LBL-22282 c.2

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Presented at the Ninth Conference on the Application of Accelerators in Research and Industry, Denton, TX, November 10-12, 1986

IONIZATION AND CHARGE TRANSFER IN HIGH-ENERGY ION-ATOM COLLISIONS

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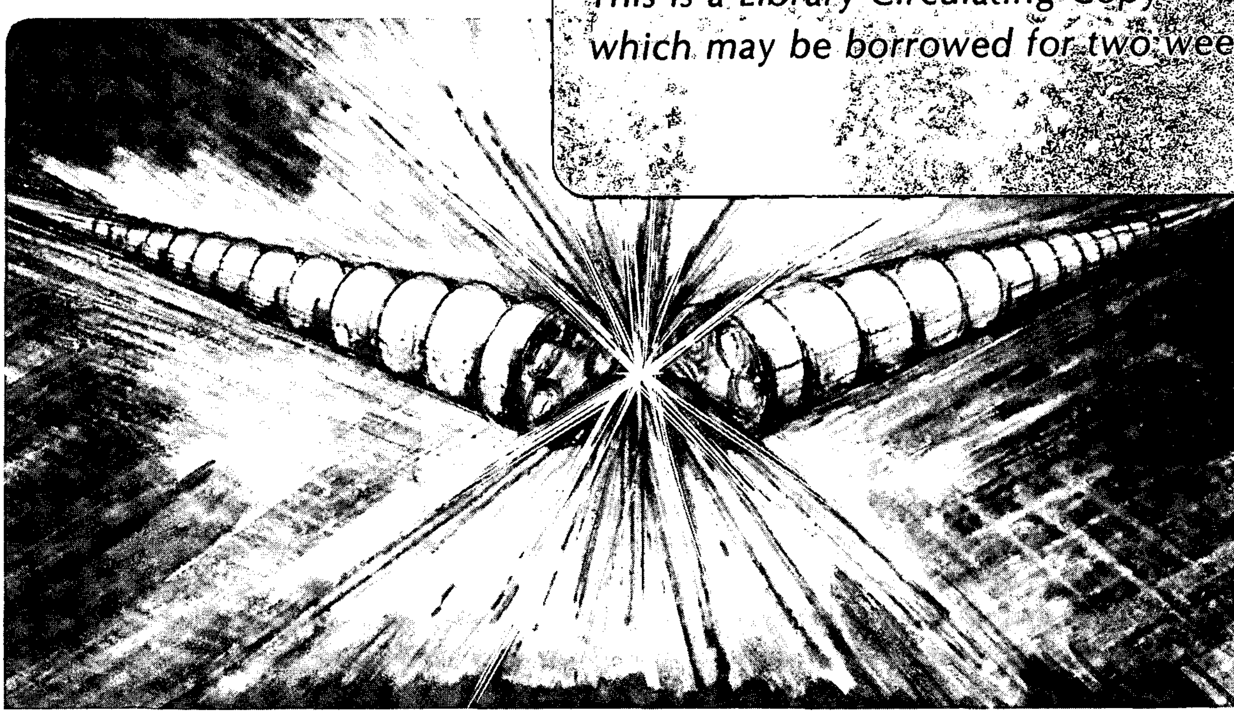
November 1986



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

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* This work was supported by the Director, Office of Energy Research, Office of Fusion Energy, Development & Technology Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098, by the Division of Chemical Sciences of the U.S. Department of Energy under Contract No. DE-AC02-83ER13116, and by the SERC, Great Britain.

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ABSTRACT

Electron capture and loss by fast highly charged ions in a gas target, and ionization of the target by passage of the fast projectile beam, are fundamental processes in atomic physics. These processes, along with excitation, can be experimentally studied separately ("singles") or together ("coincidence"). This paper is a review of recent results on singles measurements for electron capture and loss and for target ionization, for velocities which are generally high relative to the active electron, including recent ionization measurements for a nearly relativistic projectile.

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I. Introduction

Charge transfer, projectile and target excitation, and target ionization by passage of a beam of fast highly charged ions through a gas target are fundamental processes in atomic physics. A fast projectile is one for which the projectile velocity is large relative to the velocity of the active electron. These processes can be experimentally studied separately ("singles measurements") or together in a single collision ("coincidence measurements"). Many interesting processes involve 2 or more electrons whose behavior is correlated, e.g., resonant transfer and excitation, and electron capture or excitation followed by Auger-electron emission. The purpose of this paper is to review some recent experimental results for singles measurements of electron capture and loss and of target ionization, for fast ion-atom collisions. Reviews on charge transfer and ionization and their scaling properties can be found in the literature [1].

