Cross sections for excitation of sodium by impact of H^+, H_2^+, H_3^+, and H^- ions

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Apparent cross sections are reported for the excitation of Na atoms from the ground 3*s* level to the 3*d* level by incident H^+, H_2^+ H_3^+, or H^- ions with velocities in the range 0.5×10^6 to 2.2×10^6 m/s. The apparent cross section for H^+ ions has a maximum value of 4.5×10^{-16} cm^2 at an incident ion velocity of 1.7×10^6 m/s. At velocities above 1.4×10^6 m/s the apparent cross section for Na(3*d*)-level excitation by H^+ ions is the same function of the velocity as the apparent cross section for 3*d*-level excitation by electrons. The apparent cross section for excitation of Na(3*d*)-level atoms by incident H^- ions is about 45% below the apparent cross section for excitation by incident H^+ ions at velocities above 1.7×10^6 m/s. Combination of the apparent Na(3*d*) cross sections with the apparent Na(3*p*) cross sections reported earlier gives the direct excitation cross sections of Na(3*p*) by H^+, H_2^+, H_3^+, and H^- impact.

I. INTRODUCTION

In this paper we report the first measurements of the apparent cross section for the excitation of Na to the 3*d* level by H^+, H_2^+, H_3^+, or H^- ions with energies in the range 1–25 keV. The apparent cross section is the sum of the direct cross section for the formation of Na(3*d*) plus the cross section for the formation of Na(3*d*) by cascade from higher electronic levels, and is determined by measuring the $3d\rightarrow3p$ radiation produced by the ion-beam excitation. We denote these apparent cross sections by $Q^A_{H^+}$, $Q^A_{H_2^+}$, $Q^A_{H_3^+}$, and $Q^A_{H^-}$ where the subscript indicates the incident ion. These measurements together with previous measurements[1,2] of the apparent cross section for the excitation of Na(3*p*) by the same ions provide an interesting comparison of various ion excitation cross sections for a Na target.

We find that the apparent cross sections for excitation of Na(3*d*) atoms by H^+, H_2^+, or H_3^+ are the same at the same velocity of the incident ion and are about a factor of 10 less than the corresponding apparent cross sections for the excitation of Na(3*p*) atoms. We also find that the apparent cross sections for excitation of Na(3*d*) atoms by H^- ions are about a factor of 13 less than the corresponding apparent cross section for the excitation of Na(3*p*) atoms. Finally, we find that at high velocities the apparent cross sections for the excitation of Na(3*d*) atoms by H^+, H_2^+, or H_3^+ ions are nearly the same function of the velocity as the apparent cross section for the excitation of Na(3*d*) atoms by electrons, but that at high velocities the apparent cross section for the excitation of Na(3*d*) by H^- ions is substantially less than the apparent cross section for the excitation of Na(3*d*) atoms by electrons.[3] By combining the apparent excitation cross sections of Na(3*d*) with those of Na(3*p*), we obtain the direct-excitation cross sections of Na(3*p*) by H^+, H_2^+, H_3^+, and H^- ion impact.

II. APPARATUS

The apparatus used in this experiment is shown in Fig. 1(a). It is very similar to the apparatus used in previous measurements of the apparent cross sections for the excitation of Na(3*p*) atoms by ions. A duoplasmatron ion source is used. Either positive or negative ions can be directly extracted from the ion source by simply adjusting the location of the extraction aperture of the ion source. The ion beam is accelerated, focused, momentum analyzed by a 10° bending magnet, and collimated by two 1.5×10^{-3}-m holes separated by 1 m. The collimated ion beam passes between two capacitor plates. When the appropriate voltage is applied between the plates the ion beam is deflected into an off-axis suppressed Faraday cup. This enables us to measure the ion-beam current before it enters the Na target.

The Na vapor target is a stainless-steel box with an interior length of 15 cm and a square interior cross section 3.8 cm on a side. The ion beam enters the target through a stainless-steel tube 5.1 cm long and with a 0.64-cm i.d. The Na reservoir is suspended below the center of the target and is connected to the target by a 1.8-cm-i.d. tube. The light can exit either side of the target through 1.9-cm diameter sapphire windows. The Na target and reservoir are heated electrically. Both the target and windows are maintained about 110°C hotter than the reservoir in order to prevent condensation of Na in the target. The density of Na inside the target is determined by the temperature of the reservoir, the temperature of the target, the conductance of the tube connecting the reservoir and the target, and the conductance of the tubes connecting the target and the vacuum chamber in which the target is mounted. In this experiment a typical number density of Na inside the target is 3×10^{12} atoms/cm^3.

