CHARGE-CHANGING COLLISIONS

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Abstract

Recent results for charge-changing collisions of interest for cyclotrons and other particle accelerators are presented. Scaling rules, where available, are emphasized.

Introduction

Information on atomic charge-changing collisions is important for the design and operation of cyclotrons and other particle accelerators.[1,2] Collisions can occur in an external ion source, during beam transport and injection, and during acceleration. Particles which change their charge are lost, thereby attenuating the output beam. Particles which are lost to the beam may strike the cyclotron and cause radioactivation[3] with attendent health hazards. As heavier ions are accelerated in cyclotrons, the vacuum requirements become more stringent, and additional charge-changing information is required.

The purpose of this paper is to review recent results of charge-changing processes relevant to cyclotrons and other particle accelerators. The energy range included is from eV/u to hundreds of MeV/u, projectiles from the entire periodic table (Li to U), and the total range of charge states for which information is available. Various targets are considered, especially H, H_2, and He; although these are not predominant in the background gas in a cyclotron, they have been more thoroughly studied than CO, CO_2, H_2O, O_2, N_2, and hydrocarbons likely to be found in the residual gas in a cyclotron. I shall be especially concerned with scaling rules applicable for a wide variety of projectile-target systems, as data for a particular collision system of interest are normally not available.

Two processes dominate charge-changing collisions in accelerators: single-electron capture (electron pickup)

$$A^{q+} + B \rightarrow A^{(q-1)+} + [B^{+}] \qquad (1)$$

and single-electron loss (stripping)

$$A^{q+} + B \rightarrow A^{(q+1)+} + [B + e^{-}] \qquad (2)$$

where A and B are projectile ion and target atom, and q^{+} is the charge state of the ion before the collision. The brackets indicate that the target charge state is undetermined. Cross sections for two-electron transfer are generally an order of magnitude smaller than for one-electron transfer; two-electron-loss cross sections can be appreciable for very fast projectiles in low charge states.

Electron Capture at Low Energies

Low energy is used here to mean that the projectile velocity v is much less than the orbital velocity of the electron being captured - usually from the outer shell of the target. For the hydrogen-atom ground state the velocity of the electron is $v_0 = 2.2 \times 10^{8}$cm/s or about 25 keV/u. Electron-capture cross sections for low-energy multiply charged ions have been extensively studied, especially by Salzborn's group[4] in Giessen. Cross sections are generally independent of velocity, and directly proportional to the charge of the projectile. An approximate scaling rule[4] can be used for this velocity range:

$$\sigma_{q,q-1} = 1.43 * 10^{-12} * q^{1.17} * I^{-2.76} \text{ cm}^2 \qquad (3)$$

where $\sigma_{q,q-1}$, is the electron-capture cross section in cm^2, q is the projectile charge state, and I is the first ionization potential of the target in eV. The same experimenters[4] subsequently extended the range of target I, finding an I^{-2} behavior for smaller values of I. Typical results[5] are shown in Figs. 1 and 2.

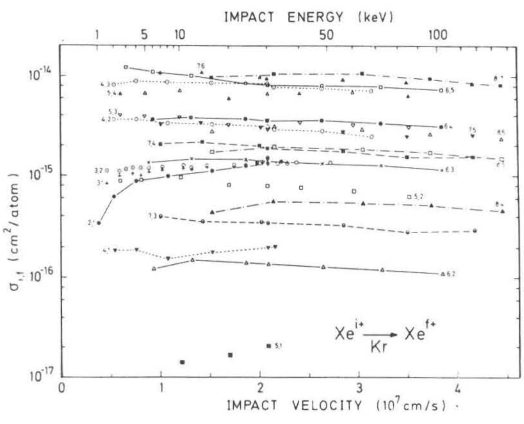

Fig. 1 Electron-capture cross sections for low-energy Xe ions in a Kr target, from measurements by Salzborn and Müller.[4,5]