II. Ionization

A gas atom or molecule can be ionized by passage of a fast, highly charged ion:

$$X^{q+} + Y \rightarrow X^{q'+} + Y^{i+} + (q'-q+i)e^{-} \qquad (1)$$

where q and q' are the projectile charge before and after the collision, and i is the charge state of the target recoil ion; σ_i is the cross section for recoil-ion production. Measurements are generally of σ_i; projectile and recoil-ion coincidences; or measurement of total charge produced in the target (net ionization), whose cross section is σ_I.

$$\sigma_I = \sum i\sigma_i \ . \qquad (2)$$

A fast, highly charged ion, is an efficient tool for producing highly charged, very slow, recoil ions in a gas target [2]. The average recoil-ion charge state q increases strongly with increasing charge state of the projectile. Therefore, completely stripped uranium ions should be very effective for the production of highly ionized target recoil ions. To investigate this behavior at relativistic beam velocities, measurements of multiple ionization of several different target atoms by 420 MeV/u uranium projectiles with an average charge state of about 91+ have been made [3]; the measurements were performed at the Lawrence Berkeley Laboratory's BEVALAC accelerator. The experimental arrangement is shown schematically in Fig. 1. The passage of a projectile through the gas target was determined by the coincidence of signals from two scintillators, one in front of and one behind the target. Recoil ions were extracted perpendicular to the beam direction and detected by a channeltron. The recoil-ion charge state q was determined by measuring the q-dependent time of flight of the recoil ions. The electrons originating in the ionization process were detected in a second channeltron mounted opposite to the recoil-ion detector; triple coincidence was essential for reducing background.

Figure 2 shows the measured ionization cross sections [3] as a function of recoil-ion charge-state. The cross sections are large, e.g., greater than 10^{-18} cm^2 for producing Kr recoils ions in charge states around 20+ and iodine recoil ions in charge states above 25+. Additional experiments with reduced background are planned to measure cross sections for production of nearly fully ionized Ar and Kr ions.

III. Charge Transfer

Two fundamental charge-transfer processes are single-electron capture:

$$X^{q+} + Y \rightarrow X^{(q-1)+} + [Y^{+}] \qquad (3)$$

with cross section $\sigma_{q,q-1}$ and single-electron loss

$$X^{q+} + Y \rightarrow X^{(q+1)+} + [Y + e^{-}] \qquad (4)$$

with cross section $\sigma_{q,q+1}$, where X and Y are projectile ion and target atom, and q+ is projectile charge state. The brackets indicate that the target charge state after the collision is undetermined. Cross sections for two-electron transfer are generally an order of magnitude smaller than for one-electron transfer; however, two-electron-loss cross sections can be appreciable for very fast projectiles in low charge states.

Recent measurements of electron capture for fast projectiles ($v > v_o$), where v is the projectile velocity and v_o is the Bohr velocity, have covered a wide range of energies and charge states [4-7]. The energy and charge-state dependence of electron-capture cross sections for a fast highly charged projectile [6] are shown in Figs. 3 and 4: energy dependence for V^{20+} ions in He (Fig. 3) and charge-state dependence for 8.55 MeV/u V^{q+} ions in He (Fig. 4). For these collisions $v/v_o = 18.4$, which is a high-velocity regime for electron-capture. The Oppenheimer-Brinkman-Kramers (OBK), eikonal, continuum intermediate-state, continuum distorted-wave and Bohr-Lindhard theories all predict a q^3 scaling for electron capture. In the limit of high energies the OBK and second Born approximations predict a q^5 dependence for electron-capture cross sections. The charge-state dependence of the single-electron-capture cross sections in helium, shown in Fig. 4, is $q^{3.8\pm0.4}$. Born-approximation calculations predict an electron-capture cross section energy dependence which should reach a limit of $E^{-5.5}$ (second Born) or E^{-6} (first Born) at asymptotically high energies. The electron-capture data shown in Fig. 3 have an energy dependence of approximately $E^{-4.2}$ for the higher energies.

Electron-loss collisions are generally considered in terms of the velocity of the electron most likely to be lost in the collision by the projectile, v_e; for 8.55 MeV/u vanadium ions, v/v_e is about 1.8 for the L-shell electrons ($q \leq 20$) and about 0.8 for the K-shell electrons ($21 \leq q \leq 22$). Classical theory predicts that the energy dependence of the electron-loss cross sections should exhibit a broad maximum, with a peak at an energy where $v \simeq (1-2)v_e$. The energy dependence of electron-loss cross sections shown in Fig. 3 exhibits a broad maximum; since v_e changes with the projectile charge state, the energy at which the maximum in the electron-loss cross section occurs will also change. A significant feature of the charge-state dependence for electron loss is the pronounced discontinuity between q=20 and q=21, as seen in Fig. 4. This can be attributed to the shell structure of the V ion; electrons in the K shell of V ions are bound with about 6.5 keV, whereas L-shell electrons are bound by 1.57 keV or less. The L-shell electron-loss cross sections for $V^{18,19,20+}$ show a $q^{-12 \pm 1}$ dependence, while, for the K-shell electrons, $V^{21,22+}$, the charge-state dependence is $q^{-14 \pm 2}$.

