ACCELERATOR- BASED ATOMIC PHYSICS AT THE LAWRENCE BERKELEY LABORATOTY: COLLISIONS OF FAST, HIGHLY- CHARGED IONS WITH ATOMS

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ABSTRACT

Research on accelerator – based atomic physics at the Lawrence Berkeley Laboratory super – HILAC and Bevalac accelerators is described. This research covers several important topics in collisions of fast, highly charged ions with atoms: charge transfer, ionization, and excitation. Multiple – electron processes are emphasized. Electron correlation is important in some of these processes, e.g., resonance transfer and excitation (RTE) multiple – electron capture in close collisions. A variety of experiments and results for energies from 1 to 420 MeV/u are presented.

Keywords: Accelerator Atomic physics Collisions of ions with atoms

I . INTRODUCTION

Atomic physics is essentially the study of electrons, where the electron is the exchange particle of the electromagnetic force. Electrons play an important role in chemistry as they essentially hold molecules toghether. The purpose of this paper is to describe atomic physics of highly charged ions produced by accelerators and the use of nuclear physics techniques for these studies, which were carried out at the Super HILAC and Bevalac accelerators at the Lawrence Berkeley Laboratory.

An important parameter in ion – atomic collisions is the velocity of the projectile ion relative to that of the active electron, which can be an electron on the projectile ion or on the target atom. The active electron is the electron being captured, removed, or excited. A characteristic velocity is the Bohr velocity, approximately 2.2×10^{8}cm/s, which corresponds to a specific energy of 24.9 keV/u. A collision in which the projectile velocity is large relative to the active electron is a sudden or impulse collision; the electrons barely move during the collision. When the projectile velocity is small relative to that of the active electron, the collision can often be considered in the context of a quasi – molecule. Another characteristic property of an atom is its size: the Bohr radius, or the mean radius of an electron in the ground state of a hydrogen atom, is about 5×10^{-9}cm. While this is large compared to nuclear dimensions (10^{-13} cm), it is small (0.05 nm) relative to the wavelength of visible light (approximately 500nm). Thus, atoms cannot be "seen" directly.

Accelerator – based atomic physics often uses a fast ion as a probe to study the interaction of projectile and target nuclei and their electrons. An accelerator provides a beam of fast ions, usually at a given velocity and selected to be in a given charge state. The target is usually a gas or foil. Detectors are used to detect the charge state of projectile and target after the collision and electrons or X – rays emitted by the projectile or target. Sophisticated techniques, such as measurements differential in angle and /or energy, are often used. Other nuclear physics techniques are time – of – flight and coincidence measurements, which can be used to determine simultaneity. This is a powerful tool in the study of multi – electron processes, such as transfer ionization and RTE; detailed information about the collision process can be obtained.

A generic equation for an ion – atom collision is shown in equation 1.

$$X^{q+} + Y \rightarrow X^{q+j} + Y^{i+} + \textit{electrons} \qquad (1)$$

where X^{q+} is a projectile ion in charge – state q before the collision; X^{q+j} is a target atom before the collision; is the projectile ion after the collision, where it has captured or lost j electrons (j can be positive or negative); and Y^{i+} is the target (recoil ion) in charge state i after the collision. Electrons and/or X – rays can also be liberated in the collision.

Charge transfer, ionization, and excitation are fundamental processes in fast ion – atom collisions. Each of these processes can occur alone in a collision, or more than one process can take place in the same collision. When more than one electron is involved, electron correlation, due to an electron – electron interaction, can be important, as in resonant transfer and excitation(RTE), or in Auger – electron emission. When electron correlation is not important, the process can be described by an independent electron model, as is generally the case, for high – energy ion – atom collisions, in continuum – electron emission, multiple – electron capture in close collisions, and recoil – ion production.

These processes have been studies at the Lawrence Berkeley Laboratory, using fast ion beams from the Super HILAC and Bevalac accelerators. The topics discussed in this paper are charge transfer, recoil – ion production, continuum – electron production, multiple – electron capture in close collisions and RTE.

