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CHARGE-TRANSFER COLLISIONS FOR POLARIZED ION SOURCES*

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ABSTRACT

Charge-transfer processes relevant to polarized ion sources are discussed and results are summarized. The primary atom discussed is hydrogen, with particular emphasis on H\(^-\) formation. Heavier negative ions are briefly discussed.

INTRODUCTION

Many atomic charge-transfer processes must be understood and atomic data utilized in the design of polarized ion sources, discussed in other papers presented at this conference. Charge-transfer data have been summarized in articles\(^1\)-\(^5\); data on charge-transfer in metal-vapor targets have been summarized mainly in conference proceedings.\(^6\)-\(^9\) This paper contains discussion and summary of charge-transfer processes for hydrogen atoms and ions, primarily in metal-vapor targets, with an emphasis on H\(^-\) formation. Formation of metastable H(2s) for Lamb-shift polarized ion sources is also discussed, as are (briefly) formation of He\(^-\) and heavier negative ions.

Formation of negative hydrogen ions is of both basic and applied interest: for basic physics research, for injection into accelerators, and for attachment to low-energy atoms for energy analysis. Furthermore, fast H\(^-\) can be readily converted to H\(^0\) with high efficiency, with applications to heating of fusion plasmas and to weapons. There are three methods of creating H\(^-\) ions: charge transfer, (passage of H\(^+\) or H\(^0\) through a vapor or gas target), surface production (backscattering or desorption of H\(^-\) from a low work function surface by ion or atom impact), and "volume" production (direct production of H\(^-\) in a discharge). Only charge transfer will be discussed here, since all
H⁻ polarized ion sources known to the author use charge transfer for the H⁻ production. (Surface ionization has been used in positive polarized ion sources.) The discussion will concentrate on metal-vapor targets as charge-transfer media, the reason for which can be seen in Fig. 1, which shows the equilibrium yield of H⁻ for typical gaseous and metal-vapor targets; the metal-vapor targets are a factor of 10 more efficient than are gas targets in converting H⁺ or H⁰ to H⁻ at low energies (< 10 keV). There are, of course, other considerations in the selection of a charge-transfer medium, e.g., the energy of the hydrogen beam, scattering in the target, the target thickness required for charge-state equilibrium, target temperature required, and ease of pumping and of handling the target material.

Results for hydrogen and deuterium are intermixed in this paper. Hydrogen and deuterium projectiles at the same velocity have been found to have the same total cross sections and yields over the energy range considered; therefore results for D projectiles will be treated as if the experiment had been performed using H at half the energy, and vice versa. This does not hold for differential cross sections nor for partial cross sections (scattering into or outside of a given angle), for which H and D must be separately considered.

SYSTEMATICS OF CHARGE TRANSFER

This section contains a general discussion of the systematics of charge transfer; the reader is also referred to Refs. 3 and 4 and to the appendix of Ref. 10.

A beam of intensity I_\text{inc} is incident on a target of thickness \( \ell \) (Fig. 2). Target thickness \( \ell \) is the integral of the target density along the beam path:

\[
\ell = \int_0^\ell n(x)dx \equiv \ell \text{ eff}
\]

where \( n(x) \) is density, \( x \) is measured along the beam path, \( \ell \) is the total distance over which \( n(x) \) is non-zero, \( \ell \) is the average
density, and $\ell_{\text{eff}}$ is the effective target length. The beam in Fig. 2 is shown leaving the target in 3 charge states, with intensities $I_+$, $I_0$, and $I_-$. More generally, the fraction of the beam leaving the target in charge state $i$ is $F_i(\pi)$.

$$F_i(\pi) = \frac{I_i(\pi)}{\sum_j I_j(\pi)} \quad (2)$$

By definition

$$\sum_i F_i(\pi) = 1 \quad (3)$$

The equilibrium yield, $F_i^-$, is the fraction in charge state $i$ of the beam leaving the target relative to the total beam after the target, for a very thick target.

$$F_i^- = \lim_{\nu \to -\infty} F_i(\pi) \quad (4)$$

Some experimenters measure the conversion efficiency $\eta_i(\pi)$ rather than $F_i(\pi)$; $\eta_i(\pi)$ is the fraction of beam in charge state $i$ leaving the target relative to the incident beam.

