INVERTED CASCADES IN ENERGETIC NEUTRAL HYDROGEN BEAMS*

John R. Hiskes
Lawrence Radiation Laboratory, University of California, Livermore, California
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Neutral hydrogen beams produced either by charge exchange or by collisional dissociation of molecular ions are formed with a population distribution covering all excited states. For hydrogen atoms in the energy range from 20 keV to 10 MeV, about one percent are in excited states above $n = 6$ after drifting approximately one meter beyond the neutralizing cell.[1-3] In a fusion experiment employing the Lorentz ionization of these excited states as the trapping mechanism, only a small fraction, of order 10^{-4} of the total neutral beam, can be effectively utilized due to the broad range of Lorentz ionization thresholds. This paper describes a process whereby the collisional excitation of the excited atoms with the plasma ions and electrons can lead to an upward cascade of the population distribution, resulting in the almost complete Lorentz ionization of these excited states.

The cross sections for collisional excitation and de-excitation of the excited states of the hydrogen atom are rapidly increasing functions of principal quantum number n, varying approximately as n^4; these cross sections are of the order of 10^{-12} cm^2 for $n = 9$ in the case of 10-eV electron collisions or 20-keV proton collisions.[4,5] Primary excitations from a particular state are to states of neighboring n value, and are those excitations which allow n and l to change in the same sense; excitations in which n changes by other than unity or in which n and l do not change in the same sense are generally less probable by almost a factor of ten or more. Scattering processes which lead to a redistribution among the various l states belonging to a particular n value may also be important. It has been suggested that such processes are sufficiently rapid to ensure a statistical distribution among the different l states.[6] Neglecting these redistribution processes, the successive excitation and de-excitation occur along distinct chains linking successive n, l states; no crossing of chains occurs; the chains are terminated at their lower end at the point of intersection with the s state. Including the redistribution processes, the successive excitations and de-excitations are given by the statistically weighted cross sections for the successive n states. The conclusions of this paper are not sensitive to either of these limiting cases.

As a model for a low-energy neutral injection system, we consider the following five-level cascade: an $n = 6$ sink; any transitions downward to this level are assumed to result in the loss of atoms participating in the cascade. The $n = 7, 8, 9$ levels are initially populated, and any excitations to the $n = 10$ level are assumed to result immediately in the Lorentz ionization of the $n = 10$ level. The time dependence of the population fractions of the 7, 8, 9 levels is determined by three coupled first-order rate equations; these equations are readily solved by elementary methods to give the time dependence for the $n = 9$ level population fraction.

In Fig. 1 is plotted the fraction excited from the $n = 9$ level into the $n = 10$ level as a function of the ion density for the case of a 20-keV neutral beam, and a plasma 5 centimeters in extent; for a plasma

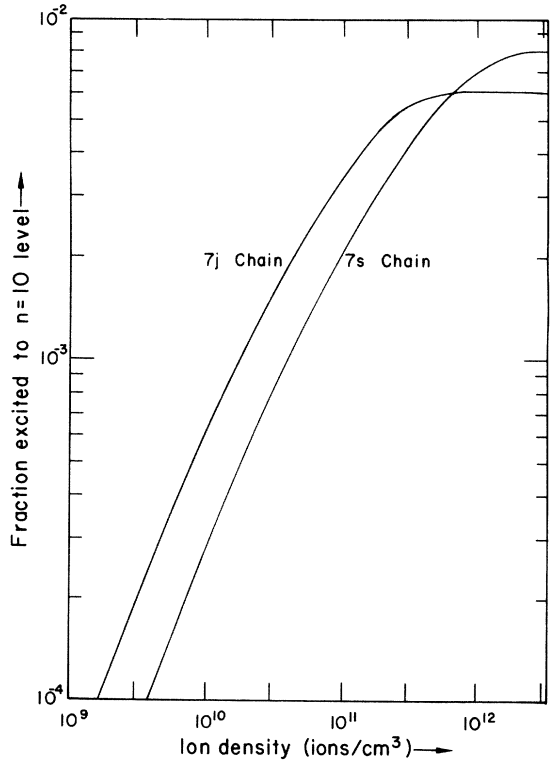

FIG. 1. Fraction of the total neutral beam excited to the $n = 10$ level for the $7s$ and $7j$ chains as a function of ion density and for a 5-cm path length.

