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Charge Exchange Collisions between Hydrogen Ions and Alkali Vapour in the Energy Range of 1 to 20 keV

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Summary. Charge exchange collisions have been studied for H^+ and D^+ ions incident on the alkali vapours Cs, K, Na and Li. Measurements of the positive and negative beam components after passage through the target were made in the energy range of 1 to 20 keV. Also the one- and two-electron charge exchange cross section σ_{10} and σ_{1-1} were determined in this energy range. The value of the maximum of the negative beam component decreases monotonically from approximately 20% of the incident beam intensity at about 1 keV for Cs to 6% at 4 keV for Li. The maxima of Cs and K are quite sharp, whereas the maxima of Na and Li show a much broader behaviour, such that, for these latter elements, the yield at 10 keV is higher by a factor 2 to 5. The maximum of the cross section σ_{10} for all the elements measured is approximately 10^{-14} cm^2. The cross section σ_{1-1} has the maximum value of $8 \cdot 10^{-17}$ cm^2 for Li, $5 \cdot 10^{-16}$ cm^2 for Na, $6 \cdot 10^{-17}$ cm^2 for K and $6 \cdot 10^{-17}$ cm^2 for Cs. An analysis of the results shows that the adiabatic parameter postulated by Massey is dependent on the nature of the colliding particles.

I. Introduction

The production of a high-intensity negative-ion beam is of considerable practical interest in the development of ion sources for cyclotrons and tandem electrostatic accelerators. During the construction of a polarized ion source for the ETH tandem Van de Graaff, studies of a gas charge exchanger have been made in an effort to achieve higher negative ion beam intensities and better beam quality. It was found that an alkali vapour charge exchanger has several advantages over a foil exchanger, although, when used in conjunction with a polarized beam, precautions must be taken to minimize beam depolarization. A solution to the beam depolarization problem was the subject of an earlier letter [1]. The measurements of the various charge exchange cross sections yield important information on the collision process and provide a valuable test for the theories of such processes.

Earlier studies by other authors have been concerned with the charge exchange of low energy protons incident on hydrogen and the inert gases [2, 3], organic compounds [4] and atomic hydrogen [5]. In these experiments the yield of negative ions was generally quite low. Charge exchange of H^+ ions in alkali vapours has been studied in a number of experiments. Il'in et al. [6] have measured the charge exchange cross section σ_{10} and the cross section for the production of highly excited neutral hydrogen atoms in collisions with alkali and other vapours in the energy range of 10 to 180 keV.

The cross section σ_{10} and the neutral equilibrium yield for H^+ ions incident on K and Na have been measured by Niemann and Donahue [7, 8] in the energy range of 4 to 30 keV. Earlier measurements from our laboratory [9] were concerned with the equilibrium fractions and the cross sections σ_{10} and σ_{1-1} for H^+ on K in the energy range of 2.5 to 22 keV. Measurements on the yields of H^- for H^+ incident on Cs and K in the energy range of 0.5 to 2 keV were reported by Bohlen et al. [10], at 1 keV by Donnally et al. [11] for K and by Drake et al. [12] for Cs. Schlachter et al. [13] have measured the equilibrium fractions and the cross sections for H^+ ions and ground state H^0 atoms incident on Cs vapour.

The purpose of the present work was to investigate systematically the one- and two-electron charge exchange processes with low energy positive hydrogen ions in various alkali vapours and to study their dependence on the incident energy. In a short letter, we have reported the results of the yields of negative hydrogen ions [14]. The alkali vapours Li, Na, K and Cs have been investigated.

II. Theory

The evolution of the fractions of the charge components in a beam of particles can be described by a system of differential equations [15], namely,

$$dF_1/d\pi = -F_1(\sigma_{10} + \sigma_{1-1}) + F_0\,\sigma_{01} + F_{-1}\,\sigma_{-11}\,, \tag{1}$$

$$dF_0/d\pi = F_1\,\sigma_{10} - F_0(\sigma_{01} + \sigma_{0-1}) + F_{-1}\,\sigma_{-10}\,, \tag{2}$$

$$dF_{-1}/d\pi = F_1\,\sigma_{1-1} + F_0\,\sigma_{0-1} - F_{-1}(\sigma_{-10} + \sigma_{-11})\,. \tag{3}$$

The F_i's are the charge fractions of the beam, the subscripts 1, 0 and -1 refer to the positive, neutral and negative charge states, π is the charge exchange target thickness and the σ_{if} are the cross sections of the charge exchange reactions. For a thick target, the F_i reach an equilibrium value $F_{i\infty}$. The solutions of the system of differential equations is given by Allison [15] who also discusses the possibility of a maximum of $F_i(\pi)$ before the charge equilibrium is attained. For an incident beam with only one charge component the determination of a single cross section is greatly simplified. For instance, if there is an incident proton beam, the cross section for double capture is given by

$$\sigma_{1-1} = [dF_{-1}(\pi)/d\pi]_{\pi\to 0}$$

which means, that the cross section is proportional to the slope of the linear part of the $F_{-1}(\pi)$. The presence of excited states of the particles complicates the description of the evolution of the beam. The σ_{if} in the differential equations (1) to (3) have to be replaced by combinations of the appropriate cross sections for the excited states, superposition of which yields the measured charge exchange cross sections.

According to the Massey-hypothesis [16], the charge exchange cross section has a maximum if the condition

$$a\,|\Delta E|/h\,v_{max} \approx 1$$

is satisfied. Here, a is the so-called adiabatic parameter dependent only on the type of process involved and not on the nature of the colliding particles [17, 18], the

quantity v_{max} denotes the velocity at which the maximum occurs, h is Planck's constant. The energy defect ΔE is determined by

$$\Delta E = \Delta E_\infty - E_c - E_p - E_x$$

where ΔE_∞ is the energy defect for infinite separation and is calculated from the relevant ionisation potentials and electron affinities of the reactants, E_c is the coulomb interaction, E_p the polarisation interaction and E_x the excitation energy of the products of the reaction.

Considering only ΔE_∞, Hasted [17] has calculated an average value of $a_\infty = 8$ Å for a single charge exchange and Fogel [18] determined a value of 1.5 Å for double charge exchange. Taking into account the influence of E_c and E_p an average value $a = 7$ Å$/m$ is obtained, where m denotes the number of electrons transferred [17]. Since for a given energy defect, only the velocity of the incident particles is of importance for the position of the maximum, the value v_{max} will be the same for reactions induced by protons or deuterons.

A process for which the energy defect is very small i.e. $\Delta E \approx 0$, is termed a near resonant process and the cross section is expected to be high.

III. Apparatus and measurements

The experimental arrangement is shown in Figure 1. Positive hydrogen ions produced in a radio-frequency ion source were focused, and then deflected by a magnetic analyser through an angle of 40°. Ions emerging from the analyser were collimated by two defining apertures, 2.5 mm in diameter placed 150 mm apart, and directed into the collision chamber consisting of a cylindrical oven 30 mm in diameter having a concentrical exchange tube 10 mm in diameter and 100 mm long. The alkali metals were vaporized in the cylindrical oven and the vapours passed through a hole 8 mm in diameter in the middle of the exchange canal. The oven could be heated

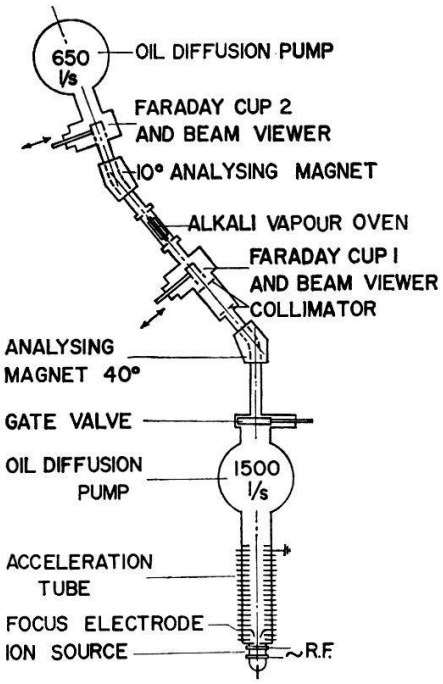

Figure 1
Schematic diagram of the apparatus.

electrically to a maximum temperature of 600 °C, which could be measured by means of a thermoelectric couple. Based on the measured temperature the vapour density was determined.