$$\eta_i(\pi) = \frac{I_i(\pi)}{I_{\text{inc}}} \quad (5)$$

For a given geometry, there is some optimum value of $\pi$ such that $\eta_i(\pi)$ exhibits a maximum: $\eta_i^{\text{opt}}$. Because scattered beam can be lost from a target,

$$\sum I_i \leq I_{\text{inc}} \quad (6)$$

and

$$\lim_{\nu \to -\infty} \eta_i(\pi) = 0 \quad (7)$$

We have shown in the appendix to Ref. 10 that

$$\eta_i^{\text{opt}} \leq F_i^- \quad (8)$$

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Also, $F_1$ is independent of target geometry, while $\eta_1$ is dependent on the geometry of the target.

A schematic example showing fluxes and charge-state fractions for a typical 3-state system is shown in Figs. 3a and 3b. The equilibrium charge-state fractions are apparent in Fig. 3b, while optimum fluxes (equivalent to $\eta_1$) are evident in Fig. 3a.

There are certain (unusual) 3-state systems in which $F_1$ exhibits an optimum value (Fig. 4a). An example is the fraction $F_0$ for fast $H^-$ incident on a target; $F_0$ is optimal for some value of $\pi$, then decreases with further increase of target thickness.

Charge transfer for a 4-state system is often different, especially when one or more states is fragile, i.e., the fragile state is generated only from a particular state which disappears after several collisions, while the fragile state itself is readily destroyed in collisions subsequent to its formation (Fig. 4b). An example of a 4-state system is hydrogen including the metastable 2s state: $H^+$, $H^0(1s)$, $H^0(2s)$, and $H^-$. $H^0(2s)$ is the fragile charge state; it is created by electron capture of low-energy $H^+$ in a metal vapor, and is quenched (de-excited) in subsequent collisions. Another example is helium, in which 4 states are considered: $He^+$, $He^0(t)$, $He^0(s)$, and $He^-$, where $He^0(t)$ and $He^0(s)$ are atoms in triplet and singlet states. The $He^0(t)$ and $He^-$ are both fragile.

Two related quantities are referred to for metastable $H(2s)$: $f_{2s}$ and $F_{2s}$ or $f_m$ and $F_m$. $F_{2s}$ is the fraction of total beam leaving the target in the metastable 2s state, consistent with the definition in Eq. 2, while $f_{2s}$ is the fraction of neutral atoms in the metastable 2s state.

Cross sections, charge-state fractions, and equilibrium yields are related by a set of coupled linear first-order differential equations:

$$\frac{dF_i}{d\pi} = \Sigma F_{j \rightarrow i} - \Sigma F_{i \rightarrow j}.$$ (9)
For $n$ states there are $n(n-1)$ cross sections, e.g., 2 cross sections for 2 states, 6 for 3 states, and 12 for 4 states. Solutions to Eq. 9 can be found analytically\textsuperscript{3,4} or by numerical integration.

A particularly simple and useful result is obtained for 2 states:

$$F_i = \frac{\sigma_{ji}}{\sigma_{ji} + \sigma_{ij}}$$

and

$$F_j = \frac{\sigma_{ij}}{\sigma_{ji} + \sigma_{ij}}$$

For the case of $F_0$ and $F_\infty$, Eq. 10 becomes

$$F_\infty = \frac{\sigma_{0-}}{\sigma_{0-} + \sigma_{-0}}$$

and

$$F_0 = \frac{\sigma_{-0}}{\sigma_{0+} + \sigma_{-0}}$$

EXPERIMENTAL APPROACH

A typical experimental apparatus\textsuperscript{10} for measurement of charge transfer in an alkali-metal vapor target is shown in Fig. 5. A momentum-analyzed beam of $D^+$ (or $H^+$) is incident from the left. The target is a heat pipe, designed to recirculate alkali metal to minimize loss out the ends of the target. Use of a heat pipe for Cs, Rb, and Na is described in detail in Ref. 10. The beam after the collision is charge-state analyzed in a transverse electric field. The $D^+$ and $D^-$ are detected by magnetically-suppressed Faraday cups, while the $D^0$ beam is detected with a
pyroelectric detector. Detection of the D\textsuperscript{0} beam is the aspect of the experiment most subject to uncertainty in the measurement of equilibrium yields. The pyroelectric detector is linear, sensitive (\textasciitilde\text{IV/Watt}), and its response is independent of the charge state of the projectile hitting it, hence it can be calibrated with an ion beam of known intensity. The D\textsuperscript{+} beam incident on the target is modulated, and the AC voltage generated on the pyroelectric detector is measured with a lock-in amplifier. Details can be found in Refs. 10 and 12-14.

