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The Electron Temperature of a Partially Ionized Gas in an Electric Field

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THE ELECTRON TEMPERATURE OF A PARTIALLY IONIZED GAS IN AN ELECTRIC FIELD

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ABSTRACT

The electron temperature of a partially ionized gas in an electric field can be determined by the collision rate for momentum transfer and the collision rate for energy transfer. Mean values of these rates are defined such that a simple expression for the electron temperature is obtained, and which depends, among other things, on the ratio of these mean rates. This ratio is calculated in the Lorentz approximation for power law cross sections, and also as a function of the degree of ionization for a helium plasma. It is pointed out that the complete results of refined transport theory can be used in calculating electron mobility and electron temperature in a multicomponent plasma without undue difficulty.

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1. INTRODUCTION

In a partially ionized gas where only elastic collisions are considered the electron temperature will be given by a balance between the energy input to the electrons, due to their drift in the electric field, and the energy loss due to elastic collisions with the cooler atoms. In this balance two different average collision frequencies are involved, one for the electron mobility, and one for the electron energy lost in elastic collisions, and in this paper the relation between these two collision frequencies is examined.

In section 2 some justification of the assumption of an elevated electron temperature is made. In section 3 the energy balance is considered and results are given for a Lorentz gas, where electron-electron collisions are neglected in the calculation of the mobility. In section 4 larger fractional ionizations are considered, and, as a practical example, the dependence of the electron temperature of a helium plasma on the degree of ionization is calculated. It is shown there that the use of a "mixture rule" in combining the mobilities as computed separately for neutral atoms and ions can lead to significant corrections.

2. ELECTRON TEMPERATURE ASSUMPTION

For an electron distribution function f which is space and time independent, the Boltzmann equation for the electron component of a plasma in an electric field $\underline{E}$ can be written as [1]

$$- \frac{e}{m_e} \underline{E} \cdot \frac{\partial f}{\partial \underline{c}} = J(f) \qquad (1)$$

where $\underline{c}$ is the peculiar velocity of the electrons, e is the electron charge, m_e is the electron mass, and J(f) is the collision integral. In the Lorentz limit, where electron-electron collisions are neglected, this equation can be solved, resulting in a solution in the form $f = f_o + f_1$, where f_o is isotropic in velocity space [2]. For a sufficiently small electric field f_o is a Maxwellian distribution function at the atom temperature, while for larger fields the form of f_o depends on both $\underline{E}$ and the electron-atom cross section. In the special case of Maxwell molecules, which have a cross section inversely proportional to the velocity of approach, f_o is given by a Maxwellian distribution at an elevated electron temperature.

For other than Maxwell molecules, and with larger electric field, the first effect of taking electron-electron collisions into account will be to make f_o tend towards a Maxwellian distribution. The following argument will estimate the degree of ionization which is necessary so that the distribution function will be nearly Maxwellian. A "self collision time" for the electrons, which gives the time for both energy and momentum to be distributed among the main body of the electrons, is given by [3]

$$t_{ee} = \frac{(4\pi \varepsilon_o)^2 m_e^{1/2} (3kT_e)^{3/2}}{5.6\pi n_e e^4 \ln \Lambda} \tag{2}$$

where m_e is the electron mass, e is the electronic charge, k is Boltzmann's constant, T_e is the electron temperature, n_e is the electron density, and Λ is the ratio of the Debye length to the inpact parameter for 90° collisions, taken at a mean temperature. The relaxation time required for energy to be transferred from the electrons to the atoms in elastic collisions is approximately given by

$$t_{ea} = m_a / (2m_e n_a Q \bar{v}_e) \tag{3}$$

where m_a is the atomic mass, n_a is the atomic number density, Q is an average collision cross section, and $\bar{v}_e$ is an average electron thermal velocity. If we now require that $t_{ee} << t_{ea}$, as a reasonable condition for the existence of a Maxwellian distribution among the electrons, we find that

$$n_e/n_a >> 5.2 (4\pi \varepsilon_o)^2 m_e Q (k T_e)^2 / (\pi^{3/2} m_a e^4 \ln \Lambda) \tag{4}$$

