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CHARGE AND ANGULAR CORRELATED INELASTICITIES IN MeV/NUCLEON ION-ATOM COLLISIONS*

H. SCHÖNE, R. SCHUCH†, S. DATZ, P. F. DITTNER, J. P. GIESE, H. F. KRAUSE, M. SCHULZ and Q. C. KESSEL§

Physics Division, Oak Ridge National Laboratory
P. O. Box 2008, Oak Ridge, Tennessee 37831-6377 USA

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Abstract

Using an Elbek high-resolution magnetic spectrograph, we measured energy loss and angular distributions of MeV/nucleon projectile ions in coincidence with target recoil-ion charge state. We investigated collisions of 10 and 20 MeV C^{6+} on He, Ne, Ar, and Kr where the target atom is multiply ionized and the projectile emerges in charge state q or q-1. The amount of energy transfered to the continuum electrons exeeds, by far, the sum of the values of the ionization potentials and shows a strong target Z dependence. Both an n-body classical-trajectory Monte Carlo method (nCTMC) and an energy deposition model are used for comparison with the experimental data.

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†Present address: AFI, Research Institute of Physics, Frescativägen 24, S-104 05, Stockholm 50, Sweden.

§Department of Physics, University of Connecticut, P. O. Box U-46, Storrs, Connecticut 06268.

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A tractable theoretical treatment of ion-atom collisions requires a reduction in the number of free parameters for the various possible reaction channels during the impact. Most atomic collision calculations for multi-electron transitions are based on either the sum of independent single electron transitions [1,2] or a statistically weighted energy deposition model [3,4]. Both approaches have been shown to have validity [2,5]. In this paper, we report on simultaneous measurement of scattering angle, recoi charge state, and inelasticity in MeV/nucleon collisions. These constraints eliminate the need for an **ad hoc** scattering potential to deduce the projectile inelasticity via the scattering angle [6]. In general, for inelastic collisions of this type, much of the energy is carried off by either direct ionization or by ionization following inner-shell ionization or excitation. We find that a large fraction of the total transfered energy is carried off by the continuum electrons. In an earlier communication [7] dealing only with 10 MeV C + Ne collisions an n-body Classical-Trajectory Monte Carlo calculation (nCTMC) by R. E. Olson was found to be in reasonably good agreement with the data.

In the experiments, a 10 and 20 MeV carbon beam was poststripped after passing through a 90° magnet. The C^{6+} beam was energy and charge state selected by using a second 90° magnet in combination with two sets of slits. The angular divergence was limited by a third slit in front of the gas cell. The gas target was isolated by three stages of differential pumping. The emerging projectile charge state, kinetic energy, and angular distribution was measured simultaneously in a high-resolution ($\Delta E/E_0 \approx 10^{-4}$) magnetic spectrograph. The degree of multiple target ionization produced by a given

projectile was determined by a time-of-flight technique. A more detailed description of the setup has been given elsewere [8]. A two-dimentional (2D) position-sensitive multichannel plate, placed in the focal plane of the Elbek magnetic spectrograph [9], was used to detect the recoiling projectiles. Since the spectrograph is double focussing in the plane of dispersion (corresponding to the 'X' direction of the detector) and non-focusing in the perpendicular plane (Y), a displacement in Y is a measure of the angular differential cross section $d\sigma/d\theta_y$. With the given properties of detector and spectrograph, the angular resolution is limited to 0.005°.

Some projections of the 2D distribution onto the Y-axis are shown in fig. 1. Here, we show θ_y distributions for single capture producing Ne^+ and Ne^{4+}, and for pure ionization to produce Ne^+ as well as Ne^{4+}. Differential cross sections calculated with the nCTMC method [7] are also shown in fig. 1 for the Ne^{4+} case. The theoretical values have been convoluted with the experimental parameters to take into account the focussing in the horizontal plane of dispersion and are in reasonable agreement with the experiment. Although the total measured cross sections for ionization to produce $C^{6+} + Ne^{4+}$ and with transfer to yield $C^{5+} + Ne^{4+}$ are similar ($\sigma \approx 10^{-17}$ cm^2), there is a noticable difference in the shapes of the differential cross sections. With direct ionization, larger impact parameters are favored more than in the transfer reaction and the differential cross sections are more sharply peaked at small angles. The impact parameter range probed by Ne^{4+} production in either the transfer or direct ionization channel is $\approx$ 0.6 a.u. $\pm$ 0.4 a.u. The Ne L-shell electrons dominate this reaction since collisions that remove K-shell electrons give rise to much higher stages of Ne^{q+}