Inside the target is an electron gun, which is shown in Fig. 1(b). The electron gun has electrodes for focusing the electron beam and a suppressed Faraday cup. The apertures in the electrodes and the Faraday cup are coaxial with the ion-beam axis. The apertures in the electrodes are all 0.64 cm in diameter or larger so that the ion beam can pass through without striking the electrodes. The electron gun cathode is a tungsten filament. The tungsten filament can be rotated on or off the ion-beam axis. When the filament is rotated off axis the ion beam passes through the electrodes and is collected by the Faraday cup. When the filament is rotated on axis the ion beam is blocked off and an electron beam is formed. The electron beam is also collected by the Faraday cup. The electron beam and the ion beam pass along identical paths in the Na target.

The $3d \rightarrow 3p$ radiation from the Na target exits the target and the surrounding vacuum chamber via a pair of windows. A dichroic polarizer is used to select either polarization parallel to or perpendicular to the electron-beam axis. A narrow-band interference filter with its transmission centered at 820 nm is used to isolate the radiation from the Na $3d \rightarrow 3p$ transition. After passing through the interference filter the $3d \rightarrow 3p$ radiation is focused onto the cathode of a photomultiplier. The output current from the photomultiplier I_{PM} and the ion (or electron) beam current I_0 are measured simultaneously.

The quantity I_0 is the ion current passing through the region viewed by the photomultiplier. The current collected by the Faraday cup is slightly less than I_0 due to charge-changing collisions of the incident ions with the Na atoms. The charge-changing collisions convert a small fraction of the ion beam into neutrals between the viewing region and the suppressed Faraday cup. We correct for this using the known charge-changing cross sections[4-6] and the Na atom density in the target. Typically the difference between I_0 and the current measured at the Faraday cup is $0.05I_0$ or less at the Na target densities used in our experiments.

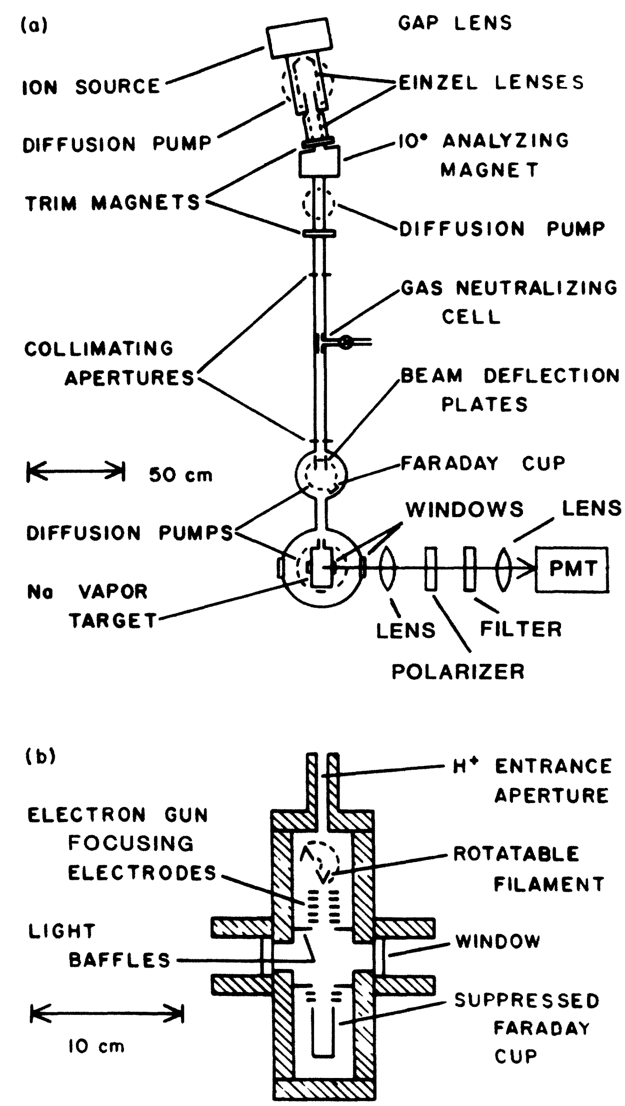

FIG. 1. Schematic diagram of the apparatus. (a) Overview, (b) detail of the Na vapor target including the electron gun.

