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FORMATION OF NEGATIVE IONS BY CHARGE TRANSFER: He^- to Cl^-

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ABSTRACT

Formation of energetic beams of negative ions of elements with atomic numbers 2-17 (helium to chlorine) by charge transfer in metal vapors is discussed.

INTRODUCTION

Negative ions are useful for atomic physics, for injection into accelerators, and for plasma physics. Energetic negative ions can be efficiently converted into neutral atoms, for which many uses are known or proposed relating to magnetically confined plasmas of fusion interest. Fast beams of H^0 and D^0 produced by electron detachment from H^- or D^- are presently being developed for heating of plasmas for fusion. Grisham and co-workers[1] have proposed using multi-MeV neutral beams of heavier atoms for plasma heating, made by neutralization of negative ions. The energy per atom is greater than that for H or D at the same velocity, so that less current would be needed to achieve a desired level of heating power. They also suggest that the injected beam could be used to drive current in a tokamak or for tandem-mirror-reactor end plugs.[2] Post and coworkers have discussed the use of a fast light-atom beam, e.g., multi-MeV Li^0, as a diagnostic for fast confined alpha particles resulting from deuterium-tritium reactions in a magnetically contained plasma: 2-electron transfer would neutralize alpha particles, allowing them to escape from the plasma. Afrosimov[4] has discussed neutral-particle diagnostics of plasmas.

Negative ions can be formed by several methods: a) direct formation by volume processes in a discharge; b) sputtering, backscattering, or desorption from a surface; and c) charge transfer of fast positive ions in an appropriate gas or vapor target. Method b) is used for high-current H^- and D^- sources,[5] in "universal" sources of heavy ions,[6] and is often used with tandem accelerators. Method c) has been used for production of intense beams[7,8] of H^-, D^-, and He^-, as well as heavier ions, and is the subject of this review, in which results of formation of negative ions heavier than H^- or D^- by charge transfer are summarized. The Aarhus group has made many of the measurements on heavy negative ion formation.[9] Tykesson has previously presented considerable data on this subject, and much of the data presented here is from that review

or from papers by Heinemeier and Hvelplund. Binding energies of negative ions have been summarized by Hotop and Lineberger.[10]

Experimenters measure equilibrium charge-state fractions (equilibrium yields, F_i^{∞}) or optimum conversion efficiency (η_i^{opt}). The latter is dependent on the geometry of the experimental arrangement, and is a lower bound to the former.[11] Since data are sparse for formation of negative ions other than H^- and D^- by charge transfer, both are presented here. The reader is reminded that η_i^{opt} can be lower than F_-^{∞} by an unknown amount.

Several systems considered here have more than 3 states, in which case charge-state fractions as a function of target thickness can exhibit complex behavior. An example is helium,[12] for which a minimum of 4 states must be considered: He^+, $He^0(1s^2)^1S$, $He^0(1s2s)^3S$ and He^-; other states, e.g., He^0 $(1s2s)^1S$ or the P states must sometimes also be considered. The He^- fraction exhibits an optimum fraction, F_{opt}, at a target thickness less than that for equilibrium (see discussion below).

He^-, Ne^-, Ar^-

Donnally and Thoeming[13] showed in 1967 that He^- is produced from He^+ by a two-step process in cesium vapor, in which He triplet metastable atoms $(1s2s)^3S$ are produced in the first collision and He^- in the second; Jorgensen et al.[14] had previously noted the role of the metastable He atom in He^- formation. The process is

$$He^+ + Cs \longrightarrow He^0\,(1s2s)^3S + Cs^+$$

$$He^0\,(1s2s)^3S + Cs \longrightarrow He^-\,(1s2s2p)^4P + Cs^+.$$

This two-step process is necessary because He^- is a quartet state, requiring all three electron spins to be aligned. Schlachter et al.[15] made a detailed study of this process, using a 4-state model to demonstrate the role of the He^0 triplet metastable state in He^- formation. Charge-state fractions for 25-keV He^+ in cesium vapor are shown in Fig. 1a; the He^- fraction is seen to reach a maximum at a target thickness of less than 1×10^{15} cm^{-2}. Singlet and triplet metastable atom fractions are shown in Fig. 1b, which were obtained from the data in Fig. 1a by use of a 4-state-component model; the triplet metastable fraction also has a maximum at less than 1×10^{15} cm^{-2}. Helium negative ions are created by electron attachment to triplet metastable atoms.