Cross sections for electron capture by a fast projectile are rarely available for the desired projectile specie, charge state, and target over a large energy range. There has therefore been considerable interest in scaling of electron-capture cross sections with these parameters. Schlachter et al. [7] took a generalized approach to scaling electron-capture cross sections for a large variety of projectiles and targets. They found that electron-capture cross sections reduced to a common curve in scaled coordinates for high-energy ion-atom collisions. An example for electron capture of multiply charged ions is a He target is shown in Fig. 5, in which data for S^{13+} He by Clark et al. [8] and for Ca and V ions in He by Graham et al. [6] are shown in reduced coordinates. The line shown has been adjusted to fit the data. At high reduced energies the cross section for He(Z=2) approaches

$$\sigma = 3.7 * 10^{-9} q^{3.3} Z^{3.3}/E^{4.1}, \qquad (5)$$

where Z is target atomic number. Scaling for 2-electron capture also has recently been obtained [9].

Theoretical and experimental studies of electron capture in fast collisions between ions and atoms have shown this process to be a monotonically decreasing function of the projectile energy. The first observation of structure in the energy dependence of single-electron-capture cross sections [10] in fast collisions has recently been reported for 97- to 368-MeV highly charged Ca ions incident on H_2. This structure is attributed to the contribution of resonant transfer and excitation [11] to electron capture. These collisions, for which v/v_o is in the range 9.8-19.1, are in the intermediate- to high-energy regime for electron capture. Measurements were performed using the SuperHILAC accelerator at the Lawrence Berkeley Laboratory. Figure 6 shows measurements of the single-electron-capture cross section, $\sigma_{q,q-1}$, for Ca^{17+} ions in H_2; the dashed line indicates the expected monotonic energy dependence, $E^{-4.2}$. Figure 6 also shows the cross sections for single-electron capture in coincidence with projectile K-x-ray emission, σ_{KX}^{q-1}, for Ca^{17+} ions in H_2; the maxima in σ_{KX}^{q-1} are due to resonant transfer and excitation (RTE), in which a projectile electron is excited simultaneously with the capture of a bound target electron in a single collision, followed by emission of a projectile x-ray. RTE proceeds by a mechanism which is analogous to the inverse of the Auger effect and, hence, is a resonant process. The cross sections for RTE have a pronounced energy dependence associated with the resonant nature of RTE and, as seen in Fig. 6, two maxima are observed for Ca^{17+} ions in H_2; these maxima in $\sigma_{q,q-1}$ occur at the same energies as the maxima in σ_{KX}^{q-1}. The structure, observed in $\sigma_{q,q-1}$ for all the projectile charge states investigated, can be explained as the contribution of resonant transfer and excitation to single-electron capture.

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Figure Captions

Fig. 1 Schematic diagram of apparatus used to measure ionization of Ne, Ar, Kr, and I atoms by nearly relativistic U^{q+} ions (q≃91) at the Bevalac [Kelbch et al., Ref. 3].

Fig. 2 Recoil-ion charge-state dependence of cross sections for the production of target recoil ions by 420 MeV/u U^{q+} ions (q≃91) measured at the Bevalac. Uncertainties shown do not include a systematic uncertainty of a factor of 2 [Kelbch et al., Ref. 3].

Fig. 3 Energy dependence of single-electron capture ($\sigma_{q,q-1}$) and loss ($\sigma_{q,q+1}$) cross sections for V^{20+} ions incident on He atoms, measured at the SuperHILAC [Graham et al., Ref. 6].

Fig. 4 Projectile charge-state dependence of single-electron capture ($\sigma_{q,q-1}$) and loss ($\sigma_{q,q+1}$) cross sections for 8.55 MeV/u V^{q+} ions incident on He atoms, measured at the SuperHILAC (Graham et al., Ref. 6].

Fig. 5 Single-electron-capture cross section for fast highly charged ions in He, plotted in reduced coordinates of Ref. 7.

Fig. 6 Energy dependence of cross sections for Ca^{17+} ions incident on H_2, measured at the SuperHILAC. Filled circles are for single-electron capture, $\sigma_{q,q-1}$; open circles are for single-electron capture coincident with projectile K-x-ray emission, σ_{KX}^{q-1}; the dashed line shows the expected $E^{-4.2}$ energy dependence for $\sigma_{q,q-1}$ [Graham et al., Ref. 10].

