ is the X-ray detector efficiency, and $F(E_0, \Delta E_0)$ is a correction factor associated with X-ray absorption and ion energy loss in the film[17]. Some terms in this factor are based on the assumption that the X-ray production cross section $\sigma_{L_i}(E)$ and the stopping power $S(E)$ are proportional to $E^\alpha$ and $E^\beta$, respectively [18], in an interval around $E_0$. Theoretical ionization cross-sections were calculated using the ISICS code. The atomic parameters of Puri et al. [19], and Campbell and Wang [20] were employed instead of those of Krause [21], and Scofield [22], as suggested by Miranda et al. [10].

3. RESULTS

For He ions the ECPSSR theory agrees well with the experimental data from the present work (figure 1). However, for ions like B, C, O, and F the results obtained with ECPSSR-UA model predicts the experimental X-ray production cross-sections more accurately (figure 2). Using atomic parameters of Krause [21] or Puri et al. [19], the ECPSSR theory underestimates the experimental data; however, the database of Puri et al., provides better results than those of Krause [21] (figure 2). When the Krause [21] and Puri et al. [19] databases are included in the ECPSSR-UA theory, the latter produces more accurate predictions than the Krause [21] parameters. The Puri et al. [19]
parameters used in ECPSSR-MI theory overestimate the experimental data, and in the ECPSSR-UA-MI model they produce the higher values found in this work. Therefore the agreement of the X-ray production cross-section calculations using the Puri et al. tables suggests that this database may be used in further work, as proposed by Miranda et al. [10].

![Figure 1](image1.png)
**Figure 1.** $L_{\beta_1}$ x-ray production cross sections from Nd. Theory and experiment are in good agreement. He ions were used as projectiles.

![Figure 2](image2.png)
**Figure 2.** $L_{\alpha}$ x-ray production cross section from Ce. B ions were used as projectiles. Results from different theories and database combinations are shown.

The experimental results from Mahli and Gray [23] have also been considered in order to compare their data with those in the present work (figure 3). The most complete information can be obtained by comparing the theoretical and experimental X-ray production cross section ratios with the reduced velocity parameter, $\xi_R^L$ (figure 4) [24]. There it is possible to see an underestimation of experimental cross sections by the ECPSSR-UA theory, especially at low energies.

![Figure 3](image3.png)
**Figure 3.** The ECPSSR-UA model and the experimental results from Mahli and Gray [23] and those of the present work. Yb targets were bombarded with F ions.

![Figure 4](image4.png)
**Figure 4.** Experimental and theoretical production cross section ratios as a function of the reduced velocity parameter. F ions were used as projectiles over the rare earth elements.

4. CONCLUSIONS

The results given here show that the theory that gives a better fit to the experimental data is the EPCSSR-UA (ECPSSR plus United Atom). There is not enough data from other authors to appropriately compare experimental results, so more experiments must be made to cover a wider energy range, more target elements and heavy ions. The use of MI according to the model of Lapicki et al. does not seem to be adequate to explain the experimental results.
Theoretical models for direct ionization do not consider the electronic configuration of the ions, so improvements to the theories should include this difference in the projectile ions. Electron capture is not expected to affect the results from this work in a crucial way [25].

The agreement of the X-ray production cross section calculations using the ECPSSR-UA and Puri et al. tables, like those in which B and F ions were used, suggest that existing theoretical models may not require further refinement to predict the experiments accurately [1].

ACKNOWLEDGMENTS

The authors acknowledge to Dr. J. Rickards for manuscript revision, the technical assistance of K. López and F.J. Jaimes for accelerator operation, and M. Galindo for sample preparation. This work was partially supported by CONACyT, contract 40122-F.

REFERENCES