II. CHARGE TRANSFER

Cross sections for electron capture and electron loss have been measured for a wide rariety of multiply charged ions for energies from 0.3 to 8.5 MeV/u at the Super HILAC, and energy and charge – state dependences have been determined[1-3]. An example is shown in Figs. 1 and 2, in which cross sections for electron capture and electron loss are shown as a function of energy for lithium – like V^{20+} in He and as a function of projectile charge state for 8.55 MeV/u vanadium ions in He. Fig.1 shows energy dependence of electron – capture and electron – loss cross sections for V^{20+} in He. The figure shows the broad maximum expected for electron loss near the maximum of the cross section; it also shows the steep decrease in electron capture with increasing projectile energy. The electron – capture data shown have an energy dependence of appreximately $E^{-4.2}$ for the highyer energies. Born – approximation calculations predict an electron – capture energy dependence which should reach a limit of $E^{-5.5}$ (second Born) or E^{-6} (first Born) at asymptotically high energies. Fig.2 shows the charge – state dependence of electron – capture and electron – loss cross sections for 8.55MeV/u V^{20+} in He. Clearly seen is the shell effect in electron loss: the cross section decreases by a large factor for removal of a projectile *K* electron. This discontinuity for electron loss between q = 20 and q = 21 marks the boundary between the vanadium *L* and *K* shells. Electrons in the *K* shell of vanadium are bound by about 6.5 keV, while those in the *L* shell are bound by less than 1.6 keV. The *L* – shell electron – loss cross section is found to scale as q^{-12},, while the *K* – shell electron – loss cross section scales as q^{-14}. The electron – capture cross sections scale as $q^{-3.8}$, midway between OBK scaling for intermediate velocities of q^3 and the second – Born approximation high – energy prediction of q^5. Early charge – transfer results have been summarized[4] and a scaling rule for electron capture has been determined[5]. This scaling rule is useful for predicting the magnitude of as – yet – unmeasured cross sections. Projectile electron loss and excitation have also been reported[6]. Similar measurements at much higher energies have been made by Gould and co – workers[7] at the Bevalac.

Ⅲ. IONIZATION: RECOIL- ION PRODUCTION

Multiple ionization of rare – gas atoms by highly charged uranium ions has been studied at the Bevalac[8,9]. Two experiments have been performed to measure the recoil – ion charge – state distribution by a coincidence time – of – flight method. Cross sections for multiple ionization of Ne, Ar, Kr and I atoms by 420 MeV/u U^{q+} ($q \sim 91$) were measured; recoil – ion charge states up to approximately 0.5 times the target atomic number were identified. Fig.3 shows the measured ionization cross sections as a function of recoil – ion charge state. The cross sections are large, i.e., greater than 10^{-18} cm^2 for producing Kr recoil ions in charge states around 20+. Error bars on *i* arise from uncertainty in the time calibration. Similar measurements have been made in Ne, Ar and Kr targets for 120 MeV/u U^{90+} projectiles.

Ⅳ. CONTINUUM- ELECTRON PRODUCTION

Electron – emission cross sections differential in angle and electron energy have been measured for 6 MeV/u U^{38+} and Th^{38+} in Ar and He targets[10]. Fig.4 shows double differectial cross sections for 6-MeV/uU^{38+} in Ar for a forward angle (30^0) and a backward angle (150^0) along with a Plane Wave Born Approximation(PWBA) calculation. The electron emission shows an enhancement at forward angles and a decrease at backward angles relative to scaled cross sections based on the Born approximation, arising from the two-center nature of the collision. Also seen in the figure is a feature due to Ar L-Auger-electron emission.

V. RESONANT TRANSFER AND EXCITATION (RTE)

Resonant transfer and excitation (RTE) is an example of electron correlation in ion-atom collisions. Electron correlation arises from the electron-electron interaction, RTE, in which one electron is captured from a target atom by a highly charged projectile ion while another electron in the projectile is simultaneously excited, is the ion-atom analogue of dielectronic recombination, which is the formation of an excited intermediate state via an inverse Auger transition. RTE is resonant when the projectile velocity is such that the energy of a target electron in the rest frame of the projectile is equal to one of the Auger electron energies. Many intermediate excited states are possible, each one corresponding to an allowed Auger transition. The intermediate excited state produced in the RTE process can stabilize by X-ray emission, in which case its signature is detection of an X-ray in coincidence with a projectile which has captured an electron. The intermediate excited state can also stabilized by Auger-electron emission.