A heat pipe cannot be used for alkaline-earth vapors in the density range of interest for charge transfer, because the melting temperature of the alkaline earth is higher than the operating temperature of the target. A typical design of a target\textsuperscript{12} used for alkaline-earth vapors is shown in Fig. 6. An iron oven is heated by quartz lamps to obtain the temperature required, typically 400-800\textdegree C.

Data for 1-keV D\textsuperscript{+} incident on cesium vapor\textsuperscript{10} and for 3-keV D\textsuperscript{+} on barium vapor\textsuperscript{12} are shown as a function of target thickness or number density in Figs. 7 and 8. Charge-state equilibrium is apparent in both cases. Also shown in each figure is total beam transmitted through the target. It should be noted that the angle defined by the exit aperture of the alkaline-earth target was about half that of the alkali-metal target, so transmitted beam cannot easily be compared. Figure 7 also shows\textsuperscript{15} the fraction F\textsubscript{2s}, i.e., the metastable-atom fraction of the beam (as well as F\textsubscript{0}, the total neutral fraction of the beam), showing that H(2s) play no role in production of H\textsuperscript{-} in a thick cesium-vapor target.

A major difficulty in measuring equilibrium yields is measurement of the flux of atoms, as discussed above. Minor difficulties include insufficient target thickness, unequal collection efficiency for scattered beams, and assorted problems related to the metal vapor. Cross-section measurements are generally more difficult; the major problems are (1) measurement of the atom flux, (2) incomplete collection and detection of scattered beams, and
(3) measurement of target thickness (usually measurement of the mean target density and effective path length). An additional difficulty in the measurement of H(2s) or H(2p) formation is the detection and collection efficiency of the Lyman-alpha detector. Measurement of 2-electron-transfer cross sections is complicated by the background single-step process (beam contamination) and the competition of two single-step processes.

RESULTS: ALKALI TARGETS

A selection of cross-section and thick-target results for H atoms in alkali-metal vapor targets is presented here. The emphasis is on new and/or otherwise interesting results; more complete results can be found in Refs. 6-10, 12, 16, and the references therein.

The cross sections \( \sigma_{+0} \), \( \sigma_{+-} \), and \( \sigma_{-+} \) for D and H in cesium vapor are shown\(^6\) in Fig. 9. Calculated cross sections \( \sigma_{+0} \) by Kimura et al.\(^{17}\) in cesium and in sodium are shown in Figs. 10 and 11. Figures 10 and 11 show calculations of electron capture from both ground-state and optically excited targets; electron capture from Na\(^{+}(3p)\) is seen to be larger than from Na\(^{+}(3s)\) at low energies. Experiment and calculations for \( \sigma_{0-} \) and \( \sigma_{-0} \) are shown\(^8\),\(^{10}\) in Figs. 12 and 13. The large values of \( \sigma_{+0} \) and \( \sigma_{0-} \) for H in cesium and the small value of \( \sigma_{+-} \) shows that H\(^-\) formation is dominated by the 2-step process, and that direct formation of H\(^-\) from H\(^+\) is almost negligible. Calculated cross sections \( \sigma_{00} \) by Olson and Liu are shown in Fig. 14, showing also the contribution (dashed line) due to electron transfer rather than electron detachment.

The effect of angular scattering in various collision processes has been calculated by Olson and colleagues. Figure 15 shows\(^ {19}\) the acceptance angle needed to collect 50 percent and 90 percent of H\(^-\) produced by collision of H\(^0\) in cesium. Elastic scattering of H\(^0\) is an important process in charge transfer. Olson has calculated the percent of \( \sigma_{00} \) (elastic scattering)
outside a given angle for $H^0$ in cesium (Fig. 16) and in sodium$^7$ (Fig. 17).

