

ATOMIC CHARGE EXCHANGE  
BETWEEN FAST SINGLY- AND DOUBLY-IONIZED HELIUM IONS  
IN TARGETS FROM CARBON TO BISMUTH AT  $\beta = 0.36$

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Atomic charge exchange between singly- and doubly-ionized helium atoms in atomic collisions depends on the speed of the helium atoms and the atomic charge of the target foils. Atomic stripping (ionization) and capture cross sections contribute to this phenomenon, and both of these cross sections can in principle be determined individually. However, in targets of thickness greater than typically  $50 \mu\text{g}/\text{cm}^2$  an equilibrium charge-state distribution is established. Only equilibrium charge-state distributions were determined in this work.

While neutral atoms must in principle be included in the equilibrium charge-state distribution, their contributions can be neglected at the ion speeds considered in the present experiment. Therefore, in equilibrium we have

$$dN(\text{He}^+)/dt = -dN(\text{He}^{++})/dt = \sigma_{cap} N(\text{He}^{++}) - \sigma_{strip} N(\text{He}^+) = 0 \quad (1)$$

and hence

$$N(\text{He}^+)/N(\text{He}^{++}) = \sigma_{cap}/\sigma_{strip} . \quad (2)$$

The present experiment was performed with a beam of fully ionized  ${}^3\text{He}^{++}$  ions of energy  $E({}^3\text{He}) = 200 \text{ MeV}$  and speed  $\beta = 0.36$  impinging on targets of  ${}^{\text{nat}}\text{C}$ ,  ${}^{28}\text{Si}$ ,  ${}^{56}\text{Ni}$ ,  ${}^{90}\text{Zr}$ ,  ${}^{\text{A}}\text{Sn}$  ( $A = 112, 114, 116, 117, 118, 119, 122, 124$ ),  ${}^{165}\text{Ho}$ ,  ${}^{181}\text{Ta}$ ,  ${}^{209}\text{Bi}$ , i.e. for  $Z = 6, 14, 28, 40, 50, 67, 73$ , and  $83$ . The number of singly-ionized  ${}^3\text{He}^+$  ions of energy  $200 \text{ MeV}$  was measured by detecting them individually in the focal plane of the K600 magnetic spectrometer (together with tritons from the  $({}^3\text{He}, t)$  reaction), and the number of fully ionized  ${}^3\text{He}^{++}$  particles was measured by recording the charge collected in a beam stop located at the inner surface of the first dipole magnet of the K600 spectrometer.

The ratio  $N({}^3\text{He}^+)/N({}^3\text{He}^{++})$  was found to vary from about  $3 \times 10^{-9}$  for  $Z = 6$  to  $2 \times 10^{-7}$  for  $Z = 83$ . The results are shown as data points in Fig. 1. The statistical errors

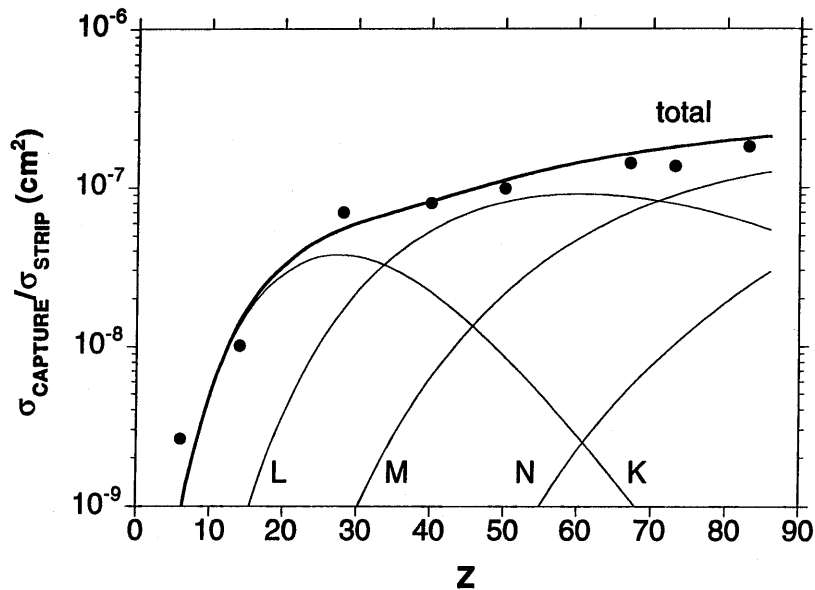


Figure 1. Experimental ratios  $N(^3\text{He}^+)/N(^3\text{He}^{++})$  and calculated ratios of atomic stripping and capture cross sections (solid lines) as functions of the atomic number  $Z$  of the target atoms. The calculated cross sections are decomposed into the contributions for capture from the atomic shells  $K \rightarrow N$ .