more extensive than 5 cm, the requisite ion density is reduced proportionately. We have indicated the excitation population distributions for the $7s$ and $7j$ chains, and shall assume these distributions are representative of the entire cascade. The population distribution taking into account the redistribution processes was found to be intermediate between the $7s$ and $7j$ distributions. An initial population fraction of 8×10^{-3} for either chain was assumed to be distributed uniformly over the 7, 8, 9 levels, a value taken as representative of the population distribution for low-energy neutral beams.[3] In the limit of high densities the fraction excited into $n=10$, n_{10}, for the $7s$ chain is just the initial population of the 7, 8, 9 levels, 8×10^{-3}. For the $7j$ chain, however, the limiting value for n_{10} is 6×10^{-3}; for this chain approximately 25% of the initial distribution is lost to the $n=6$ sink. Including the redistribution processes, the limiting value for n_{10} is 6.2×10^{-3}.

It is of interest to consider to what extent the cascade influences the growth of the ion density in the case of neutral injection into a mirror machine. The rate of increase of ion density, n, as a function of time can be expressed as

$$dn/dt = a + bn + cn^2 + d + e. \qquad (1)$$

Here a is a collision term proportional to the beam current and the neutral gas density; b is a factor expressing the difference between the collision rate due to ionization on the plasma and the charge exchange loss of the ions; c is a negative factor expressing the multiple scattering loss rate out the mirrors; d is the Lorentz ionization rate of atoms initially in the $n=10$ level; and e is the Lorentz ionization rate due to the cascade. Neglecting the cascade term, the solutions to this equation can be divided into two categories, depending on whether b is greater than or less than zero. If b is greater than zero, there is an exponential growth of the ion density terminated by the cn^2 term; if b is less than zero, the ion density is terminated at a substantially lower value, given by the ratio $(a+d)/|b|$.

The cascade term, e, differs from the direct Lorentz ionization term, d, in that it is a function of the ion density. From Fig. 1 we note that for low ion densities the e term is approximately a linear function of n, allowing one to write $e \approx e'n$; combining this approximation with the b term in Eq. (1), one has a new criterion for an exponential growth of ion density, namely, $b+e'>0$. Expressed in terms of the equivalent neutral beam current (I/e), trapping and excitation length L, containment volume V, neutral background gas density n_0, ion velocity v, and ionization, excitation, and charge exchange cross sections, σ_i, σ_{9-10}, and σ_{10}, respectively, this criterion is written

$$[2(I/e)(L/V)(\sigma_i + \sigma_{9-10}n_9^0) - n_0\sigma_{10}v] > 0, \qquad (2)$$

where n_9^0 is the initial population of the $n=9$ level. It is clear from the inequality (2) and the large value of the σ_{9-10} excitation cross section that for values of $n_9^0 \approx 10^{-3}$, the cascade permits an exponential growth of the ion density for base pressures an order of magnitude higher than for exponentiation relying solely on collisional ionization ($\sigma_i \approx 10^{-16}$ cm^2). In terms of the parameters of contemporary neutral injection experiments,[7,8] the cascade allows for exponentiation for base pressures in the range 10^{-8} to 10^{-9} mm Hg, compared with required base pressures in the range 10^{-9} to 10^{-10} mm Hg in the absence of a cascade. In addition, the growth of the cascade may place less emphasis on the initial rate of Lorentz ionization (the d term) and allow for greater flexibility in the choice of magnetic field profiles.

