Cross Sections for Cu K-Vacancy Production in Fast Heavy Ion Collisions

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Extensive experimental and theoretical activity over the past three decades has led to a detailed understanding of target atom inner-shell vacancy production in light ion ($Z_1 \leq 2$) collisions [1]. In the case of heavy ion collisions, additional mechanisms, such as electron capture and (at low velocities) molecular orbital promotion, must be taken into account. This, coupled with complexities pertaining to the presence of electrons on the projectile, causes both the theoretical description and the experimental investigation of inner-shell vacancy production in heavy ion collisions to be challenging problems.

Several rather formidable problems complicate the direct comparison of experiment with theory. One of them is associated with the fact that the ionic charges of the incident projectiles are generally much lower than their average equilibrium charges inside the target. This means that the most important electron capture channels are initially closed. As the projectile enters the target, many of its electrons are stripped away and an equilibrium distribution of vacancy states quickly develops. During this equilibration process, target K-vacancy production by electron capture to the projectile can dramatically change. Therefore, the experimentally determined cross section is really a complicated average over target thickness. Two approaches have been explored in the present study. In the first, the cross sections were determined from measured K x-ray yields for a range of target thicknesses and extrapolated to zero thickness to obtain the direct ionization cross sections. The second approach involved determining the cross sections for equilibrated projectiles and comparing them with the appropriate theoretical values averaged over target thickness.

Another problem is associated with the fact that K-shell ionizing collisions of heavy ions simultaneously cause the ejection of many electrons from the L and higher shells of target atoms. This multiple ionization must be taken into account in calculating the fluorescence yield used to convert the K x-ray production cross sections to ionization cross sections. To facilitate this task, high resolution spectral measurements with a crystal spectrometer were performed in order to accurately establish the numbers of L- and M-shell vacancies produced in the Cu targets by each of the different ion beams.

Theoretical cross sections for Cu K-shell vacancy production by 10 MeV/amu projectiles are presented in Fig. 1. The cross sections were calculated within the framework of the ECPSSR theory and include contributions from direct K-shell ionization [2] and K-electron capture to the projectile [3]. For the purposes of illustration, calculation of the electron capture contribution, which depends on the electronic configuration of the projectile, were performed both for bare projectiles and for equilibrated projectiles in their electronic ground states. The latter choice was selected to demonstrate the effect of electrons attached to the projectile.

For comparison with the present experimental results, electron capture cross sections averaged over target thickness were computed. These calculations required

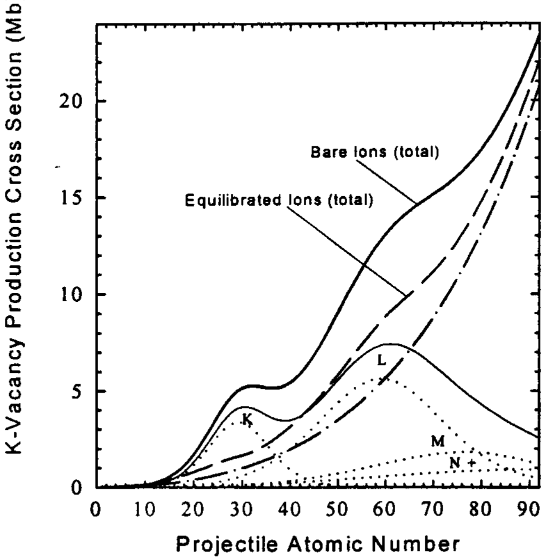

Figure 1. Theoretical (ECPSSR) K-vacancy production cross sections for bare ions (where the thick solid curve is the total cross section, the dot-dashed curve is the direct ionization cross section, and the thin solid curve is the total electron capture cross section) and for projectiles with equilibrium charges and ground-state electron configurations (dashed curve). The cross sections for target K-electron capture to various shells of bare projectiles are shown by dotted curves.

