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On the Z^2-Dependence of the X-Ray Production Cross Section by 5 MeV/amu Heavy Ions*

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ABSTRACT

Large deviations from a Z^2-dependence for the x-ray production cross sections are found for K x-rays of Ti, Fe, Co, Zr, Sn, and Nd and L x-rays of Sn and Nd using 5 MeV/amu He, C, O, and Ne ions as projectiles. At least in the case of the K x-rays of Zr, Sn, and Nd, these deviations very likely reflect the behavior of the ionization cross section and point out the necessity of adding a Z^3 term to the expression for the ionization cross section. In the other cases the uncertainty of the fluorescence yield prevents the drawing of any definite conclusions.

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The binary-encounter model for the ionization of inner shell electrons by ions predicts a simple scaling law for the ionization cross section σ_I:[1]

$$\sigma_I = f(\frac{E}{\lambda U}) \frac{Z^2}{U^2} , \quad (1)$$

where E, Z, and λ are the energy of the projectile, the charge, and the mass of the projectile in units of electron mass respectively, and U is the ionization energy of the electron. A similar scaling law follows from calculations based on the PWBA approximation.[2] This scaling law can be tested experimentally by measuring the dependence of the x-ray production cross section σ_x on the Z of the projectile while keeping the velocity of the projectiles constant, and assuming that the fluorescence yield ω_x is independent of Z.

Such a test has recently been made by Lewis <u>et al.</u>[3] using α-particles and deuterons ranging from 6.25 to 20 MeV/amu on Ti, Cu, and Au, and by Basbas <u>et al.</u>,[4] who bombarded Al and Ni targets with H, D, He, and Li ions of kinetic energies between 1 and 7.5 MeV/amu. In both experiments a significant deviation from the Z^2-dependence of σ_x was observed. We measured the cross section σ_x for the production of the K x-rays of Ti, Fe, Co, Zr, Sn, and Nd and of the L x-rays of Sn, Nd, and Au by 5 MeV/amu He, C, O, and Ne ions, and we also observed large deviations from a simple Z^2-dependence. In addition we measured σ_x for 10 MeV/amu C ions on the same targets. The 5 MeV/amu projectiles were obtained by accelerating He^{1+}, C^{3+}, O^{4+}, and Ne^{5+} ions in the Oak Ridge Isochronous Cyclotron.

An absolute value of the x-ray production cross section σ_x can be obtained by comparing the x-ray yield with the yield of Coulomb scattered particles. This method eliminates the need to measure target thickness and beam current and makes it easier to perform accurate absolute measurements.

The x-ray yield was measured at an angle of 150° with respect to the incoming beam by using a Si(Li) detector with a resolution of about 250 eV at 5.9 keV. The target thicknesses ranged from 200 to 1000 μg/cm^2, and the x-ray yield was corrected for self-absorption effects in the target. The scattered particle yield was measured with two surface barrier counters at angles of +11° and -11° with respect to the beam, so that corrections could be made for small changes in beam direction and position. For most cases the absolute uncertainty in σ_x is ± 6% while the uncertainty in the ratio between σ_x for different projectiles is generally better than ± 2%.

Figure 1 shows the quantity $U_K^2\ \sigma_I^K/Z^2$ as a function of $E/\lambda U_K$ for the 5 MeV/amu He ions and the 10 MeV/amu ^{12}C ions. The σ_I^K are calculated from the relation $\sigma_x^K = \omega_K\ \sigma_I^K$. The fluorescence yields that were used are summarized in Table 1. The curve is the prediction of the binary-encounter model of Ref. 1. In general there is a reasonable agreement between the predicted and experimental values for the He ions.

In order to illustrate the Z^2-dependence of the x-ray production cross sections, we define the quantity $R(Z_1,Z_2) = [\sigma_x(Z_1)/\sigma_x\ (Z_2)](Z_2/Z_1)^2$. Figure 2 shows $R(Z_1,Z_2)$ for $Z_2 = 2$ and $Z_1 = 6$, 8, and 10 as a function of $\xi = E/\lambda U$ where U is the binding energy of the K shell or a suitable average of the binding energy of the L shells. The experimental data suggest the following systematic trends: (i) for each projectile R changes from value > 1 to values < 1 at $\xi \sim 0.25$; (ii) For each value of ξ, the value of $|R-1|$ increases with increasing Z_1; (iii) The behavior of R is approximately the same for K and L x-rays. It is interesting to note that the same systematic trend can be observed in the data reported in Ref. 4 obtained with quite different projectiles, targets, and energies. Also the data reported in Ref. 3 agree with the observed systematics in the sense that $R > 1$ for $\xi > 0.25$.