The beam intensity was measured at the entrance of the collision chamber with a removable Faraday cup 20 mm in diameter. Secondary electrons from the latter were rejected by a suppressor electrode placed in front of the cup. After passing through the collision chamber, the beam was again analysed magnetically by selective deflection of the positive or negative ions through an angle of 10° into a second Faraday cup 32 mm in diameter and equipped with a suppressor electrode. The positive or negative ions were selected by changing the direction of the field in the magnet. A 1500 l/s oil diffusion pump equipped with a baffle and liquid nitrogen trap was used to pump the volume between r.f. source and alkali oven. The volume after the oven was pumped by a 650 l/s oil diffusion pump having a baffle and liquid nitrogen trap.

The intensity of the primary beam entering the collision chamber I_{inc} and that of the positive and negative beam components after charge exchange, I_1 and I_{-1} have been measured and used to determine the charge components F_i. The transmission T through the oven and the 10° analysing magnet was measured for positive ions with the oven at room temperature. The small collimator openings and the much greater diameter of the exchange canal assure that the beam passes through the alkali target and enters the second Faraday cup without striking the exchange canal. It is therefore safely assumed that the transmission is constant during a measurement with constant energy, except when very high target densities cause considerable multiple scattering. It is further assumed that the transmission for negative ions is equal to that for positive ions. Generally 70 to 100% transmission was obtained depending on the energy of the incident ions, however for some measurements at very low energies the transmission was as low as 50%. The charge components were calculated using the relation

$$F_i = \frac{I_i}{I_{inc}\, T} \quad \text{where } i = 1, -1 \,.$$

The intensity of the neutral component F_0 is then given by the expression

$$F_0 = 1 - (F_1 + F_{-1}) \,.$$

The measurements have been carried out carefully for a fixed energy, the temperature having been increased until an equilibrium state of the charge components $F_{i\infty}$ was reached. A typical example of such a measurement is shown in Figure 2 for a proton energy of 7.08 keV and a potassium target. A correction was applied to the F_{-1} component for the fraction of the negative ions formed by collision with the residual gas following the first analyzing magnet. The value of this correction was measured with the alkali oven at room temperature and was only a small fraction of F_{-1} at higher temperatures. The pattern of the curve F_{-1} in Figure 2 shows that the maximum value $F_{-1\,max}$ is not identical with the equilibrium value $F_{-1\infty}$. At higher energies this maximum disappears and all three beam components approach charge equilibrium monotonically. At the lowest energies measured in this experiment, the negative ion yield passes through a maximum and then decreases with increasing

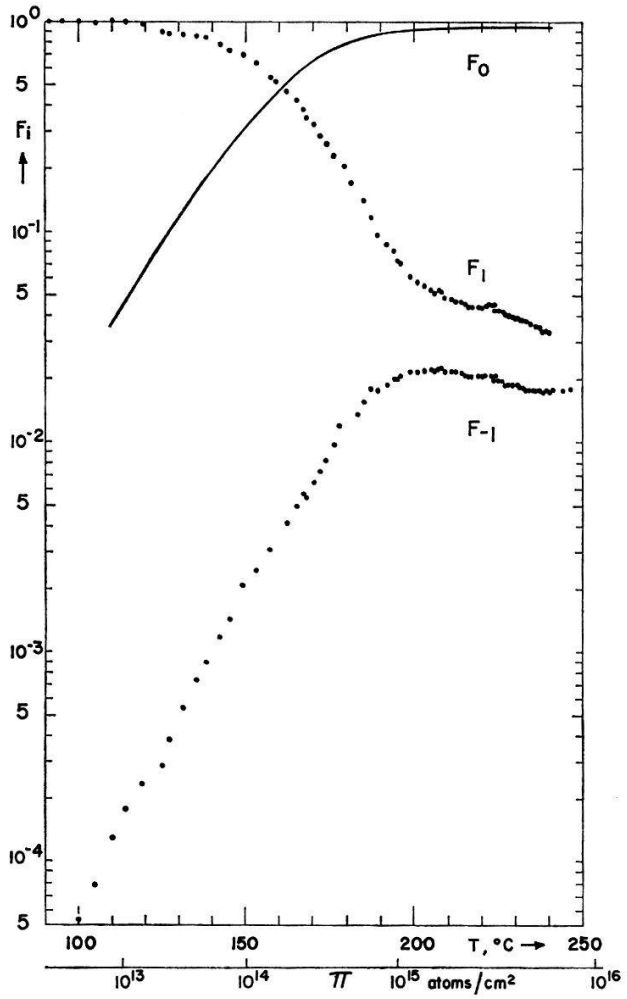

Figure 2
Variation of the charge components F_i as a function of the oven temperature for a proton energy of 7.08 keV.

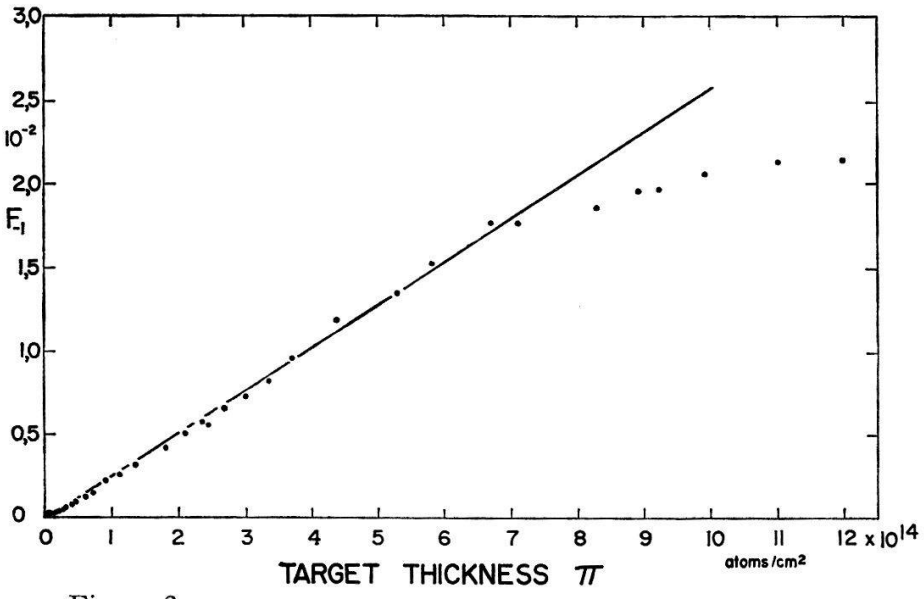

Figure 3
The charge component F_{-1} as a function of the potassium target thickness π for a thin K-target. The incident proton beam energy is 7.08 keV. The straight line indicates the linear portion of the data.

vapour density. This pattern is caused by multiple scattering. The determination of the equilibrium value from such data is more difficult, since the attenuation of the beam due to multiple scattering is unknown. For such cases, measurement of the neutral beam component would be very helpful.