Measurements have been carried to lower energies by use of special sources of ions: a laser-produced plasma,[6] and recoil ions produced by a fast ion beam and stored in an ion trap.[7] Phaneuf[6] has measured electron capture for Fe^{q+} ions ($q \leq 3 \leq 14$) in H and H_2 at energies in the range 10-95 eV/u. For Fe^{5+} and Fe^{6+}, for which higher-energy data exist, the cross section for electron capture is essentially independent of velocity over the energy range 17-2000 eV/u. Vane, Marrus, and Prior[7] at LBL have measured electron-capture cross sections for highly stripped Ne ions stored in an electrostatic trap. They found that the electron-capture cross section for 7-45 eV Ne^{10+} in Ne is velocity independent; however, other collision partners, e.g., Ne^{7+} in Ne and Xe, showed a cross section decreasing with increasing velocity in the energy range 1-70 eV.

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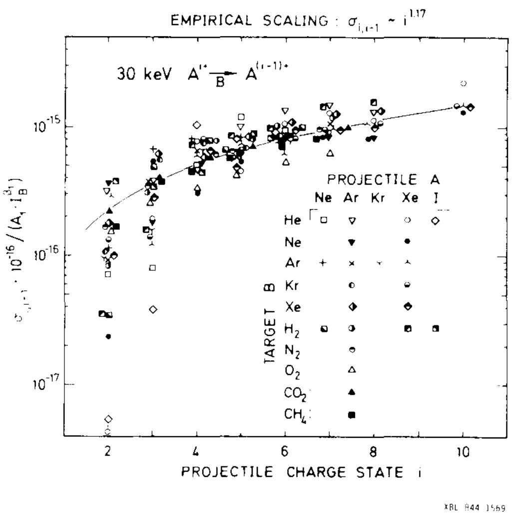

Fig. 2 Scaled one-electron-capture cross sections for various 30-keV projectile-target combinations (Eq. 3), by Salzborn and Müller.[4,5]

Electron Capture at High Energies

Electron capture for fast projectiles ($v > v_0$) has been extensively studied. Recent measurements with cyclotrons and linacs have extended the range of projectiles studied to high energies and charge states.[8] Most measurements are at energies lower than 10 MeV/u; a notable exception is a recent measurement at 962 MeV/u using the LBL Bevalac.[9]

An apparatus used by the LBL group[8] for measuring charge-transfer cross sections (electron capture and loss) is shown in Fig. 3. A beam of ions from the LBL SuperHILAC is incident on a thin carbon foil. Ions in a single charge state are selected by a magnet located downbeam from the foil, and, after suitable collimation, pass through a differentially pumped gas target in which the pressure is measured with a capacitance manometer. Ions in the initial charge state as well as those which capture or lose one or two electrons are analyzed in a second magnet and are detected with solid-state detectors. Cross sections are determined from the rate of growth of the signals for ions which change charge in the gas cell. Cross sections are readily detemined to an approximate accuracy of ±20 percent. Sample cross sections[8,10] are shown in Figs. 4 and 5.

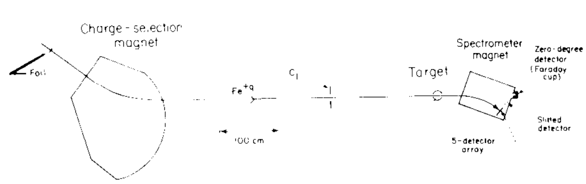

Fig. 3 Schematic diagram of apparatus used by the LBL group to measure charge-transfer cross sections.[8] A beam of ions from the Super-HILAC was incident from the left.

A considerable number of cross sections for electron capture have been measured for multiply charged ions incident on H and H_2 at intermediate energies, i.e., typically at velocities up to 3 v_0. For example, the Oak Ridge group[11] has made measurements for a variety of ions, including Fe^{q+} ($4 \leq q \leq 15$). The Belfast group has also reported[12] many measurements in H and H_2 targets, e.g., B and C ions. Olson and co-workers[13] have had considerable success in calculating electron-capture cross sections at intermediate velocities using the classical trajectory Monte Carlo method.