Considering, for instance, helium atoms with $T_e = 2000\ ^oK$, Eq.(4) gives

$$n_e/n_a >> 8.6 \times 10^{-8}.$$

3. ENERGY BALANCE

Consider now a reference frame in which the atoms are at rest, f_o is a Maxwellian distribution at temperature T_e, and the atoms have a Maxwellian distribution at T_a. When Eq. (1) is multiplied by c^2 and integrated over all electron velocities, the result can be put in the form

$$-e\,\underline{E}\cdot\underline{U}_e = \nu_E\, 3/2\, k(T_e - T_a) \tag{5}$$

where $\underline{U}_e$ is the mean electron drift velocity and ν_E is the average rate (in s^{-1}) at which electron energy is lost due to collisions with atoms. The integral which determines ν_E has been derived by many authors (for example, reference 4 and the references cited in reference 5), and ν_E is given by

$$\nu_E = \frac{2^{3/2} n_a m_e^{7/2}}{3\pi^{1/2} m_a (kT_e)^{5/2}} \int_0^\infty \exp(-m_e g^2/2kT_e)\, g^5\, Q(g)\, dg \tag{6}$$

where Q(g) is the velocity dependent momentum transfer cross section and g is the electron velocity. In this formula the electron drift velocity is considered to be small compared to the electron thermal velocity and has been neglected.

From the definition of the electron mobility μ the mean electron drift velocity is given by

$$\underline{U}_e = \mu\underline{E}\,. \tag{7}$$

The electron mobility (or alternatively, the conductivity of an ionized gas) is the subject of an enormous number of papers, both theoretical and experimental. In order to put our final results into a simple form, we want to consider both the first Chapman-Enskog approximation [1] to μ, which we will denote as $\mu(1)$, as well as the "correct" value, which we will simply denote as μ, asymptotically approached by the higher approximations of the Chapman-Enskog theory. The first approximation does not take into account the "skewing" of the distribution function, and is equivalent to assuming for f a Maxwellian distribution displaced in velocity by $\underline{U}_e$ [2]. Let us define a mean collision frequency for momentum transfer ν_M by the equation

$$\mu(1) = e/(m_e \nu_M). \tag{8}$$

From the formula for $\mu(1)$, given, for instance, in reference 1, it is seen that the integral is identical to that in Eq. (6) for ν_E, and it can be shown that

$$\nu_E/\nu_M = 2\, m_e/m_a, \tag{9}$$

independent of the form of the cross section.

If the Chapman-Enskog theory for μ is carried to the infinite approximation (equivalent to the theory given in reference 6), the correct (in the Lorentz approximation) value of μ is obtained, and we will define a mean collision frequency for mobility ν_μ by

$$\mu = e/(m_e \nu_\mu). \tag{10}$$

For electron-atom cross sections which depend on electron velocity as

$$Q(g) = A g^{\alpha}, \tag{11}$$

the integrals for both $\mu(1)$ and μ can be carried out analytically, and we find for the ratio ν_μ/ν_M [7, 8] (which is just $\mu(1)/\mu$)

$$\nu_\mu/\nu_M = 9\pi/\left[16\, \Gamma(2-\alpha/2)\, \Gamma(3+\alpha/2)\right] \tag{12}$$

where $\Gamma(x)$ is the gamma function. This ratio is plotted vs α in Fig. 1. It is equal to unity for Maxwellian molecules ($\alpha = -1$), 0.850 for hard sphears ($\alpha = 0$) and is symmetric about $\alpha = -1$. Thus the effect of the higher order approximations is to decrease ν and increase the mobility. Physically, this results from the "skewing" of the distribution function, so that those electrons with smaller collision frequencies drift faster in the electric field. For the Coulomb potential ($\alpha = -4$) this effect results in a decrease of ν by the factor 0.293.