The one- and two-electron charge exchange cross sections σ_{10} and σ_{1-1} can easily be determined from a representation in which F_0 and F_{-1} are plotted in function of the target thickness π. The cross section is then given by the slope of the linear portion of the curve i.e. the part where the charge exchange is a one-step process, an example of which is shown in Figure 3 for potassium at 7.08 keV.

IV. Results

The charge equilibrium components have been measured with beams of protons and deuterons in the energy range between 1 and 20 keV for the alkali vapours

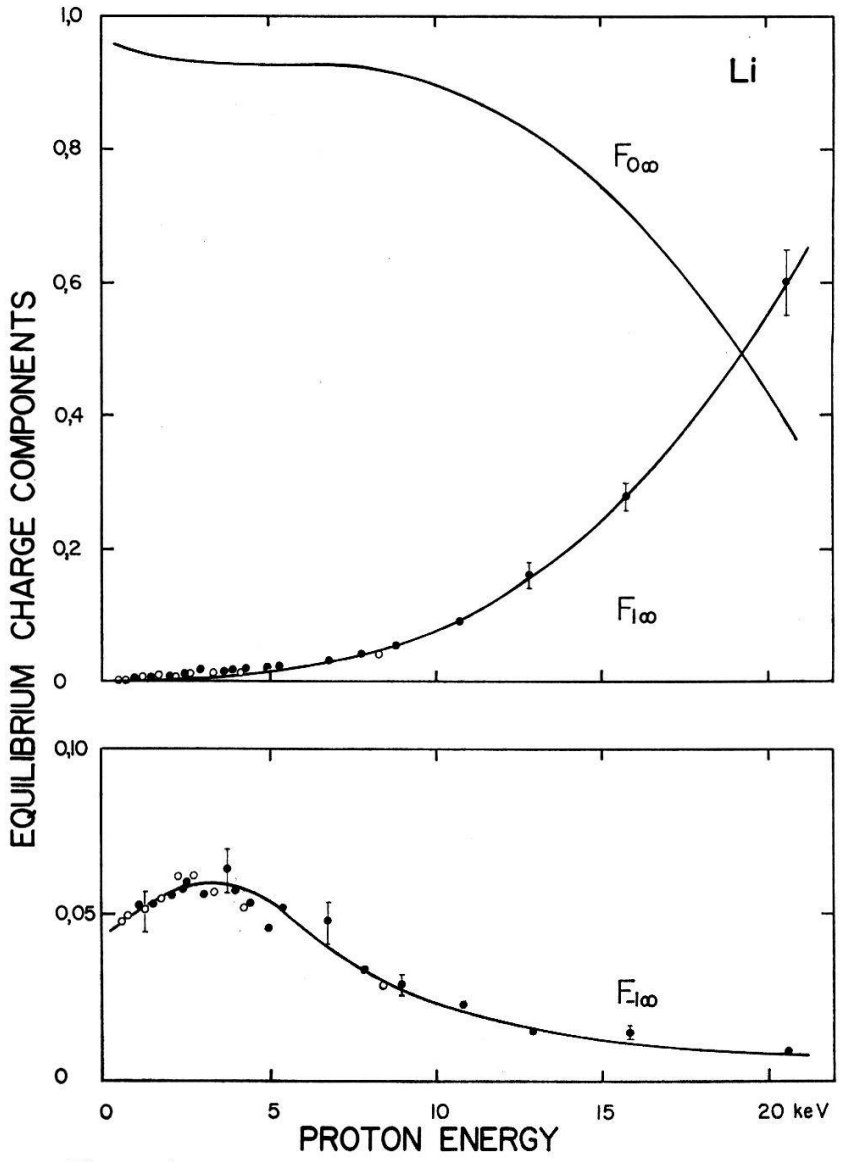

Figure 4

Equilibrium yields $F_{1\infty}$, $F_{0\infty}$ and $F_{-1\infty}$ for Li as a function of the incident beam energy. Closed dots represent data with H^+ as the incident beam, open dots represent data with D^+ as the incident beam plotted at half their energy.

lithium, sodium, potassium and cesium. They were determined from data similar to that shown in Figure 2. The cross sections for the one- and two-electron charge exchange were also determined. The results are given in Figures 4 to 11. The closed dots represent measurements with protons, the open dots measurements with deuterons plotted at half their energy. In the figures showing the charge components, representative error bars have been indicated in order to show the course of the uncertainty as a function of the incident ion energies. Because of the logarithmic scale in the cross section, each data point is shown with its estimated error bar. For the sake of clarity a curve is drawn through the corresponding data points. Generally, the positive charge component is small at lower energies and increases with increasing energy. The negative component is larger at lower energies, has a maximum value at an energy depending on the particular alkali vapour and later decreases monotonically at higher energies. The neutral component, being the predominate fraction at low