The fact that $R \neq 1$ can be due to a Z-dependence of the fluorescence yield ω or it can indicate that σ_I does not scale as Z^2. Most probably both effects have to be taken into account.

From the energy shifts observed in the x-ray lines[5] it is clear that the number of multiple inner shell vacancies created simultaneously with a K shell vacancy dpends on the Z of the projectile and this will very likely lead to a Z dependence of ω. For Zr, Sn and Nd the average number of additional L vacancies created by 5 MeV/amu Ne ions is approximately 1, while for Fe this number would be 2 to 3.[5] In order to estimate the effect of multiple vacancies on the fluorescence yield, we assume that the K-L radiative transition rate is proportional to the number of L electrons, n_L, that the non-radiative rate is proportional to $n_L(n_L-1)$, and that the single particle transition probabilities are not affected by multiple inner shell vacancies. Using this oversimplified model, the effect of one additional L-shell vacancy for Sn on the fluorescence yield is 3%. This leads us to the assumption that the effect of the multiple vacancies on the fluorescence yield for Zr, Sn, and Nd is rather small and that the observed discrepancy of the Z^2-dependence of the x-ray production cross section σ_x is mainly due to the behavior of the ionization cross section σ_I. The same assumptions indicate that in the case of 5 MeV/amu Ne ions on Fe, the fluorescence yield might be increased by as much as 30%, accounting for a large part of the effect observed for Fe, Co, and Ti.

If we assume that the ionization cross section σ_I can be written as $\sigma_I = \sigma_I^o[1 + \delta(Z/Z_t) + O(Z/Z_t)^2]$ where σ_I^o is given by (1) and Z_t is the charge of the target atom, then the quantity $|R(Z_1,Z_2)-1|Z_t/(Z_1-Z_2)$ should be independent of Z_1. Table 2 shows that this is approximately true for the Zr, Sn, and Nd targets. For the lighter elements one first would have to establish either experimentally or theoretically the effect of multiple vacancies on the fluorescence yield before such an evaluation can be made. A similar remark can be made with respect to the L x-rays of Sn, Nd, and Au, although it might be meaningful that all the data indicate the same trend of R vs E/λU.

Table 1. Fluorescence yields.

Element	ω_K
Ti	0.221
Fe	0.344
Co	0.366
Zr	0.737
Sn	0.86
Nd	0.91

Table 2. $|R(Z_1,Z_2)-1|Z_t/(Z_1-Z_2)$ with $Z_2 = 2$ for the K x-ray cross section.

Target	Projectile		
	C	O	Ne
Ti	3.3 ± 0.1	2.9 ± 0.1	2.6 ± 0.1
Fe	1.7 ± 0.1	2.34 ± 0.1	2.2 ± 0.1
Co	1.4 ± 0.1	2.0 ± 0.1	1.4 ± 0.1
Zr	2.5 ± 0.2	2.3 ± 0.2	2.0 ± 0.1
Sn	5.1 ± 0.1	4.6 ± 0.2	4.1 ± 0.2
Nd	4.2 ± 1.0	4.7 ± 0.9	5.2 ± 0.5