From the energy balance given by Eq. (5), with use of Eqs. (7), (8), and (10), we can now obtain an expression for the electron temperature,

$$3/2\ k\ T_e = 3/2\ k\ T_a + 1/2\ m_a\ \mu\,\mu(1)\ E^2 \tag{13}$$

$$= 3/2\ k\ T_a + 1/2\,(\nu_\mu/\nu_M)\, m_a\ U_e^2 .$$

This equation is correct as long as the electron density is large enough so that f_o is a Maxwellian distribution at T_e. It will be correct at large electron densities where the Lorentz apptoximation is not satisfied, as long as correct values of μ and (ν_μ/ν_M) are used. In this case ν_μ/ν_M will not be given by Eq. (12). In reference 9 the kinetic theory of two temperature plasmas is developed in some detail, and a more rigorous justification of Eq. (5) and the assumption of a Maxwellian for f_o, subject to Eq. (4), is given. Their energy balance equation is developed for a model which is more general, and contains more terms than Eq. (5).

It is common in calculations of the electron temperature to assume that μ and $\mu(1)$ are equal in Eq. (13), which is equivalent to assuming that ν_μ/ν_M is unity. The magnitude of the error in this approximation is given by the deviation of ν_μ/ν_M from unity, shown in Fig. 1 in the Lorentz approximation.

Eq. (13) has a particularly simple interpretation when ν_μ/ν_M is equal to unity. In this case the electron energy is just equal to the atom energy as seen from a reference frame moving at the electron drift velocity. This relation is similar to that for the stagnation temperature of a flowing gas, except in this latter case the factors 3/2 are changed to 5/2 to account for the compression work. When all the electrons have the same mean drift velocity $\underline{U}_e$ it also seems quite reasonable from an intuitive thermodynamic argument that the electron energy will be equal to the atom energy, in the reference frame where no work is being done on the electrons by the electric field.

In reference 5 Morse has derived formulas for the energy and momentum exchange between two gases, assuming displaced Maxwellians for the distribution functions. As mentioned previously, this is equivalent to the assumption that $\nu_\mu/\nu_M = 1.0$. His result for the electron temperature is the same as Eq. (13) with $\nu_\mu/\nu_M = 1.0$ *)

4. LARGE FRACTIONAL IONIZATION

The ratio ν_μ/ν_M (shown in Fig. 1) is only 0.293 for the Coulomb potential. The Lorentz approximation used in calculating ν_μ is not at all valid for a fully ionized gas, though, and the electron-electron collisions result in a reduction in the "skewing" of f_1, so that ν_μ/ν_M is closer to unity. According to Spitzer and Härm [10] ν_μ must be decreased by a factor 0.582, and we find that, for a fully ionized plasma

$$\nu_\mu/\nu_M = 0.505. \tag{14}$$

In partially ionized gases where the electron-ion collisions cannot be neglected, Eq. (13) must be generalized to a multicomponent plasma. If it is assumed that all the different atoms (and ions) have a temperature T_a we find that

$$3/2\, k\, T_e = 3/2\, k\, T_a + 1/2\, \nu_\mu \sum_s (m_s/\nu_{Ms})\, U_e^2, \tag{15}$$

where subscript s denotes the various components. In this equation it is understood that ν_μ will be calculated from the mobility μ according to Eq. (10), and that μ is the appropriate value for a multicomponent plasma. We use ν_{Ms} (simply related to ν_{Es} by Eq. (9)) instead of ν_{Es} in order to explicitly display the dependence on the atomic mass m_s.

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*) Although Morse's results are derived for the relaxation of energy and momentum differences, they are valid for a steady drift velocity maintained by an electric field, under the assumption of a displaced Maxwellian distribution function. Although he has no energy input term on the left hand side of the Boltzmann equation, when taking the electron energy moment he has taken a reference frame in which the electrons are at rest for evaluation of the collision integral, so that no energy input term is required. Also, while he shows that Eq. (9) is satisfied for three specific forms of the cross section, it is possible to show this in general from his Eqs. (3) and (6), for $K\Delta\, U^2 \ll 1$.

The calculation of the mobility for partially ionized gases is a matter of some complexity. In the work of Frost [11] it was proposed that the expression for the mobility in a mixture of gases in the Lorentz approximation be used, but with an effective electron-ion collision frequency adjusted so as to give for the asymptotic limit in the fully ionized case the correct value, including electron-electron collisions. In the extensive calculations of Schweitzer and Mitchner [7, 8], using the Chapman-Enskog technique to third order, the procedure proposed by Frost was shown to have adequate accuracy in view of present day knowledge of the collision cross sections. Schweitzer and Mitchner give detailed results for several values of α which are very useful in assessing the relative corrections involved in practical cases. Since their results are given in terms of integrals which can be performed with arbitrary cross sections, practical evaluations of μ can also be carried out with their method. (In reference [12] Devoto has given a simplified procedure for practical evaluation of the transport properties of ionized gases).