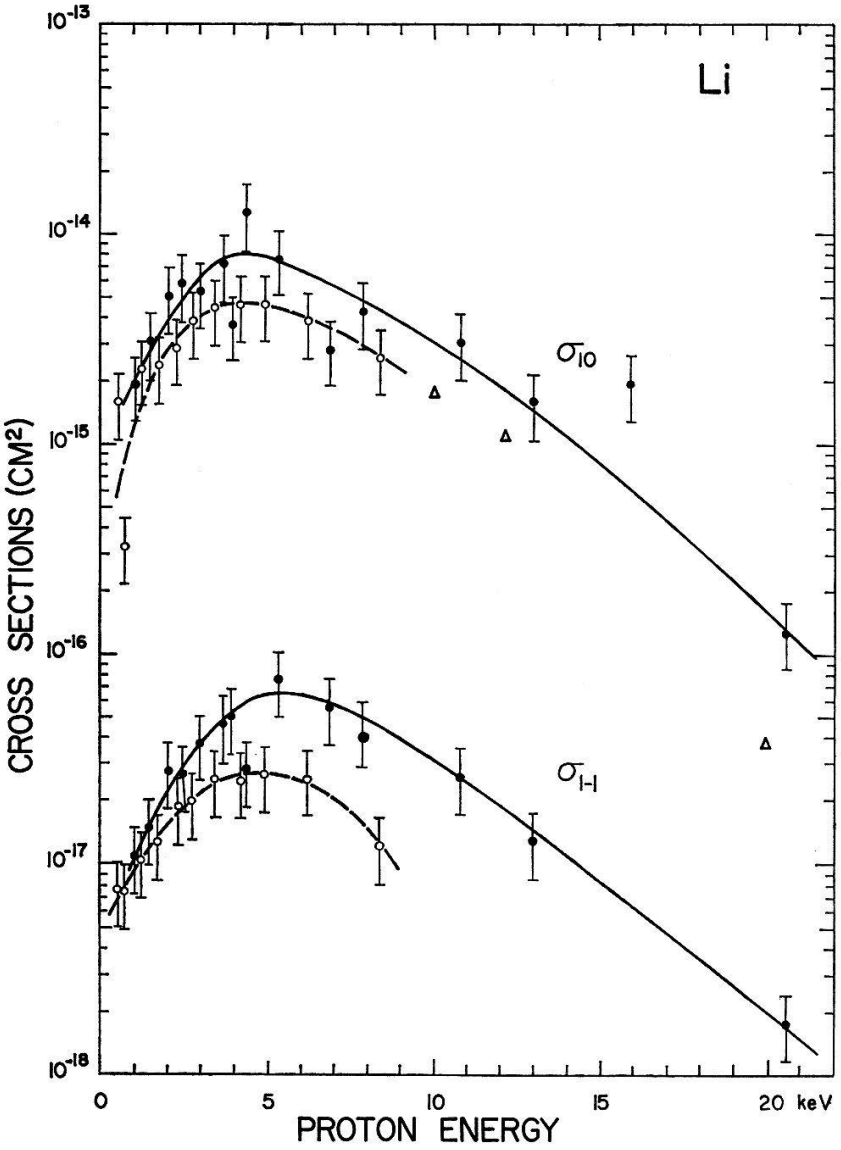

Figure 5

Cross sections σ_{10} and σ_{1-1} for Li as a function of the incident beam energy. Closed dots represent data with H^+ as the incident beam, open dots data with D^+ as the incident beam, plotted at half their energy, triangles indicate data from Ref. 6. Solid curves are drawn through the corresponding proton data and dashed curves through the corresponding deuteron data.

energy, decreases with increasing energy. The cross sections all show the same pattern; at low energies there is a more or less well-marked maximum which decreases rapidly at higher energies. The triangles indicate measurements of the cross sections σ_{10} of Ref. [6].

A. *Lithium*

The measurements with lithium vapour proved to be the most difficult of all the alkali vapours measured so far, since the temperature in the oven had to be raised to 600 °C in order to attain equilibrium. At this temperature outgasing decreases the qua-

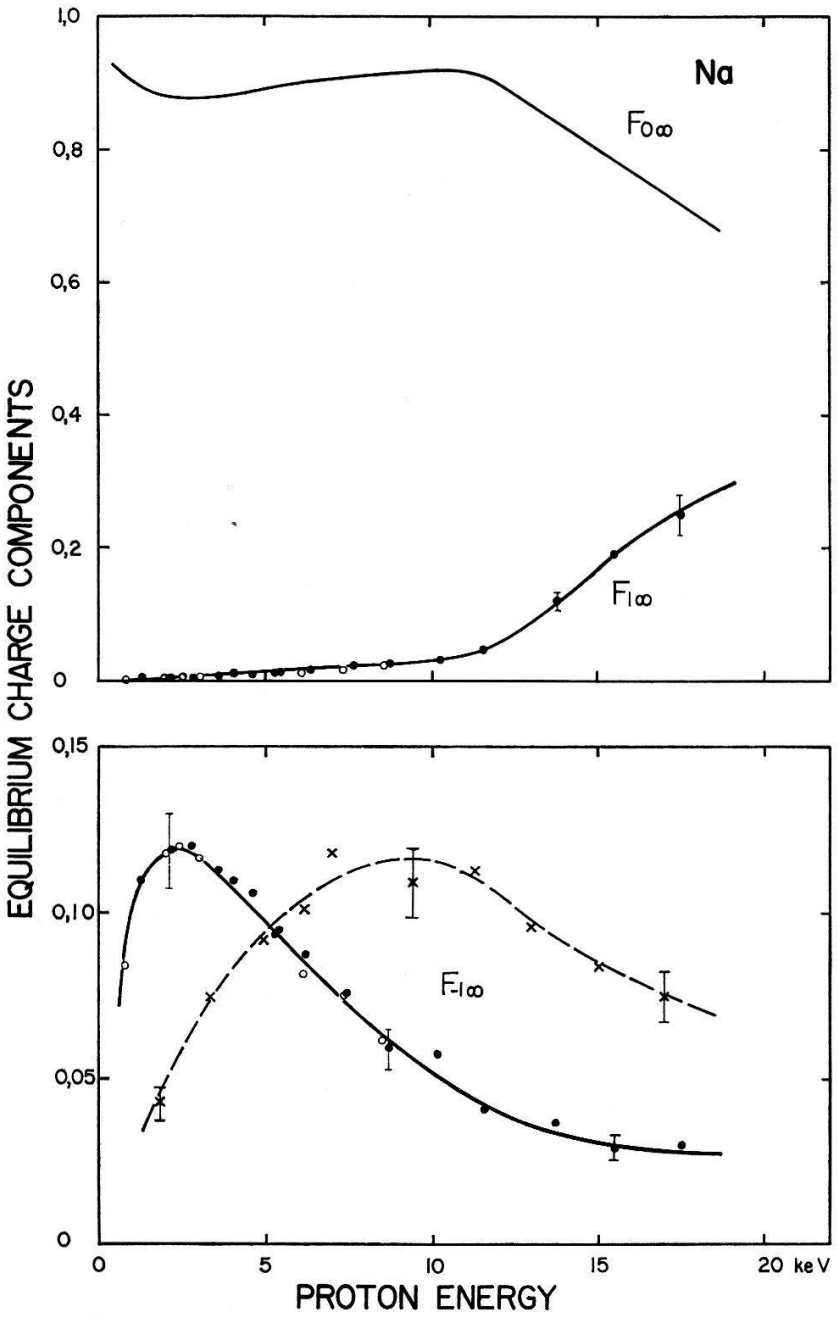

Figure 6

Equilibrium yields $F_{1\infty}$, $F_{0\infty}$ and $F_{-1\infty}$ for Na as a function of the incident beam energy. Closed dots represent data with H^+ as the incident beam, open dots represent data with D^+ as the incident beam plotted at half their energy, crosses represent the maximum yield of H^- ions when H_2^+ ions are incident on the sodium target.

lity of the vacuum and causes charge exchange of the beam in the collimator preceding the lithium target. Hence, the uncertainty in the charge components as well as in the cross sections is larger than that for the other alkali vapours. The equilibrium charge components are shown in Figure 4 and the cross sections in Figure 5. The negative charge component $F_{-1\infty}$ has a broad maximum at about 4 keV, its value, however, does not exceed 6%. The measurement of σ_{10} by Il'in [6] shown by triangles is in satisfactory agreement with our measurements. In Figure 5 solid curves through the proton data and dashed curves through the deuteron data are drawn by hand. Although the position of the maxima is the same for corresponding curves, the values of the maxima seem to be slightly different.

B. *Sodium*

The equilibrium fractional yields are shown in Figure 6 and the cross sections in Figure 7. The negative component rapidly attains a maximum value of about 12% at 2.5 keV and decreases then slowly at higher energies. This feature is very interesting especially when sodium is used to produce negative ion beams. The neutral component is nearly constant over a large energy range and decreases only slowly at higher energy. Figure 6 also shows the yield of H^- ions when H_2^+ ions are incident on the sodium target. This process is interesting in connection with a polarized ion source,

