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A Scaling Law for L-Shell X-Ray Production Cross Sections Induced by Impact of $^{4}He^{+}$, $^{9}Be^{2+}$, and $^{14}N^{2+}$ Ions

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Abstract Experimental results of L-subshell X-ray production cross sections induced by the impact of several ions heavier than protons were compiled in order to propose possible scaling laws. The ions of interest in this work are $^{4}He^{+}$, $^{9}Be^{2+}$, and $^{14}N^{2+}$. A feasible universal scaling for the x-ray production cross sections of the L_α (L_3M_4 + L_3M_5) line is based on a reduced velocity parameter ξ_L^R. In this scheme, the experimental data follow well resolved curves for each ion. A similar scaling for the L_γ line (L_2N_4 + L_1N_2 + L_1N_3 + L_1O_3 + L_1O_2 + L_2N_1 + L_2O_4) is also recommended, based on a different reduced velocity parameter $\xi_{L1,2}^R$. These results appear to be useful for all the studied projectile-target combinations covered in this work, supporting the idea that more theoretical studies in this direction should be done. However, the behavior of the fitting does not seem to follow the previously observed one.

Keywords: X-rays, cross sections, heavy ion impact, PIXE.

1. INTRODUCTION

The production of characteristic x-rays following the impact of photons, electrons, or protons has been extensively studied. Nevertheless, the collision with heavier ions produces other phenomena that do not occur in the other cases. The creation of molecules with a short life, the capture of electrons from the target atom by the projectile, and stronger multiple ionizations of the target atom, are only a few examples. Moreover, the ionization cross sections are also higher than those induced by protons. Because of this, there is interest in using x-ray production by heavy ion impact for analytical applications [6, 12].

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The most frequently used model to compare with experimental data is the ECPSSR theory of Brandt and Lapicki(1981). This model is based on the plane wave Born approximation, with modifications due to the energy loss (E) and Coulomb deflection (C) of the incident ions as well as for perturbed stationary states (PSS) and relativistic (R) effects of the inner-shell electrons. Recently, the model was refined to include exact limits of integration and renamed as eCPSSR [17]. It seems that this theory predicts very well the experimental cross-sections [6]. There are other efforts to improve it, such as the ECPSSR plus United Atom (UA) model [15], (correction in the binding energies of the target electrons due to the presence of the projectile), multiple ionization (MI) of outer shells by the projectiles [4] (changing the atomic parameters involved in the x-ray), and the correction due to intra-shell coupling (IS), which considers vacancy sharing among the different L subshells, due to secondary transitions occurring after the direct ionization of the target atom by the ion impact [15]. Thus, the ionization of one subshell is not independent from that of the other subshells.

In spite of all these advances about the cross section estimates, several questions still remain open. When heavy ions are used, the appropriate behavior with the projectile atomic number Z_1 is not well understood, in particular when L x-ray emission is studied. The theoretical models predict a Z_1^{-2} dependence, which has not been completely demonstrated due to the lack of a suitable scaling of the cross sections for all projectiles [2]. Therefore, in a previous work [8] the proposal of a universal scaling was presented for experimental L_ax-ray production cross sections (XRPCS) induced by the impact of several ions (^{4}He, ^{7}Li, ^{10}B, ^{12}C, ^{16}O and ^{19}F). To continue on this course, the goal of the present work is to apply the same scaling to other ions (^{9}Be and ^{14}N) for which more recent experimental results were obtained [10, 11], and the addition of the exhaustive compilation published for ^{4}He ions [7]. The validity of this scaling will be verified.

2. SCALING AND EXPERIMENTAL DATABASE

The proposed "universal" scaling for the L_α line is based on the reduced relativistic velocity parameter defined by [9]:

$$\xi_L^R = \frac{1}{4}\left(\xi_{L_1}^R + \xi_{L_2}^R + 2\xi_{L_3}^R\right)$$

where the reduced relativistic velocity for the L_i subshell is expressed as:

$$\xi_{L_i}^R = \left(m_i^R\right)^{1/2} \xi_{L_i}$$

Here, m_i^R is the relativistic mass as defined by [2], while ξ_{L_i} represents the dimensionless reduced velocity, which in turn is given by the equation:

$$\xi_{L_i} = \frac{v_1}{\frac{1}{2}\theta_{L_i} v_{2,L_i}}$$

with the reduced binding energy θ_{L_i}:

$$\theta_{L_i} = \frac{n^2 \hbar\omega_{2L_i}}{Z_{2L}^2 \Re}$$

and v_1 the projectile velocity, $v_{2,Li}$ the electron velocity in the atomic subshell L_i, $\Re$ = 13.6 eV the Rydberg constant, n the principal quantum number, $\hbar w_{2Li}$ the electron binding energy in subshell L_i, while $Z_{2L} = Z_2$ -4.15 is the screened target atom atomic number.