Lamb-shift polarized ion sources require a beam of $H$ atoms in the metastable 2s state. Selective electron capture$^{20}$ is required to form $H^-$ from polarized $H(2s)$.

Formation of the metastable $H(2s)$ state for $H^+$ incident on alkali-metal vapors has been studied in a number of experiments,$^{15, 21-23}$ usually by de-excitation of the $H(2s)$ (quenching) in an applied electric field. The resulting Lyman-alpha radiation is polarized. Cross sections $\sigma_{m}$ and $\sigma_{r}$ (formation of the metastable 2s state and the radiative 2p state) has been measured in cesium by Pradel et al.$^{15}$ shown in Fig. 18; the metastable fraction $F_{2s}$ of the total beam for $H^+$ in cesium as a function of target thickness $\tau$ is shown$^{15}$ in Fig. 19. A summary of measurements of the fraction $f_{2s}$ of metastable $H(2s)$ relative to the neutral beam is shown in Fig. 20. We see that both $\sigma_{m}$ and $f_{2s}$ show a peak at about 500eV for $H^+$ in cesium vapor, and that $f_{2s}$ is large, of the order of 30-50 percent. Similar results by Nagata$^{23}$ are shown in Fig. 21 for other alkali vapor targets.

The equilibrium yield $F^-$ for $D^-$ and $H^-$ formation in cesium vapor is summarized$^{10}$ in Fig. 22; optimum conversion efficiency $\eta_{opt}$ in cesium is shown in Fig. 23. The yield $F^-$ in cesium vapor is seen to be large: 20-35 percent at low energies. Similar results$^{10}$ for sodium vapor are shown in Fig. 24 and 25; the yield $F^-$ is seen to be of the order of 10 percent at intermediate energies.

The equilibrium yield can be compared with cross sections using Eq. 11. This is shown for cesium vapor$^{10}$ in Fig. 26; measured $F^-$ is seen to agree with $F^-$ calculated from cross sections.

RESULTS: ALKALINE-EARTH TARGETS

Recent results for $F^-$ in alkaline-earth vapor targets are
summarized in Ref. 12, in which a maximum $F_-^*$ of 50 percent is reported for charge transfer in a thick strontium-vapor target at an energy of 250eV/amu. Results by different experimental groups are in excellent agreement for alkaline-earth vapor targets. An example is shown in Fig. 27, which shows three measurements of $F_-^*$ in strontium vapor.

Cross sections for charge transfer in alkaline-earth vapors have recently been measured; results for $\sigma_{^0+}$, $\sigma_{^+0}$, $\sigma_{0^+}$, and $\sigma_{0^-}$ are shown in Figs. 28-31, along with $\sigma_{0^-}$ deduced from $F_-^*$ measurements and Eq. 11. It is to be noted that $\sigma_{0^-}$ increases with decreasing energy in strontium vapor, while $\sigma_{-0}$ is relatively flat with energy, which is responsible for the large value of $F_-^*$ in strontium vapor at low energy.

Formation of $\text{H}(2s)$ by collisions of $\text{H}^+$ in alkaline-earth vapors has been reported. Results are shown in Figs. 32-33.

**SUMMARY: $\text{H}^-$ FORMATION**

Results for $F_-^*$ in various alkali and alkaline-earth vapors are shown in Fig. 34. Strontium vapor gives an $F_-^*$ of as large as 50 percent at an energy of 250 eV/amu. Cesium gives 35 percent at lower energies, rubidium gives a high yield at intermediate energies, and sodium gives the highest yield for energies above 2 keV/amu.

**HEAVIER NEGATIVE IONS**

Formation of $\text{He}^-$ by charge transfer in a metal vapor requires consideration of (at minimum) a 4-state system. The $\text{He}^-$ ion is a quartet state; it is created by electron capture of a helium atom in a triplet state. Both the $\text{He}^0(t)$ and $\text{He}^-$ fractions show optimum values, and are very small for thick targets. Results are shown in Figs. 35 and 36; Fig. 37 shows that the maximum $F_{\text{opt}}^*$ for $\text{He}^-$ in cesium is 1.4 percent at 6 keV.
Formation of heavier negative ions has been surveyed in sodium and magnesium vapor targets. Results are shown in Figs. 38 and 39. Yields approaching 100 percent are possible for favorable cases.

