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EXCITED STATE POPULATIONS AND CHARGE-EXCHANGE OF FAST IONS IN SOLIDS

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Abstract

Excited state populations and charge state fractions of 445 MeV Cl ions have been measured for a range of thicknesses of solid C targets. Cross sections for electron capture, loss, excitation and excited state quenching have have been determined and these data are found to predict a quantitative difference between equilibrium charge state distributions from gases and solids for a special case of the Bohr-Lindhard density effect model.

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1. Introduction

It is experimentally observed that when fast heavy ions pass through equilibrium thicknesses of gas or solid targets, the charge state distribution is richer in the higher charge states for solid targets than for gases. This density effect on charge state distributions is thought to arise as a consequence of the much shorter intercollision times in solids relative to gases. Two models, not mutually exclusive, have been proposed to account for this effect based on the consequences of these short intercollision times. The Bohr-Lindhard [1] model emphasized the rapid collisional ionization in a solid of excited states formed by electron capture or excitation. This process leads to an increase in the loss probability and a decrease in the capture probability for an ion traversing a solid relative to an ion traversing a gas target. Grodzins [2] proposed a model in which multiple vacancies with lifetimes in excess of the solid target transit time build up by collisions too rapid to allow projectile de-excitation; the projectile then changes charge after leaving the target by Auger emission.

If we choose a sufficiently high energy projectile where the bare nucleus and one electron ions dominate the charge state distribution, then Auger emission becomes negligible. If we then measure the capture, excitation, ionization, and quenching cross sections, we can calculate the charge state distributions for a solid and for a gas and infer the density effect in a case where the Betz-Grodzins mechanism is essentially absent.

The case chosen was 445 MeV Cl ions (12.7 MeV/amu) passing through a range of thicknesses of carbon foils. The incident ions were Cl^{16+} and Cl^{17+}. The range of carbon foil thicknesses was from 6 to 400 μgms/cm^2 or from ~12 to 800 atoms/Å^2. For each foil and charge state two measurements were made (1) the charge state distribution of ions leaving the foil was determined by electrostatic analysis using a position sensitive detector. (2) Excited state fractions were determined using a Si(Li) detector to measure the total intensity of Ly_α and Ly_β photons. The field of view of the detector was such as to observe decays from the exit of the foil to a point sufficiently down stream to include decay from states as high as about 16p. The detector resolution including Doppler spread was ~150 eV so that Ly_α and Ly_β transitions at 2.9 and 3.4 keV respectively could be well resolved, and higher Lyman series lines could be detected but not resolved. The efficiency-solid angle product was measured in place with a well calibrated Fe^{55} source. Beam charge was integrated and the previously measured charge state distributions were used to derive absolute excited state fractions. An example of this data for incident Cl^{16+} is shown in fig. 1.

This non-eqilibrium charge state and excited state fraction data was then fitted by a set of rate equations following the method discussed by Datz [3] and by Betz and Grodzins [2].

$$\frac{d\phi_i}{dx} = \sum_{j\neq i} (\phi_j \sigma_{ji} - \phi_i \sigma_{ij}) \tag{1}$$

The measured charge state and excited state fractions ϕ_i and their errors, including statistical errors and target thickness uncertainties, thus, were used with a non-linear least squares fitting routine to derive the state-changing cross sections, σ_{ij} and their errors. These results are given in table 1.

Before discussing the density effect we may compare these measured cross sections to some theoretical predictions. Gillespie [4] has recently given Born approximation calculations of ionization and excitation of fast H-like ions colliding with He, N, and Ar. The cross sections were scaled as $6^2/Z_t^2$, where Z_t is the appropriate He, N, or Ar nuclear charge. These estimates are included in table 1 were appropriate. The ionization cross sections for excited states was simply estimated by the Bohr [5] result

$$\sigma_{n\to\infty} = n^2 \ \sigma_{1s\to\infty}.$$

Electron capture cross sections have been calculated using Eichler's [6] code for the Eickonal approximation. Capture was calculated separately for capture from the C target K shell and L shell. The Z_2 parameter of Eichler's calculations was chosen following Slater's rule. The electron screening parameter θ was calculated according to Eichler's prescription. The effective screened target charge Z_t was chosen as 3.25 for capture from the target K shell and 1 for the capture from the target L shell so as to give good agreement between previous gas target total capture cross sections [7,8] and the total capture cross section of the Eickonal approximation. The capture probability to different excited states is seen to be in reasonable accord with the data, table 1.

Using these experimentaly determined cross sections, we can calculate the solid target equilibrium charge state distributions ($d\phi_i/dx = 0$ in eq. (1) These fractions are the large carbon thickness values shown by the solid curves in fig. 1. Likewise, the gas equilibrium fractions can be estimated by assuming that the excited state ionization probability is small compared to the radiation or de-excitation probability. This condition can be simulated in eq. (1) by setting the excited state ionization cross sections to zero and letting the de-excitation cross sections approach asymptotically high values. The resulting equilibrium fraction for gases are the values at large carbon thicknesses shown as dashed lines in fig. 1.

In conclusion, cross sections for electron capture, loss, and excitation; and cross section limits for excited state quenching have been determined for 12.7 MeV/amu Cl ions incident on C foils. It has been shown that for this case where Auger emission is negligible these cross sections lead to a sizeable density effect on charge state distributions which is consistent with the emphasis placed on excited state ionization by the Bohr-Lindhard model.