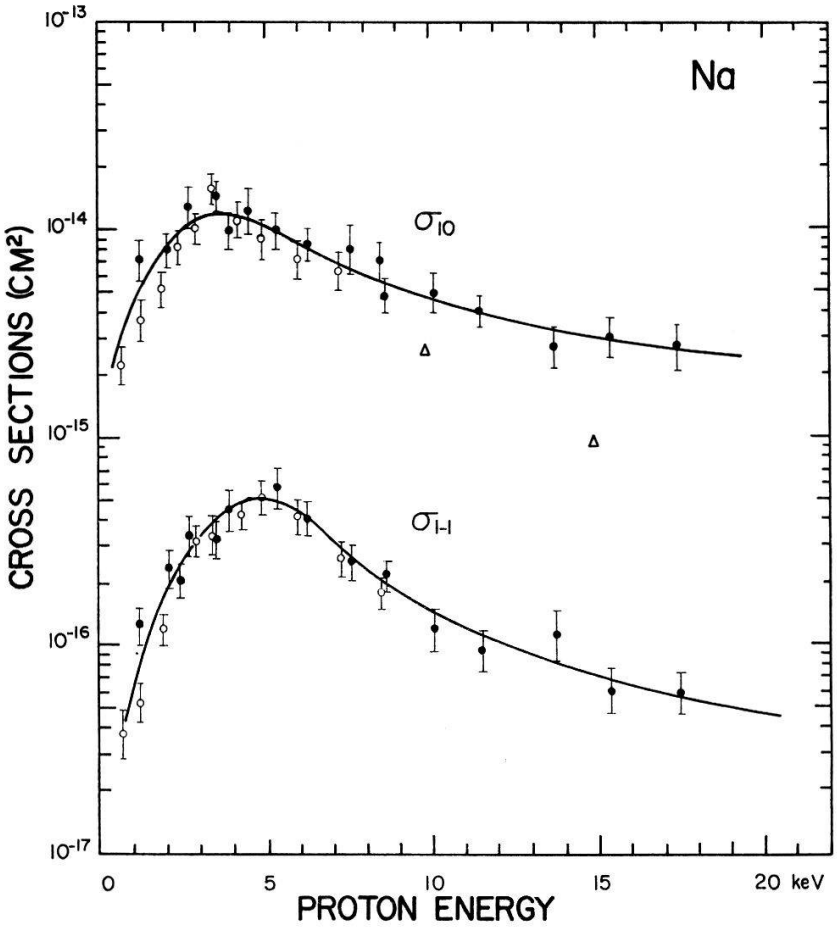

Figure 7

Cross sections σ_{10} and σ_{1-1} for Na as a function of the incident beam energy. Closed dots represent data with H^+ as the incident beam, open dots data with D^+ as the incident beam, plotted at half their energy, triangles indicate data from Ref. 6.

since it creates unwanted unpolarized negative ions. The measured data are indicated by crosses and a dashed curve is drawn through them for the sake of clarity. The curve has a broad maximum at about 10 keV of approximately the same value as the negative ions produced from protons and deuterons. The fact that the maximum is shifted towards higher energy is very helpful in the design of polarized ion sources. The cross section σ_{10} agrees satisfactorily with the data of Il'in [6] indicated by triangles.

C. *Potassium*

The equilibrium charge components are shown in Figure 8 and the cross sections in Figure 9. The data points of the $F_{1\infty}$ and $F_{0\infty}$ values lie on smooth curves, increasing

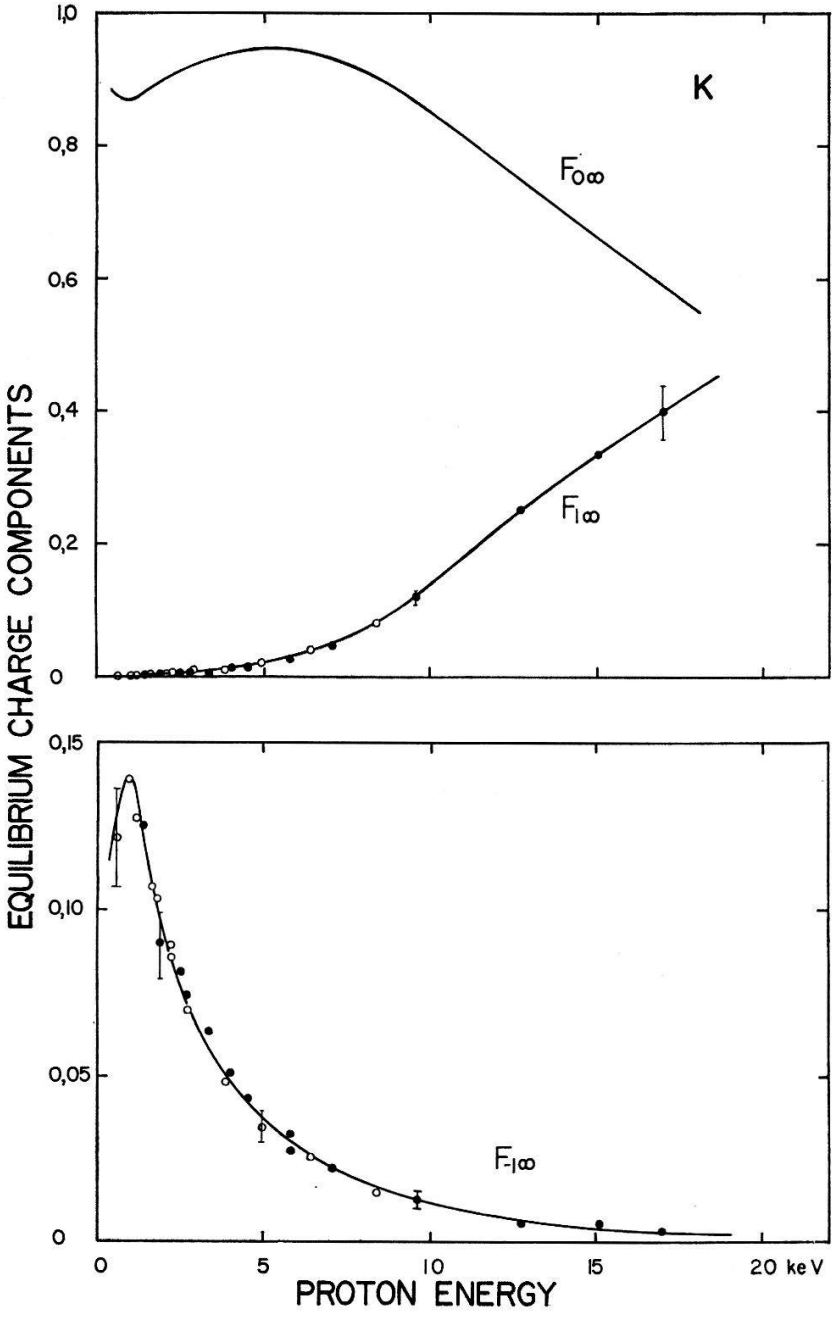

Figure 8

Equilibrium yields $F_{1\infty}$ and $F_{0\infty}$ and $F_{-1\infty}$ for K as a function of the incident beam energy. Closed dots represent data with H^+ as the incident beam, open dots represent data with D^+ as the incident beam plotted at half their energy.

or decreasing at higher energy. The $F_{-1\infty}$ component shows a sharp maximum value of 14% at about 1 keV, falling off rapidly at higher and lower energies, reaching a value of only a fraction of a percent at 15 keV.