ionization, and would show a minimum inelasticity of ≈1 keV (i.e., the energy required to remove a K-shell electron). The $d\sigma/d\theta_y$ values are very different for the production of Ne^+ by charge capture vis-a-vis by direct ionization; this is due to the total ionization cross section being approximately two orders of magnitude larger than that for capture, with ionization being dominated by Ne^+ production at large impact parameters.

For the system $C^{6+} + Ne \rightarrow C^{6+} + Ne^{q+}$, the projections of the C^{6+} position distributions on the X-axis of the two-dimentional detector are (Elbek plane of dispersion) are shown in fig. 2a for 10 MeV and in fig. 2b for 20 MeV incident ions. Each distribution was obtained in coincidence with a given Ne-recoil charge state. Because of the offset of the spectrum in coincidence with Ne^+ to the incident beam, the energy could not be determined accurately. We used the mean energy of the particles in coincidence with Ne^+, indicated by a dashed line, as an arbitrary reference point for energy loss. The 10 MeV data (fig. 2a) clearly show increased energy loss for an increased degree of target ionization. At 20 MeV (see Fig. 2b), we have a poorer energy resolution since the spectrometer resolution, $\Delta p/p$, is a constant. Nonetheless, it is clear that the inelastic losses are considerably smaller than those obtained for 10 MeV collisions.

In general, the inelasticity is given by the sum of (1) recoil-ion energy, (2) target-atom excitation leading to radiation, (3) in the case of capture, a balance between energy gain (or loss) due to an increase in binding energy on the projectile and energy loss due to an increase in translational energy of the captured electron and (4) energy transfered to the kinetic energy of the continuum electrons. The energy transfered to a recoil ion (1) can be

neglected in an evaluation of energy balances since the calculated recoil energy, even for producing Ne^{8+}, is less than 10 eV [10]. Energy loss due to excitation (2) cannot exceed the binding energy of the last bound electron. As for (3), an energy loss of ~450 eV is expected because of the increased kinetic energy (lab) of the transfered electron and is modified according to its binding energy difference between projectile and target. Additional energy might be transfered into the kinetic energy of continuum electrons in both direct ionization or capture plus multiple ionization channel. Subtracting the sum of the ionization potentials (ΣIP) necessary to create a given ionization state in Ne from the relative inelasticity (RI), we obtain (assuming that the recoil energy and excitation energy is low) the total kinetic energy of the continuum electrons. In fig. 3a, we plot total energy given to continuum electrons for direct ionizing collisions of 10 MeV C^{6+} with He, Ne, and Ar. In fig. 3b, we show the data for charge capture collisions of 10 MeV C^{6+} with He, Ne, Ar, and Kr targets. Here again, we use Q = 1 as an arbitrary zero of inelasticity. Statistical errors are in most cases smaller than the data point symbols.

Systematic errors are indicated only for Ne. In either channel, the kinetic energy is quite high with, i.e., 100 - 200 eV per emitted electron. Furthermore, for both reaction channels, the kinetic energy per continuum electron decreases with higher target Z.

A qualitative understanding of these processes can be made using the heuristic assumption that the electrons are ejected by a binary encounter mechanism. We can write the projectile energy loss simplified as:

$$\langle \Delta E_{DI} \rangle = \int P_{DI}(b) \langle T(b) \rangle \, b \, db \quad \text{for direct ionization} \tag{1}$$

or

$$\langle \Delta E_{EC} \rangle = \int \sigma_{EC}(b) \, P_{DI}(b) \langle T(b) \rangle \, b \, db \text{ for electron capture} \tag{2}$$

plus multiple target ionization, where $P_{DI}(b)$ is the impact parameter dependent direct ionization probability and $\sigma_{EC}(b)$ is the electron capture cross section. In the approximation of an unperturbed projectile path, $\langle T(b) \rangle$ is the energy transfer to a free electron with the spatial distribution for a given atomic wavefunction [5]:

$$\langle T(b) \rangle = \int |\psi(\vec{r})|^2 \; T(b, \frac{1}{\vec{r}^2}) \, d^3 \vec{r} \, . \tag{3}$$

