# X-Ray Production Cross Sections*

J. D. Garcia
*Department of Physics, University of Arizona, Tucson, Arizona* 85721
(Received 4 December 1969)

Recent high-energy measurements of $K$-shell x-ray yields produced by proton impact are compared with the binary-encounter–impulse approximation and with previous measurements. The scaling law derived from the binary-encounter model is found to be in good agreement with experiment.

In a recent publication,[1] we examined the applicability of the classical binary-encounter model to the ionization of inner shells by proton impact. Since that time, some higher-energy (2–28 MeV) measurements[2] have been made on Ca, Ti, and Ni. The purpose of this paper is to indicate that this simple model satisfactorily explains these data. In addition, the use of the scaling law obtainable from the model displays the consistency of all available $K$-shell ionization data.

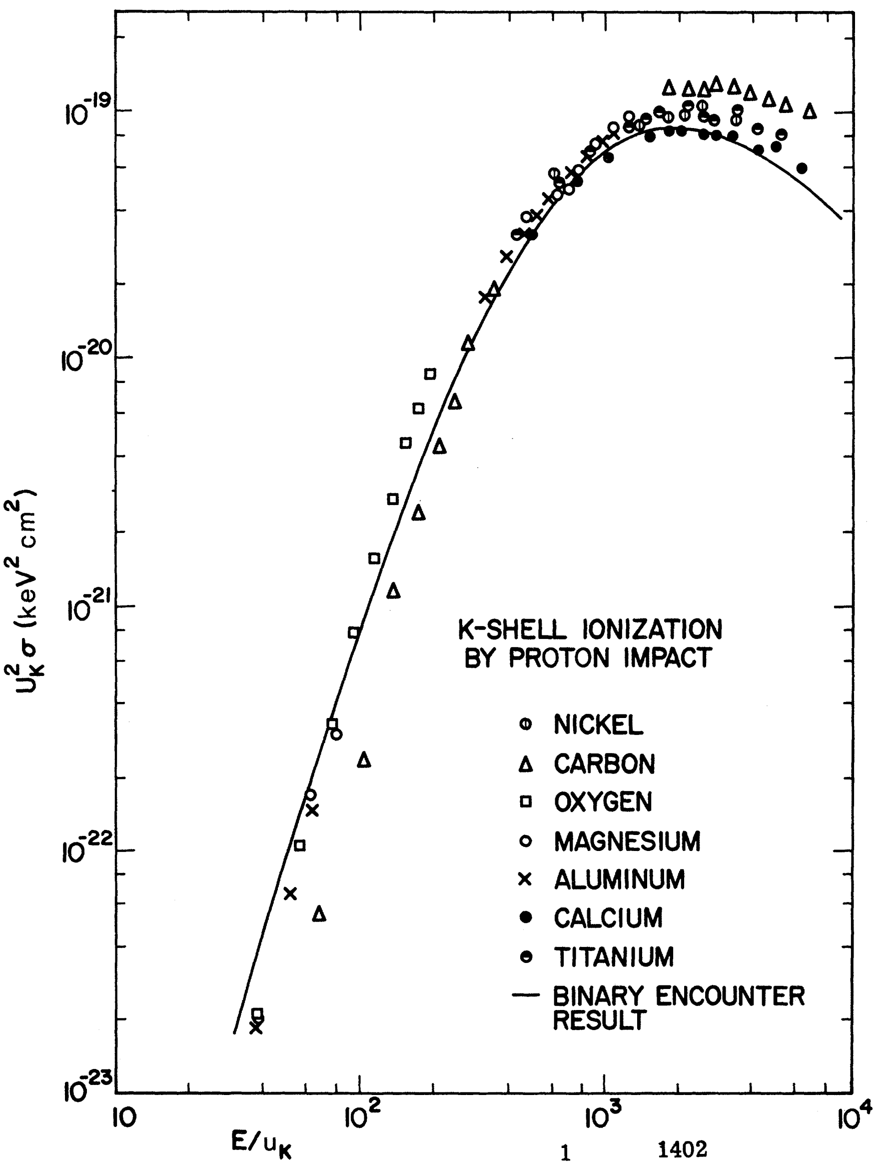


FIG. 1. Scaled $K$-shell ionization cross sections for proton impact. Solid curve, binary-encounter result. Experiment: triangles, carbon (Ref. 1); squares, oxygen (Ref. 2); open circles, magnesium (Ref. 1); crosses, aluminum (Ref. 1); solid circles, calcium (Ref. 2); half-circles, titanium (Ref. 2); circles with vertical bar, nickel (Ref. 2).