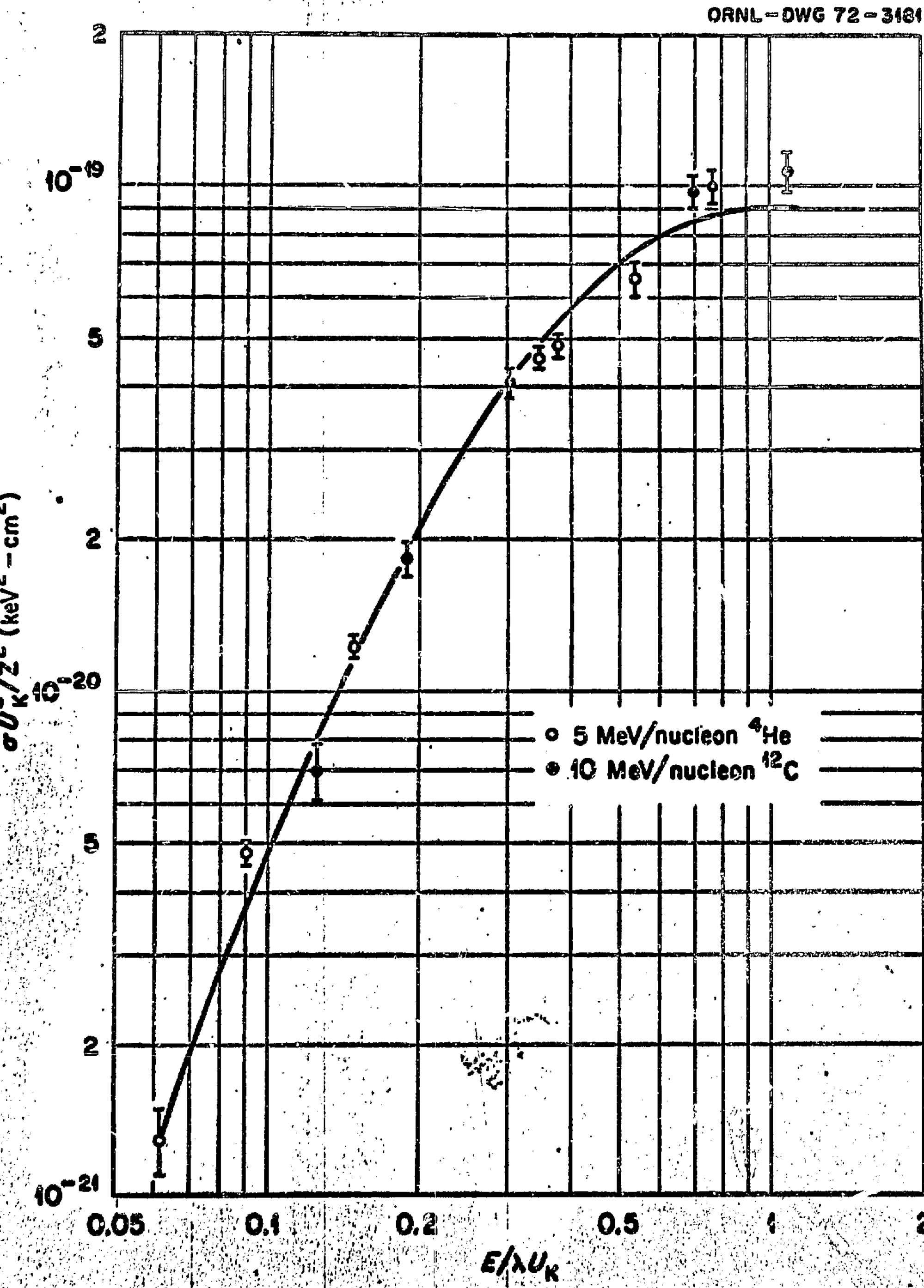
REFERENCES

1. J. D. Garcia, Phys. Rev. A1, 280 (1970); Phys. Rev. A4, 955 (1971).
2. E. Merzbacher and H. W. Lewis, Encyclopedia of Physics (Springer-Verlag, Berlin, 1958), Vol. 34, p. 166.
3. C. W. Lewis, J. B. Natowitz, and R. L. Watson, Phys. Rev. Letters 26, 481 (1971).
4. G. Basbas, W. Brandt, R. Laubert, A. Ratkowski, and A. Schwarzschild, Phys. Rev. Letters 27, 171 (1971).
5. M. J. Saltmarsh, A. van der Woude, and C. A. Ludemann, these Proceedings.

FIGURE CAPTIONS

Fig. 1. K ionization cross sections measured with 5 MeV/amu He and 10 MeV/amu C projectiles. The solid line is the prediction of Garcia's Binary Encounter Model.[1]

Fig. 2. The ratio of the reduced x-ray production cross section σ_x/Z^2 for 5 MeV/amu, C, O, and Ne projectiles, to that for 5 MeV/amu He ions, plotted as a function of the reduced energy $E/\lambda U$.