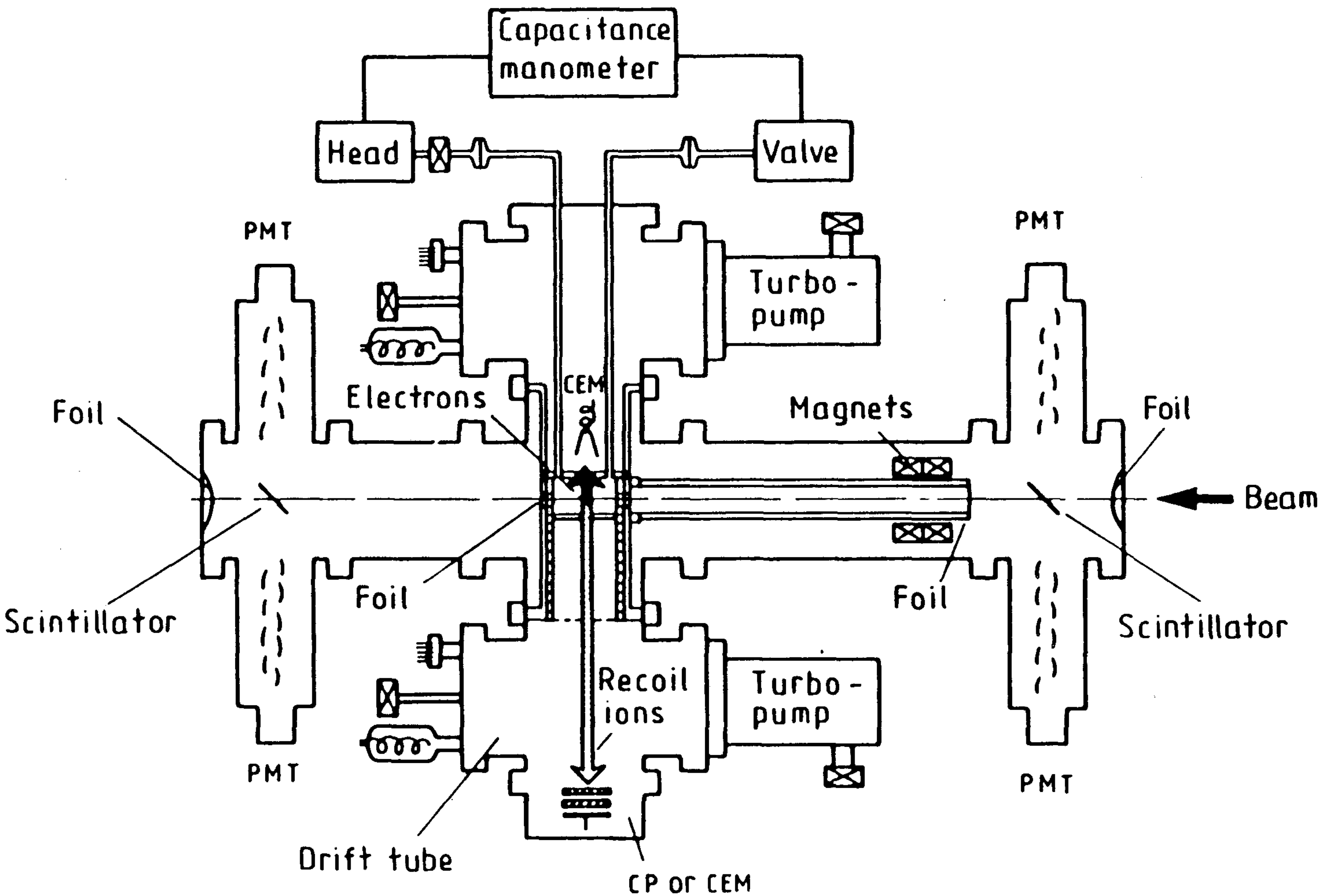

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Fig. 1

Fig. 2