In Fig. 2 are plotted the solutions of Eq. (1) for the $7s$ and $7j$ chains assuming a base pressure of 3×10^{-9} mm Hg and using the solutions of Fig. 1. Other parameters have been chosen appropriate to contemporary neutral injection experiments.[7,8] Also indicated in the figure is the ion density assuming no Lorentz ionization but only collisional ionization of the ground state, and a base pressure of 2×10^{-10} mm Hg. The time scale for ex-

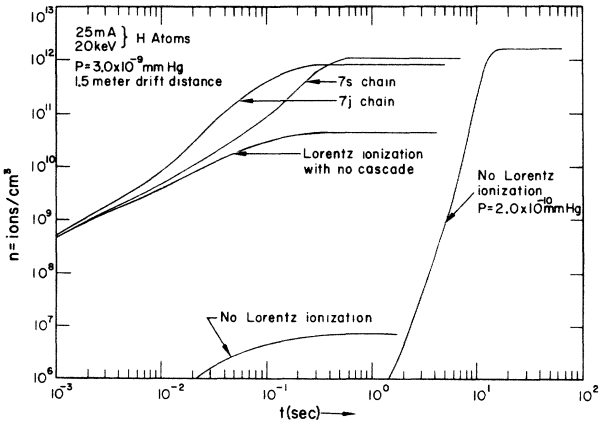

FIG. 2. Ion density versus time for a 25-mA, 20-keV hydrogen atom beam, base pressure 3.0×10^{-9} mm Hg, and a 1.5-meter drift space. Also shown is the exponential growth of the ion density in the case of collisional ionization from the ground state at a base pressure of 2.0×10^{-10} mm Hg.

ponentiation in this latter case is approximately two orders of magnitude longer than required for the exponentiation via the cascade.

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RESONANCE IN THE ELASTIC SCATTERING OF ELECTRONS IN HELIUM*

G. J. Schulz
Westinghouse Research Laboratories, Pittsburgh, Pennsylvania
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Several authors have recently discussed the possibility that the elastic cross sections of atoms by electron impact exhibit one or more sharp resonances. Baranger and Gerjuoy[1] postulate the existence of a compound state (He^-) in order to interpret experimental excitation cross sections to the $2\,^3S$ level in helium. Subsequently they have urged[2] that the elastic scattering of electrons by helium be re-examined with better energy resolution, since observation of structure in the elastic cross section would support the idea of the compound model. Recent theories[3] on the elastic scattering of electrons in atomic hydrogen show a sharp resonance below the first electronic state of hydrogen.

Thus, it seemed desirable to examine experimentally the elastic cross section in helium, using electrons with an energy spread considerably narrower than used previously. A sharp resonance is found in the scattered electrons at 72 degrees at an energy of 19.3 ± 0.1 eV, i.e., below the onset of the first excited state, $2\,^3S$ (19.8 eV).

A double electrostatic analyzer, similar to that described previously,[4] is used for the experiment. Figure 1 shows the experimental arrangement. The first electrostatic analyzer is used for production of an electron beam with a half-width of 0.06 eV.[4] The electrons are accelerated into the collision chamber where they are crossed with a beam of helium atoms. Electrons elastically scattered at an angle of 72 degrees are admitted to the second electrostatic analyzer and passed through a slit into an electron multiplier. A vibrating reed electrometer operated at +2000 V is used to measure the current. A simple servomechanism brings the output of the electrometer to ground potential, and the signal is applied to the Y axis of an X-Y recorder.

The vacuum system consists of two 300-liter/sec oil diffusion pumps with liquid nitrogen traps. One pump is used for evacuating the chamber in which the double electrostatic analyzer is located, and the other reduces the pressure still further in the chamber in which the electron multiplier is located.

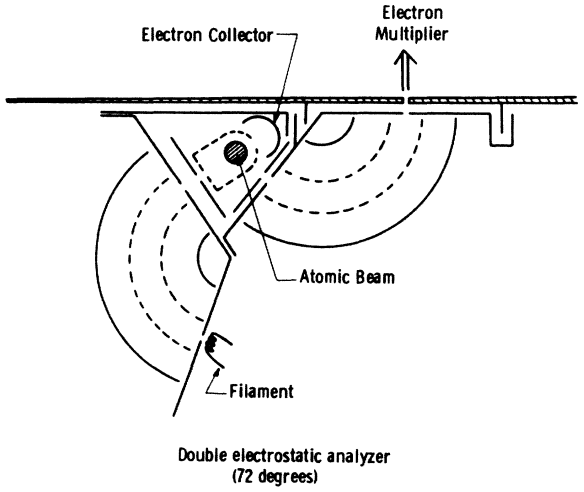

FIG. 1. Schematic diagram of double electrostatic analyzer.