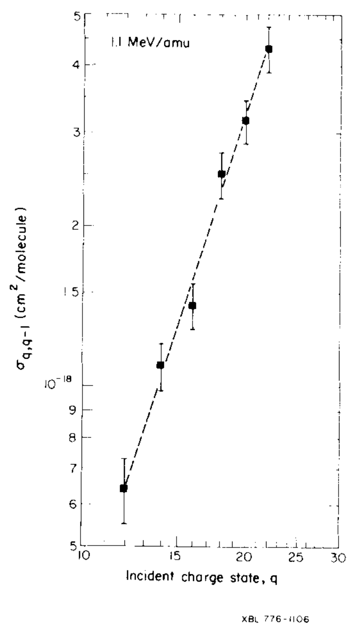

Fig. 4 Electron-capture cross sections for 1.1 MeV/u Fe^{q+} ($q = 12\text{-}22$) ions in an H_2 target, measured by the LBL group.[8] The line is $\sigma = 2.6 \times 10^{-22}\, q^{3.15}$.

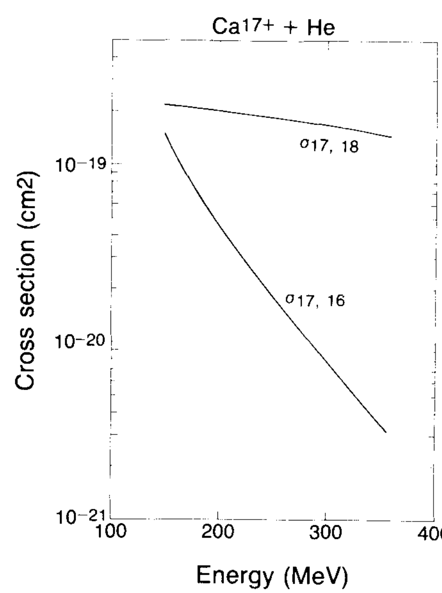

Fig. 5 Electron-capture and -loss cross sections for Ca^{17+} ions in a He target, measured by the LBL group.[10]

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Cross sections for electron capture by a fast projectile are rarely available for the desired projectile specie and charge state in the desired target over a large energy range. There has therefore been considerable interest in scaling of electron-capture cross sections with these parameters. Berkner et al. found a scaling rule[8] for electron capture by fast highly charged iron ions in an H_2 target. The electron-capture cross section σ was described by

$$\sigma = 1.2 \times 10^{-8} q^{3.15} E^{-4.48} \text{ cm}^2 \quad (4)$$

for projectile energies greater than 275 keV/u, where E is the energy of the iron projectile in keV/u and q is the projectile charge state. Alonso and Gould[14] found, for fast lead and xenon ions in N_2, a q dependence of approximately 2.9-3.3; in addition, these authors found a velocity dependence of about $v^{-5.8}$ or $E^{-2.9}$, based on data over a limited range of velocities. Knudsen et al.[15] found that electron-capture cross sections scale in reduced coordinates σ/q and $E/q^{4/7}$ in a given target; based on the Lenz-Jensen atomic model, cross sections could be described in reduced coordinates $\sigma Z^{2/3}/q$ and $E/(q^{4/7} Z^{16/21})$, where Z is the target atomic number. Ryufuku[16] has found that cross sections in atomic hydrogen could be scaled in the reduced coordinates $\sigma/q^{1.07}$ and $E/q^{0.35}$, while Janev et al.[17] found $E/q^{0.5}$ to be a suitable scaling parameter for electron capture from inner shells of Ar atom targets.