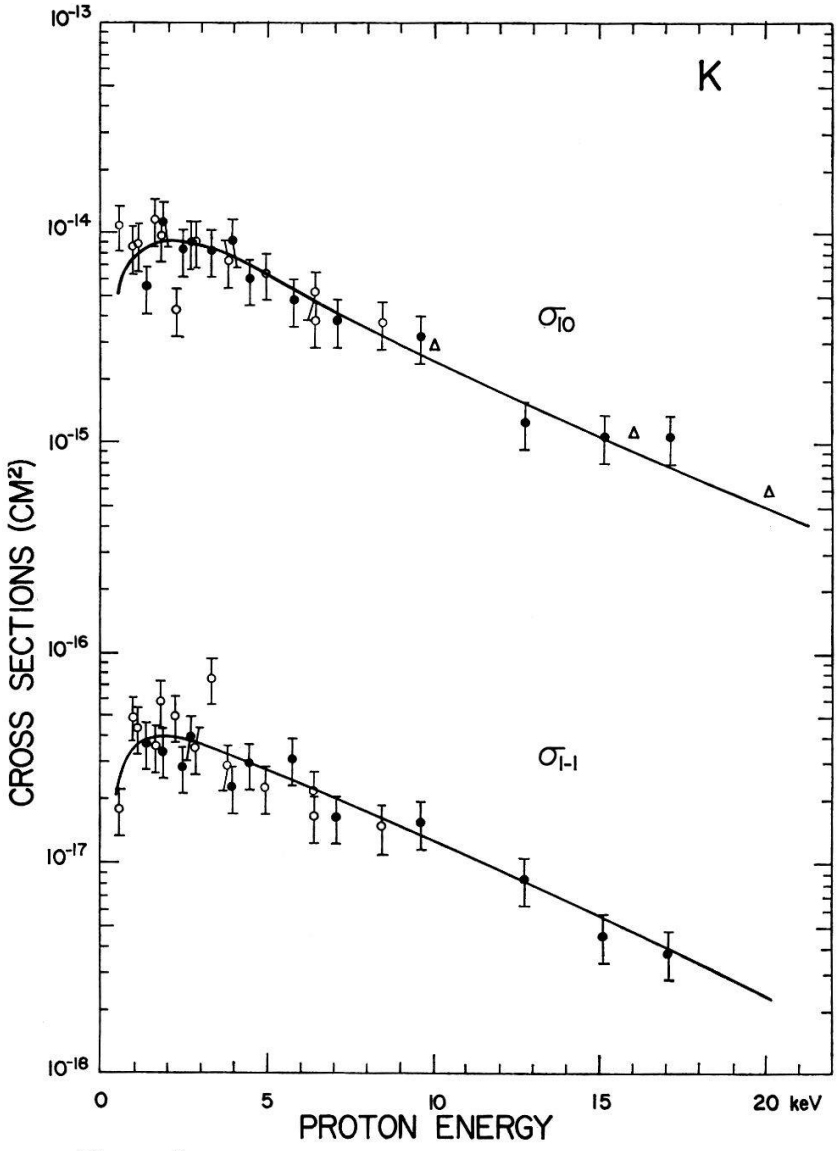

Figure 9

Cross sections σ_{10} and σ_{1-1} for K as a function of the incident beam energy. Closed dots represent data with H^+ as the incident beam, open dots data with D^+ as the incident beam plotted at half their energy, triangles indicate data from Ref. 6.

The earlier measurement of Schmelzbach et al. [9] has been repeated whereby the present results of the charge components show deviations at energies larger than 5 keV. The cross sections of the earlier measurements differ by a considerable amount from the new results. The reason for this difference lies in the improved experimental arrangement especially that of the oven and the temperature measurement; therefore the older measurements should be disregarded. Measurement of σ_{10} by Il'in [6] indicated by triangles agree well with the present data.

D. *Cesium*

Figure 10 shows the equilibrium charge fractions and Figure 11 the cross sections for cesium. The results have the same pattern as those of K. The slope of $F_{-1\infty}$ is even higher than for potassium. Schlachter et al. [13] report a maximum $F_{-1\infty}$ value of 0.21 ± 0.04 at 0.75 keV which is compatible with the present results. The results of Ref. [13] in the energy range measured in the present work are indicated in Figure 10 and 11 by crosses. As can be seen, their results of the charge components are consistent with the present ones except for $F_{1\infty}$ and $F_{0\infty}$ at the highest energy. Since Schlachter et al. have not only directly measured F_1 and F_{-1} but also the neutral component F_0 and their results agree well at most energies, one may regard all the present results

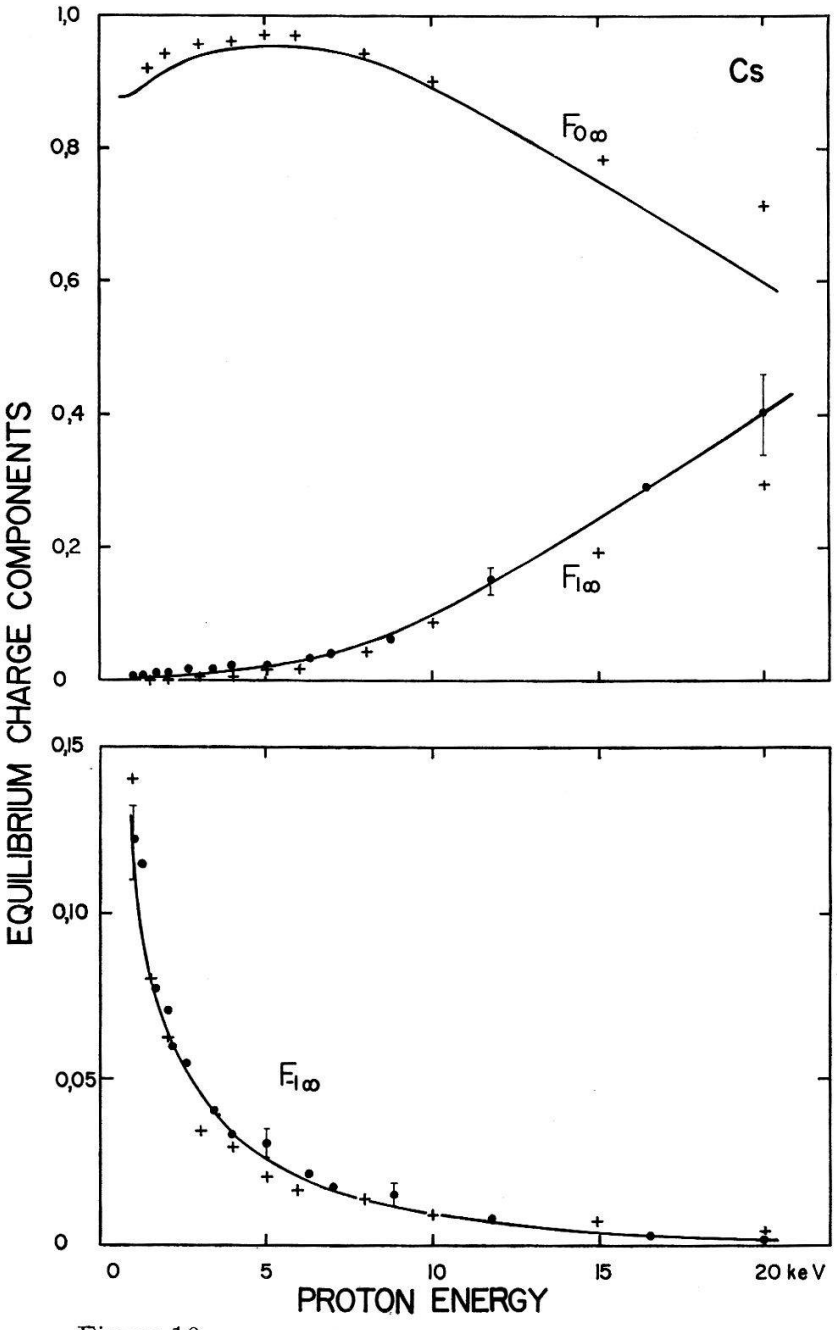

Figure 10
Equilibrium yields $F_{1\infty}$, $F_{0\infty}$ and $F_{-1\infty}$ for Cs as a function of the incident proton energy. Closed dots represent data of the present measurement, crosses data of Ref. 13.

with confidence. It seems that multiple scattering is a problem only at energies higher than approximately 15 keV.