Schlachter et al. measured an optimum He^- fraction of 1.4% for 6-keV He^+ in cesium vapor. The Belfast group studied similar systems.[16] Formation of He^- by charge transfer has been studied in metal-vapor targets other then cesium[17]; results are shown in Fig. 2. A He^- beam of 70mA at 10.5 keV has been produced by charge transfer in sodium vapor.[8]

The He^- ion is believed to have only one bound state, the $(1s2s^2p)^4P_J$ state (J = 5/2, 3/2, 1/2), with a binding energy of 0.078 eV and a lifetime of about 500μs (J = 5/2). Some experimenters have claimed the existence of a long-lived $(1s2p^2)^2p$ state of He^-; recent calculations[19] and photodetachment[20] studies do not support the existence of this state. There is no bound state of Ne^-, nor of the other rare gases (except He).

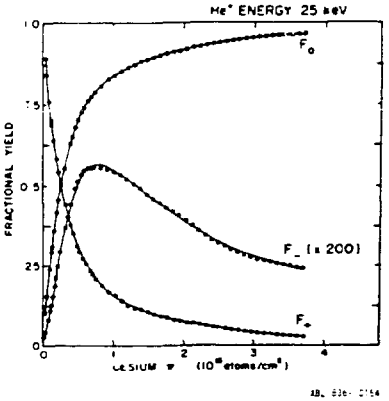

Fig. 1a Charge state fractions as a function of target thickness for 25-keV He^+ in cesium vapor.[15]

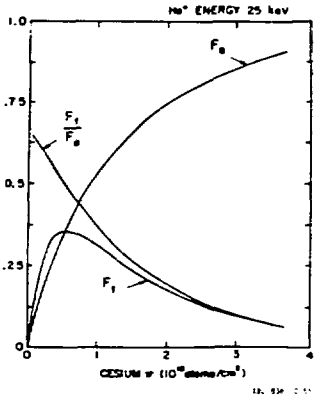

Fig. 1b Computed fractions of He atoms in singlet and metastable triplet states for 25-keV He^+ in cesium vapor.[15]

Li^-, Na^-

The Li^- ion is $(1s^22s^2)^1S$ and is bound by 0.62 eV. Equilibrium yields have been reported by the Aarhus group[9] for Na, K, and Cs vapor targets; conversion efficiencies at low energies have been reported by Steffens.[21] Results are shown in Fig. 3; the conversion efficiencies (1-20 keV) clearly lie below the equilibrium yields, as would be expected. The Na^- ion is $(3s^2)^1S$, with a binding energy of 0.55 eV. The only results for formation by charge transfer are shown in Fig. 4 (Aarhus group[9]).

Be^-, Mg^-

The Be^- ground state is not bound; the Be^- ion observed is metastable, probably $(1s^2 2s 2p^2)^4P$, with a binding energy of 0.24 eV. Results for Be^- formation from the Aarhus group[9] are shown in Fig. 5. The Mg negative ion is metastable, $(3s3p)^3P$, with a binding energy of 0.32 eV. Tykesson reports a conversion efficiency of less than 10^{-6} for Na and K targets at 20 keV.

B^-, Al^-

The B^- ion is $(2s^2 2p^2)^3P$, with a binding energy of 0.28 eV. Results from the Aarhus group are shown in Fig. 6. The Al^- ion yield is shown in Fig. 7 (measurements by the Aarhus group).[9] The binding energy of the ion is 0.46 eV for the $(3p^2)^3P$ state. There is also a metastable $(3p^2)^1D$ state.

