TABLE II. Total energy of He_2^+.

R (a.u.)	E_{HF} (a.u.)	E_{CI} (a.u.)	E_{exact} (a.u.)
2.0	−4.923 09	−4.993 69	•••
2.044[a]	•••	−4.993 89[a]	−4.994 39 ± 0.0002[b]
2.0625	−4.922 70	−4.993 85	•••
2.125	−4.921 53	−4.993 21	•••
∞	−4.861 63	−4.903 16	−4.903 72[c]

[a]Interpolated values for the energy minimum.
[b]Estimated value for the exact energy.
[c]See C. L. Pekeris, Phys. Rev. 112, 1649 (1958), and 115, 1216 (1959).

tion including all singles and doubles.

The difference between the computed minimum for He_2^+ and the exact nonrelativistic energy for $He + He^+$ gives a lower bound of 2.454 eV for the dissociation energy. This rules out the $E_e(A\,^1\Sigma_u^+)$ value of 2.402 ± 0.012 eV, since it appears well established that the barrier height is ~0.05 eV.[1,9] Results in Table I and experience with other molecules, such as H_2 and H_3, lead this writer to believe that the correlation error for the computed energy minimum lies between 0.003 and 0.0007 a.u. Since the correlation error in $He + He^+$ is 0.0005 a.u., this leads to a best value of 2.469 ± 0.006 eV for the dissociation energy of ground-state He_2^+. This is in good agreement with $E_e(A\,^1\Sigma_u^+) = 2.549 \pm 0.012$ eV obtained from Sando's vibrational assignment, and supports a barrier height of 0.080 ± 0.018 eV.

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Energy Transfer in Electron-Exchange Reactions at Low Kinetic Energies*

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The energy transferred in single-electron-exchange processes in Ar^{++}-He and Ar^{++}-D_2 collisions has been experimentally determined for relative kinetic energies below 9 eV. The results confirm the "nearest-resonance" hypothesis for these two representative systems.

The internal energy states of product species resulting from single electron transfer in asymmetric atomic or molecular systems are usually assumed to be those states which are consistent with minimum interchange between kinetic and internal energy. That is, for the process

$$A^+ + B \rightarrow B^+ + A + \Delta E, \quad (1)$$

ΔE, the energy defect, is assumed to be small. This "nearest-resonance" hypothesis has been a

major constituent of many models that have been used to describe the charge-exchange process.[1-5] For many systems this condition demands the production of one or more of the product species in excited internal-energy states. It is the purpose of this paper to report experimental results which confirm the nearest-resonance hypothesis for two representative systems.

Ion-beam studies of electron transfer can yield quantitative data for the reaction energetics if kinetic-energy analysis of the product ion is performed. However, reactions of the type represented by Eq. (1) are characterized by low momentum transfer to the target so that the B^+ ion has very low laboratory kinetic energy. Collection efficiencies at these low energies are poor,[6] and extraction by externally applied fields can alter the kinetic energy distribution. This difficulty may be circumvented by the use of incident doubly charged ions and subsequent kinetic energy analysis of the (singly charged) forward scattered "acceptor" species. The two systems investigated in this work were

$$Ar^{++} + He \rightarrow Ar^{+} + He^{+} \quad (2)$$

and

$$Ar^{++} + D_2 \rightarrow Ar^{+} + D_2^{+}, \quad (3)$$

over the incident-ion kinetic-energy range 30–100 eV. A search of the literature indicates that investigations of collisions between doubly charged ions and gaseous molecules have not previously been reported for these low kinetic energies. Among the reasons for choosing these two systems is the favorable mass ratio for obtaining low relative energies (100 eV laboratory kinetic energy corresponds to about 9 eV in the center-of-mass system); at low relative energies many highly endothermic processes are precluded. In addition, the well-defined energy levels for the Ar^{++}-He system allow calculation of the possible values of ΔE for this system. Finally, the kinematics for Reactions (2) and (3) are the same.

The apparatus[7] consists of a primary ion gun which directs a momentum-selected electron-impact–produced Ar^{++} beam into a small collision cell. Sufficient Ar^{++} intensity could not be retained for electron-impact energies below about 65 eV; long-lived excited states may, therefore, be present in the primary ion beam. Ions emerging from the collision cell at laboratory scattering angle $\chi = 0° \pm 2.5°$ are analyzed for kinetic energy with a 127° cylindrical electrostatic sector,[8] analyzed for mass with a quadrupole mass filter,

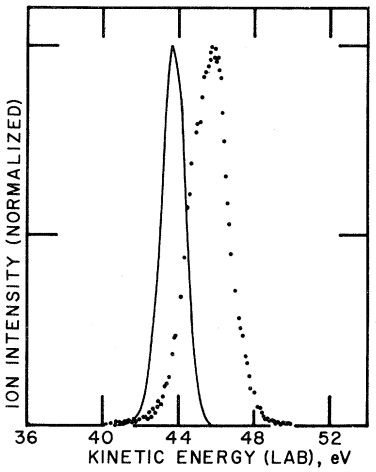

FIG. 1. Kinetic-energy profiles of Ar^{++} (solid line) and product Ar^{++} (closed circles) for the Ar^{++}-He system.