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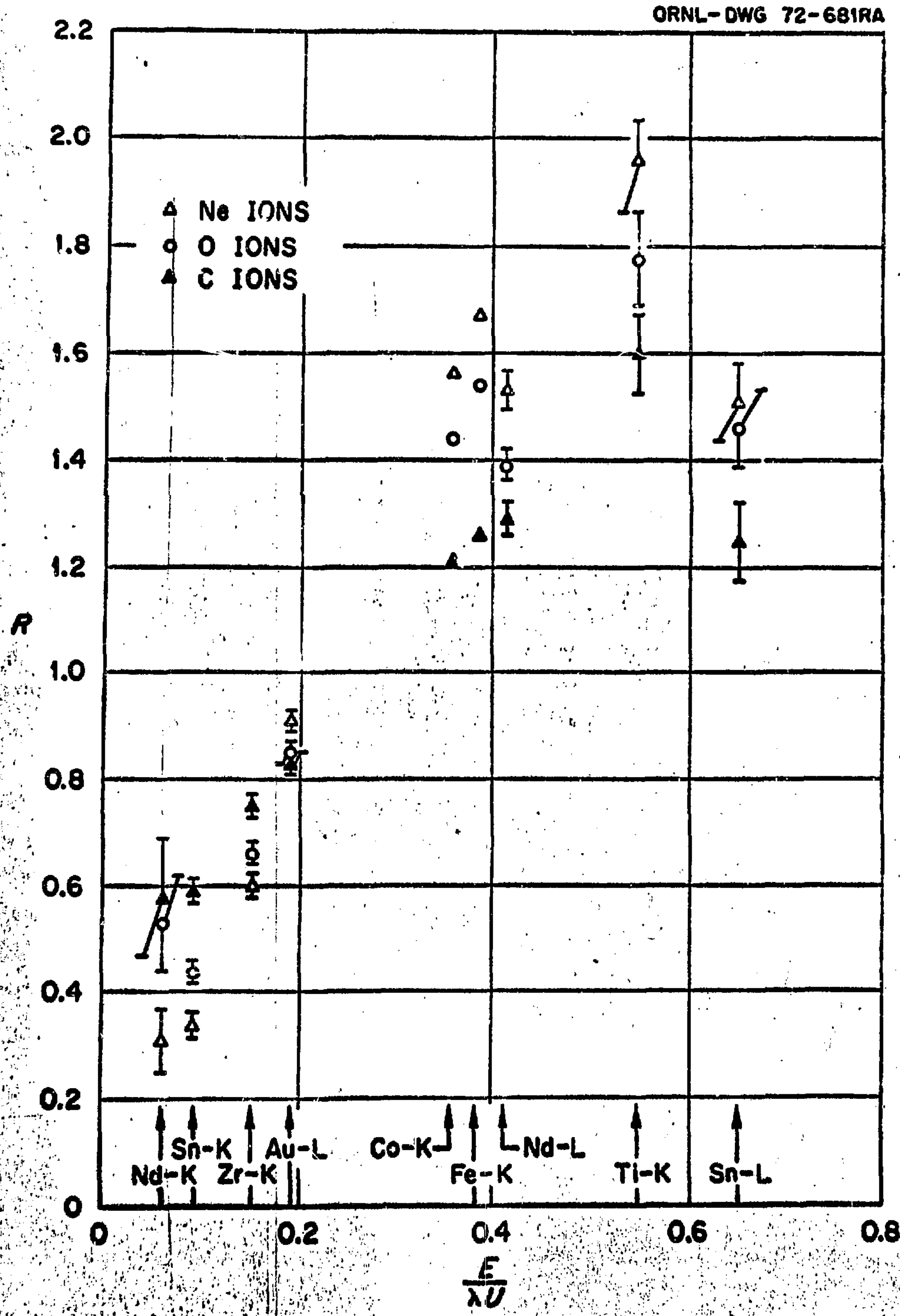
$\sigma U_K^2/Z^2$ (keV^2-cm^2)
2
10^{-19}
5
2
10^{-20}
5
2
10^{-21}
0.05
0.1
0.2
0.5
1
2
$E/\lambda U_K$
o 5 MeV/nucleon ^{4}He
• 10 MeV/nucleon ^{12}C

Figure 1



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Ne IONS
O IONS
C IONS
R
Nd-K
Sn-K
Zr-K
Au-L
Co-K
Fe-K
Nd-L
Ti-K
Sn-L
$\frac{E}{\lambda U}$

Figure 2