As discussed in Ref. 1, the classical binary-encounter model yields the same results as does a quantum mechanical impulse approximation. The analytical form of the expression for the cross section obtained in this model can be written in a form which shows that the product $u^2\sigma$ is a universal function of the ratio of the incident proton energy to the binding energy $u$ of the atomic electron in the target atom, and is otherwise independent of target-atom parameters. When the model is modified to include the repulsion of the proton by the nucleus, the final expression also depends on the charge of the target-atom nucleus. However, this dependence on charge is never very large and is less important for higher $Z$. In fact, the modified expression for $u^2\sigma$ reaches an asymptotic limit[3] as $Z \to \infty$, and the differences for $Z > 10$ are negligible. This suggests that if the $K$-shell ionization cross sections are multiplied by the square of the $K$-shell binding energy $u_K$ and plotted as a function of $E/u_K$, they should define a universal function.

The uncertainties in the fluorescent yields $\omega_K$ make difficult the comparisons of experimental x-ray cross sections with theoretical ionization cross sections.

We have used theoretical estimates for $\omega_K$ in our comparisons.[4] Figure 1 shows a plot of $u_K^2\sigma$ versus $E/u_K$ for all available ionization cross sections taken from Refs. 1 and 2. The values of $\omega_K$ and $u_K$ used are given in Table I. Also shown is the function predicted by the binary-encounter model. It can be seen that the cross sections for oxygen through nickel define a universal function reasonably well, and that the impulse approximation provides a good approximation to this function. One should keep in mind that the points represent data for proton energies ranging from 20keV-28MeV.

TABLE I. Binding energies and fluorescent yields.

| Element | $u_K$(keV) | $\omega_K$ |
|---|---|---|
| C | 0.284 | $1.45\times10^{-3}$ |
| O | 0.535 | $2.6\times10^{-3}$ |
| Mg | 1.305 | $1.8\times10^{-2}$ |
| Al | 1.559 | $2.4\times10^{-2}$ |
| Ca | 4.038 | 0.12 |
| Ti | 4.966 | 0.17 |
| Ni | 8.332 | 0.359 |

The only anomalous behavior is that of carbon, and it does not seem possible to explain that behavior on the basis of incorrect fluorescent yield *alone*. However, the carbon data are thick-target measurements and their reduction involves stopping powers. This suggests that it may be desirable to repeat the carbon measurements (at least at low energies) using thin targets.

It should be pointed out that the Born approximation does not provide as good a description of the energy dependence of these cross sections as does the impulse approximation, for the values of $E/u$ thus far examined. (This can be seen from the individual comparisons in Refs. 1 and 2). Note also that the parameters used in the scaling of Fig. 1 are much simpler than the Born parameters $\theta_K$ and $\eta_K$ though there are obvious similarities.

Even disregarding the use of the impulse approximation, Fig. 1 provides a basis for predicting approximate values for unknown fluorescent yields, using the experimentally determined function.

*Supported in part by NASA Grant NGR 03-002-017, ONR Contract No. N00014-67-A-0209-005, and Aerospace Research Labs USOAR Contract No. F33615-70-C-1007.

[1]J. D. Garcia, Phys. Rev. (to be published).

[2]G. A. Bissinger, J. M. Joyce, E. L. Ludwig, W. McEver, and S. M. Shafroth, Phys. Rev. (to be published).

[3]B. K. Thomas and J. D. Garcia, Phys. Rev. 179, 94 (1969).

[4]The expression used is $\omega_K = (1 + a/Z^4)^{-1}$, with the parameters as given by R. W. Fink, R. C. Jopson, H. Mark, and C. D. Swift, Rev. Mod. Phys. 38, 513 (1966).