**SUMMARY**

Recent theoretical calculations and experimental results are providing a coherent understanding of $\text{H}^-$ formation by charge transfer in metal vapors, although some disagreement exists between different experimental results or between experimental and theory in a few cases. The $\text{H}^-$ yield is especially large in cesium vapor at low energies, exceeding 30 percent for energies below 400 eV/amu, and in strontium vapor, where the yield is 50 percent at 250 eV/amu. Charge transfer leading to formation of metastable $\text{H}(2s)$ and to $\text{He}^-$ and other heavier negative ions is briefly discussed. Additional considerations for application of charge transfer to polarized ion sources, e.g., angular scattering of beams, are also mentioned. The data and references in this report should be useful for the design of polarized ion sources requiring charge transfer.

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Figure Captions

1. Summary of equilibrium yield $F^-$ for H in typical metal vapors (Sr, Cs, Na) and gases (H$_2$, Xe).

2. Schematic diagram of experiment to measure charge-state fractions. A flux $I_{inc}$ is incident on a target of thickness $\tau$. Fluxes $I_+$, $I_0$, and $I_-$ in charge states $+, o$, and $-$ leave the target. 8

3. Schematic behavior of currents and charge-state fractions as a function of target thickness $\tau$ for a 3-state system $(+, o, and -)$ with the incident beam in charge-state $. Figure 3a shows currents $I_i$, indicating optimum values of the $o$ and $-$ charge states; Fig. 3b shows charge-state fractions $F_i$, indicating equilibrium values. An example is low-energy $H^+$ incident on an alkali-vapor target.

4. Schematic behavior of charge-state fractions $F_i$ as a function of target thickness $\tau$ for 2 systems having an $F_{opt}$. Figure 4a shows an unusual 3-state system, e.g., fast $H^-$ incident on a gas target; the $F_0$ fraction shows an optimum value. Figure 4b shows moderate energy He$^+$ incident on a metal-vapor target; the fractions $F_0(m)$ and $F_-$ both have an optimum value.

5. Schematic diagram of apparatus used by the LBL group 10 to measure charge-state fractions in alkali-metal vapors. A heat-pipe target is shown. A transverse electric field is used to charge-state analyze the beam after the target; Faraday cups are used to detect the $D^+$ and $D^-$ ions, and a pyroelectric detector is used to detect the $D^0$ atoms.

6. Schematic diagram of apparatus used by the LBL group 12 to measure charge-state fractions in alkaline-earth vapors. The target was heated by quartz lamps.

7. Charge-state fractions, $F_i$, as a function of cesium-target thickness, $\tau$, for 1-keV D$^+$ incident on cesium vapor. 10 Also shown are charge-state fractions including the fraction in the metastable D(2s) state measured by Pradel et al. 15 and the total beam transmitted through the target. 10

8. Charge-state fractions $F_i$ and total transmitted beam as a function of target number and line densities for 3-keV D$^+$ incident on barium vapor. 12 Line density has an uncertainty of 50 percent.

9. Cross sections for D ions and atoms in cesium vapor. 6

10. Electron-capture cross sections for H$^+$ + Cs(6s) (solid lines) and H$^+$ + Cs(6p) collisions (dashed lines), calcula-
The heavy solid and dashed lines belong to the total capture cross sections. The detailed H(2s) and H(2p) cross sections are labeled. Experimental cross sections of Nagata are given by solid circles for total electron capture and by solid triangles for H(2s) production for collisions of H^+ with ground state Na(3s).

11. Calculated electron-capture cross sections for H^+ + Na(3s) collisions (solid lines) and H^+ + Na* (3p) collisions (dashed lines) calculated by Kimura et al. Same notation as in Fig. 10.

12. Cross section \( \sigma_{0-} \) for deuterium in cesium vapor. Experimental results are shown as points, calculations as lines.

13. Cross section \( \sigma_{0-} \) for deuterium in cesium vapor. Experimental results are shown as points, calculation as lines.