Resonant transfer and excitation involving excitation of a K-shell electron has been measure by X-ray particle coincidence techniques[11, 12]. An example is shown in Fig.5, for neon-like to hydrogen-like Ca^{q+} ions in H_2,. The structure with energy is explained by two groups of intermediate excited states. These measurements have been extended to excitation of an L-shell electron for heavier projectiles[13].

The first observation of non-monotonic behavior in the energy dependence of an electron-capture cross section for a high-energy ion-atom collision was reported in Ref.[14]. Structure in the energy dependence of high-energy electron capture was found to be attributable to RTE. This result is shown in Fig.6, for Ca^{17+} + H_2. The ratio of the cross section for RTE relative to that for direct electron capture is expected to be greater at higher projectile velocities. Recent measurements[15] have looked for RTE in a single-electron-capture measurement for U^{89+} on C at energies from 130 to 160MeV/u at the LBL Bevalac accelerator. Results are presently being analyzed.

VI. MULTIPLE ELECTRON CAPTURE IN CLOSE COLLISIONS

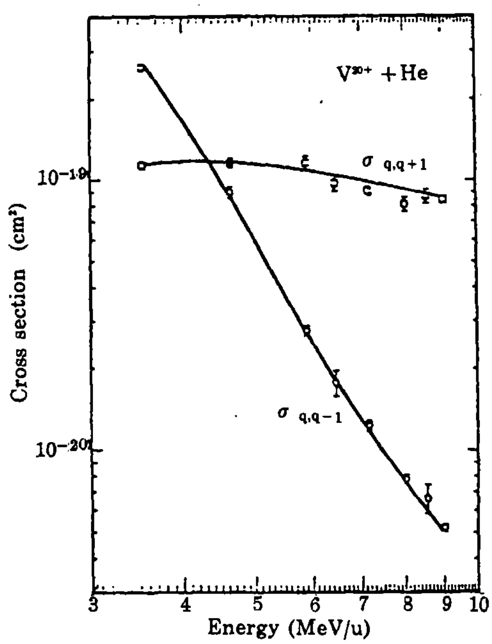

Fig.1 The energy dependence of the single-electron-loss cross sections, $\sigma_{q,q+1}$ (□), and single-electron-capture cross sections $\sigma_{q,q+1}$ (○), for V^{20+} ions incident on He

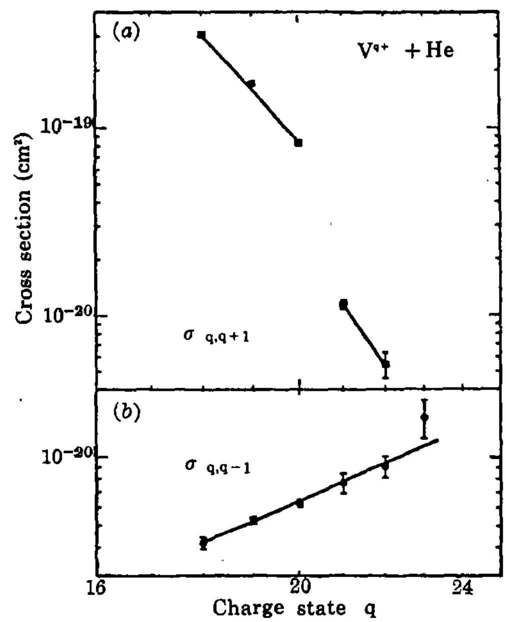

Fig.2 Single-electron-loss sections, $\sigma_{q,q+1}$ (■), and single-electron-capture cross sections, $\sigma_{q,q+1}$ (●), for 8.55 MeV/u V^{q+} ions incident on He