III. MEASUREMENTS AND ANALYSIS

A. Polarization measurements

The polarization of a given transition is given by

$$P=(I^{\parallel}-I^{\perp})/(I^{\parallel}+I^{\perp})=[1-(I^{\perp}/I^{\parallel})]/[1+(I^{\perp}/I^{\parallel})] ,$$

where $I^{\parallel}$ and $I^{\perp}$ are the components of the light intensity observed at right angles to the ion or electron beam and polarized parallel to and perpendicular to the light beam, respectively. The photomultiplier currents produced by $I^{\parallel}$ and $I^{\perp}$ are called $I_{PM}^{\parallel}$ and $I_{PM}^{\perp}$, respectively. The ratio $I_{PM}^{\parallel}/I_{PM}^{\perp}$ is directly proportional to $I^{\parallel}/I^{\perp}$ so that $I_{PM}^{\parallel}/I_{PM}^{\perp}=cI^{\parallel}/I^{\perp}$, where the constant of proportionality c depends on the response of the detection system including the transmission of the interference filter and the response of the photomultiplier to the two polarizations. We measure $I_{PM}^{\parallel}/I_{PM}^{\perp}$ for the $3d \rightarrow 3p$ transition for excitation by electrons or fast hydrogen ions.

In our measurements, we use a narrow-band interference filter to isolate the Na $3d \rightarrow 3p$ radiation. The interference filter passes all the $3d \rightarrow 3p$ transitions. The experiments of Phelps and Lin with electron excitation measured separately the polarization of the $3d \rightarrow 3p$ lines ending on the $^2P_{1/2}$ and $^2P_{3/2}$ levels of Na.[3] We have obtained the polarization of the entire group of the $3d \rightarrow 3p$ transitions by combining the polarization data of Phelps and Lin with appropriate weightings. From the polarization of the $3d \rightarrow 3p$ transition we obtain $(I^{\parallel}/I^{\perp})_e$ and from our measurements we obtain $(I_{PM}^{\parallel}/I_{PM}^{\perp})_e$, where the subscript e indicates electron incident. Combining these we obtain the constant c.

From our measurements of $I_{PM}^{\parallel}/I_{PM}^{\perp}$ for excitation by fast ions and using the value of c obtained from the measurements with electrons incident we obtain the polarization of the $3d \rightarrow 3p$ radiation for fast ions incident. For the $3d \rightarrow 3p$ transition, we find experimentally that the polarization is the same for H^+, H_2^+, H_3^+, and H^- ions

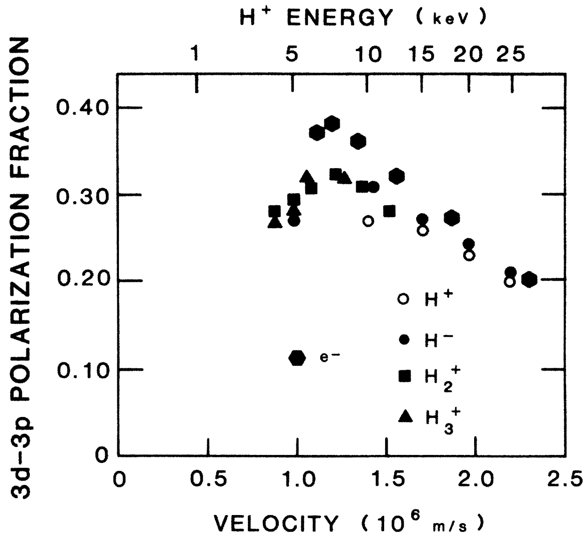

FIG. 2. Experimental polarization of the Na $3d \rightarrow 3p$ transition for excitation by H^+, H_2^+, H_3^+, and H^- ions as a function of ion velocity. For comparison, the $3d \rightarrow 3p$ polarization for excitation by electrons is shown as a function of electron velocity.

with the same velocity for velocities in the range 0.9×10^6 to 2.2×10^6 m/s, and that the values of the $3d \rightarrow 3p$ polarization for electrons and hydrogen ions with the same velocity are nearly the same, in the velocity range 1.3×10^6 to 2.3×10^6 m/s. Figure 2 shows the polarization of the $3d \rightarrow 3p$ radiation for excitation by H^+, H_2^+, H_3^+, and H^- ions as a function of the velocity of the incident ion. The polarization of the $3d \rightarrow 3p$ transition for excitation by electrons, obtained from the polarization measurements reported by Phelps and Lin, is also shown in Fig. 2 as a function of electron velocity.[3]

We have also measured the polarization of the $3p \rightarrow 3s$ radiation for excitation by fast ions. We find that the polarization of the $3p \rightarrow 3s$ radiation is less than 5% for excitation by H^+ and H^- ions in the velocity range of 0.9×10^6 to 2.2×10^6 m/s.