14. Cross section \( \sigma_{0-} \) calculated by Olson and Liu for the electron-loss reactions H^+ + Alk \( \rightarrow \) H^0 + .. where Alk = Na, K, Rb, and Cs (solid lines). The components of the electron loss that are due to electron transfer, H^- + Alk \( \rightarrow \) H^0 + Alk^-, are given by the dashed lines. The difference between the above cross sections represents direct detachment of the H^+ + Na + e^- continuum and production of autodetaching states of H^+Na^-*.

15. Calculation of acceptance angle required to observe 50 percent or 90 percent of the negative ion formation for H^0 on cesium, calculated by Olson. The calculations on H^- production in H^0 + Cs collisions are given by solid lines while the measurements of Cisneros et al. for D^- production in D^+ Cs collisions are given by dashed lines.

16. Percent of the total elastic cross sections found outside various angles for the H^0 + Cs collision system, calculated by Olson.

17. Percent of the total elastic cross section found outside various angles for the H^0 + Na collision system, calculated by Olson.

18. Cross sections \( \sigma_{m} \) and \( \sigma_{r} \) for protons in cesium vapor, measured by Pradel et al. \( \sigma_{m} \) is the cross section for electron capture in the metastable 2s state, \( \sigma_{r} \) for electron capture in the radiative 2p states. \( \bigcirc \): incident H^+; \( \bullet \): incident D^+ (shown at equivalent H^+ velocity).

19. H(2s) fractional yield as a function of Cs target thickness \( t \) for incident H^+ energies between 0.5 and 2.5 keV, measured by Pradel et al. The H(2s) fraction shown in this figure is the fraction of outgoing beam in the 2s state relative to
the total outgoing beam; ordinate corresponds to a 10 percent fractional yield.

20. Summary of measurements of metastable atom fraction \( f_{2s} \) in neutral beam for \( H^+ \) in cesium vapor.

21. Metastable atom fraction \( f_{2s} \) in neutral beam for \( H^+ \) in alkali vapors, measured by Nagata.\(^{23}\)

22. Equilibrium yield, \( F^- \), for \( D \) in cesium vapor.\(^{10}\)

23. Optimum negative-ion conversion efficiency, \( \eta_{\text{opt}} \), for \( D \) in cesium vapor.\(^{10}\)

24. Equilibrium yield, \( F^- \), for \( D \) in sodium vapor.\(^{10}\)

25. Optimum negative-ion conversion efficiency, \( \eta_{\text{opt}} \), for \( D \) in sodium vapor.\(^{10}\)

26. Equilibrium yield, \( F^- \), for \( D \) in cesium vapor, comparing direct measurement with yield calculated from cross sections (Eq. 11).\(^{8}\)

27. Equilibrium yield, \( F^- \), for \( D \) in strontium vapor.\(^{12}\)

28. Single-electron-capture cross sections \( \sigma_{11} \) for collisions of \( H^+ \) with Mg,\(^{25}\) Ba,\(^{25}\) Sr and Ca\(^{24}\) vapor targets, measured by Mayo et al.\(^{24}\)

29. Double-electron capture cross sections \( \sigma_{11} \) for collisions of \( H^+ \) with Mg,\(^{25}\) Ba,\(^{25}\) and Sr and Ca\(^{24}\) vapor targets, measured by Mayo et al.\(^{24}\)

30. Single-electron capture, \( \sigma_{01} \) and loss, \( \sigma_{00} \), cross sections for collisions of \( H^0 \) with Sr, measured by Mayo et al.\(^{24}\)

31. Electron-detachment cross section \( \sigma_{00} \) for \( H^- \) in collisions with Ca and Sr vapor targets. \( \bullet \), Ca target; \( 0 \), Sr target, inferred from \( \sigma_{0-} \) and \( F^- \) measurements.\(^{24}\)

32. Cross section for formation of \( H(2s) \) atoms in Ar, He, Ba, and Mg targets reported by Morgan and Eriksen.\(^{25}\)

33. \( H(2s) \) metastable atom fraction of the neutral beam as a function of proton energy for Cs, Mg, and Ba targets, reported by Morgan and Eriksen.\(^{25}\)

34. Summary of equilibrium yield, \( F^- \), for \( H \) in Sr, Ca, Cs, Ba, Rb, Mg, and Na vapors.\(^{12}\)
35. Charge-state fractions for 25-keV He$^+$ in cesium vapor$^{25}$ as a function of target thickness $\tau$.