The cross section also agrees satisfactorily up to about 5 keV. At higher energies our results have systematically lower values. The disagreement is particularly marked for the two-electron charge exchange cross section σ_{1-1}. On the other hand, the cross section of Ref. [13] also has a considerably smaller value than the measurement of Il'in et al. [6]. This disagreement may be due to the difficulties encountered in the determination of the absolute target thickness. Cross section measurements have been reported for $H^+ + Cs \rightarrow H(2s) + Cs^+$ in Ref. [19] and [20]. Sellin et al. [20] assumed that electron pickup into the $n = 2$ states dominates at a proton energy of 10 keV and further assumed that 1/4 of the atoms produced in the $n = 2$ state were in the 2 s state. Their measured cross sections $\sigma_{10}(2s)$ are larger by a factor of two than the total cross section σ_{10} presented in Figure 11, however, their measurement follows the slope of our data over the whole energy range. Also, the data of Donnally et al. [19] are in good agreement taking into account a factor 1/4 for the 2 s state atoms.

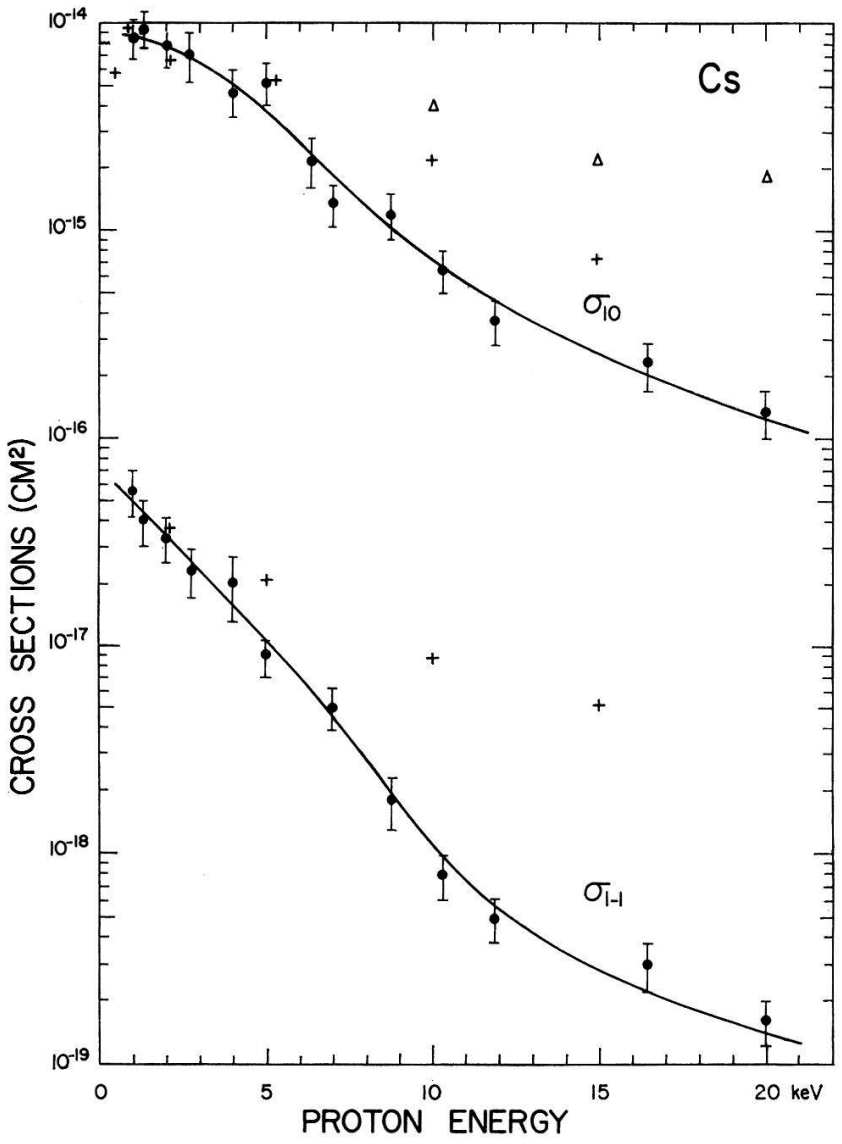

Figure 11

The cross sections σ_{10} and σ_{1-1} for Cs as a function of the incident proton energy. Closed dots represent the present measurement, the crosses results of Ref. 13 and the triangles data of Ref. 6.

V. Errors

The primary beam contains H^0 and H^- particles produced by collision with the edges of the defining apertures and the residual gas molecules.

The fraction of the H^- present in the primary beam was measured with the alkali oven at room temperature and was found to be typically lower than 5×10^{-4}. This was considered to be a constant background and subtracted from the amount of H^- produced with an alkali vapour in the oven.

Since the cross section for the production of H^0 is generally two orders of magnitude greater than that for the production of H^-, it can roughly be estimated that the fraction of H_0 in the primary beam is approximately 5×10^{-2} or even less. These particles also undergo charge exchange reactions with the alkali vapour. However, the fraction of H^- present in the beam is so small, that the production of H^+ and H^0 in the oven can be neglected.

The systematic error arising from the presence of H^0 in the primary beam can be evaluated for the charge exchange cross sections in Cs, where all the cross sections needed for the computation are known from Ref. [13]. This contribution to the equilibrium charge yields can be neglected as well as the error for σ_{10} which was found to be smaller than 1%. However, the neutral component in the incident beam can simulate absolute cross section values σ_{1-1} which are 15 to 20% too high, depending on the energy of the primary beam. Most probably these values do not differ much for the other alkali vapours.

Another source of inaccuracy is the charge exchange between the products emerging from the oven and the residual gas molecules in the analysing system. Since the vacuum was sufficiently high and the path comparatively short, this effect can be neglected.

The primary uncertainty in the measurements of the equilibrium charge fraction yields is caused by the variation of the transmission. The transmission was measured before and after each run of a fixed energy with a cold oven. Although these measurements showed a transmission variation of only a few percent, attenuation at higher target thickness due to multiple scattering cannot be excluded. Furthermore, there is the uncertainty of a few percent from the current measurement of the charge components. Hence, a total uncertainty of about 10% was estimated for the equilibrium charge components.

Another important uncertainty in the values of the cross section arises from the uncertainty in the determination of the slope of the linear portion of the charge component data. Generally, it could be determined only to approximately 10%. In addition to this, the target thickness is not well known. For a first approximation one can assume that the vapour density is constant over the length of the exchange canal. A correction made to this assumption is 20%, which was found by calculation with a vapour density distribution over the exchange canal. The total uncertainty of the relative cross sections was estimated to be 20 to 25%. A further uncertainty in the absolute calibration of the cross sections arises from the determination of the vapour density by the temperature measurement. Vapour density values found in the literature differ considerably from author to author.