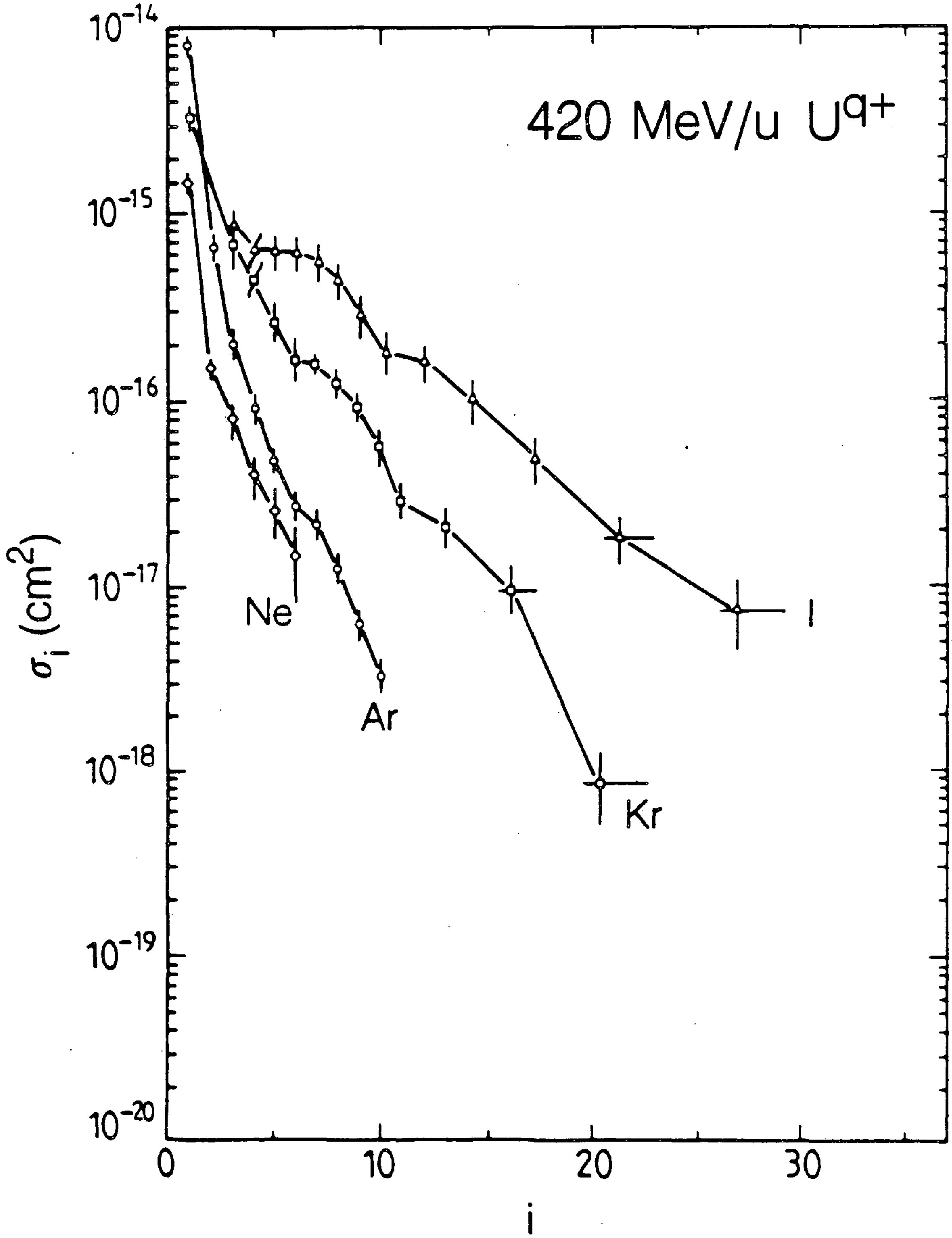

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Fig. 3

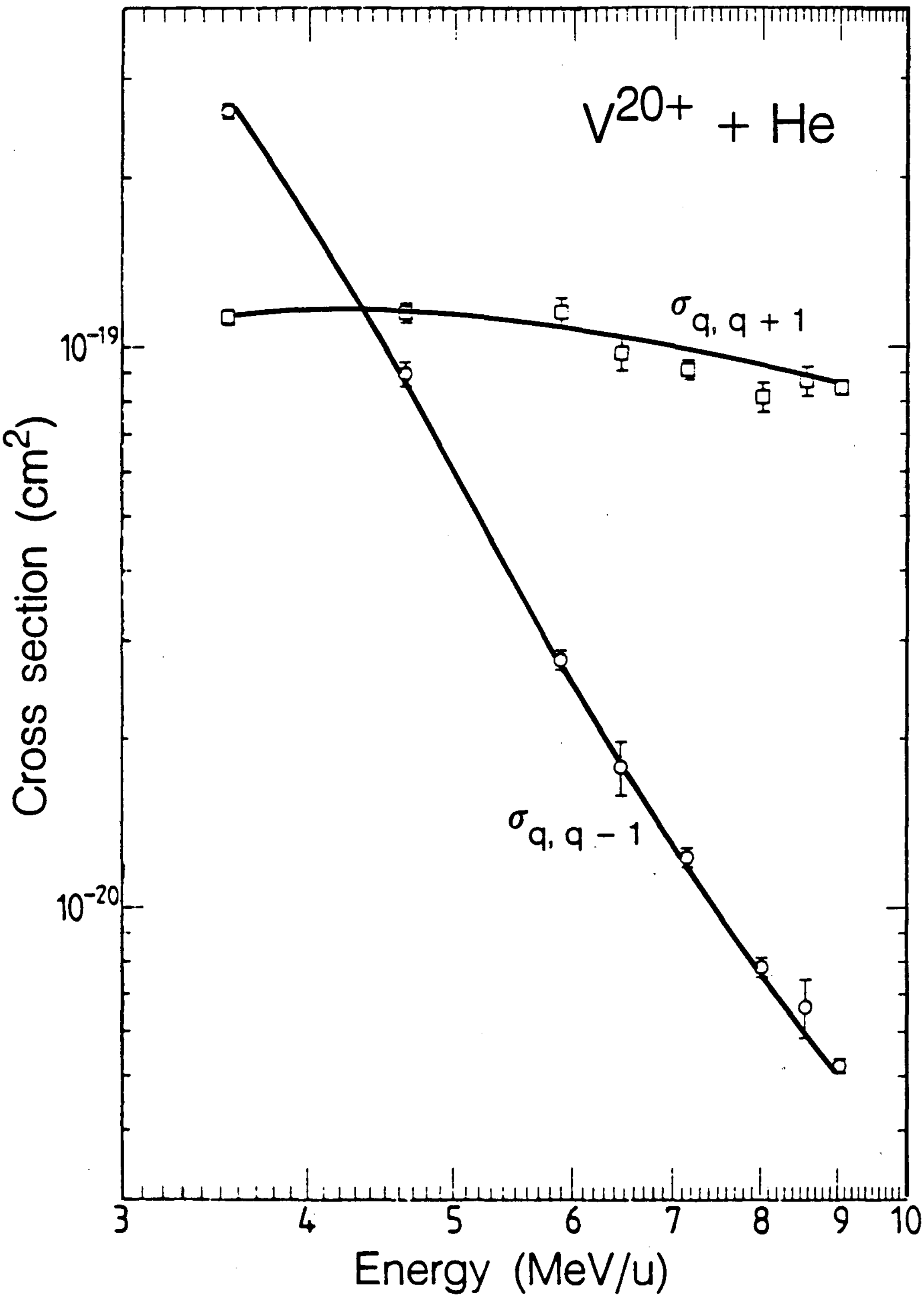