The impact parameter for ionizing a given target electron can extend up to 5 to 10 times the electron radius [2] and, hence, extends to larger impact parameters for higher target Z. The $P_{DI}(b)$ for He^+ production peaks at about 2.5 a.u., Ne^+ at 4 a.u., and 5.5 a.u. for Kr^+. Hence, for high Z targets, we expect relatively less energy transfer to the removed electrons due to larger impact parameters, eqn. (3). This trend is reflected in the ionization measurements (fig. 3a).

Turning now to the results of fig. 2, we note that even at 10 MeV we are well above the maximum ionization cross section for L-shell electrons. At 20 MeV, we expect the total cross section to decline, but the impact parameter dependence of the cross section should peak at and extend to larger distances (see, e.g., the semiclassical treatment of Bang and Hansteen [11]). The experimental finding of decreased inelasticity with increasing energy is, therefore, in agreement with our expectations from eqns. (2) and (3) which predict less energy transfer for distant collisions.

In eqn. (2), we make the simplifying approximation that capture and ionization can be treated as independent processes. $\langle \Delta E_{EC} \rangle$ may be treated likewise as direct ionization only with a smaller impact parameter range defined by the requirement of simultaneous capture. For example, in the in the case of neon, we calculate capture to go predominantly to C^{5+} (n=2) (44% of the total flux). The impact parameter range for this process is 0.1 to 0.8 a.u. For Ar and Kr correspondingly, higher impact parameter ranges are obtained. As a result, the continuum electron energies are lower for increasing target Z, while for a given target Z, the kinetic energy of an ejected electron is larger in coincidence with electron capture than for direct ionization. Since one electron in the capture channel is not released to the continuum, recoil charge state Q-1 corresponds to charge state Q for direct ionization. The direct comparison of both channels shows qualitatively good agreement with this simple model. This independent particle model assumes that a one electron transition leaves the remainder unperturbed and, therefore, it can not explain the differential cross section for production of recoil ions or the angular dependence of the differential cross section.

These projectile inelasticities are confirmed by electron energy measurements in coincidence with either capture or direct ionization respectively [12]. Electron energy distributions in coincidence with capture showed a pronounced binary encounter peak at around 1800 eV, whereas the peak was not evident in coincidences with initial charge state ions.

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Figure Captions

Fig. 1. Angular differential cross sections as a function of the projectile scattering angle for Ne^{+} and Ne^{4+} recoil ions produced by pure ionization (q=6) and by electron capture (q=5) of 10 MeV C^{6+}.

Fig. 2. Projectile energy distributions in coincidence with recoil ion charge state for $C^{6+} + Ne \rightarrow C^{6+} + Ne^{q+}$ at (a) 10 MeV and (b) 20 MeV.

Fig. 3. Total energy deposited into continuum electrons (=measured projectile energy loss relative to recoil-ion charge state 1+ (RI) minus the sum of the ionization potentials (ΣIP)) necessary to form that charge state number of continuum electrons for (a) direct ionization and (b) charge capture into C^{5+} plus multiple ionization of 10 MeV C^{6+}.