and detected with a particle multiplier; output pulses from the multiplier are counted using conventional techniques. Kinetic-energy distributions of ions were taken with the mass-filter setting fixed; the kinetic energy transmitted by the velocity selector was also fixed (usually at 60 eV for singly charged ions). Ions were either accelerated or decelerated by a grid prior to entrance into the selector. The accelerating voltage was varied stepwise in increments of 0.1 V and the count rate recorded at each voltage. Figures 1 and 2 show typical kinetic-energy distributions of Ar^+ resulting from He and D_2 collisions, respectively; also included in the figures is the kinetic-

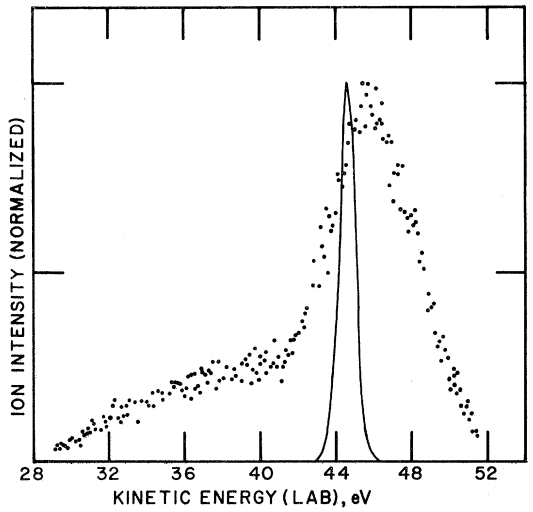

FIG. 2. Kinetic-energy profiles of Ar^{++} (solid line) and product Ar^+ (closed circles) for the Ar^{++}-D_2 system.

energy profile of the Ar^{++} beam.

Conservation of energy for Reactions (2) and (3) may be written

$$E_1+E_2=E_3+E_4-\Delta E, \tag{4}$$

where E_1 and E_3 are the laboratory kinetic energies of the incident Ar^{++} and product Ar^{+} ions, and E_2 and E_4 are the laboratory kinetic energies of the target and ionized target, respectively. A positive value for ΔE indicates an exothermic reaction. Using conservation of momentum (for $\chi = 0$) and the assumption that $E_2 = 0$ for the room-temperature target, E_4 may be eliminated to yield

$$\Delta E = 9E_1 + 11E_3 - 20(E_1E_3)^{1/2} \tag{5}$$

for both Reactions (2) and (3). By obtaining E_1 and E_3 from the position of the peaks in the kinetic-energy distributions, ΔE may be determined. The magnitude of the expected uncertainty in ΔE as estimated from Eq. (5) is ± 0.6 eV. An equation similar in form to (5) above may be obtained if He^+ and D_2^+ are the detected species; however, neither He^+ nor D_2^+ (nor D^+) were detected in these experiments. This last is consistent with the kinematics and energetics for both systems.

The energetics for the Ar^{++}-He system are well defined; the electronic recombination energy (RE) from the Ar^{++} ground state to the ground state of Ar^+ is 27.6 eV, and the ionization potential of He is 24.6 eV. Since the first excited state of He^+ is 40.8 eV above the ground state, it is not expected to participate at these low kinetic energies. The most nearly resonant process is the one involving only the ground states of all species for which $\Delta E = 3.0$ eV. Figure 3 contains the results of a number of measurements for the Ar^{++}-He system (solid circles). The mean of these determinations is $\langle \Delta E \rangle = 2.8 \pm 0.6$ eV, in good agreement with the expected value. No evidence for a reaction between excited Ar^{++} ions and target He atoms was observed.

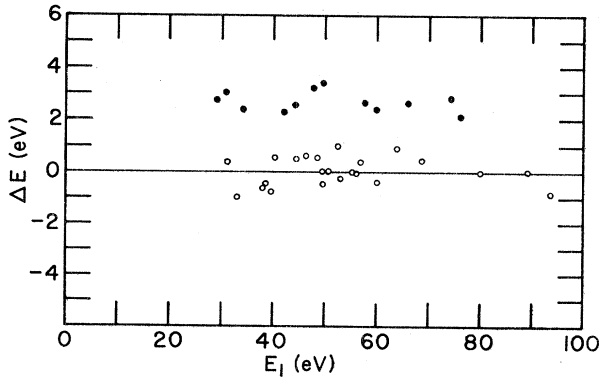

FIG. 3. ΔE as a function of E_1 for Ar^{++}-He (closed circles) and Ar^{++}-D_2 (open circles) charge-exchange reactions.

