Total One-Electron Capture Cross Sections for Ar$q^+$ and I$q^+$ Ions in Slow Collisions on $H_2$ and He

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Argon and iodine recoil ions were produced by a 2 GeV $U^{75+}$ beam and total one electron capture cross sections are measured for 198 eV/q Ar$q^+$ ($4 \leq q \leq 15$) and $F^+$ ($5 \leq q \leq 27$) on $He$ and $H_2$. The cross section can be approximately reproduced by $1/2 \pi R^2$ according to the classical barrier model. The $q$-dependences exhibit significant fluctuations even for high charge states.

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Introduction

In recent years much attention has been paid to the study of charge exchange processes between highly charged ions and neutral particles [1–6]. The interest for accurate theories describing such complex collision systems was challenged by the progression of experimental data, whose importance for plasma, astrophysical and laser applications are most quoted. In the low-energy collision regime with projectile velocities much smaller than the orbital velocities of electrons, a molecular description like the perturbed - stationary - state method or the atomic-orbital expansion method [22] may be used to account for detailed features of charge exchange processes. Because laborious numerical calculations are required for high accuracy only a small number of cases can be compared to experimental data. Instead of detailed calculations for specific collision partners, general estimates using single analytical expressions may be applied to a wide variety of systems. The classical barrier model [7, 8] (CB) as a very simple approach allows one to calculate a geometrical cross section from the capture radius $R_c$ as a function of the ionic charge $q$ and the ionization potential $I_p$ of target electron. Alternatively the multiple curve crossing case is discussed for highly charged ions by Olson and Salop in the absorbing sphere model (AS) [9]. Using a modified Landau Zener treatment it gives a capture radius depending not only on $q$ and $I_p$ but also on the projectile velocity. In both cases assumptions are made about the transition probability at the crossings. For lower charge states ($q < 10$) an oscillatory dependence of capture cross sections on $q$ is observed in several experiments [4, 5, 10–12]. It is attributed to the extreme state selectivity of capture at low velocities due to the discreteness of final states available for impact parameters $b \sim R_c$ where capture is possible. For large $q$ values ($q \geq 10$) however, oscillations of capture cross section are expected to vanish as the number of available states in the close vicinity of a maximum capture radius $R \sim R_c$ is always large. This tendency was reported by the Kansas Group [5] to be observed for single-electron capture from lithium atoms into $q \leq 10$ ions and by the Nagoya Group [18] who measured single capture cross sections for $F^+$ ($q \leq 41$) and $Kr^{q^+}$ ($q \leq 25$) collisions on $He$ at energies $E_p \approx 1$ keV/q.

In this work total one electron capture cross sections for collisions of $F^+$ ($q \geq 27$) and $Ar$ ($q \geq 15$) ions on $H_2$ and $He$ with $E_p \approx 200$ eV/q are reported. The results are compared with CB and AS model calculations and with other experiments of similar collision systems.

Experimental Methods

Ions were produced in a "recoil ion source" as used by several experimentators [3, 14, 15]. A gas beam of typically 1 μbar pressure was bombared by urani-
um projectiles (1.4 ... 8 MeV/u Uq+q = 40 ... 75) from the UNILAC. The slowly recoiling ions extracted perpendicular to the incident projectiles were charge state and momentum analyzed by a double-focussing magnetic 180°-spectrometer having a momentum resolution $\Delta p/p \approx 0.3\%$. Then the slow ions are directed through a gas cell (Fig. 1) of 2 cm length and 0.1 cm and 0.5 cm diameter entrance and exit apertures, respectively. Two concentric hemispherical grids closely behind the cell allowed one to decelerate the ions by a positive retardation voltage $U_b$. A channeltron of 1 cm diameter sensitive area with $-3$ kV acceleration voltage applied to the cone was used for ion detection. Charge-state changing collisions with $E_{\text{exo}} \ll E_p$ ($E_{\text{exo}}$ = exoergic energy defect from capture) exhibit as function of $U_b$ step like drops of the count rate indicating contributions from lower charge states as shown for collisions of Ar$^{6+}$ on He in Fig. 1. The collection efficiency defined by the gas cell-geometry covers scattering angles up to 20° with respect to incident projectiles. This ensures essentially complete collection of projectiles, since the loss of capture events due to larger scattering angles is expected to be negligible [13]. The gas pressure was monitored by a spinning rotor viscosity gauge VISCOVAC* of $\sim 1\%$ accuracy for absolute measurements connected directly with the cell by a short copper tube of 1 cm diameter. A typical pressure of $P \leq 1$ μbar was adjusted corresponding to a capture rate of $\leq 10\%$ of primary beam intensity ensuring single collision conditions. This was also verified by a linear dependence of capture intensity on $P$. An effective length $l^* = 1.1 \times l$ ($l$ = geometrical length) of the gas cell was estimated from the ratio $P_{\text{cell}}/P_{\text{chamber}} \approx 140$ and from a distance of 25 cm to the magnetic selector. For each measurement multiple sweeps of $U_b$ averaged possible fluctuations of primary beam intensity. Background contributions of capture from rest gas atoms and possibly from collisions on surfaces of apertures and on the copper mesh are measured separately for each $q$ without target gas and were subtracted from the measurements with gas. Other possible background induced by the violent ionizing collisions of the UNILAC-beam was completely suppressed due to the separation of recoil ion source and charge exchange-scattering chamber.

Results and Discussion

Figure 2 displays an example of charge state spectrum of iodine recoil ions produced by 2 GeV U$^{75+}$ collisions on HI gas. HI was used instead of Xe because iodine is an isotopically pure gas avoiding blending of close values $q/m$ ($m$ = nuclear mass) after passing the magnetic selector. Furthermore, the kinetic energy transfer to $F^+$ ions by the molecular Coulomb explosion is negligibly small for HI as most energy goes into $H^+$, so it does not affect much the extractability of $F^+$ ions. Charge states up to 40+ were obtained, demonstrating that low energy ions (energy spread 0.2 eV/q FWHM) of very high charge states can be produced in single collisions by highly energetic heavy ion projectiles [14] and used for secondary collision experiments. The production of $q \geq 43$ seems to be feasible for higher projectile energies and with improved extraction geometry.

Total one-electron capture cross sections are listed in Table 1 for collisions of Ar$^{q+}$ ($4 \leq q \leq 15$) on He and H$_2$ with $E_p = 198$ eV/q specific energy and in Table 2 for $F^+$ ($5 \leq q \leq 27$) ions, respectively. The quoted uncertainties represent relative uncertainties of both the counting statistics and the reproducibility of four measurements taken for most charge states over a time period of three days. For most cases the reproducibility was better than 5%. The major part of systematic uncertainties ($\pm 15\%$) result from the estimate of effective length $l^*$ of target cell. Hence

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* VISCOVAC VM210, Leybold Heraeus GmbH, Köln, FRG