Excitation of the Na($3p$) Level by H^- Ions and H^0 Atoms

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Cross sections are reported for the excitation of Na atoms from the ground level to the $3p$ level by 1–25-keV incident H^- ions or H^0 atoms. The cross section for excitation by incident H^- rises from 1.4×10^{-15} cm^2 at 1 keV to a maximum of 3.8×10^{-15} cm^2 at 15 keV and then falls to 3.6×10^{-15} cm^2 at 25 keV. The cross section for excitation by H^0 falls from 1.3×10^{-15} cm^2 at 1 keV to 2.7×10^{-16} cm^2 at 25 keV. These cross sections are compared with previously measured cross sections for excitation of Na by protons and electrons.

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We report measurements of the apparent cross sections, denoted by $Q_{H^-}{}^A$ and $Q_{H^0}{}^A$, respectively, for the excitation of ground-level Na atoms to the $3p$ level by 1–25-keV H^- ions or H^0 atoms. The apparent cross section is the sum of the direct cross section for the production of Na($3p$) atoms plus the cross section for the production of Na($3p$) atoms by cascade from higher electronic levels. Together with previously reported values of $Q_e{}^A$ and $Q_{H^+}{}^A$, the apparent cross sections for incident electrons[1] and protons[2], respectively, our measurements of $Q_{H^-}{}^A$ and $Q_{H^0}{}^A$ provide a comparison of the excitation cross sections for a variety of simple projectiles incident on the same target. This comparison is especially interesting for the following reasons. (i) This is the first measurement of an atomic excitation cross section using incident negative ions. (ii) This is one of only a few excitation cross sections measured with incident fast neutral atoms. (iii) The unique apparatus permits quick and accurate direct comparisons of the cross sections for electron excitation with those for other incident particles. (iv) The energy dependence of the cross sections for charged particles is very different from that of fast neutrals in the energy range studied.

The apparatus used to measure the cross section $Q_{H^-}{}^A$ is shown in Fig. 1. A H^- beam is extracted from a duoplasmatron ion source, accelerated, and focused. The beam is momentum analyzed by a 10° bending magnet and collimated by two apertures 1.5 mm in diameter and 100 cm apart. The H^- beam enters the Na vapor target. The target is a stainless steel box with an interior length of 15 cm and an interior square cross section 3.8 cm on a side. Suspended directly beneath the center of the target is a reservoir containing liquid Na, connected to the target by a 1.8-cm-i.d. tube. The Na number density in the target is governed by the temperature of the liquid Na in the reservoir and by the temperature of the target. The target is kept 150° hotter than the reservoir to prevent Na from condensing on the

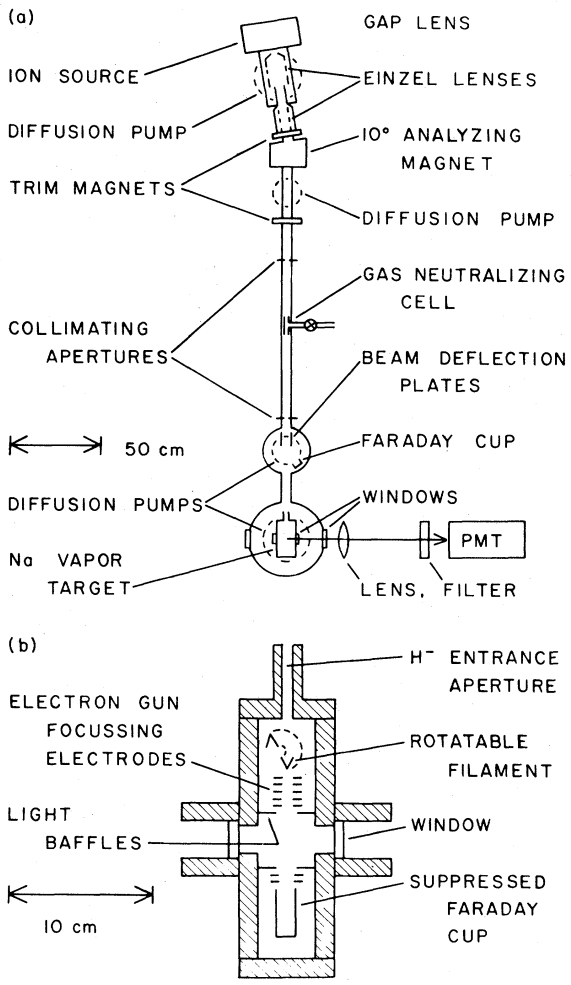

FIG. 1. Schematic diagram of the apparatus: (a) overview, (b) detail of the Na vapor target including the electron gun.