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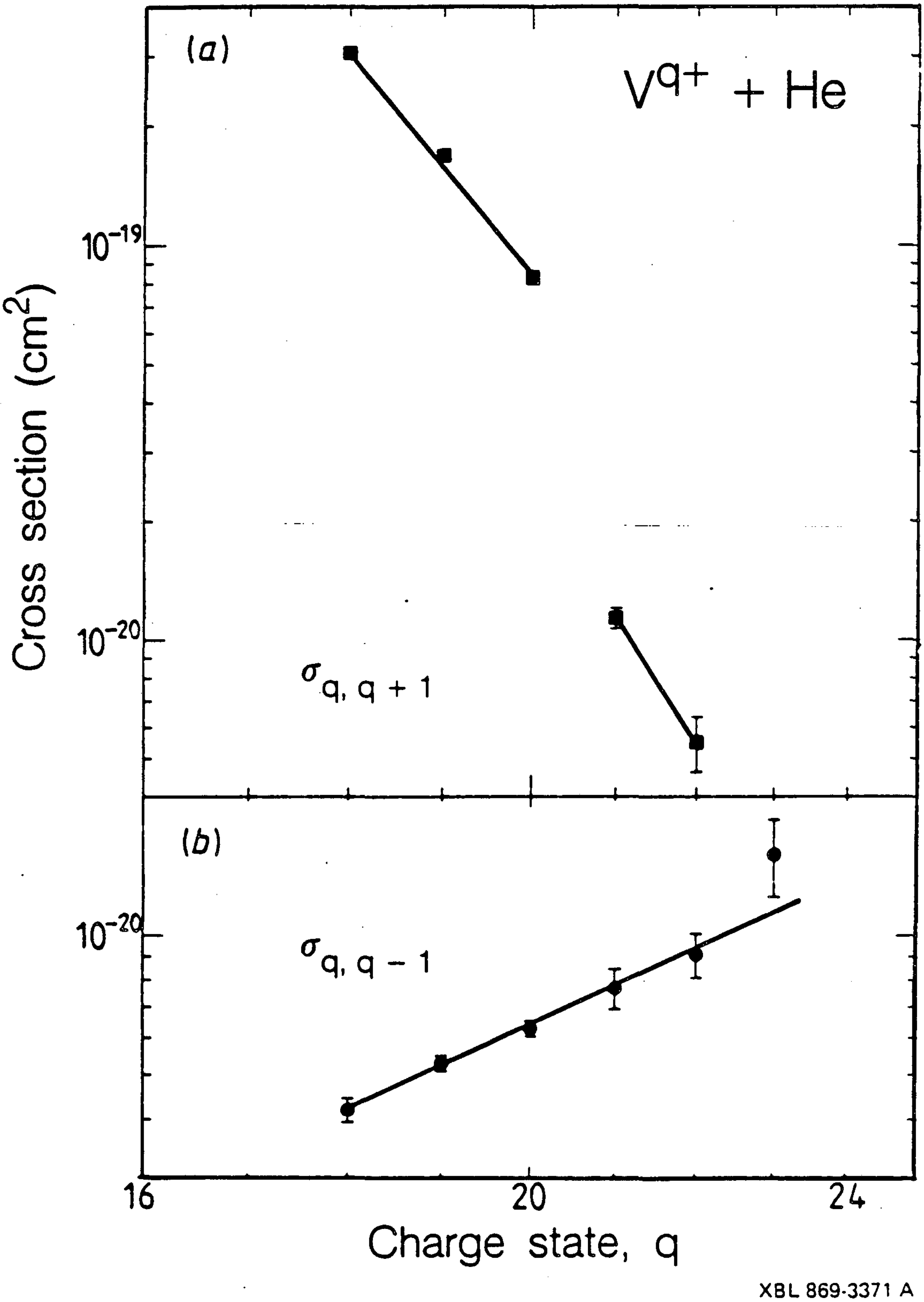
Fig. 4