are smaller than the data points, but systematic errors of about  $\pm 10\%$  must be assumed. As expected, no differences within error bars were observed for the different isotopes with  $Z=50$ .

A complete theoretical interpretation of the data was carried out using calculated stripping<sup>1</sup> and capture<sup>2</sup> cross sections. The equations and procedures used are similar to those employed earlier for lower-energy data by Katayama, *et al.*<sup>3</sup>

Three expressions for the stripping cross sections have been reported<sup>1</sup> for low- $Z$ , medium- $Z$ , and high- $Z$  targets. However, it was found, in agreement with earlier results,<sup>3</sup> that the equation

$$\sigma_{strip} = \pi a_0^2 \frac{Z_t^{2/3}}{Z_p V_1} \quad (3)$$

for medium- $Z$  targets agrees quite well with all data except for the lowest values of  $Z$ . Here,  $a_0$  is the Bohr radius,  $Z_p$  and  $Z_t$  are the charges of the projectile and target, respectively, and  $V_1$  is the velocity of the projectile in atomic units, i.e., the ratio with respect to the Bohr velocity. An adopted stripping cross section was used in the present work equal to that of Eq. (3) except for the range  $Z = 6$  to  $14$  which was interpolated between the expressions for low- $Z$  and medium- $Z$ .

Fig. 2 displays experimental and theoretical atomic capture cross sections. The experimental values were obtained from the measured ratios  $N(^3\text{He}^+)/N(^3\text{He}^{++})$  multiplied by the adopted stripping cross sections. Theoretical predictions from the first- and second-order Oppenheimer-Brinkman-Kramer (OBK) approximations based on asymptotic expressions are displayed in the figure as dotted curves. The agreement with the data is very poor. However, the theoretical predictions based on the equations reported by Nikolaev<sup>3</sup> give very good agreement. These equations represent a generalization of the OBK method including arbitrary external and internal screening corrections. One-electron hydrogen-like wave functions are employed. The atomic binding energies were taken from a recent tabulation,<sup>4</sup> and the screening corrections and effective charges were calculated using the Slater rules. Fig. 2 also shows the decomposition of the contributions from the various atomic orbits of the target nuclei. It is quite apparent that the cross section is dominated by capture from the K orbit only for atoms up to about  $Z = 25$ . For the heaviest atoms contributions up to principal quantum numbers  $n = 4$  and even 5 (N and O orbits) must be included. The maxima for the contributions for capture from the K and L orbits occur when the speed of the projectile is close to the speed of the electrons in the respective orbit of the atom with the given  $Z$ . Corresponding experimental ratios  $N(^3\text{He}^+)/N(^3\text{He}^{++})$  and calculated ratios  $\sigma_{cap}/\sigma_{strip}$  are shown in Fig. 1. They display similar characteristics.