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target walls and windows. The ion beam enters the target through a stainless steel tube 5.1 cm long and 0.64 cm i.d. and is collected in a suppressed Faraday cup located inside the target.

Also located inside the target is an electron gun which consists of a tungsten filament and five annular focusing electrodes which are coaxial with the H^- ion beam. The holes in the annular electrodes are at least 0.64 cm in diameter so as not to intefere with the passage of the H^- beam in the target. The tungsten filament rotates on and off the beam axis. When the filament is rotated off-axis, the H^- beam enters the target and is collected in the suppressed Faraday cup inside the target. When the electron gun filament is rotated on axis, the H^- beam is blocked and an electron beam is formed and is collected in the suppressed Faraday cup. The Na $3p$-$3s$ resonance radiation from the collision region in the center of the target exits from the target and surrounding vacuum chamber through a pair of windows. The light passes through a narrow-band interference filter centered at 589 nm and is focused onto the cathode of a photomultiplier tube. The H^- and electron beams follow the identical path in the Na vapor target. We determine directly the ratio of the apparent cross section for Na($3p$) production by H^- ions with a given energy E to the apparent cross section for Na($3p$) production by 100-eV electrons from the ratio of the intensity of the $3p$-$3s$ emission per incident H^- ion with energy E to the $3p$-$3s$ emission per incident 100-eV electron at a fixed low value of the target density (typically $n \leq 2\times 10^{13}$ atoms/cm^3). The absolute apparent cross section for production of Na($3p$) by H^- ions incident at energy E is obtained from this ratio by use of the absolute cross section for Na($3p$) production by 100-eV electrons measured by Phelps and Lin.[1]

For measurements of $Q_{H^0}{}^A$, a H^- beam is produced and is stripped in Ar gas to form a H^0 beam. The H^0 beam passes through a pair of condenser plates that deflect remaining ions out of the H^0 beam and quench any metastable H($2s$) atoms in the H^0 beam. The beam flight time from the neutralizer to the plates (about 10^{-6} sec for 15-keV ions) is long enough that excited levels of H^0 with $n \leq 8$ will radiatively decay to either the ground level or the $2s$ metastable level.[3]

The Na vapor target used for measurements of $Q_{H^0}{}^A$ does not contain an electron gun or a Faraday cup. Instead, the target has an exit aperture identical to the entrance aperture. The H^0 beam passes through the target and is measured by collecting the electrons ejected when the fast H^0 atoms hit a heated, polished Cu surface. The calibration of this detector is described by Howald, Anderson, and Lin.[4]

A H^- beam instead of a H^0 beam can be sent through the target by shutting off the Ar gas to the neutralizing cell and grounding the condenser plates. After passing through the target, the H^- beam is deflected by a magnet into a suppressed Faraday cup located 4° off of the beam axis. Alternate measurements of the photomultiplier current with known incident H^0 atom flux and H^- ion current, with n held fixed, determine the ratio $Q_{H^0}{}^A/Q_{H^-}{}^A$. Since $Q_{H^-}{}^A$ has been determined absolutely, this gives absolute values of $Q_{H^0}{}^A$.