(a)
V^{q+} + He
10^{-19}
10^{-20}
$\sigma_{q,\,q+1}$
(b)
10^{-20}
$\sigma_{q,\,q-1}$
Cross section (cm^2)
16
20
24
Charge state, q
XBL 869-3371 A

Fig. 5

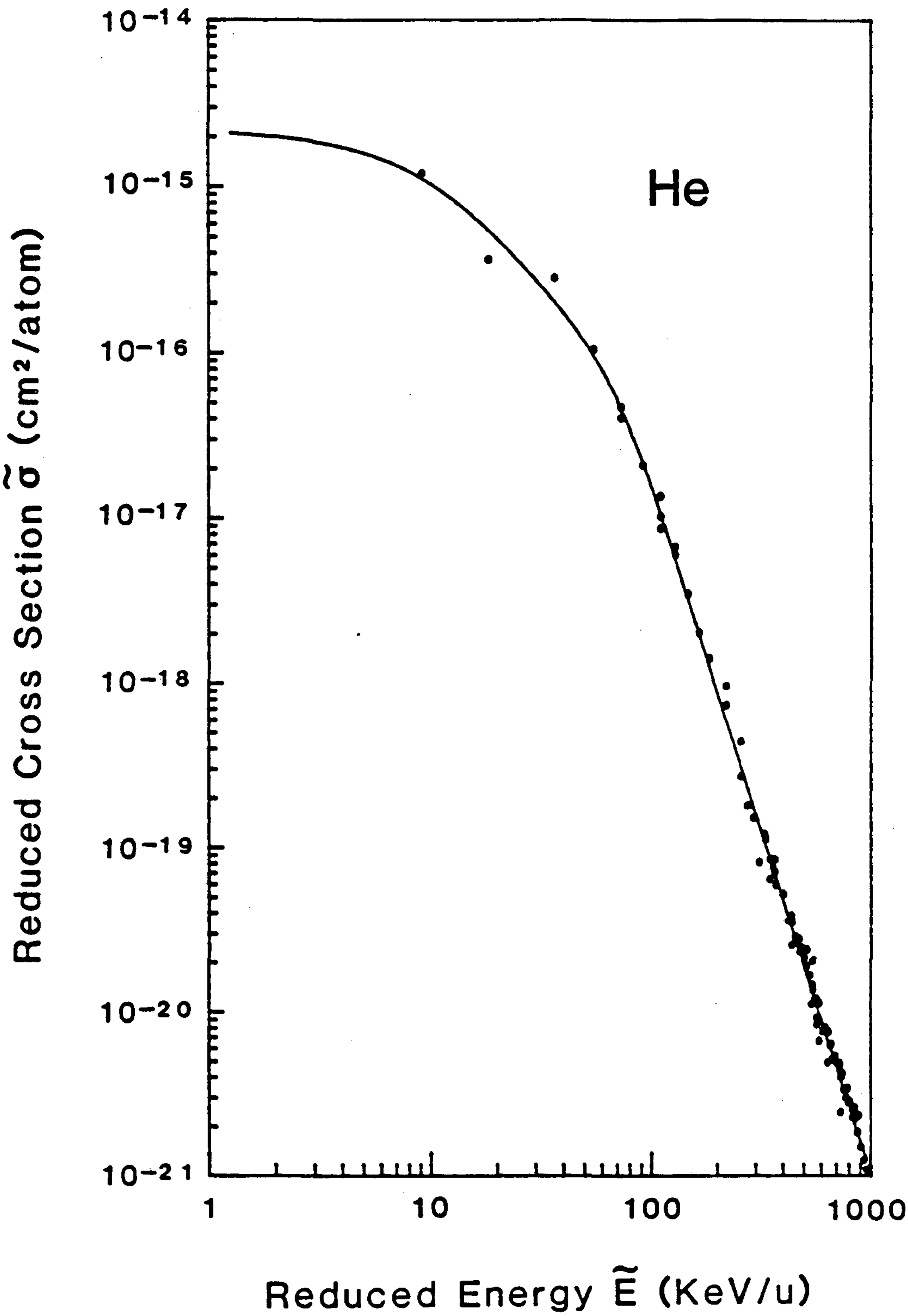