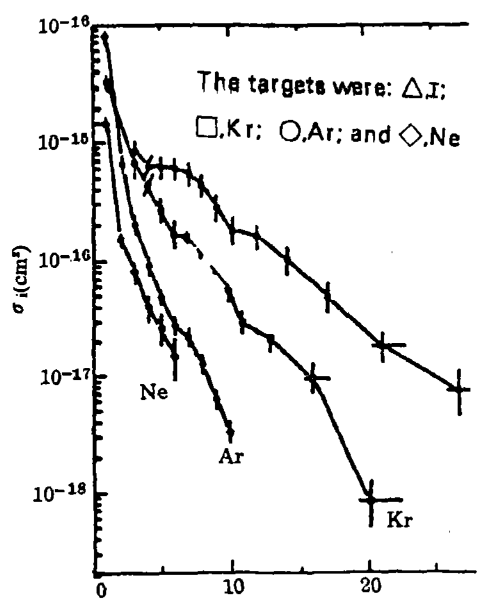

Fig.3 Measured cross sections σ (i) for the production of recoil ions by 420 MeV/u U^{q+} impact (q ≦91) versus recoil-ion charge state, i.

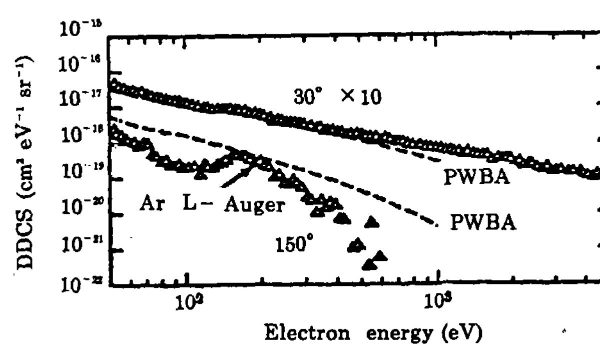

Fig.4 Doubly differential cross section for electron emission in collisions of 6 MeV/u U^{38+} in ar

The dashed line shows the Plane-Wave Born Approximation calculation. Results are shown at forward (30°) and backward (150°) angles

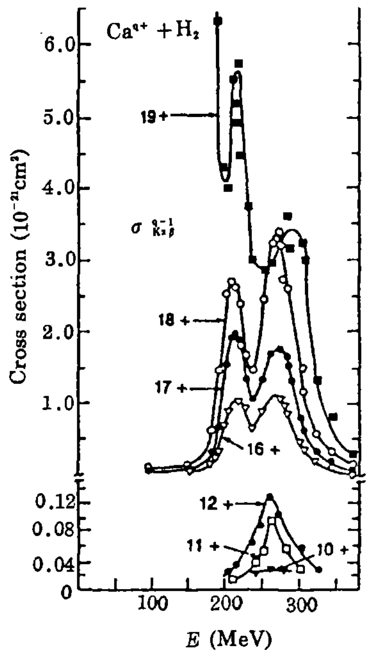

Fig.5 Cross sections for projectile X- ray coincident with single- electron capture, $\sigma^{q-1}_{K\alpha\beta}$, for collisions of Ca^{q+} ions with H_2(q=10,11,12,16, 17,18, and 19) The solid curves are drawn to guide the eye. (Note the scale change for the $Ca^{10,11,12+}$ data)