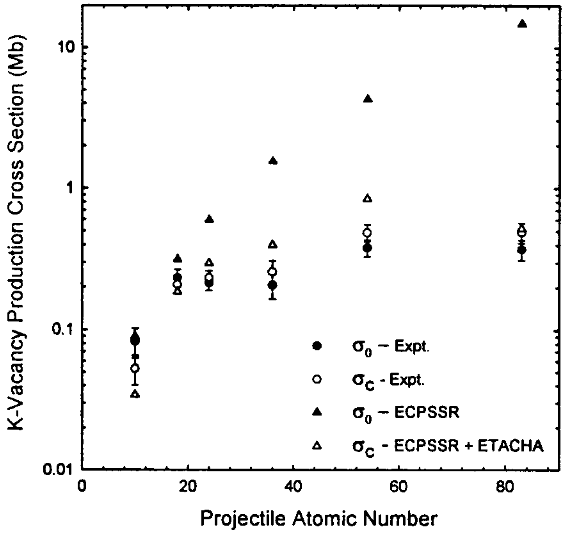

Figure 2. Comparison of the experimental zero-thickness cross sections σ_0 and the total capture cross sections σ_C with theoretical (ECPSSR) cross sections for direct ionization an K-electron capture. In the case of capture, the cross sections for the most probable electron configurations of the projectile (as determined using ETACHA) were averaged over target thickness.

knowledge of how the distribution of projectile electronic configurations evolves with target thickness. This information was obtained by means of the program ETACHA written by Rozet et al. [4]. Binding energies for electrons captured into each of the of the contributing projectile configurations were obtained using the Dirac-Fock program of Desclaux [5].

The experimental and theoretical direct ionization and total capture cross sections are compared in Fig. 2. It is evident that the direct ionization cross sections are in good agreement for Ne and Ar projectiles, but beyond Ar, the theoretical cross sections quickly rise above the experimental cross sections. The total capture cross sections, on the other hand, display rather good agreement with each other over the whole range of projectiles. It should be noted that the theoretical σ_C rely on both the electron capture formulation in the ECPSSR and the configuration distributions predicted by ETACHA, while the theoretical σ_0 depend only on the validity of the ECPSSR description of direct ionization.

The K-shell vacancy production cross sections for equilibrated projectiles are plotted in Fig. 3. The measured cross sections display a plateau centered in the region around $Z_1 = 27$ where $Z_1/Z_2 \sim 1$ and they level off above $Z_1 = 54$. These two features may be associated with the occurrence of maxima in the cross sections for target K-electron capture to the projectile K-shell around $Z_1 = 30$ and to the projectile L-shell around $Z_1 = 60$ (see Fig. 1). Comparing the measured cross sections with the theoretical cross sections, it is again seen that good agreement is achieved for Ne and Ar projectiles, but beyond Ar, the theoretical cross sections rapidly become much larger than the experimental cross sections. For Bi projectiles, the theoretical cross section is a factor of 18 larger than the experimental cross section. Moreover, it is evident from the curve shown in Fig. 3 that the data fall far below a Z_1^2 scaling law beyond $Z_1 = 24$.

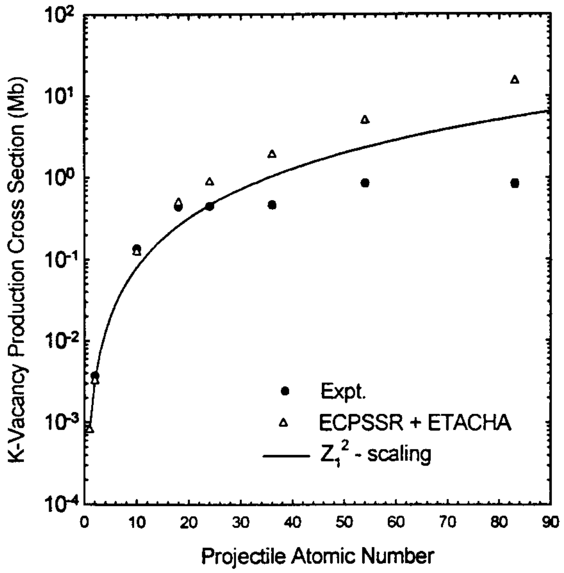

Figure 3. Comparison of the K-vacancy production cross sections for equilibrated projectiles with theoretical (ECPSSR+ETACHA) total cross sections that have been averaged over target thickness.

References

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