Schlachter et al.[18] took a generalized approach to scaling electron-capture cross sections for a large variety of projectiles and targets. A non-linear least-squares fitting routine was used to adjust a multi-parameter formula to selected electron-capture cross-section data.[8,19-21] The best values for the reduced parameters were found to be

$$\tilde{\sigma} = \sigma Z^{1.8} / q^{0.5}$$
$$\tilde{E} = E/(Z^{1.25} q^{0.7}) \quad (5)$$

where σ is the electron-capture cross section in cm^2, q is the projectile charge state, E is the projectile energy in keV/u, and Z is the atomic number of the target. The best fit to the data in reduced coordinates is

$$\tilde{\sigma} = \frac{1.1 \times 10^{-8}}{\tilde{E}^{4.8}} \left[1-\exp(-0.037\, \tilde{E}^{2.2})\right] * \left[1-\exp(-2.44 \times 10^{-5} \tilde{E}^{2.6})\right]. \quad (6)$$

Cross-section data in reduced coordinates for a wide variety of targets are shown in Figs. 6 and 7; the curve is the representation of Eq. 6. Approximately 70 percent of all data tested lie within a factor of 2 of the curve, subject to several restrictions:

$$10 < \tilde{E} \quad (7a)$$

where $\tilde{E}$ is defined in Eq. 5, with energy E in keV/u;

$$q \geq 3 \quad (7b)$$

and $$\tilde{E} < 1000. \quad (7c)$$

It is possible that the curve will continue to bend with increasing steepness for higher values of $\tilde{E}$.

At high reduced energies, Eq. 6 asymptotically approaches

$$\sigma = 1.1 * 10^{-8} q^{3.9} Z^{4.2} / E^{4.8} \quad (8)$$

in normal coordinates. The target atomic-number dependence allows prediction of electron-capture cross sections for many targets.

Crothers and Todd[22] have shown that semiclassical theory accounts for q^3 scaling in electron capture in atomic hydrogen at intermediate energies, and that semiclassical OBK, eikonal, continuum intermediate-state and continuum distorted-wave theories all lead to q^3 scaling. In the limit of high velocities, OBK and more modern theories[23] predict a q^5 dependence. The asymptotic charge-state dependence observed in the present result is $q^{3.9}$.

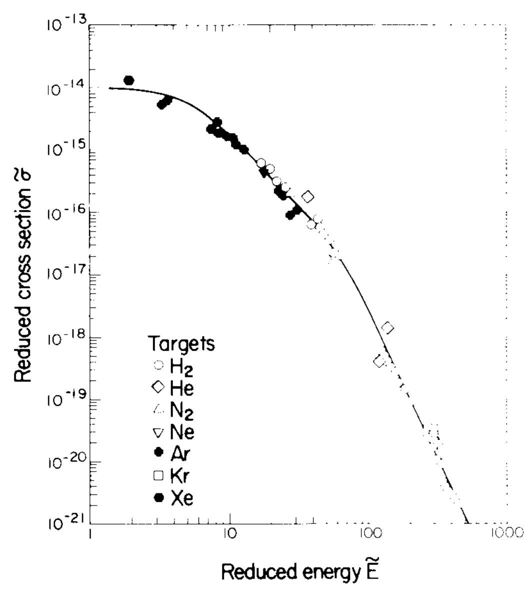

Fig. 6 Reduced plot of electron-capture cross sections[18] for fast highly charged ions in gas targets, in scaled coordinates (Eq. 5). The line is Eq. 6.

Eichler and Narumi[24] have compared the Born approximation with the classical-trajectory eikonal approximation: the second Born approximation gives rise to a v^{-11} term ($E^{-5.5}$), which will dominate the first Born term, which varies as v^{-12} (E^{-6}), while the classical-trajectory eikonal approximation only predicts the v^{-12} (E^{-6}) velocity dependence. The scaling rule shows a $v^{-9.6}$ dependence on velocity for large velocities, rather than the theoretically expected v^{-11} or v^{-12}. It seems likely that, were data to exist for much higher reduced energies, the asymptotic behavior observed (Eq. 8) would have to be modified. The q dependence may approach q^5 and the velocity dependence v^{-12}.