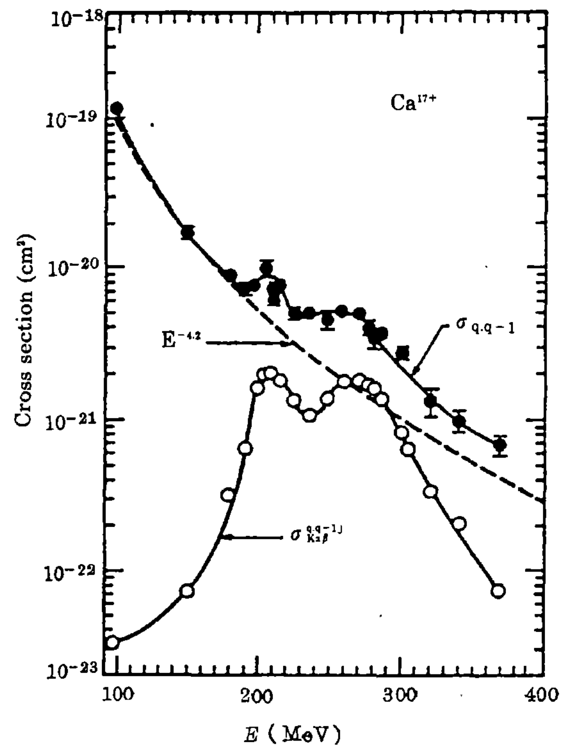

Fig.6 Cross sections for Ca^{17+} in He_2

• single electron capture, $\sigma_{q,q-1}$; o single-electron capture coincident with x-ray emission $\sigma^{q-1}_{K\alpha\beta}$ — is drawn toguide the eye - - $E^{-4.2}$ energy dependence normalized to the point at 150 MeV

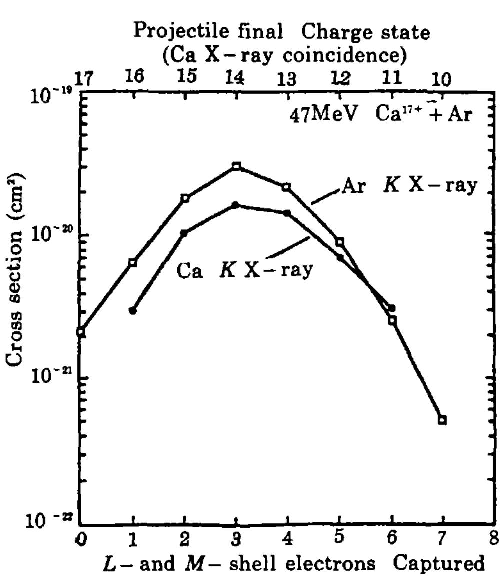

Fig.7 Cross sections for electron capture in X- ray for 47 coincidence with Ar or Ca K MeV Ca^{17+} in Ar, as a function of the number of K- and L- shell electrons captured

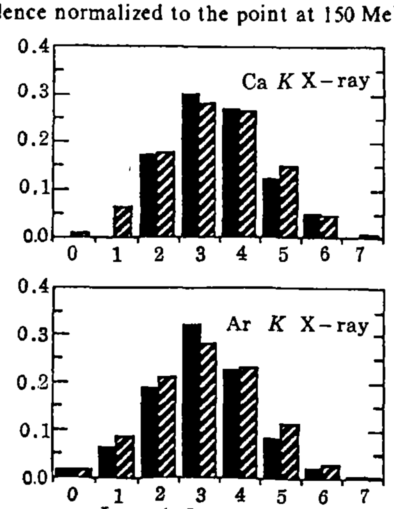

Fig.8 Relative electrons- capture probabilities for 47 MeV Ca^{17+} in Ar as a function of the number of *L*- and *M*- shell electrons transferred for coincidence with a Ca *K* or Ar *K* X- ray

Close collisions between an energetic projectile ion and a target atom can be selected by detection of a projectile or target *K* X-ray is evidence that a *K*-shell vacancy was produced in a collision at small impact parameter. If one selects a projectile with an empty or nearly empty *L*-shell, as is the case for 47-MeV Ca^{17+} in an Ar target[16,17], the cross sections for capturing several electrons are bound to exceed that for the capture of only one electron. This result is shown in Fig.7. The corresponding electron-capture charge-state distribution can be fit with a binomial distribution, as shown in Fig.8, giving an electron-capture probability of nearly 0.5. The agreement of the data with a binomial distribution is consistent with independent electron capture, and suggests an absence of electron correlation in the multiple-electron-capture process. Total electron-capture cross sections, in which close collisions are not selected, are found to be much larger than the X-ray coincidence cross sections, and to decrease monotonically with increasing number of electrons captured (see Fig.9).