By the time a H^- or H^0 beam reaches the center of the Na vapor target, which is viewed by the photomultiplier, some fraction of the beam has undergone charge-changing collisions to form other charge states of hydrogen. These other charge components in the incident beam (e.g., H^- and H^+ for the case of incident H^0) also produce excitation in the Na target. We use the Na atom density in the target, determined from the known vapor pressure as a function of temperature,[5] and the measured Na charge-changing cross sections σ_{-0}, σ_{-+},[4] σ_{0+}, and σ_{0-}[6] to determine the actual charge compositions of the incident beam at the center of the target. The beam composition and known cross section[2] $Q_{H^+}{}^A$ are used to determine, self-consistently, values of $Q_{H^0}{}^A$ and $Q_{H^-}{}^A$. Because the target density is kept low, these corrections are at most 20% of Q^A.

The cross section for 1-keV H^- ions and H^0 atoms are determined with 2 keV D^- ions and D^0 atoms, which have the same velocity as H^- and H^0 and are assumed to have the same values of the apparent excitation cross section. We check this assumption by comparing cross sections for H^- and H^0 at 2, 4, and 6 keV with the cross sections for D^- and D^0 at 4, 8, and 12 keV, respectively. In all cases, the hydrogen cross sections are found to be the same as the deuterium cross sections at the same velocity.

Absolute values for the apparent cross sections $Q_{H^-}{}^A$ and $Q_{H^0}{}^A$ as functions of the incident energy are shown in Fig. 2. Also shown, for comparison, are the cross sections $Q_{H^+}{}^A$ and $Q_e{}^A$ at the same velocity from Refs. 2 and 1, respectively. We estimate the uncertainty in the relative values of $Q_{H^-}{}^A$ and $Q_{H^0}{}^A$ as functions of energy to be ±10% and ±15%, respectively, and the uncertainty in the absolute values to be ±15% and ±20%, respectively.

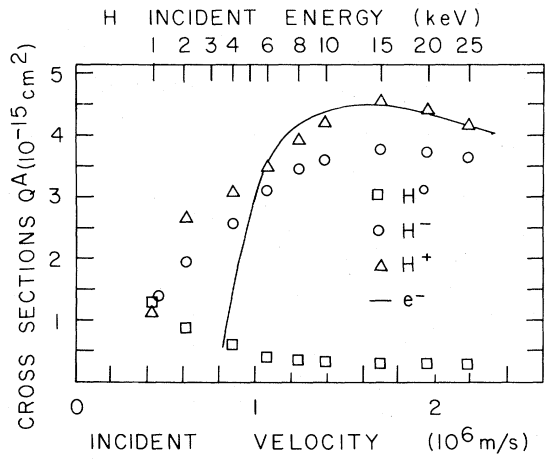

FIG. 2. Experimental values of the apparent cross sections $Q_{H^-}{}^A$ and $Q_{H^0}{}^A$ for excitation of Na atoms by H^- ions and H^0 atoms, respectively, as functions of hydrogen velocity. For comparison, the cross sections $Q_e{}^A$ and $Q_{H^+}{}^A$ for excitation by electrons and protons, respectively, are shown at equal velocities.

At incident velocities greater than about 1.5×10^6 m/s, the cross section $Q_{H^-}{}^A$ is similar to, but somewhat less than, either $Q_{H^+}{}^A$ or $Q_e{}^A$ at the same velocity. The cross sections for incident H^+, $H_2{}^+$, and $H_3{}^+$ are identical within experimental error,[2] and the cross section $Q_{H^0}{}^A$ is considerably smaller than $Q_{H^+}{}^A$, $Q_{H^-}{}^A$, or $Q_e{}^A$ in this velocity region. This indicates that at incident velocities comparable to or higher than the rms velocity of the target atom's valence electron, the dominant excitation mechanism is the direct interaction of the charge of the projectile with the oscillating dipole moment of the target.

The oscillator strength of the Na $3p$-$3s$ transition is nearly 1. Since the primary excitation mechanism at high energies is the interaction of the projectile charge and the oscillating dipole moment of the target, one expects the direct cross section to be nearly equal to the apparent cross section for H^-, H^+, or electrons incident at high energy. For electron-impact excitation, cascades contribute about 15% of $Q_e{}^A$.[1] We expect that for incident H^+ or H^- ions with velocities greater than 1.5×10^6 m/s the direct and apparent cross sections differ by about 15%.

