L-SUBSHELL IONIZATION WITH HIGH VELOCITY POSITIVE IONS†

J.F. Morgan,* S.L. Blatt,** W.D. Ploughe** and M.A. Kovash**

Despite the increasing activity in recent years in the area of inner shell ionization very little work has been done with high-velocity ions. In their summary of L-shell data in 1976, Hardt and Watson1) list no proton or deuteron data above 30 MeV or helium data above 80 MeV, and in actuality there are very little data of any kind above 6 MeV. The authors know of no other reports of high-velocity L-shell ionization in the literature since this summary appeared.

One reason for the lack of high-velocity data has been the long-held belief that in the high-velocity region the assumptions necessary for application of the Born Approximation are well satisfied; since PWBA theories should give a good account of the cross section in this region, it was not thought to be an interesting area for experimental investigation. Recently, however, Reading and collaborators2) have called this belief into question, suggesting deviations larger than 5% from PWBA theories for K-shell ionization with projectile velocities above 20 MeV/amu on medium-weight elements. Such effects could also be important for L-shell ionization; in order to explore these possibilities, we have measured relative inner subshell ionization cross sections with 66 MeV deuterons and 132 MeV alpha particles on Ta, Pt and Au. K-shell ionization effects in lighter elements were also measured; these results will be the subject of a future publication.

The experiment was performed at the Indiana University Cyclotron Facility (IUCF). Self-supporting targets, approximately 1 mg/cm^2 in thickness, were mounted in the IUCF low-background area. X-rays from the targets were viewed through a 0.5 mil mylar window, at 90° to the incident beam direction, with a conventional Si(Li) detector. Data were recorded on magnetic tape and later analyzed at Ohio State University. The L-shell spectra were similar in appearance to those obtained at lower velocities.3) The spectra were fit with a gaussian peak-fitting routine, and conventional atomic parameters were used to convert from x-ray production cross sections to L-subshell cross sections as described by Chang et al.3) Although the electronics used for data collection included advanced pile-up rejection circuitry, beam currents had to be restricted to < 1 nA in order to maintain system resolution, and absolute charge collection was difficult to achieve. However, the statistical accuracy of each spectrum was such that satisfactory ratios of x-ray yields for each run could be obtained. In what follows, therefore, we will discuss only ratios of cross sections.

The behavior of these L-subshell ratios at high velocities is interesting to explore, since at low velocities they show significant departure from theory.3,4,5) The results, for both alpha and deuteron ionization, are shown in Fig. 1. The errors in the experimental data, including both statistical and fitting errors, are smaller than the data points. The lines in the figure show the PWBA prediction taken from the table of Choi et al.6) As Fig. 1 clearly shows, the ratio of $\sigma_{L_I}/\sigma_{L_{II}}$ has the target-Z dependence predicted by PWBA, but is systematically lower than the theoretical values both for deuteron and α-particle bombardment. The ratio $\sigma_{L_{III}}/\sigma_{L_{II}}$ appears to vary with target-Z with a slope opposite to the PWBA prediction; again this result is true for both projectiles.

---

† Work supported in part by the U.S. National Science Foundation

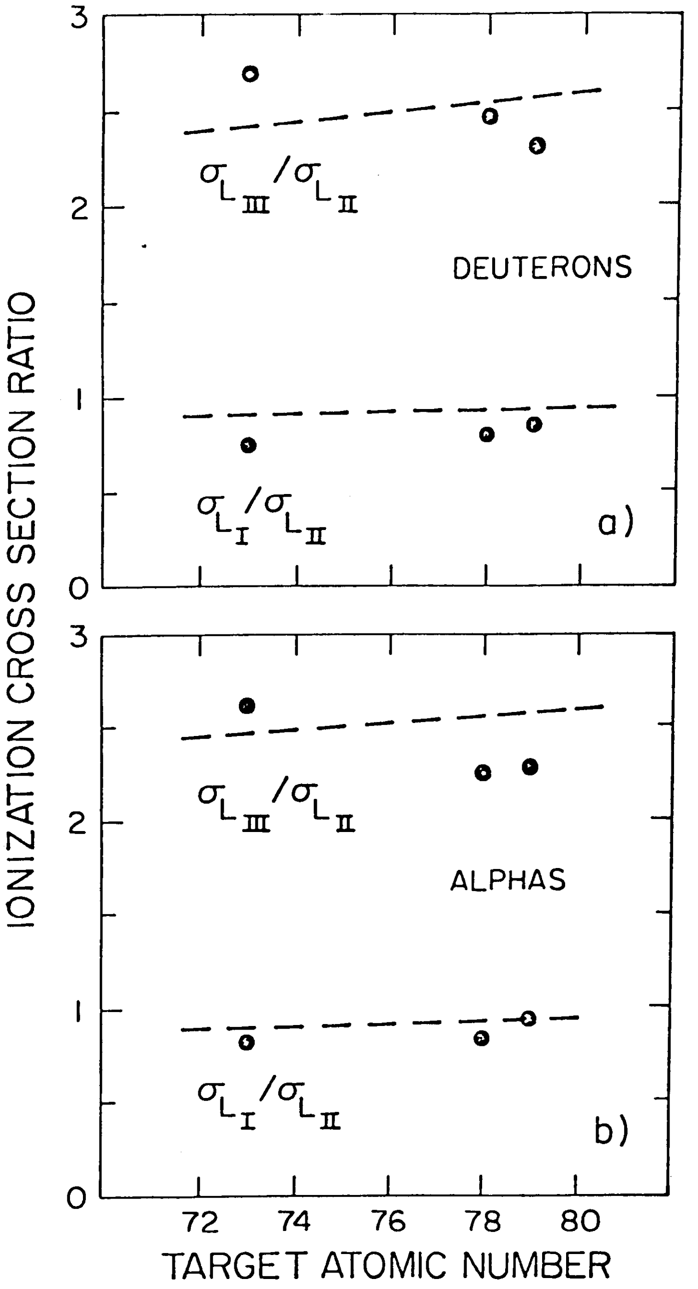

Figure 1. Ratios of L-subshell ionization cross sections vs. target atomic number for a) 66 MeV deuterons and b) 132 MeV alpha particles. The dashed lines show PWBA predictions.

