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ENERGY DEPENDENCE OF PROTON INDUCED L-SUBSHELL IONIZATION CROSS SECTION RATIOS FOR Ag

A.M. COSTA, F. PARENTE, M.T. COSTA-LIMA and M.T. RAMOS

Departamento de Física and Centro de Física Atómica da Universidade de Lisboa (INIC), Avenida Pr. Gama Pinto, 2, P-1699 Lisboa Codex, Portugal

ABSTRACT

Thick targets of Ag were bombarded by 0.6 - 1.8 MeV protons accelerated by the 2 MV Van de Graaff generator at Sacavem, Portugal. The L\textsubscript{2,3} X-ray spectra were obtained with a plane crystal spectrometer and a position-sensitive detector. The energy resolution of the system is such that all the diagram lines of the spectra are well resolved. From the L\textsubscript{2,3} X-ray line intensities and using other inner-shell quantities taken from the literature, the ratios \( \sigma_2/\sigma_1 \) and \( \sigma_3/\sigma_1 \) were obtained as function of proton energy and compared to other theoretical and experimental results.

1. Introduction

The ionization of atomic inner shells by charged particles has been the object of intense research in the last two decades. A great deal of experimental and theoretical work can be found in the literature [1]. Although the K-shell can be considered very well studied and understood, for the L-shell problems still remain. There exists clearly a need of experimental work to test the theoretical models which have been proposed to describe L-shell ionization by protons, such as the classical binary encounter approximation (BEA), the semiclassical approximation (SCA) and the plane-wave Born approximation (PWBA), with different types of corrections.

In this work we report experimental results on the relative L-subshell ionization cross sections of Ag, obtained with bombarding protons in the energy range 0.6 - 1.8 MeV and a high-resolution spectrometer.

Benka et al. [2] published experimental values of relative ionization cross sections \( \sigma_2/\sigma_1 \) and \( \sigma_3/\sigma_2 \), for Ag, Sb and Au in the proton energy range 0.2 - 0.9 MeV. Rosato [3] reported L-subshell ionization cross sections for proton bombardment of Ag, In, Sn and I in the proton energy range 0.3 - 5.0 MeV. Both these authors used
Si(Li) detectors. Kropf [4] measured L-subshell ionization cross sections for elements in the range $40 \leq Z \leq 51$, for proton energies $0.1 - 0.9$ MeV, using a crystal spectrometer and a proportional counter. Experimental results on L-shell X-ray production and ionization cross sections for proton impact have been summarized by Sokhi et al. [5].

On the theoretical side, Cohen et al. [6] published K- and L-shell ionization cross sections for protons and helium ions calculated in the PWBA approximation with corrections for energy loss, Coulomb deflection, perturbed stationary state and relativistic effects (ECPSSR).

2. Experimental Method

Proton beams in the energy range $0.6 - 1.8$ MeV were obtained from the 2 MV Van de Graaff accelerator at Sacavem and analysed within $\pm 1$ keV. An aluminum target chamber of 70 cm diameter was used. In this chamber a plane crystal spectrometer was placed, fitted with a quartz crystal. The 1010 planes ($d=4.250 \times 10^{-4}$ μm) were used to Bragg scatter the X radiation emitted by a Ag foil 0.026 g/cm$^2$ thick placed in

![FIG. 1. (a) Fit of Lβ Ag X-ray spectrum, for 1.64 MeV protons, with the function described in the text. (b) Residuals given as multiples of one standard deviation.](image-url)
the proton beam. A thick target had to be used due to the poor efficiency of the analysing system.

The target foil was kept at an angle of 45° relative to the beam direction. We used a commercial backgammon-type position sensitive detector manufactured by INEL. The detector has a 50 mm x 12 mm Be window 250 μm thick.

3. Results

The Lα lines of Ag, for 7 values of proton energy, were recorded in a Camberra multichannel analyser and computer analysed by a least squares method. As shown in fig. 1, the spectrometer was able to completely separate the Lβ₁, Lβ₃, Lβ₄, Lβ₆ and Lβ₂ lines of Ag. The fitting function was a quadratic background and several peak functions, each one being an admixture of a Lorentzian and a Gaussian function.

The relative L-subshell ionization cross sections were computed from the expressions:

\[
\begin{align*}
\sigma_{\text{Lβ}_1} &= (f_{12} \sigma_1 + \sigma_2) \omega_2 F_{\text{β12}} \\
\sigma_{\text{Lβ}_2} &= ((f_{13} + f_{12} \sigma_{23}) \sigma_1 + f_{23} \sigma_2 + \sigma_3) \omega_3 F_{\text{β23}} \\
\sigma_{\text{Lβ}_3} &= \sigma_1 \omega_1 F_{\text{β31}} \\
\sigma_{\text{Lβ}_4} &= \sigma_1 \omega_1 F_{\text{β41}}
\end{align*}
\]

where the \( \sigma_{\text{Lβ}_j} \) (for \( j=1,4 \)) and the \( \sigma_i \) (for \( i=1,3 \)) are the X-ray production and ionization cross sections, respectively. The Coster-Kronig yields \( f_{ij} \) (\( i=1,2; j=2,3 \)), and the subshell fluorescence yields \( \omega_i \) (\( i=1,3 \)) are taken from Krause [7]. The \( F_{\text{βij}} \) (\( i=1,4; j=1,3 \)) are the fraction of the radiative transition to the \( j \) subshell associated to the \( \text{Lβ}_i \) peak. Values of \( F_{\text{βij}} \) were obtained from Scofield [8].

One advantage of the method is that we can obtain the relative ionization cross

![FIG. 2. Experimental and theoretical ratios \( \sigma_2/\sigma_1 \) of Ag L-subshell ionization cross sections.](image-url)

- Cohen [6]; △- Kropf [4]; □- Benka [2]; ●- present work.
sections using different combinations of line intensities from the same spectrum. Thus, the $\sigma_2/\sigma_1$ ratio was computed separately from $I_{L\beta_1}/I_{L\alpha}$ and $I_{L\beta_2}/I_{L\beta_4}$, and the $\sigma_3/\sigma_1$ ratio from $I_{L\beta_2}/I_{L\beta_3}$ and $I_{L\beta_2}/I_{L\beta_4}$, where $I_{L\beta_i} (i=1,4)$ is the intensity of line $L\beta_i$.

In figures 2 and 3 are plotted the ratios $\sigma_2/\sigma_1$ and $\sigma_3/\sigma_1$, respectively, obtained in this work, as function of proton energy, together with theoretical and experimental values of other authors.

The uncertainties in the atomic parameters used in the calculation (fluorescence yields and Coster-Kronig rates) are the main source of error and lead to 30-35% error bars in the ionization cross sections. The correction factors due to detector efficiency and crystal reflectivity on the intensity ratios are negligible. The target thickness corrections are included in the error bars.

The experimental ionization cross section ratios obtained in this work are in better agreement with theoretical values than those of Benka et al. [2]. However, theoretical predictions (ECPSSR) appear overestimated. The experimental values of Kropf [4] are higher than theoretical ones in the low energy region but are in agreement with ours for proton energies around 0.8 MeV.

References