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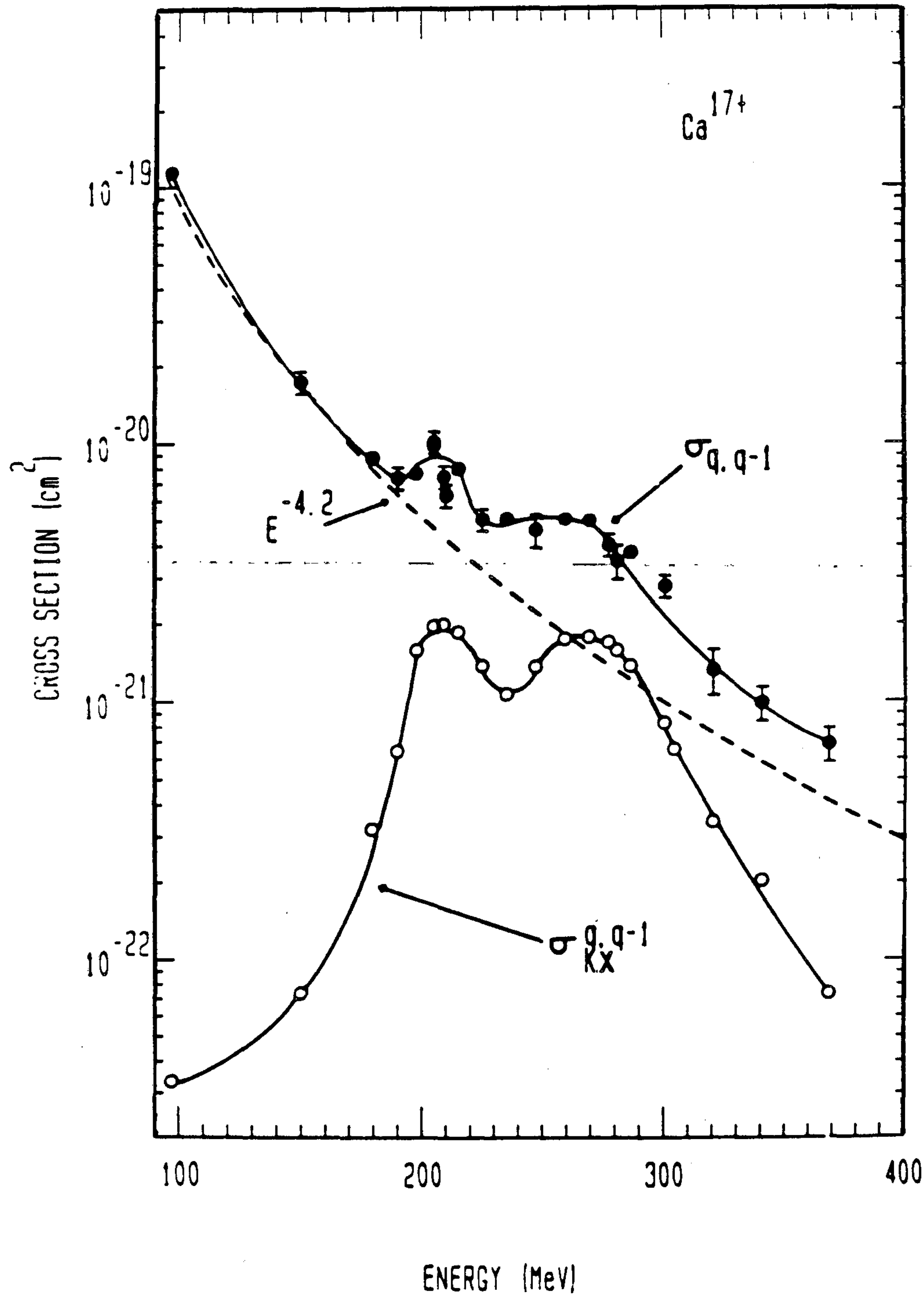
Fig. 6



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