The electron excitation cross section $Q_e{}^A$ falls to zero at its 2.1-eV threshold, corresponding to a threshold velocity of $v_{th} = 8.6 \times 10^5$ m/s. At v_{th}, incident H^+ and H^- ions have energies well above threshold.

For incident velocities less than about 1×10^6 m/s, where target and projectile valence electrons begin to adjust their motion in response to the slow approach of the nuclei, $Q_{H^+}{}^A$ and $Q_{H^-}{}^A$ must be examined in terms of NaH^+ and NaH^- molecular potential curves. Curves for NaH^+ have been calculated by Kimura, Olson, and Pascale[7] and Kubach and Sidis,[8] and for NaH^- by Olson and Liu.[9] Even at the lowest incident velocity of this experiment the energy uncertainty inherent in the collision, $\Delta E \cong hv/a$, where a is the size of the Na-H system and v is the projectile velocity, is comparable to the 2.1-eV energy defect of Na $3s$-$3p$ excitation making the initial and final channels "near resonant." As the interatomic separation R decreases from the asymptotic region, the spacings between the potential curves vary smoothly. Under near-resonant conditions the excitation cross sections are expected to be relatively insensitive to the details of the potential curves, especially since large cross sections correspond to large impact parameters. This may help to explain the similar magnitudes of $Q_{H^+}{}^A$ and $Q_{H^-}{}^A$ at low velocities. Low-energy nonresonant cross sections are much smaller than near-resonant cross sections, and thus we expect the cross sections for $3s$-$3p$ excitation by H^- or H^+ impact to be much larger than those for exciting the higher levels (energy defect > 3.2 eV). Thus for H^- or H^+ incident at low energies the direct production of Na($3p$) is much larger than the production of higher energy levels making cascades a small fraction of $Q^A(3p)$.

At low velocities the excitation cross section for H^0 impact is comparable to $Q_{H^-}{}^A$ and $Q_{H^+}{}^A$. For the excitation of Na to the $3p$ level by incident fast H^0 atoms, the initial and final channels involve only neutral species. The ionic channel $H^- + Na^+$ plays an important role, however, since its steeply falling potential curve crosses the potential curves corresponding to both initial and final channels at $R \cong 0.25$ and $R \cong 0.5$ nm, respectively. We believe that the large cross section $Q_{H^0}{}^A$ at small velocities is largely due to a double Landau-Zener-type transition from the initial channel to the ionic curve and then to the final channel. This reaction is closely related to the electron-capture reaction $H^0 + Na(3s) \rightarrow H^- + Na^+$, for which the cross section is denoted by σ_{0-}. Electron capture at small velocities is largely due to a single Landau-Zener-type transition from the initial channel to the ionic curve, without the second Landau-Zener-type transition from the ionic curve to the $H + Na(3p)$ channel. Since the mechanisms for excitation and electron capture are closely related, we expect the cross sec-

tions σ_{0^-} and $Q_{H^0}{}^A$ to also be related. We have measured the cross section σ_{0^-} for 1–25-keV H^0 atoms incident on Na. The cross section σ_{0^-} falls from 2.9×10^{-16} cm^2 at 1 keV to 1.4×10^{-16} cm^2 at 6 keV and continues to fall monotonically to 25 keV. This is similar in magnitude to $Q_{H^0}{}^A$ in the energy range 1–6 keV.

For low-energy H^0 atoms incident on Na the double Landau-Zener transition mechanism can in principle lead to excitation of higher Na levels such as $3d$ or $4s$. The lowest lying of these is the $4s$ level. For the $4s$ level the H^--Na^+ potential curve crosses the H^0-Na($4s$) potential curve at an internuclear distance of about 19 a.u. The Na($4s$) atom has a radius of about 7 a.u. At an internuclear distance of 19 a.u. the H^0 and Na($4s$) atoms are so far apart that the coupling interaction between them is very small. Thus the production of Na($4s$) atoms is very improbable. Similarly other levels, $3d$, $4p$, etc., will have a very low probability of production. Thus for low-energy H^0 atoms incident, Na($3p$) production is much larger than the production of higher levels and the direct cross section is almost equal to the apparent cross section.

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