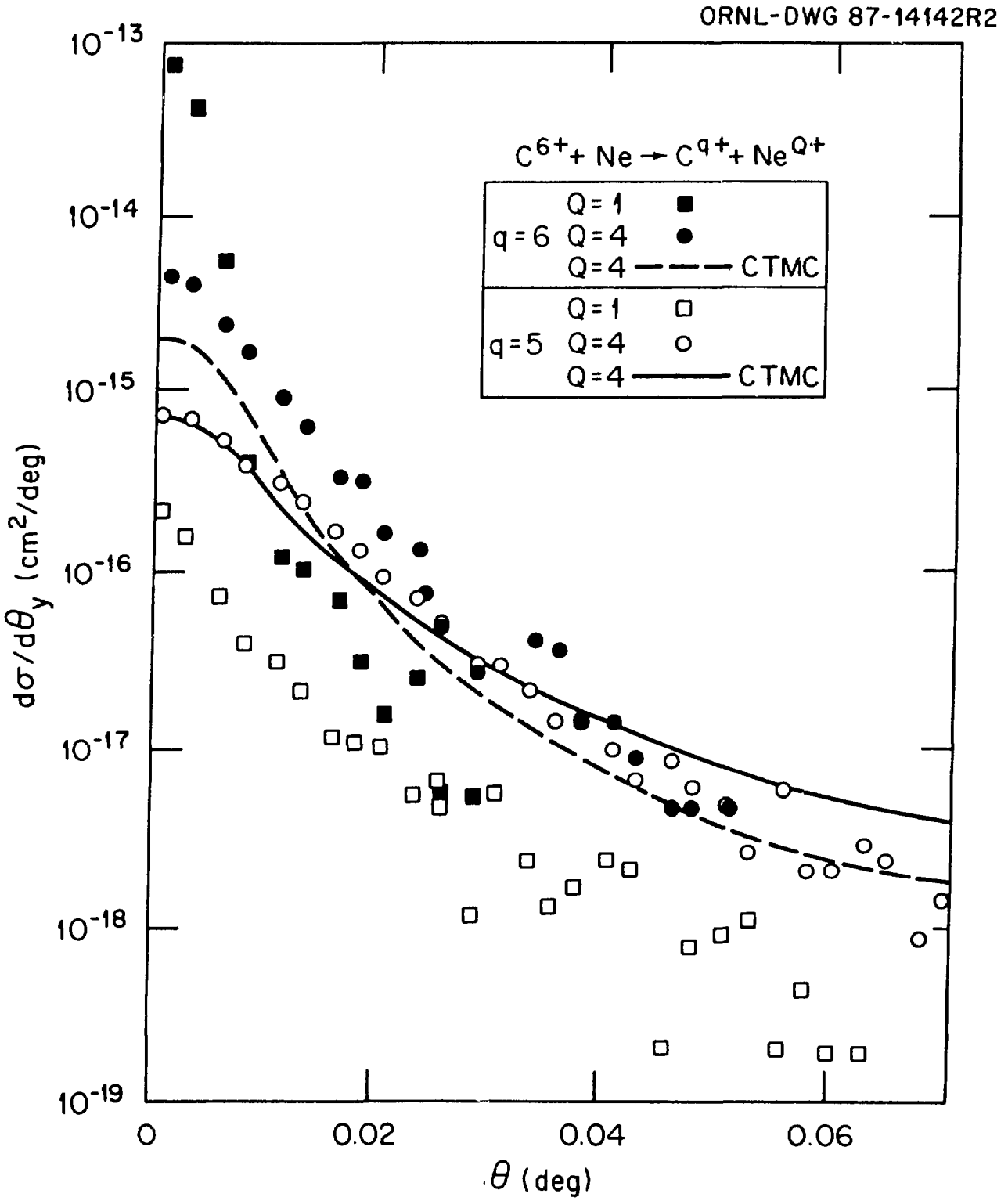
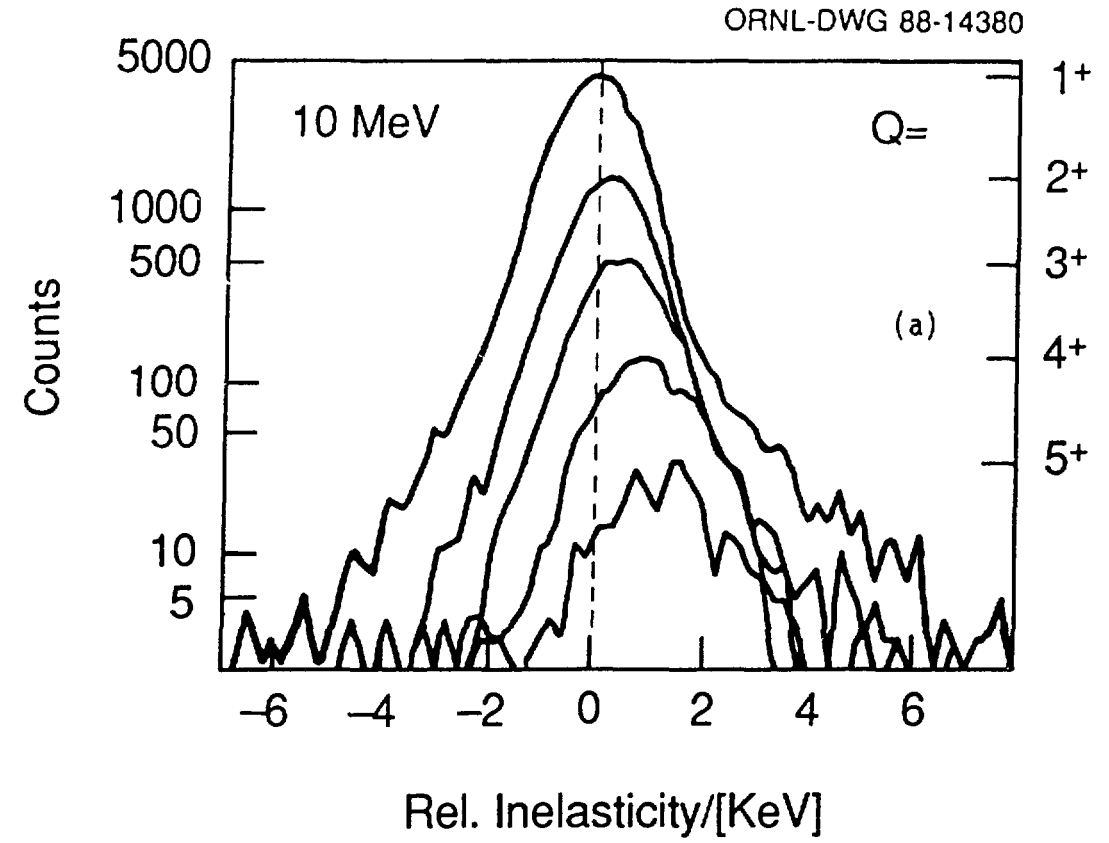