VI. Discussion

The general trend of the equilibrium yields of the three charge components is quite similar for all the alkali vapours investigated so far. The negative charge component, which is the most interesting one, shows the largest difference from element to element. Considering the measurement of Ref. [13], which gives a F_{-1} maximum of 0.21 ± 0.04 for Cs at 0.75 keV, the F_{-1} maxima shift from Cs to Li towards higher energies and decrease monotonically from approximately 0.21 to 0.06. Therefore, at first sight it seems that Cs should be the most powerful charge exchanger. However, the production of a 0.75 keV high intensity proton beam and its transport through the charge exchanger is a difficult task. The choice of Na as charge exchanger has the great advantage that the incident beam can have a much higher energy without too great a loss in the charge exchange yield. Consequently, the intensity of the primary beam is greatly increased, which in turn results in a larger negative beam intensity coupled with a superior beam quality. The charge exchange yield of Na decreases only slowly with increasing energy and suggests its use as a charge exchanger yielding reasonable results for protons up to approximately 10 keV. Sodium has been used successfully as a charge exchanger in the ETH polarized ion source for over a year.

The presence of the high maxima for all single electron cross sections at such a low energy is characteristic of a near-resonant charge exchange process, where the reaction occurs at relatively large interatomic separation. This process can be discussed in terms of the crossing-point formalism [21]. If we consider the initial and final molecular states formed during the collision, the crossing of their potential energy curves is more likely to take place at large atomic separation when the energy difference at infinite separation is small. The Stueckelberg two states theory [22] predicts a cross section of the order of πR_x^2, where R_x is the internuclear separation at the crossing point. For the reaction studied here, this distance is of the order of 6 Å, i.e. the electron transfer occurs with higher probability at a distance greater than the atomic dimension.

For a one-electron charge exchange between a hydrogen-ion and an alkali-atom, the condition for near resonance is satisfied only if the hydrogen atom is produced in an excited state. The smallest energy defect ΔE_∞ corresponds to the first excited state of the hydrogen atom ($n = 2$). The main contribution to the measured total cross section will therefore be that for the $n = 2$ state and also the measured maxima will be approximately those for the production of that state. This is specially interesting for the production of 2 *s* metastable hydrogen atoms.

In case the Massey criterion holds good, the velocity v_{max} at which the maximum of the cross section appears should be proportional to the energy defect $|\Delta E|_\infty$. Figure 12a shows that this condition is not fulfilled. The straight line is obtained by a calculation using the adiabatic parameter $a = 8$ Å. In Figure 12b the energy T_{max} of the incident particle at which the maxima occur is plotted versus the energy defect. Within the limits of the experimental errors, T_{max} appears to be proportional to the energy defect. This dependence was also observed by Oparin et al. [6] for the production of highly excited H atoms by the collision of protons with alkali and alkali-earth atoms. In our case the adiabatic criterion could be satisfied by assuming that

$$a_\infty \propto |\Delta E|_\infty^{-1/2} .$$

Theoretical justification of this dependence is given by Drukarev [23] who shows that the adiabatic parameter is no longer independent of the nature of the colliding particles.

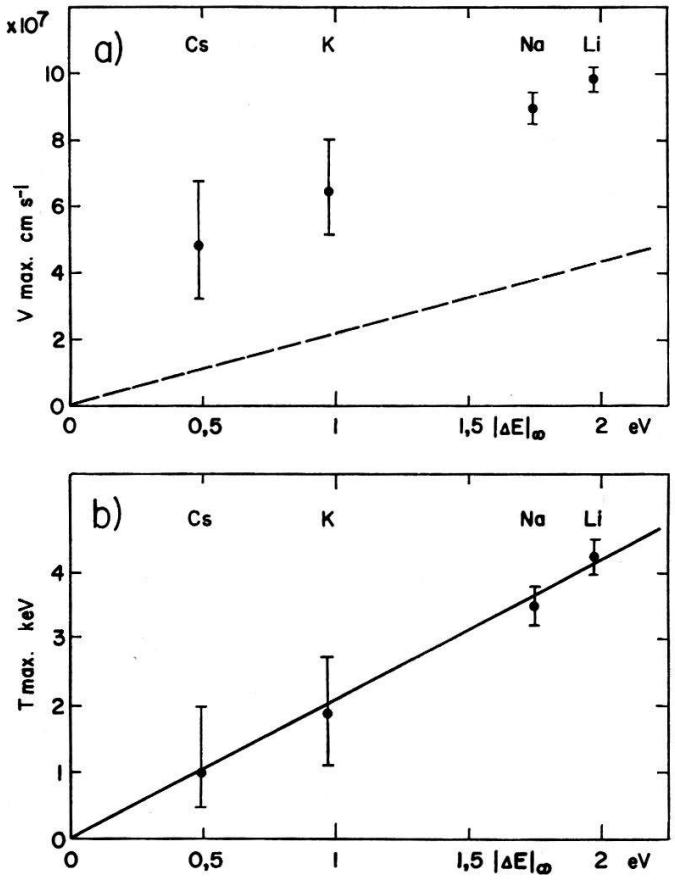

Figure 12
a) The velocity v_{max}, at which the maximum of the cross section appears as a function of the energy defect $|\Delta E|_\infty$ for Li, Na, K and Cs. The dashed line represents a calculation using an adiabatic parameter $a = 8$ Å.
b) The energy T_{max} of the incident particles at which the maxima occurs as a function of the energy defect $|\Delta E|_\infty$ for Li, Na, K and Cs. The straight line shows the proportionality between T_{max} and $|\Delta E|_\infty$.

The maxima of the double electron capture cross sections are very high and occur, for all the alkali vapours investigated so far, at low energies of the incident particle. Calculation of the adiabatic parameter according to Fogel [4] gives the values of 0.63, 1.1, 1.2, 1.8 Å for Li, Na, K, Cs, whereas inclusion of the coulomb correction of Hasted [17] yields the corresponding values of 1.4, 2.8, 12 and 21 Å. Since the polarisibilities of the alkali atoms are very high, the polarisation interaction is of importance in the calculation of the energy defect. On the other hand, the coulomb correction could probably be very inaccurate since the Hasted formula is based on the distribution of electrons of the argon atom. Nevertheless it appears that the adiabatic parameter is not independent of the nature of the colliding particles. As for σ_{10}, the maximum of σ_{1-1} shifts towards lower energy in the order Li, Na, K, Cs.

The high values of the maxima can probably be explained by the existence of a pseudo-crossing of the potential energy of the initial and final states. The coulomb interaction distorts these curves in such a manner that the energy difference at a relatively large distance becomes so small that electron exchange is highly probable.

In conclusion, one can say that the adiabatic criterion in its simple form cannot be applied satisfactorily to the charge exchange between a hydrogen ion and an alkali-metal atom. The main feature is the dependence of the adiabatic criterion on the nature of the colliding particles which seems to be due of the influence of the

weakly bound electron of the alkali-metal atom. In particular the data for Li show the difference in the cross sections when protons or deuterons are used as incident particles. However, the velocity at which the maximum occurs appears to be the same in both cases. This fact confirms the velocity dependent character of the charge exchange reactions.

For all the measured alkali metals, the results of the present work confirm Donally's multiple-step process description for the production of negative hydrogen ions in K-vapour [11], namely:

$$H^+ + A \rightarrow H(2p) + A^+ ,$$

$$H(2p) \rightarrow H(1s) + \gamma ,$$

$$H(1s) + A \rightarrow H^- + A^+ ,$$

where A represents any alkali metal.

Since the electron capture processes involved have their maxima at approximately the same projectile energy (cf. [13] for σ_{0-1}), the yield of negative ions produced in this manner is very important at this energy. In the energy region studied in this paper, the alkali metal vapours are effective targets for the production of negative hydrogen ions and 2 s metastable hydrogen atoms. In the latter case, knowledge of the ratio of 2 s metastable to ground-state atom as a function of the target thickness should be of practical interest.

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