C^-, Si^-

The C^- ion is $(2s^2 2p^3)^4S$, with a binding energy of 1.27 eV; there is also a metastable $(2s^2 2p^3)^2D$ state with a 0.035 eV binding energy. Formation by charge transfer has been measured by the Aarhus group,[9, 10] by D'yachkov and Zinenko,[22] and by Nagata.[23] Conversion efficiencies (Nagata, 1-5 keV) lie below equilibrium yields (Tykesson, 3 and 4 keV to 70 keV)), for Na and Cs targets (Fig. 8). The Si^- ion ground state, $(3p^3)^4S$, has a binding energy of 1.385 eV. There are also $(3p^3)^2P$ metastable states with binding energies of 0.52 and 0.03 eV. The only reported results for formation by charge transfer are 24 conversion efficiency for 20 keV in a Na target.[9]

N^-, P^-

The negative ion of nitrogen, N^-, has been reported[24] in a discharge, but has not been observed in charge transfer.[25] No results are known for formation of P^- whose states are $(3p^4)^3P$, 0.74 eV, and $(3p^4)^1D$, ä 0 eV.

O^-, S^-

The O^- ion is $(2s^2 2p^5)^2P$ with a binding energy of 1.46 eV. Results for formation by charge transfer are shown in Fig. 9. The results of D'yachkov et al[22] (2-8 keV) lie considerably above those of Nagata[23] (1-5 keV), probably indicating a larger angular acceptance in their apparatus. The measurements of the Aarhus group[9] (15 and 20 keV to 80 keV) are equilibrium yields. Large yields of O^- can be obtained by charge transfer in heavy noble gases.[26] Formation of S^- $(3p^5)^2P$, 2.08 eV) by charge transfer has been studied by Nagata[23] (Fig. 10), who measured conversion efficiencies.

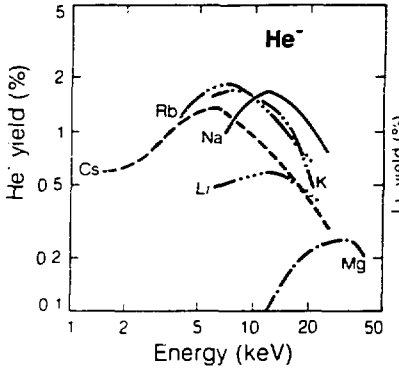

Fig. 2 Maximum yield of He^- produced by charge transfer.[15, 17]

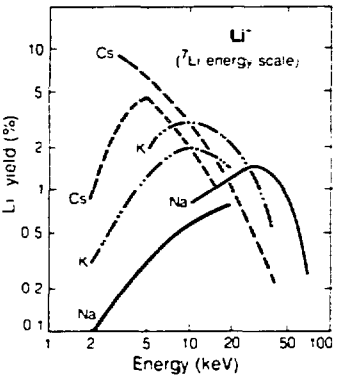

Fig. 3 Yield of Li^- by charge transfer in thick targets: equilibrium yields (3-40 keV, Cs; 5-40 keV, K; 10-70 keV, Na)[9] and conversion efficiencies (2-20 keV).[21]

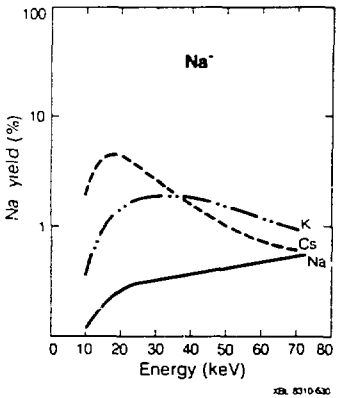

Fig. 4 Equilibrium yield of Na^- by charge transfer in thick targets (from Tykesson).[9]