Application of the scaling rule to molecular targets is not clear. Data for H_2 and N_2 were fit successfully by dividing the molecular cross section by 2 and then using the atomic number Z. This procedure is approximate at best, and is probably not applicable to molecules such as CO_2 or hydrocarbons. The projectile charge state and velocity or energy scaling, however, will nonetheless probably scale successfully.

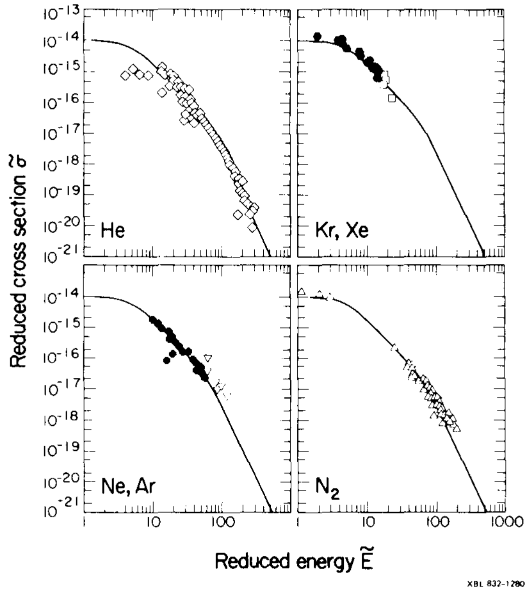

Fig. 7 Reduced plot of electron-capture cross sections[18] for fast highly charged ions in gas targets, in scaled coordinates (Eq. 5). The line is Eq. 6.

Electron Loss

There are considerably less data for electron loss than for electron capture. This renders more difficult the task of calculating the attenuation of a beam, especially for high velocities or low charge states, where electron loss generally exceeds electron capture. Furthermore, electron loss is sensitive to the binding energy of the electron to be removed, hence to the shell structure of the ion.

The electron-loss cross sections for a given ion has only a weak energy dependence. Measurements show a broad maximum with energy, peaked at a velocity of 1 to 2 times the velocity of the electron being removed,[20,21,25–27] as predicted by Bohr and Lindhard. The cross section is predicted by the Born approximation to decrease as $1/v^2$ for very high velocity,[28] although a slower decrease is often observed,[13] perhaps because the velocity is not sufficiently high. The energy at which the maximum in the cross section occurs increases with increasing charge state of the ion. Sample data are shown in Figs. 5 and 8.[10,21]

A very strong charge-state dependence is observed in electron loss. For a charge-state dependence

$$\sigma_{q,q+1} = \sigma_0 \, q^{-\alpha} \qquad (9)$$

the LBL group[8] has observed values of α as large as 9–12 for $q \geq 10$ for fast Fe, Nb, and Pb ions; values of 2–4 are observed for different projectile-target systems. Sample data are shown in Fig. 9.[8]

Alonso and Gould[8] have found a semiclassical model, based on Bohr's formula. Agreement with experiment is roughly within a factor of 2. Alton and colleagues[25] discuss a different modified Bohr formula, which agrees quite well with experiment.

$$\sigma_{q,q+1}(\mathrm{cm}^2) = N_j\left(\frac{13.6}{I_j}\right)\left(\frac{v_0}{v_1}\right)^2 * \left(Z_1^{1/3} + Z_2^{1/3}\right)^2 \pi a_0^2 \qquad (10)$$

where N_j is the number of electrons in a given subshell.

Discontinuities are observed in electron loss when a new shell is reached,[8] as in Fig. 10, which shows data for highly stripped iron ions in H_2; the abrupt decrease in cross section is due to the greatly increased binding energy of the K-shell electron to be removed, relative to the ease of removal of electrons from the L-shell.