B. Cross-section measurements

Our apparatus permits us to compare directly the apparent ion-excitation cross section at a given energy with the apparent electron-excitation cross section at some particular energy. Since the apparent electron-excitation cross section for the Na(3*d*) level as a function of the energy is known[3] this permits us to obtain the absolute value of the ion-excitation cross section. At low Na density the apparent cross section for excitation of Na(3*d*) atoms is proportional to $I_{PM}(1-P/3)/nI_0$, where n is the Na atom density in the target, I_{PM} is the photomultiplier current with the polarizer removed, and P is the polarization of the $3d \rightarrow 3p$ radiation. Thus $Q^A = kI_{PM}(1-P/3)/(nI_0)$, where k is a constant that depends on the geometry of the collision region, the transmittance of the windows and the filter, and other factors. The ratio of the apparent cross section $Q^A_{H^+}$ to the apparent electron excitation cross section Q_e^A for 100-eV electrons is obtained by measuring the ratio of $[I_{PM}(1-P/3)/I_0]_{H^+}$ for 15-keV H^+ ions to $[I_{PM}(1-P/3)/I_0]_e$ for 100-eV electrons at the same low target density n. Typically $n=(1-3)\times10^{12}$ atoms/cm^3 in these experiments. Radiation trapping is not important in these experiments because the 3*d* level is not optically connected to the ground level. The absolute value of $Q^A_{H^+}$ at 15 keV is equal to

$$Q_e^A[I_{PM}(1-P/3)/I_0]_{H^+}/[I_{PM}(1-P/3)/I_0]_e\ .$$

We use the value of Q_e^A at 100 eV reported by Phelps and Lin.[3] The value of $Q^A_{H^+}$ for H^+ energies other than 15 keV relative to $Q^A_{H^+}$ for 15-keV H^+ ions is obtained by measuring, at the same low target density, the ratio of $[I_{PM}(1-P/3)/I_0]_{H^+}$ for a given H^+ ion energy to the value of $[I_{PM}(1-P/3)/I_0]_{H^+}$ for a H^+ ion energy of 15 keV. The cross sections $Q^A_{H_2^+}$, $Q^A_{H_3^+}$, and $Q^A_{H^-}$ are obtained using a similar procedure.

We have measured the polarization of the $3d \rightarrow 3p$ radiation for electron excitation with 100-eV electrons. The $3d \rightarrow 3p$ polarization for 100-eV electrons is less than 0.03. The polarization for 100-eV electrons is neglected in the polarization correction to the apparent cross sections. The polarization correction to the apparent cross sections for hydrogen ions incident is less than 10% for velocities between 0.9×10^6 and 2.2×10^6 m/s. For ion velocities below 0.9×10^6 m/s the ion beam current is too small to permit us to measure the polarization of the $3d \rightarrow 3p$ radiation. The apparent cross sections for velocities less than 0.9×10^6 m/s are not corrected for polarization.

At an energy of 1 keV the H^- ion-beam current is too small to permit us to measure the apparent cross section for excitation of the Na(3*d*) level. We have measured the apparent cross section for the excitation of the Na(3*d*) level using D^- ions at 2 keV, which have the same velocity as 1-keV H^- ions. The value of $Q^A_{H^-}$ at 1 keV is taken as equal to the value of $Q^A_{D^-}$ at 2 keV. In order to check this we have measured $Q^A_{D^-}$ with incident ion energies of 4, 8, and 12 keV and find these cross sections to be the same, respectively, as $Q^A_{H^-}$ with incident ion energies of 2, 4, and 6 keV.

IV. RESULTS AND DISCUSSION

Figure 3 shows the apparent cross sections $Q^A_{H^+}$, $Q^A_{H_2^+}$, $Q^A_{H_3^+}$, and $Q^A_{H^-}$, for the excitation of the Na(3*d*) level as a function of the velocity of the incident ion for incident velocities between 0.5×10^6 and 2.2×10^6 m/s. Also shown are the Phelps and Lin measurements of the apparent cross section Q_e^A for the excitation of the Na(3*d*) level as a function of the incident electron velocity.[3]

The uncertainty in the polarization measurements is primarily due to random errors in the measurements and is about ±20% of the polarization. The uncertainty in the relative values of $Q^A_{H^+}$, $Q^A_{H_2^+}$, and $Q^A_{H_3^+}$ is about