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Table 1. Cross Sections for 445 MeV Cl Ions
(Units 10^{-3} Å^2/C Atom)

Process	Experiment	Theory
$\sigma_{16\to17}$	1.23 ± 0.03	1.8
$\sigma_{16(2p+3d)\to17}$	12.0 ± 9.0	7.2 to 16.0*
$\sigma_{16(3p)\to17}$	30.0 ± 100.0	16.0
$\sigma_{17\to16}$†	0.61 ± 0.1	0.84
$\sigma_{17\to16(2p+3d)}$	0.28 ± 0.04	0.3, 0.05**
$\sigma_{16(1s)\to16(2p+3d)}$	0.28 ± 0.02	
$\sigma_{17\to16(3p)}$	0.06 ± 0.02	0.1
$\sigma_{16(1s)\to16(3p)}$	0.04 ± 0.01	
$\sigma_{16(2p+3d)\to16(1s)}$	0.0 ± 8.0	
$\sigma_{16(3p)\to16(1s)}$	0.0 ± 90.0	
$\sigma_{16(1s)\to16(2s,2p)}$		1.2
$\sigma_{16(1s)\to16(3s,3p,3d)}$		0.22

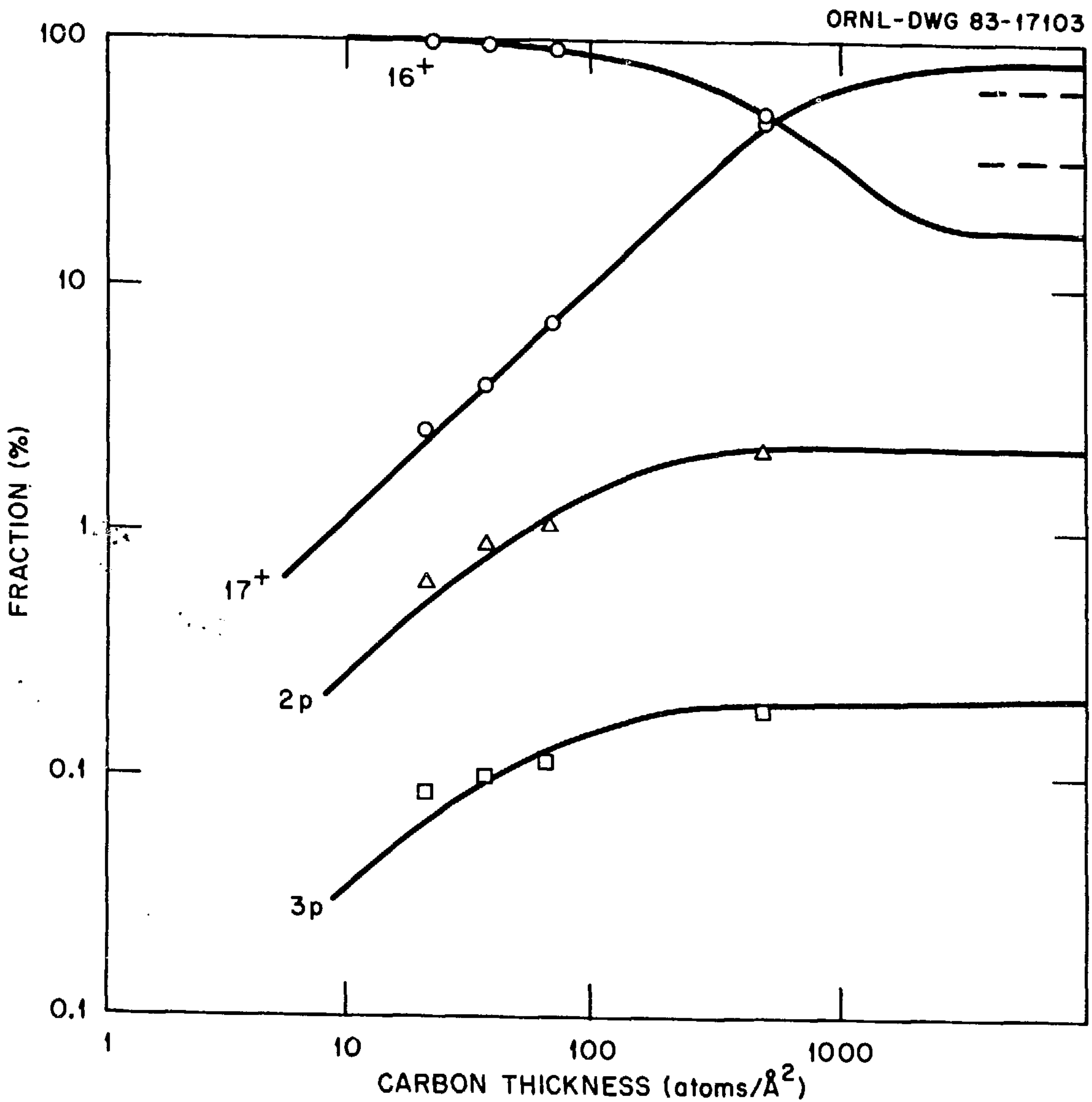
*Bohr n^2 scaling of $\sigma_{16(1s)}$ by 2^2 and 3^2

†All states

**$\sigma_{17\to2p}$, $\sigma_{17,3d}$

Figure Caption

Fig. 1 - Excited state and charge fractions from C foils versus foil thickness for Cl^{16+} ion incident. Also shown are the fits to the data using the cross sections of table 1. The calculated gas target equilibrium values are indicated by dashed lines.



ORNL-DWG 83-17103
100
10
1
0.1
0.1
16+
17+
2p
3p
FRACTION (%)
1
10
100
1000
CARBON THICKNESS (atoms/Å2)