The parameter given by eq. (1) includes ionization of the three subshells, as expected for the L_α line. For the L_γ line, which does not involve transitions towards the L_3 subshell, it is necessary to define another reduced velocity:

$$\xi_{L1,2}^R = \frac{1}{2}\left(\xi_{L_1}^R + \xi_{L_2}^R\right)$$

The data of L_α and L_γ experimental cross sections were taken from the 2014 compilation [7] for ^{4}He, the works by [1, 5, 10, 13, 14, 16] for ^{14}N, while for ^{9}Be there are only two published works [11, 5]. In these works, the results appear either in graphical or tabular form. In the first case, the values are extracted after digitizing the corresponding plots. If only ionization cross sections (ICS) were given, they were reconverted to XRPCS using the same atomic parameters employed by the authors originally.When the experiments were carried out at different detection angles (usually 90° or 135°), a correction for anisotropy was made, according to the method proposed by [3].

3. RESULTS AND DISCUSSION

The L_α XRPCS for the three ions are as a function of the reduced velocity parameter given by eq. (1) is shown in Fig. 1. Most of the experimental points seem to follow definite curves for each ion, as observed previously [8]. However, unexpectedly, the ^{9}Be curve appears above the ^{14}N curve. Following the observations by [8], being ^{9}Be an ion with a lower Z_1, it was predicted that the curve should appear between the ^{14}N and the ^{4}He curves. It must be noted that the data from the two published works for ^{9}Be have a very good

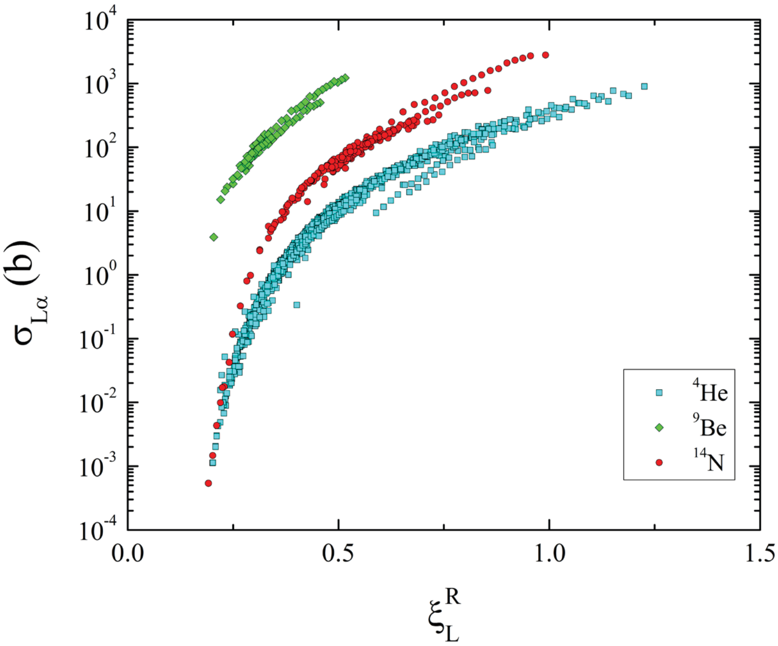

Figure 1: L_α X-ray production cross sections for $^4He^+$, $^9Be^{2+}$, and $^{14}N^{2+}$ ions as a function of the reduced velocity parameter ξ_L^R.

coincidence. Thus, this difference is not caused by possible experimental inaccuracies, but rather some still unexplained behavior for ^{9}Be ions. The ^{14}N, though, has the expected behavior, in spite of the inclusion of experimental results from several papers.

Additionally, Fig. 2 displays the curves for the L_γ line using the aforementioned projectiles, but using the corresponding reduced velocity parameter from eq. (5). Again, the data are aligned in curves for each ion, and the same situation occurs for the ^{9}Be ion curve, namely, it lies above the ^{14}N curve. So far, no explanation is found for this unforeseen behaviour.