36. Computed fractions of atoms in singlet states and triplet states for 25-keV He$^+$ in cesium vapor.$^{26}$

37. Maximum yield of He$^-$ ions for He$^+$ in cesium vapor.$^{26}$

38. Measured negative equilibrium yield vs. energy for various projectiles in sodium vapor (electron affinities in eV given in brackets) reported by Heinemeir and Hvelplund.$^{27}$

39. Measured negative equilibrium yield vs. energy for various projectiles in magnesium vapor (electron affinities in eV given in brackets) reported by Heinemeier and Hvelplund.$^{27}$
FIGURE 1

Energy (keV/amu)

F_\alpha^0 (%)

Sr
Cs
Na
Xe
H_2
FIGURE 2
FIGURE 3B
FIGURE 4A

Log $\pi$

$F_-(\pi)$

$F_0(\pi)$

$F_+(\pi)$

$F_{0B}$

$F_{0B}$

Log $F_i$

XBL 836-10264
FIGURE 4B
FIGURE 5

Neutralizer

Valve

Deflection plates

Target

Cool

Hot Cool

Aperture

Analyzer

Faraday cup ($D^+$)

Pyroelectric detector ($D^0$)

Faraday cup ($D^-$)

10 cm

XBL 78II-12779A
FIGURE 7

Transmitted beam (%) vs. Cesium target thickness (cm\(^2\)).
Approximate target thickness (cm$^{-2}$)

Transmitted beam ($\%$)

$3$ keV D$^+$ in barium

Number density ($10^{14}$ cm$^{-3}$)

$F_0$

$F_+$

$F_-$

$1 \times 10^{16}$

$2 \times 10^{16}$

FIGURE 8
FIGURE 9
FIGURE 10
FIGURE 11

CROSS SECTION (cm$^2$)

$E$ (keV)

NaH$^+$

H(2p)

H(2s)

XBL 836-10149

FIGURE 11
FIGURE 12
FIGURE 13

Cesium

\[ \sigma_0 \text{ (cm}^2) \]

\[ D \text{ energy (keV)} \]

XBL 806 - 11898

FIGURE 13
FIGURE 16
Figure 18

CROSS SECTION ($10^{-15}$ cm$^2$) vs. ENERGY (keV)

- $\sigma_+r$
- $\sigma_+m$
FIGURE 20

Energy (keV/amu)

$\text{Cesium}$

$\text{N}_{79}^a$, $\text{TGS}$, $\text{PRSSV}$

$\text{VBC}$, $\text{BVC}$
PROTON ENERGY (keV)

$\phi_{2s}(E)$

FIGURE 21
FIGURE 24

- Sodium
- SSS
- AHA
- N

F (%) vs. D energy (keV)

XBL 803 - 478A
FIGURE 26

- OL (cross sections)
- Cesium
- M (measured)
- M (cross sections)
- SSS (cross sections)
- SSS (measured)

Energy (keV)

D energy (keV)
This work

MSMK

BLPSS

FIGURE 27
FIGURE 26
FIGURE 30

CROSS SECTION (cm$^2$/atom)

H$^+$ ENERGY (keV)

$\sigma_{01}$

$\sigma_{0-1}$

H$^+$ + Sr

XBL 836-10168

FIGURE 30
FIGURE 31
FIGURE 32

CROSS SECTION, $\sigma_{\text{m}}$ (cm$^2$/atom) vs. PROTON ENERGY (keV)

$\text{Ar}$

$\text{He}$

$\text{Ba}$

$\text{Mg}$
FIGURE 35

He⁺ ENERGY 25 keV

FRACTIONAL YIELD

CESIUM \( \tau \) (10^{18} \text{atoms/cm}^2)

\( F_0 \)

\( F_- \) (x 200)

\( F_+ \)
He⁺ ENERGY 25 keV

FRACTIONAL YIELD

GESIUM $\pi \times 10^{16}$ atoms/cm$^2$

$F_s$

$F_{t}$

$F_t / F_0$

FIGURE 36
FIGURE 37
FIGURE 38
FIGURE 39

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