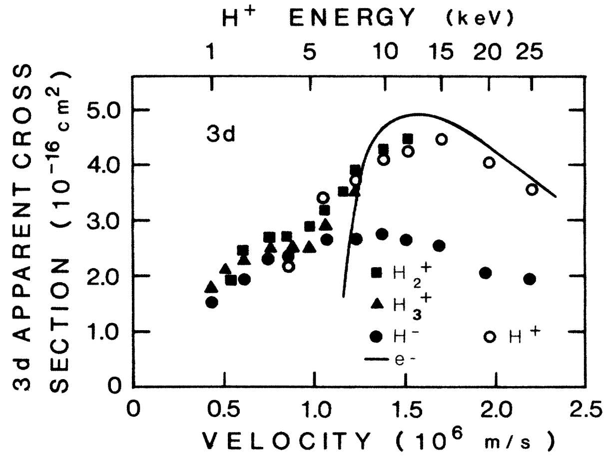

FIG. 3. Experimental values of the apparent cross sections $Q^A_{H^+}$, $Q^A_{H_2^+}$, $Q^A_{H_3^+}$, and $Q^A_{H^-}$ for excitation of the Na(3d) level by H^+, H_2^+, H_3^+, and H^- ions, respectively, as a function of ion velocity. For comparison, the apparent cross section Q_e^A for excitation of the 3d level by electrons is shown as a function of electron velocity.

20% at energies above 5 keV. At energies less than 5 keV the signal is much weaker because of the low beam current. The uncertainty at these energies is 40%. These uncertainties are due primarily to the random uncertainty in the measurements. The uncertainty in the absolute value of Q_e^A at 100 eV is 10%.[3] Adding these uncertainties in quadrature leads to an absolute uncertainty in $Q^A_{H^+}$, $Q^A_{H_2^+}$, and $Q^A_{H_3^+}$ of about 25% at energies above 5 keV and about 41% at energies less than 5 keV.

The random uncertainty in the relative values of $Q^A_{H^-}$ is about 10% at energies above 5 keV and about 20% at energies below 5 keV. The uncertainty in the absolute values of $Q^A_{H^-}$ is about 15% at energies above 5 keV and about 25% at energies below 5 keV.

We have also prepared a fast H^0 beam and have attempted to measure the cross sections $Q^A_{H^0}$, but find that these cross sections are so small that the signals are not detectable with our apparatus. It is clear that $Q^A_{H^0} < 0.3 Q^A_{H^+}$ over the energy range we have studied. We calculate that the fraction of the ion beam that has been neutralized by charge-changing collisions in the Na vapor is less than 0.15 at the viewing region. Thus the contribution to the emitted $3d \rightarrow 3p$ radiation when H^+, H_2^+, H_3^+, or H^- ions are incident due to excitation by the neutral component of the beam is less than 5% of the total $3d \rightarrow 3p$ radiation. Thus no significant uncertainty is introduced into our measurements of the ion-excitation cross sections by charge changing collisions in the Na target.

The measured apparent cross sections $Q^A_{H^+}$, $Q^A_{H_2^+}$, and $Q^A_{H_3^+}$ for the excitation of the Na(3d) level are the same function of the incident velocity. These apparent cross sections increase from 1.8×10^{-16} cm^2 at an incident velocity of 0.5×10^6 m/s to a peak value of 4.5×10^{-16} cm^2 at 1.7×10^6 m/s. At incident velocities higher than 1.4×10^6 m/s the apparent cross sections for incident H^+ ions and electrons are the same function of the velocity. Below the incident velocity 1.4×10^6 m/s, the electron-excitation cross section decreases abruptly to zero at the electron excitation threshold velocity 1.1×10^6 m/s corresponding to the 3.6-eV threshold. At this velocity the H^+, H_2^+, and H_3^+ ions all have energies well above the threshold energy, thus $Q^A_{H^+}$, $Q^A_{H_2^+}$, and $Q^A_{H_3^+}$ deviate from Q_e^A at incident velocities of 1.4×10^6 m/s or less. The same trend was observed in our previous experimental data on excitation of the Na(3p) level[1,3] by electron, H^+, H_2^+, and H_3^+ impact, which are summarized in Fig. 4. At projectile velocities above 1.0×10^6 m/s, the apparent cross sections for exciting the Na(3p) level are the same function of the incident velocity for all four different projectiles. As can be seen from Figs. 3 and 4 the apparent cross section for the formation of Na(3d) is about an order of magnitude less than the apparent cross section for the formation of Na(3p) at the same incident electron or ion velocity. The electron excitation cross section for the Na(3p) level is exceptionally large on account of the strong coupling between the 3s and 3p level as discussed in Ref. 3.