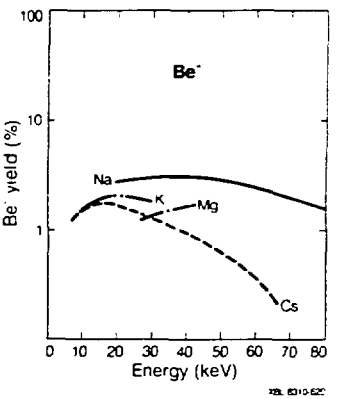

Fig. 5 Equilibrium yield of Be^- by charge transfer in thick targets (from Tykesson).[9]

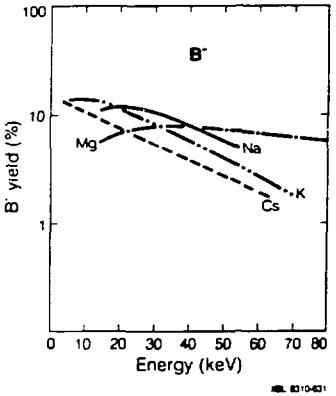

Fig. 6 Equilibrium yield of B- by charge transfer in thick targets (from Tykesson).[9]

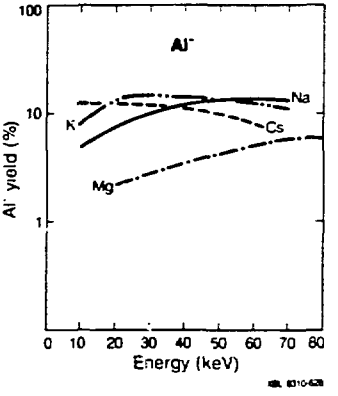

Fig. 7 Equilibrium yield of Al- by charge transfer in thick targets (from Tykesson).[9]

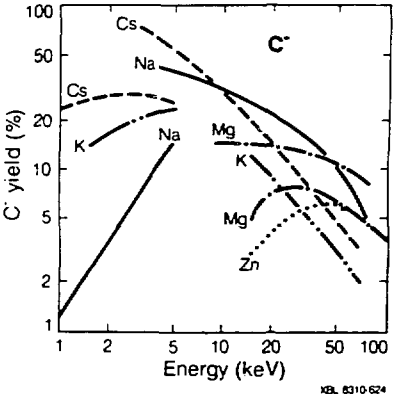

Fig. 8 Yield of C- ions by charge transfer in thick targets: equilibrium yields (3-70 keV, Cs; 4-80 keV, Na; and 9-80 keV Mg)[9] and conversion efficiencies.[22, 23]

F^-, Cl^-

There appear to be no results for formation of F^- (3.4 eV binding energy) by charge transfer. The Cl^- ion is $(3p^6)^1S$, binding energy3.6 eV. Results (Fig. 11) by the Aarhus group[9] (Mg, 15-60 keV; Na, 20-80 keV) are in considerable disagreement with the D'yachkov and Zinenko results[22] (Mg, 15-100 keV; Zn, 12.5-100 keV) for Mg, which the former speculate could be due to insufficient target thickness and scattering losses in the latter's measurements.

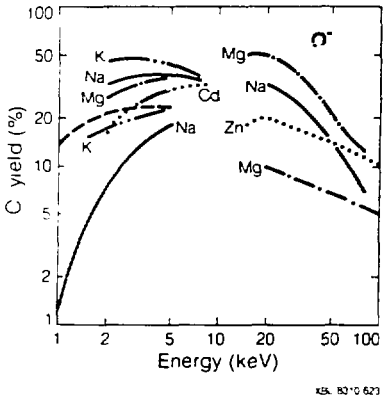

Fig. 9 Yield of O^- ions by charge transfer in thick targets: equilibrium yields (15-80 keV, Mg; 20-80 keV, Na)[9] and conversion efficiencies.[22]