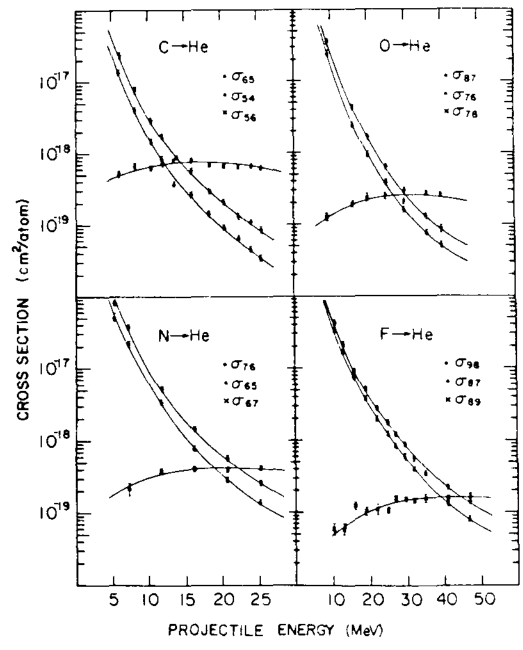

Fig. 8 Electron-capture and -loss cross sections for C, N, O, and F ions in a He target, measured by Dillingham et al.[21]

Theoretical calculations which can be compared with experimental results for fast highly stripped projectiles are generally restricted to hydrogen-like ions.[29–31] Calculations based on the Born approximation for atomic-hydrogen targets are generally in agreement with experimental cross sections for high velocities.[32] Born calculations for non-hydrogen-like ions generally underestimate experimental results by more than an order of magnitude.

The Bohr theory[33] often overestimates single-electron-loss cross sections. It does, however, provide a good first-order estimate.[25,32] Cross sections for electron loss generally increase with increasing atomic number Z of the target. Knudsen et al.[32] have shown that, for heavy gas targets at low energies and charge states, the Bohr theory gives quite good target-gas dependence. For targets heavier than nitrogen, measurements for 4.66 MeV/amu Pb^{54+} show a $Z^{0.47 \pm 0.02}$ dependence.[8] The Bohr theory[33] predicts a $Z^{0.67}$ dependence at higher energies. Other discussions of Born calculations[28] and comparison with experiment have been presented.[8,14,21,26,29] Target gas dependence is shown in Fig. 11.[35]

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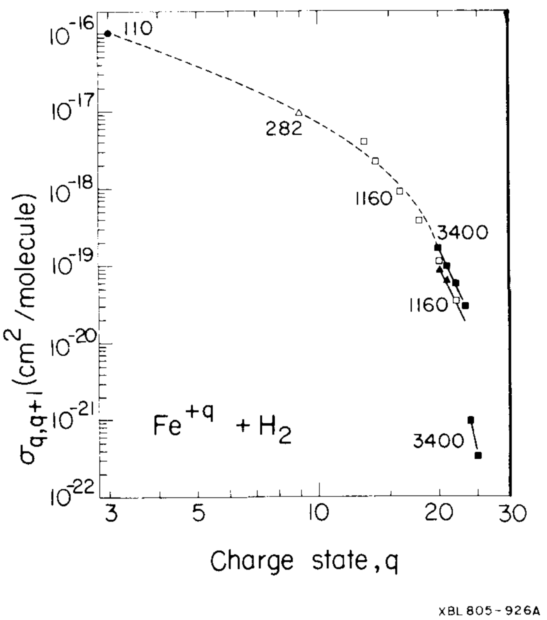

Fig. 9 Electron-loss cross sections for Fe^{q+} ions in an H_2 target, measured by the LBL group.[8] The numbers on the figure are energy in keV/u.