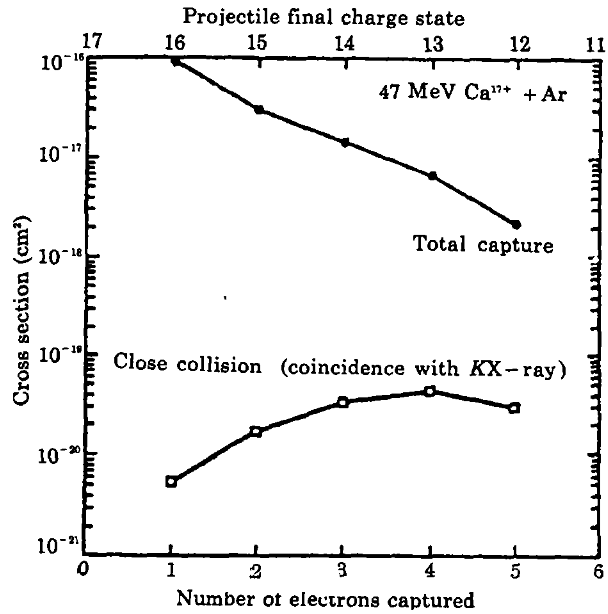

Fig.9 Electron- capture cross sections for 47- MeV Ca^{17+} in Ar, as a function of the final charge state of the projectile and the number of electrons captured

Multiple-electron capture in close collisions of highly charged Ca-ions has been studies for a variety of conditions.Increasing the Ca-ion is found to lead to a decrease in the electron-capture probability, as would be expected: the projectile is fast relative to the electrons in the *L*-shell of the target atom. Another experiment[18] was to vary the number of vacancies in the *L*-shell of the Ca projectile from one (neon-like Ca^{10+}) to seven (lithium-like Ca^{17+}). The electron-capture probability is found to be a linear function of the number of initial vacancies in the projectile *L*-shell. This suggests direct transfer of electrons from the *L*- and *M*-shells of the target to the *L*-shell of the projectile.

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REFERENCES

[1] W.G.Grahem et al., *Phys. Rev.*, **A30** (1984), 722.

[2] E.C.Montenegro et al., *Phys. Rev.*,**A38** (1988), 1848.

[3] W.G.Graham et al., *J.Phyus.*,**B18** (1985),2503.
A.S.Schlachachter et al., *Nucl. Instr. Meth.*,**B24/25** (1987),219.

[4] A.S.Schlachter, *Charge−changing collisions*, Proceedings of the tenth international conference on cyclotrons and their applications, April 30−May 3, 1984.

[5] A.S.Schlachter et al., *Phys. Rev.*, **A27** (1988),3372.

[6] Xiang−Yang Xu et al., *Phys. Rev.*,**A38** (1988),1848.

[7] Harvey Gould et al., *Phys. Rec. Lett.*, **52** (1984), 180; R.Anholt et al., *Phys. Rev. A36* (1987), 1586.

[8] S.Kelbch. J.Ullrich et al., *Phys.*, **B19** (1986), L47.

[9] H.Berg, R.Dorner et al., *J.Phys.*,**B21** (1988),3929.

[10] D.Schneider et al., *Phys. Rev.*,*A*(in press).

[11] J.A.Tanis et al., *Phys. Rev. Lett.*, **53** (1984), 2551.

[12] J.A.Tanis et al., *Phys. Rev*.,**A34** (1986), 2543.

[13] E.M.Bernstein et al., *J.Phys.*, **B20**(1987),L505.

[14] W.G.Graham et al., *Phys. Rev.*, **A33** (1986), 3591.

[15] W.G.Graham *The search for RTE in 30−38 GeV collisions of U^{89+} with carbon foils*, paper submitted to ICPEAC, 1989.

[16] A.S.Schlachter et al., *J.Phys.*, **B21** (1988), L291.

[17] A.S.Schlachter et al., *Nucl. Instr. Meth.*,**B40/41** (1989), 21.

[18] A.S.Schlachter et al., *Multiple−electron capture for 47−MeV calcium ions in argon; Projectile charge−state dependence*, paper submitter to ICPEAC, 1989.

[19] W.E.Meyerhof, Phys, Rev. Lett., **31**(1973), 1341.

[20] E.M.Bernstein et al., *J.Phys.*, **B21**(1988).L509.