York *et al.*[7] have measured the sum of H^+ impact excitation cross sections of the levels of the $2p^5 3s$ configuration and of the $2p^5 3p$ configuration of Ne at incident energies from 20 to 180 keV. Similar experiments were performed using H_2^+ as the projectile. York *et al.* presented plots of H^+ and H_2^+ impact excitation cross sections with a common linear scale in energy. Their plots for H^+ and H_2^+ excitation are qualitatively similar. We have replotted their data on the same velocity scale in Figs. 5 and 6. The coincidence between the H^+ and H_2^+ curves as functions of the projectile velocity is

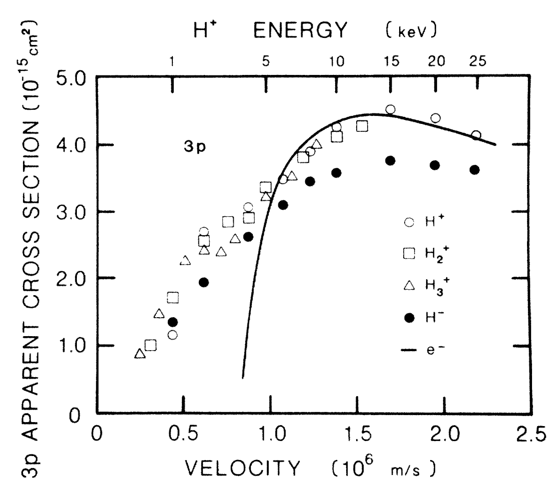

FIG. 4. Experimental values of the apparent cross sections $Q^A_{H^+}$, $Q^A_{H_2^+}$, $Q^A_{H_3^+}$, and $Q^A_{H^-}$ for excitation of the Na(3p) level by H^+, H_2^+, H_3^+, and H^- ions, respectively, as a function of ion velocity. For comparison, the apparent cross section Q_e^A for excitation of the 3p level by electrons is shown as a function of electron velocity.

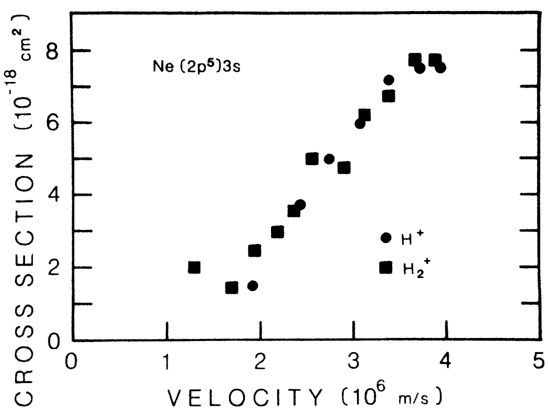

FIG. 5. Absolute cross sections for excitation of the $(2p^5)3s$ configuration of neon by H^+ and $H_2{}^+$ ions as a function of ion velocity.

quite striking. This observation is in line with our findings in H^+, $H_2{}^+$, $H_3{}^+$ excitation of Na. Cross sections for excitation of the He 4^1S state by H^+, $H_2{}^+$, and $H_3{}^+$ impact have been reported by Thomas and Bent[8] and by Van den Bos, Winter, and deHeer.[9,10] The $H_2{}^+$ impact and $H_3{}^+$ impact excitation cross sections of Thomas and Bent are very close to each other at the same velocity, but are generally about 30% higher than their corresponding H^+ impact cross sections. The H^+ impact cross sections of Thomas and Bent[8] differ significantly from those of Van den Bos *et al.*,[9] but the latter data join smoothly to the $H_3{}^+$ impact cross sections of Thomas and Bent. The H^+, $H_2{}^+$, and $H_3{}^+$ impact cross sections of the He emission lines ($4^1D \rightarrow 2^1P$ and others) reported by Van den Bos *et al.* are qualitatively similar at the same incident velocity,[10] but do not exhibit the close coincidence found in Figs. 5 and 6. In view of the very close agreement between the excitation cross sections produced by different projectiles of the H^+, $H_2{}^+$, and $H_3{}^+$ series which is observed in Na and Ne, further studies of the H^+, $H_2{}^+$, and $H_3{}^+$ impact excitation of the various emission lines of He and other atoms is desirable.