Finally, to consider the already mentioned prediction of theoretical models regarding the dependence with the projectile atomic number, that is, that XRPCS depend on Z_1^{-2} [14], Fig. 3 presents the ratios of the cross sections to the square of the projectile atomic number. It is readily seen that the comportment is not fulfilled, as the cross sections produced by ^{9}Be ion impact still remain very high as compared to the other two curves. Moreover, the ^{14}N curve seems to go below the ^{4}He one. This suggests the need to look for a more accurate estimate about this dependence or to redefine the proposed scaling.

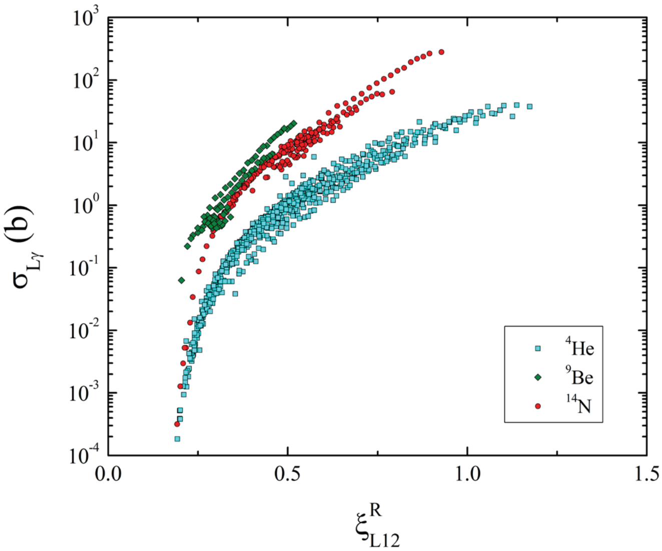

Figure 2: L_γ X-ray production cross sections for $^4He^+$, $^9Be^{2+}$, and $^{14}N^{2+}$ ions as a function of the reduced velocity parameter $\xi^R_{L1.2}$.

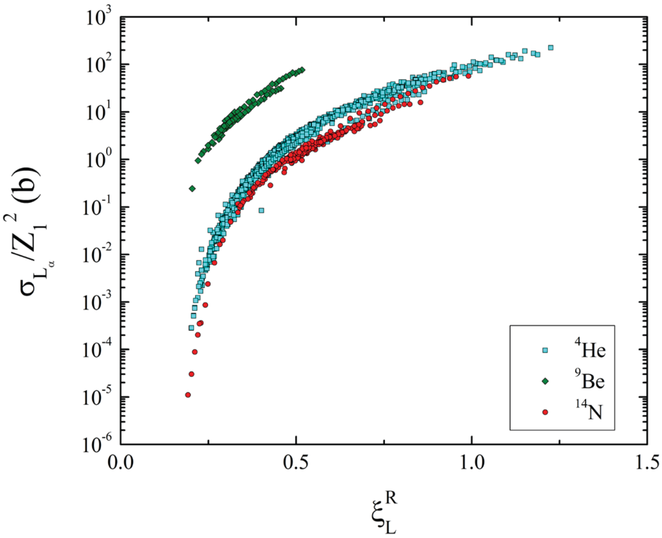

Figure 3: Ratio of L_α X-ray production cross sections for $^4He^+$, $^9Be^{2+}$, and $^{14}N^{2+}$ ions to Z_1^2 as a function of the reduced velocity parameter ξ^R_L.

4. CONCLUSIONS

The present work emphasizes the possibility of a universal scaling law for the x-ray production cross sections induced by heavy ions, especially ^{9}Be and ^{14}N, in a manner that was not studied previously, and then compared to ^{4}He ion impact. The two scaling procedures proposed for the L_{α} and L_{γ} x-ray lines induced by the impact of different ions seem to group the experimental data into individual curves for each ion. Nevertheless, the curve for ^{9}Be does not seem to follow the expected behaviour, as it lies above the ^{14}None, in contradiction with previous results [8]. In opposition to what was expected according to the basic theoretical models, the ratio to the square of the projectile atomic number does not seem adequate to concentrate all the experimental points in a single curve. Therefore, either the theory requires a refinement or the proposed scaling is not suitable to obtain a universal curve. More work will be attempted in both directions, as well as the possible extension of experiments, most probably with other target elements.

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