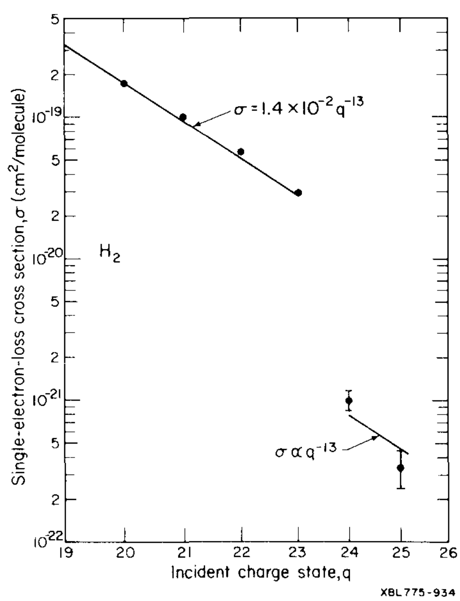

Fig. 10 Electron-loss cross sections for 3.4 MeV/u Fe^{q+} ions in H_2, from measurements by the LBL group,[8] illustrating the effect of shell structure in electron loss.

Knudsen et al.[34] have shown, for 20 MeV Fe^{4+} in gases, that multiple electron loss can be an important process for a fast, low-charge-state, heavy projectile.

Transfer Ionization

An interesting collision process which has received considerable attention recently is transfer ionization: a collision in which more electrons are lost by the target than are captured by the projectile. In its simplest form, it can be represented by:

$$A^{q+} + B \rightarrow A^{(q-1)+} + B^{2+} + e^{-}. \qquad (11)$$

The effect is that two-electron transfer to an auto-ionizing state appears as single-electron capture, rendering comparison of theory and experiment difficult.

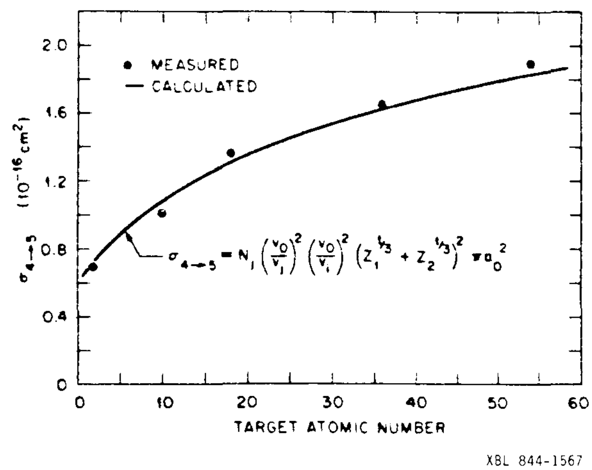

Fig. 11 Electron-loss cross sections for 20-MeV Fe^{4+} in various target gases, from measurements by Alton et al.[25] The line is Eq. 10.

Transfer ionization can be very important in slow ($v < v_0$) collisions of multiply charged ions in multi-electron targets.[35,36] These collisions have been studied by coincidence techniques, in which the target recoil ion is detected in coincidence with the charge-transferred projectile. The charge state of the recoil ion is generally determined by its time-of-flight. A slow Kr^{10+} ion can produce Xe recoil ions four- and five-times ionized. These collisions generally depend upon the internal potential energy of the collision system rather than on the projectile kinetic energy. Capture by the projectile of two or more electrons can produce even higher-charge-state recoil ions, because more potential energy is available for the release of additional target electrons.

Transfer ionization is also important in fast collisions,[37,38] in which projectile kinetic energy does play a role. For high-charge-state projectiles, transfer ionization can be of the same magnitude as single-electron capture, and much larger than double-electron capture. Thus single-electron capture accompanied by ejection of a second electron from the target is an important collision process.[38]

Additional Data

Results for charge-changing collisions have been summarized in several references. The review of Betz[19] is useful, although it is no longer up to date. Considerable current information can be found in publications[39,40] by the Institute of Plasma Physics, Nagoya University. Electron capture by multiply charged ions has been discussed in a symposium at the Kyoto ICPEAC meeting in 1979,[41] and in a symposium on collisions of multicharged ions with atoms at the 1981 Gatlinburg ICPEAC meeting.[42] Janev and Presnyakov have published an extensive report[43] entitled "Collision processes of multiply charged ions with atoms." Additional information can be found in the proceedings of the 1982 Stockholm conference on production and physics of highly charged ions,[44] or in deHeer's review[45] on electron capture and ionization.

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