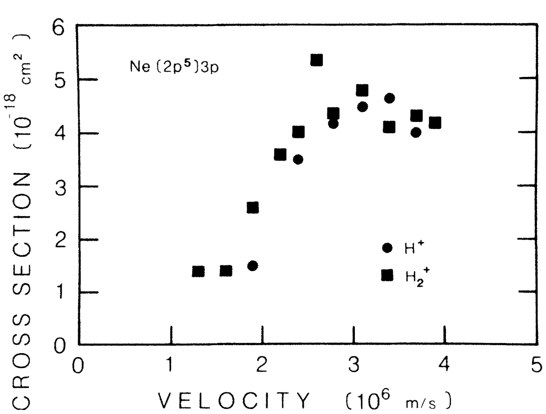

FIG. 6. Absolute cross sections for excitation of the $(2p^5)3p$ configuration of neon by H^+ and $H_2{}^+$ ions as a function of ion velocity.

The results of H^- impact excitation, which are also shown in Fig. 3, are especially interesting. For excitation of the Na(3*d*) level, $Q^A_{H^-}$ is seen to be about one-half of $Q^A_{H^+}$ at energies above 10 keV, whereas our earlier work on excitation of the Na(3*p*) level shows $Q^A_{H^-}$ only 15% below $Q^A_{H^+}$ in the same energy range.[2] A possible explanation for the difference in the Na(3*d*) and Na(3*p*) data is as follows. The H^- ion contains a loosely bound outer electron with an orbital radius of about 2 Å plus an inner electron which is tightly bound to the proton. The outer electron is mainly responsible for exciting the Na atoms at high-energy impact. For the one-configuration wave function of Silverman *et al.*,[11] the rms orbital velocity of the outer electron of H^- is 0.59×10^6 m/s. Consider a H^- ion colliding with a Na atom with an impact parameter b_0 at an incident energy above 15 keV. Since the velocity of the orbital motion of the outer electron of H^- is much smaller than the translational velocity, the orbital motion of the outer electron during the time interval of the collision is negligible. The collisional effect of the outer electron is therefore equivalent to a statistical average of the effects of an ensemble of free electrons with the same translational velocity and impact parameters ranging from $b_{\min}$ to $b_{\max}$ where $b_{\max}-b_{\min}$ corresponds roughly to the diameter of the outer-electron orbit. For illustration let us adopt an impact-parameter description for electron excitation which, though not rigorous, has been used to calculate excitation cross sections of electronic states of the H_2 molecule with considerable success[12] and therefore is adequate for the following qualitative discussion. If we designate by $P_e(b)$ the probability of exciting a particular level by an incident electron of impact parameter b, the electron excitation cross section is

$$Q_e=\int_0^\infty 2\pi P_e(b)b\,db=\int_0^\infty F_e(b)db \ . \quad (1)$$

$P_e(b)$ decreases at large b so that $F_e(b)$, which is equal to $2\pi bP_e(b)$, can be schematically represented by Fig. 7. In Eq. (1) the major contribution of Q_e comes from the region of b where $F_e(b)$ is relatively large. Similarly the cross section for H^- impact is

$$Q_{H^-}=\int_0^\infty F_{H^-}(b)db \ . \quad (2)$$

According to the model suggested earlier in this paragraph, the value of $F_{H^-}(b_0)$ can be approximated by a weighted average of $F_e(b)$ over b between $b=b_{\max}$ and $b=b_{\min}$. Suppose that the range of the $P_e(b)$ curve is comparable to or smaller than the difference between $b_{\max}$ and $b_{\min}$. Referring to Fig. 7, we see that the magnitude of $F_{H^-}(b_0)$ obtained by averaging $F_e(b)$ over b from $b_{\max}$ to $b_{\min}$ is significantly smaller than $F_e(b_0)$. In general one expects $F_{H^-}(b)<F_e(b)$ when $F_e(b)$ is relatively large, resulting in $Q_{H^-}<Q_e$. On the other hand, if the range of the $P_e(b)$ curve is so much larger than $b_{\max}-b_{\min}$ that in the major part of the $P_e(b)$ curve the value of $P_e(b)$ changes little within the span of

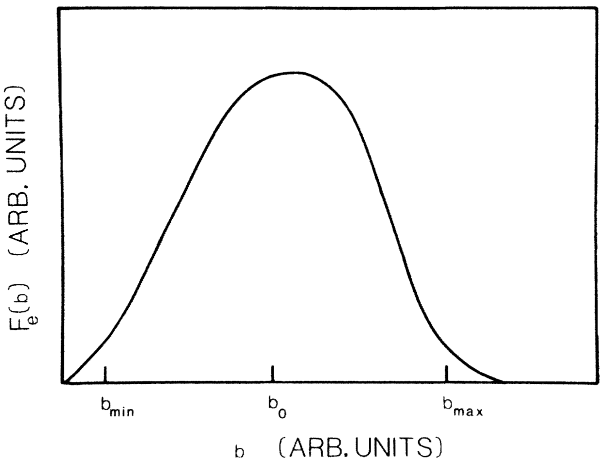

FIG. 7. Schematic representation of $F_e(b)$ as a function of electron impact parameter b.