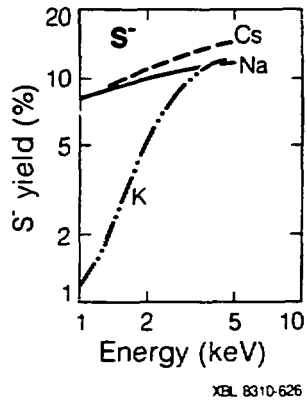

Fig. 10 Yield of S^- ions by charge transfer in thick targets.[23]

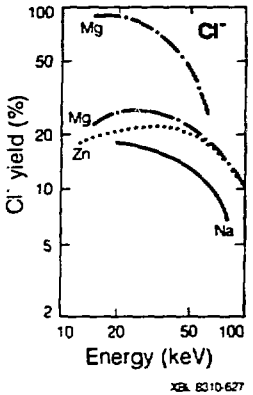

Fig. 11 Yield of Cl^- ions by charge transfer in thick targets: equilibrium yields (15-60 keV, Mg; 20-80 keV, Na)[9] and conversion efficiencies.[22]

TRENDS

Heinemeier and Hvelplund[9] comment on trends observed in their measurements on negative-ion formation for a wide variety of projectiles in magnesium-vapor and sodium-vapor targets. The most important parameter is E_a, the projectile electron affinity. They find that F_-^∞ increases with increasing E_a, and that the velocity V_{max} at which the maximum negative fraction occurs decreases with increasing E_a. For low-electron-affinity projectiles, an alkali target is generally superior to Mg, while the Mg target is particularly useful for projectiles with large electron affinity. A major consideration for accelerator applications is that V_{max} be such that the projectile energy be greater than 20 keV; beam optics are better and scattering in the target is less at this energy that at lower energies. Angular scattering and energy straggling were found to depend only weakly on the atomic number of the projectile and target, but to depend strongly on the target thickness necessary for equilibrium. Heinemeier and Hvelplund's results are summarized in Fig. 12.

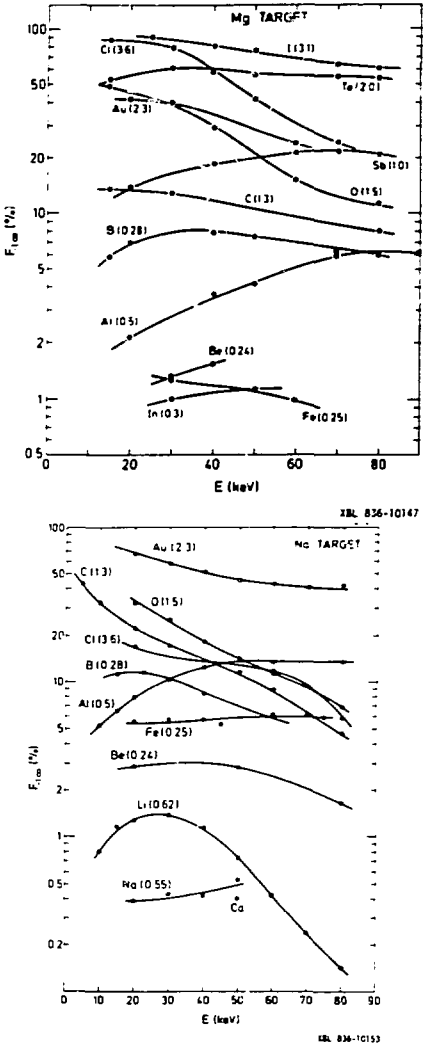

Fig. 12 Summary of the equilibrium-yield results of Heinemeir and Hvelplund (from Ref. 9), in Mg vapor (a) and Na vapor (b).

CONCLUSION

Formation by charge transfer of negative ions of species from He to Cl is reviewed in this paper. Negative ions of He, Be, and Mg are doubly excited autoionizing metastable states (Mg^- and N^- are not observed in charge transfer), and their optimal formation occurs for a target thickness less than that for equilibrium. Charge transfer is an efficient means of producing some negative ions, e.g. Cl^-, for which nearly 100% efficiency is obtained. Measurements are generally sparse; more experiments must be performed to find optimal charge-transfer media for most species.

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