ORNL-DWG 87-14142R2
$C^{6+} + Ne \rightarrow C^{q+} + Ne^{Q+}$
q = 6
Q = 1
Q = 4
Q = 4 CTMC
q = 5
Q = 1
Q = 4
Q = 4 CTMC
$d\sigma/d\theta_y$ (cm²/deg)
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
0
0.02
0.04
0.06
θ (deg)

Fig. 1


ORNL-DWG 88-14380
10 MeV
Q=
(a)
1+
2+
3+
4+
5+
Counts
5000
1000
500
100
50
10
5
–6
–4
–2
0
2
4
6
Rel. Inelasticity/[KeV]

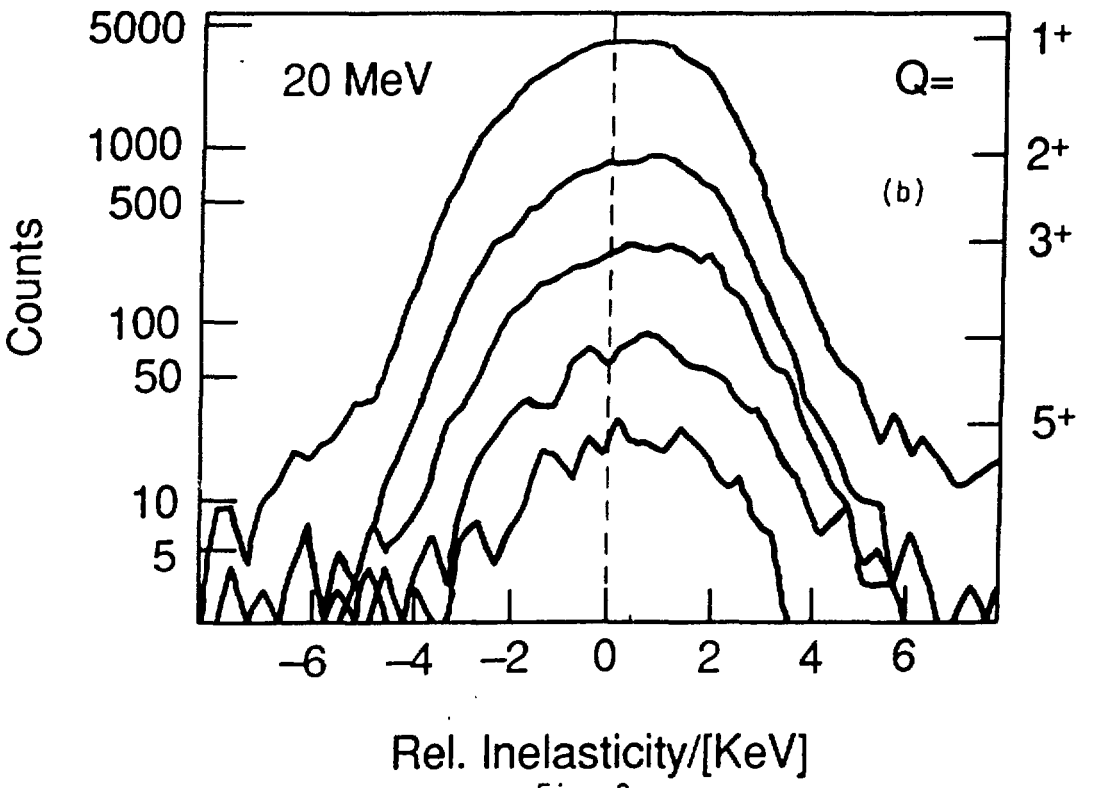
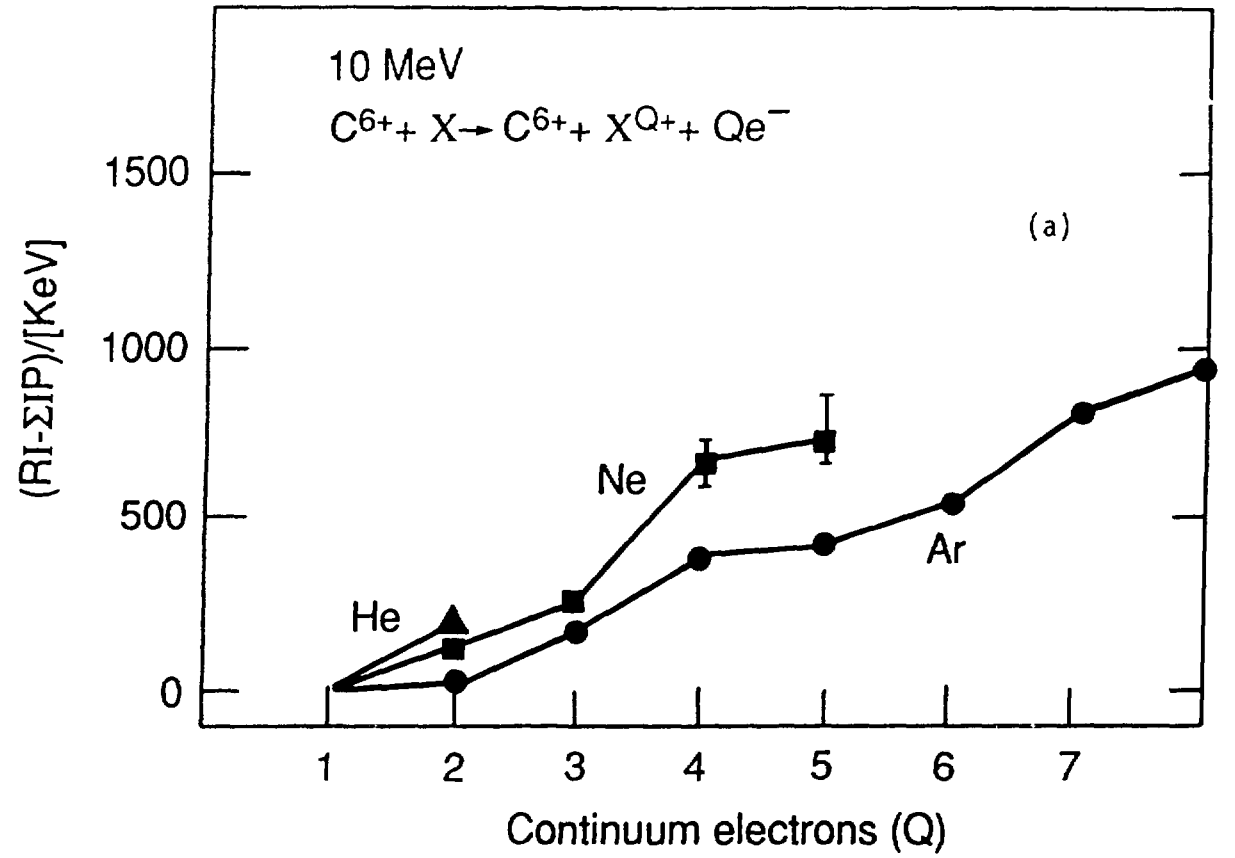