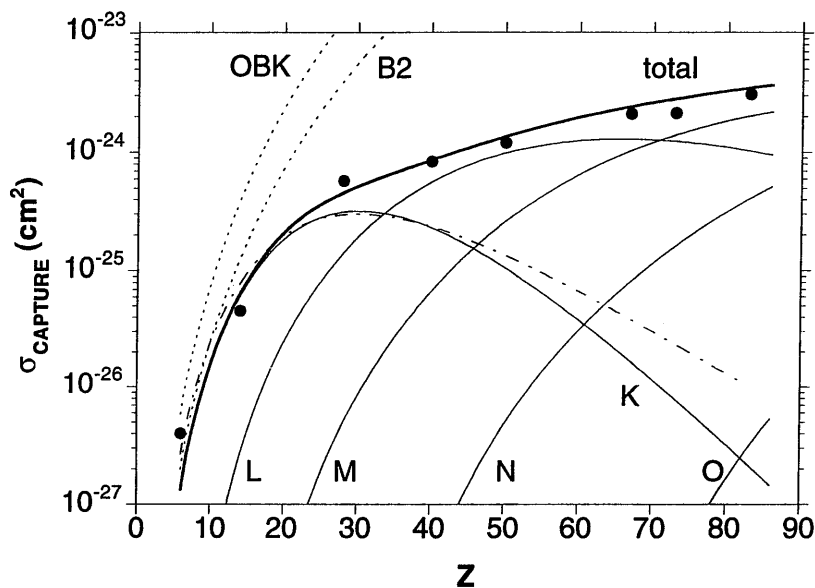


Figure 2. Atomic electron-capture cross sections for transitions  $\text{He}^{++} \rightarrow \text{He}^+$  at  $\beta = 0.36$  as function of the atomic number  $Z$  of the target atoms. The calculated cross sections (solid lines) are decomposed into the contributions for capture from the atomic shells  $K \rightarrow O$ . Predictions from the first- and second-order OBK approximations are shown as dotted curves, and predictions for capture from the K-orbits based on a relativistic equation are shown as a dashed curve. The data points are from the measured ratios  $N(^3\text{He}^+)/N(^3\text{He}^{++})$  multiplied by the adopted atomic stripping cross sections.

Recently, Anholt and Eichler<sup>5</sup> have calculated the cross sections for electron capture by relativistic projectiles in the eikonal approximation. In this formalism they were able to evaluate the cross section for electron capture into the K shell of a projectile from the K and L shells of the target atoms by a numerical integration of a two-dimensional integral. However, in the case where the target and projectile charges are small, i.e.  $\alpha Z_t$  and  $\alpha Z_p$  are much less than unity ( $\alpha$  is the fine structure constant), the integral can be expanded to first order in  $\alpha Z$  to yield an approximate formula [Eq. (4) in Ref. 5] for the  $1s_{1/2} \rightarrow 1s_{1/2}$  (K $\rightarrow$ K) cross section. By neglecting the phase distortion of the final-state wave function of the transferred electron it could be shown that this formula reduces to the relativistic OBK approximation.

We have used this formula to evaluate the K $\rightarrow$ K cross sections (only) for  $^3\text{He}$  projectiles from various nuclei at bombarding energies of 200 and 450 MeV. In this calculation, we have again used the experimental binding energies for the  $1s$  electron in the target nuclei,<sup>4</sup> and we used effective charges  $Z^* = Z_t - \Delta Z$ . The value  $\Delta Z = 0.3$  was assumed for the  $1s_{1/2}$  orbital to account for the partial shielding by inner-shell electrons. The results are included in Fig. 2 as a dash-dotted line. The agreement with the results based on the Nikolaev equations<sup>2</sup> is very good but starts to deviate for larger  $Z_t$  where the approximation  $\alpha Z_t \ll 1$  is not valid anymore. The use of calculated binding energies<sup>4</sup> and the relativistic OBK approximation give unsatisfactory results.

Calculations for  $E(^3\text{He}) = 68, 99, 130,$  and  $450$  MeV were also performed based on the equations of Nikolaev.<sup>2</sup> The agreement with the data of Katayama *et al.*<sup>3</sup> at the lower energies is very good and requires again the inclusion of atomic orbits in the target nucleus up to principal quantum number  $n=4$  (N orbits). Data for  $E = 450$  MeV will become available soon.

1. N. Bohr, K. Danske Vidensk. Selsk., Mat.-Fys. Meddr. **18**, No. 8 (1948).
2. V.S. Nikolaev, Zh. Eksp. Teor. Fiz. **51**, 1263 (1966) [JETP **24**, 847 (1967)].
3. I. Katayama *et al.*, Phys. Lett. **92A**, 385 (1982); Phys. Rev. A **27**, 2738 (1983); J. Phys. B: At. Mol. Phys. **17**, L23 (1984).
4. C.M. Lederer and V.S. Shirley, Table of Isotopes, 1989, Appendix.
5. R. Anholt and J. Eichler, Phys. Rev. A **31**, 3505 (1985).