Reading et al. have shown that the clearest manifestation of the discrepancy between PWBA theory and more complete calculations for the case of K-shell ionization can be seen in the ratio of the cross sections for two different Z projectiles of the same velocity, i.e., for the ratio

$$R_Z \equiv \frac{Z_2^2\sigma(Z_1)}{Z_1^2(Z_2)} ,$$

where $\sigma(Z_1)$ is the cross section for ionization by projectile with charge Z_1. In PWBA this ratio is one at all velocities while more complete theories predict a velocity-dependent value of R_Z. We have therefore sought such effects for the L-shell case. Table 1 shows our results for the value of R_Z using 66 MeV deuterons and 132 MeV alpha particles. Calibration of the IUCF magnet system indicates that the velocity of these projectiles should be the same to better than 1%. Since absolute charge integration was not obtained, we have normalized the values of R_Z for each subshell to the value obtained for the L_{III} subshell, which has the smallest statistical uncertainty. Referring to Table 1, it is to be noted that R_Z for the L_I subshell is systematically some 10% below R_Z for L_{III}, while the projectile dependence of L_{II} appears to be much more similar to that of L_{III} (with the possible exception of the tantalum value). While we cannot, at this point, know with certainty which subshell ionization cross sections show an absolute deviation from the PWBA predictions on projectile dependence, it is

Table 1. NORMALIZED PROJECTILE-DEPENDENT CROSS-SECTION RATIOS

Element	$R_Z^1(L_I)$	$R_Z^1(L_{II})$
Ta (73)	0.89 ± 0.04	0.97 ± 0.03
Pt (78)	0.88 ± 0.04	0.90 ± 0.03
Au (79)	0.91 ± 0.04	0.99 ± 0.03

The ratios for ionization of the $L_{I,II}$ subshells by equal-velocity deuterons and α-particles, normalized to $R_Z(L_{III})$. Thus $R_Z^1(L_I) = R_Z(Li)/R_Z(L_{III})$, where $R_Z = 4\sigma_d/\sigma_\alpha$. Note that PWBA predicts all $R_Z = 1$.

clear that the ionization of the $2s_{1/2}$ subshell shows an effect substantially different from $2p_{1/2}$ and $2p_{3/2}$ subshell ionization. Indeed, the data do not rule out a deviation of the total L-shell cross sections from PWBA, as well.

The observed effects indicate the need to use more exact wave-functions for the inner-shell electrons, a more accurate formulation of the reaction mechanism, or both. The relativistic correction described by Hönl7), which might be expected to be important in the present energy range, has been shown8,9) to be insufficient to explain deviations from non-relativistic PWBA even at lower energies. Use of more detailed structural models, such as Hartree-Fock-Slater wave functions10) or exact relativistic calculations might be expected to explain some of the observations, especially the differences between the s and p subshells;3) calculations such as these are beyond the scope of the present work.

Further clarification of the effects reported here may be forthcoming from absolute cross section measurements. It is, however, already clear from the relative cross sections measurements reported here that substantial deviations from the simple theoretical predictions exist at these high velocities; further understanding must also await an extension of detailed theoretical work to the L subshells.

*Current address: L-43, Lawrence Livermore Laboratory, Livermore, CA. 94550, U.S.A.

**Physics Department, Ohio State University, Columbus, Ohio 43210

1) T.L. Hardt and R.L. Watson, At. and Nucl. Data Tables 17, 107 (1976).

2) J. Reading and E. Fitchard, Phys. Rev. A 10, 168 (1974); J. Binstock and J. Reading, Phys. Rev. A 11, 1205 (1975).

3) C.N. Chang, J.F. Morgan and S.L. Blatt, Phys. Rev. A 11, 607 (1975).

4) C.N. Chang, J.F. Morgan and S.L. Blatt, Phys. Lett. 49A, 365 (1974).

5) T.K. Li, D.L. Clark and C.W. Greenlees, Phys. Rev. Lett. 37, 1209 (1976).

6) B.H. Choi, E. Mertzbacher and G.S. Khandelwal, Atomic Data 5, 291 (1973).

7) H. Hönl, Z. Phys. 84, 1 (1933); E. Merzbacher and H.W. Lewis, Encyclopedia of Physics, S. Flügge, ed. (Springer, Berlin, 1958) 34, 166.

8) J.F. Morgan, R.S. Sega, R.J. Schraeder, H.R. Suiter, and S.L. Blatt, Phys. Rev. A 16, 2187 (1977).

9) James R. Chen, Phys. Rev. A 15, 487 (1977).

10) M.H. Chen, B. Crasemann, and V.O. Kostroun, Phys. Rev. A 4, 1 (1971).