20 MeV
Q=
(b)
1+
2+
3+
5+
Counts
5000
1000
500
100
50
10
5
–6
–4
–2
0
2
4
6
Rel. Inelasticity/[KeV]

Fig. 2

ORNL-DWG 88-14381



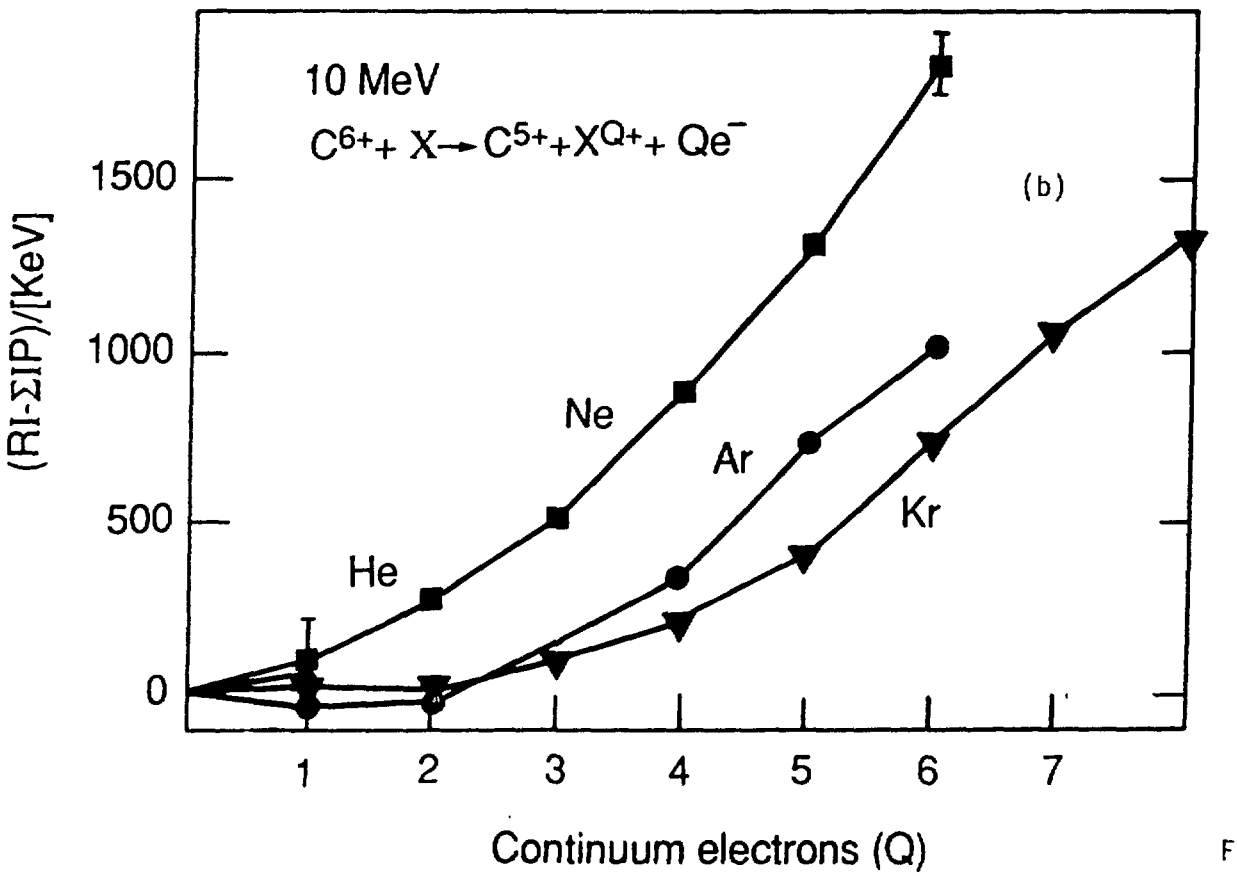


Fig. 3