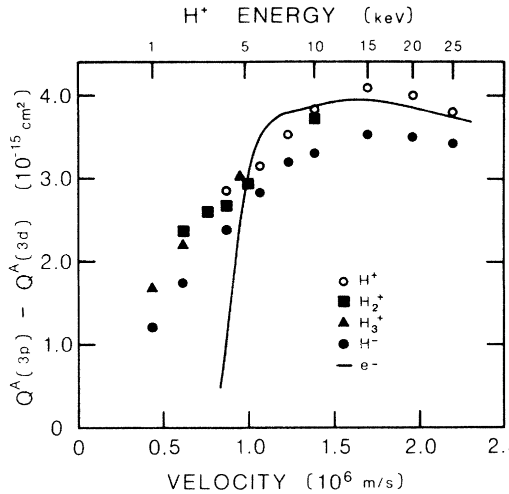

FIG. 8. The difference in the apparent cross sections $Q^A(3p)$ and $Q^A(3d)$, $Q^A(3p)-Q^A(3d)$, for H^+, $H_2{}^+$, $H_3{}^+$, and H^- impact excitation as a function of ion velocity. For comparison, $Q^A(3p)-Q^A(3d)$ for electron-impact excitation is shown as a function of electron velocity.

$\Delta b = b_{max} - b_{min}$, the averaging would have little effect and Q_{H^-} would differ only slightly from Q_e. Excitation from the 3s to 3p levels of Na corresponds to an optically allowed transition. The coupling of these two levels through the colliding electron (or proton) is a long-range function of the impact parameter and so is $P_e(b)$. The $3s \to 3d$ excitation is not an optically allowed transition, hence the coupling interaction and $P_e(b)$ for excitation of the 3d level is of shorter range. Thus the model presented above provides a simple, qualitative explanation for the large difference between Q_{H^-} and Q_e for the $3s \to 3d$ excitation compared to $3s \to 3p$ at energies above 15 keV, and may provide the basis for a more quantitative theory.

For H^- incident energies below 4 keV, the model suggested earlier is not applicable because the translational velocity of the H^- ion is comparable to or less than the orbital velocity of the outer electron. We note from Fig. 3 that Q_{H^+} and Q_{H^-} become close to each other at energies below 5 keV. At these energies it is necessary to consider the change of the valence electron cloud of the target and projectile in response to the slow encounter. Energy curves for the NaH^- and NaH^+ systems have been reported in the literature.[13–15] These curves will be important for analyzing the H^+ and H^- impact excitation cross sections at low energies.

In the experiments of electron excitation of Na reported in Ref. 3, the direct-excitation cross section of the Na(3p) level is obtained from the apparent-excitation cross section by subtracting the cross section for the formation of Na(3p) by cascade from higher levels. The total cascade cross section is determined by measuring the optical excitation cross sections for the $nd \to 3p$ ($n \geq 3$) and $ns \to 3p$ ($n \geq 4$) series. It was found that the $3d \to 3p$ cascade alone constitutes more than half of the total cascade and the sum of all cascade contributions exclusive of $3d \to 3p$ amounts to about 8% of the direct excitation cross section. If we assume a similar trend for ion excitation, then $Q^A(3p)-Q^A(3d)$ for ion excitation can be taken as a good approximation to the corresponding direct excitation cross section $Q(3p)$ since

$$Q^A(3p)-Q^A(3d)=Q(3p)+\sum_{n\geq 4} Q(nl\to 3p) \quad (3)$$

and the last term makes only a contribution of about 8%. A plot of $Q^A(3p)-Q^A(3d)$ for H^+, H_2^+, H_3^+, and H^- impact excitation as a function of the incident ion velocity is shown in Fig. 8. A plot of $Q^A(3p)-Q^A(3d)$ for electron-impact excitation as a function of incident electron velocity is also shown in Fig. 8. The values of $Q^A(3p)-Q^A(3d)$ for electron-impact excitation shown in Fig. 8 were obtained from measurements of $Q^A(3p)$ and $Q^A(3d)$ for electrons incident reported by Phelps and Lin.[3]

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