The results of the measurements for target D_2 gas are also shown in Fig. 3 (open circles). ΔE is calculated under the assumption that the undetected product is D_2^+ (rather than D^+ and D). The mean of these data is $\langle \Delta E \rangle = 0.0 \pm 0.7$ eV. Since the ionization potential of D_2 is 15.4 eV, it is clear that excited Ar^+ is produced. (Although production of electronically excited D_2^+ is not precluded, the predicted excited state of H_2^+ has never been observed.[9]) Production of vibrationally excited D_2^+ is, of course, possible and may be responsible in part for the rather wide Ar^+ profile (see Fig. 2); the vibrational spacing of D_2^+ ($\simeq 0.19$ eV) cannot be resolved with the present instrument. The low-energy tail on the Ar^+ profile could result from contributions from the dissociative charge-transfer reaction

$$Ar^{++}+D_2 \rightarrow Ar^{+}+D^{+}+D, \tag{6}$$

but is probably also a result of enhanced collection efficiency in the vicinity of $E_3 = 0.83E_1$ for this system.[7] This enhancement was not observed for target He atoms because of the low Ar^+ intensity near $E_3 = 0.83E_1$.

Table I is a listing of pertinent RE's for several low-lying, long-lived levels of Ar^{++} to the ground state and first excited state of Ar^+. The processes

$$Ar^{++}(^3P)+e \rightarrow Ar^{+}(^2S) \tag{7}$$

TABLE I. Electronic recombination energies[a] of Ar^{++}.

State of Ar^{++} Designation	J	State of Ar^+ Designation	J	RE (eV)
^3P	2	$^2P^\circ$	3/2	27.62
	1		3/2	27.75
	0		3/2	27.82
	2	$^2P^\circ$	1/2	27.44
	1		1/2	27.57
	0		1/2	27.64
^3P	2	^2S	1/2	14.14
	1		1/2	14.27
	0		1/2	14.34
^1D	2	^2S	1/2	15.88
^1S	0	^2S	1/2	18.26

[a]C. Moore, *Atomic Energy Levels*, National Bureau of Standards Circular No. 467 (U. S. GPO, Washington, D. C., 1949), Vol. I.

and

$$Ar^{++}(^1D)+e \rightarrow Ar^{+}(^2S) \quad (8)$$

are seen to have RE's sufficiently close to the ionization potential of D_2 to produce the wide Ar^+ kinetic energy distribution with $\Delta E \simeq 0$.

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Plasma Heating by High-Current Relativistic Electron Beams*

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A mechanism is proposed for the heating of a plasma with a high-current relativistic electron beam which makes essential use of the plasma return current induced by the beam. From overall energy conservation it is concluded that a large fraction of the beam energy is converted into plasma thermal energy. For reasonable parameters the heating occurs through ion sound turbulence generated by the plasma return current.

Recent developments in technology have led to the generation of beams of electrons with energies in the range 500 keV to 10 MeV and currents in the range of 50 kA to 1 MA, of pulse durations of the order of 50 nsec. The energy content in these beams is as large as 10^5 J. The possibility of using these beams in controlled fusion experiments for purposes of heating a plasma to thermonuclear temperatures is of considerable interest. In this Letter we point out one important mechanism by which a high-current beam[1] ($\nu/\gamma \gtrsim 1$) can heat a plasma, and we estimate the rate at which this heating occurs. The mechanism does not involve the collective interaction of the beam electrons with the plasma, which is expected to be weak for high-energy beams and small beam-plasma density ratios.[2]

The injection of an electron beam into a cold dense plasma ($n_p \gg n_B$, where n_p and n_B are the plasma and beam electron densities, respectively) is accompanied by a return current which acts to neutralize the magnetic field of the beam if $\lambda_E/a \ll 1$ [where a is the beam radius, $\lambda_E = c/\omega_p$ is the electromagnetic skin depth, and $\omega_p = (4\pi e^2 n_p/m_e)^{1/2}$ is the plasma frequency]. This result may be understood as follows (in the rest frame of the plasma): Assume that on a macroscopic scale the plasma may be described by the generalized Ohm's law

$$\left(\frac{\partial}{\partial t}+\frac{1}{\tau_*}\right)\vec{J}^P = \frac{\omega_p^2}{4\pi}\vec{E}+\frac{e}{m_e c}\vec{J}^P\times\vec{B}, \quad (1)$$

where τ_*^{-1} is the effective collision frequency and $\vec{J}^P(\vec{x}, t)$ is the plasma current density. External magnetic fields are not included; however, in the main the results below appear to hold also for beams propagating parallel to an external magnetic field, and indeed such fields may be essential for stability of the beams. In addition, we neglect for the moment the self-magnetic field due to the plasma and beam currents so that the Hall contribution in Eq. (1) is absent. Then by operating on Eq. (1) with $\nabla\times\nabla\times$, and using Faraday's and Ampere's laws (assuming overall charge neutrality[3]), we obtain

$$\lambda_E^2\left(\frac{\partial}{\partial t}+\frac{1}{\tau_*}\right)\nabla^2\vec{J}^P = -\frac{\partial}{\partial t}(\vec{J}^P+\vec{J}^B), \quad (2)$$

where the total current density $\vec{J}(\vec{x}, t) = \vec{J}^P(\vec{x}, t) + \vec{J}^B(\vec{x}, t)$ is written as the sum of the plasma and beam contributions. Estimating the scale of the gradient operator in Eq. (2) to be of the order of