It is interesting to see what Eq. (15) leads to in a practical example. For a mixture of helium atoms, ions, and electrons $\nu_\mu/\Sigma\,\nu_{Ms}$ has been calculated (the ion and atom masses are equal), assuming that $T_e = 2000\,^\circ K$ and that the helium atom-electron momentum transfer cross section is represented by a hard spere, with $Q = 6.1 \times 10^{-16}\ cm^2$ (13). The combined mobility was calculated with aid of the results plotted in Fig. (5) of Schweitzer and Mitchner [7], where the curve for $\xi = 3$ was used. In order to fix the parameter $\ln \Lambda$ a value of $n_a = 10^{18}\ cm^{-3}$ was assumed, but the results are very insensitive to this value. In Fig. 2 these results for $\nu_\mu/\Sigma\,\nu_{Ms}$ are plotted versus the fractional ionization $n_e/(n_e + n_a)$. A scale for the mobility ratio μ_a/μ_i, where μ_a is the electron mobility calculated for atoms alone and μ_i that for ions alone, is also indicated.

From the limiting value of 0.883 for very small ionization degree, $\nu_\mu/\Sigma\,\nu_{Ms}$ first increases, and then falls to 0.505, the limiting value for a fully ionized plasma, as the ionization degree increases. At a fractional ionization as low as 10^{-5} the effect of electron-ion collisions is noticeable. The rise to a maximum is due completely to the higher order effects on the additivity of ν_μ for the two species, and neglecting these effects would result in a symmetrical curve connecting the limiting values. (Adding ν_μ is equivalent to adding the inverse of the mobilities, a commonly used procedure [11]). Physically, the maximum is due to the fact that the "skewing" of f_1 in velocity space is opposite in sense for the hard sphere and Coulomb cross sections (in Fig. 1 these two cases lie on opposite sides of the maximum, at $a = -1$), and the initial effect of including ions along with hard spheres is to diminish the "skewing" and thus approach the Maxwellian molecule case. For atoms with $a < -1$ this is no longer the case and such a peak would not be observed.

For other practical cases, such as the argon-cesium-cesium ion plasmas considered for use in magnetohydrodynamic generators and the cesium-cesium ion plasmas used in thermoionic converters, simple power law cross sections are not adequate and the collision integrals must be evaluated numerically. In the case of argon, where the cross section increases with velocity for part of the range, the higher order effects may result in a 40 % correction to the value of ν_μ obtained by simply adding the respective ν_μ for each component, (see Fig. 6 of reference 7).

SUMMARY

The validity of a commonly used assumption for the electron temperature of a partially ionized gas in an electric field was investigated. For atoms with cross sections which differ greatly from that for Maxwellian molecules, such as ions, this assumption can be in error by almost 50 %. It is pointed out that in practical cases this problem may be solved correctly without too much difficulty.

APPENDIX

The use of Eq. (13) with $\nu_\mu/\nu_M = 1.0$

In the book by Sutton and Sherman [2], where a thorough discussion of the transport coefficients with special emphasis on their practical use in engineering magnetohydrodynamics is given, the assumption of Maxwellian molecules is made in the derivation of the electron temperature.

In the analysis of many experiments on ionization at elevated electron temperatures in cesium and potassium seeded discharges [14, 15, 16, 17] the assumption $\nu_\mu/\nu_M = 1.0$ is effectively made. The results of these experiments are probably only slightly affected by the inclusion of these effects, however. In the experiments of Bernard et al. [18] and in the analysis by Lyman [19] of the work of references 15 and 16 the correct formulation of both the mobility and ν_E in the energy balance equation are used. Lyman [19] neglects radiative losses, though, which have been shown to be important, and Bernard et al. have taken into account the effects of electron-ion and electron-electron collisions in an approximate manner with unknown accuracy.

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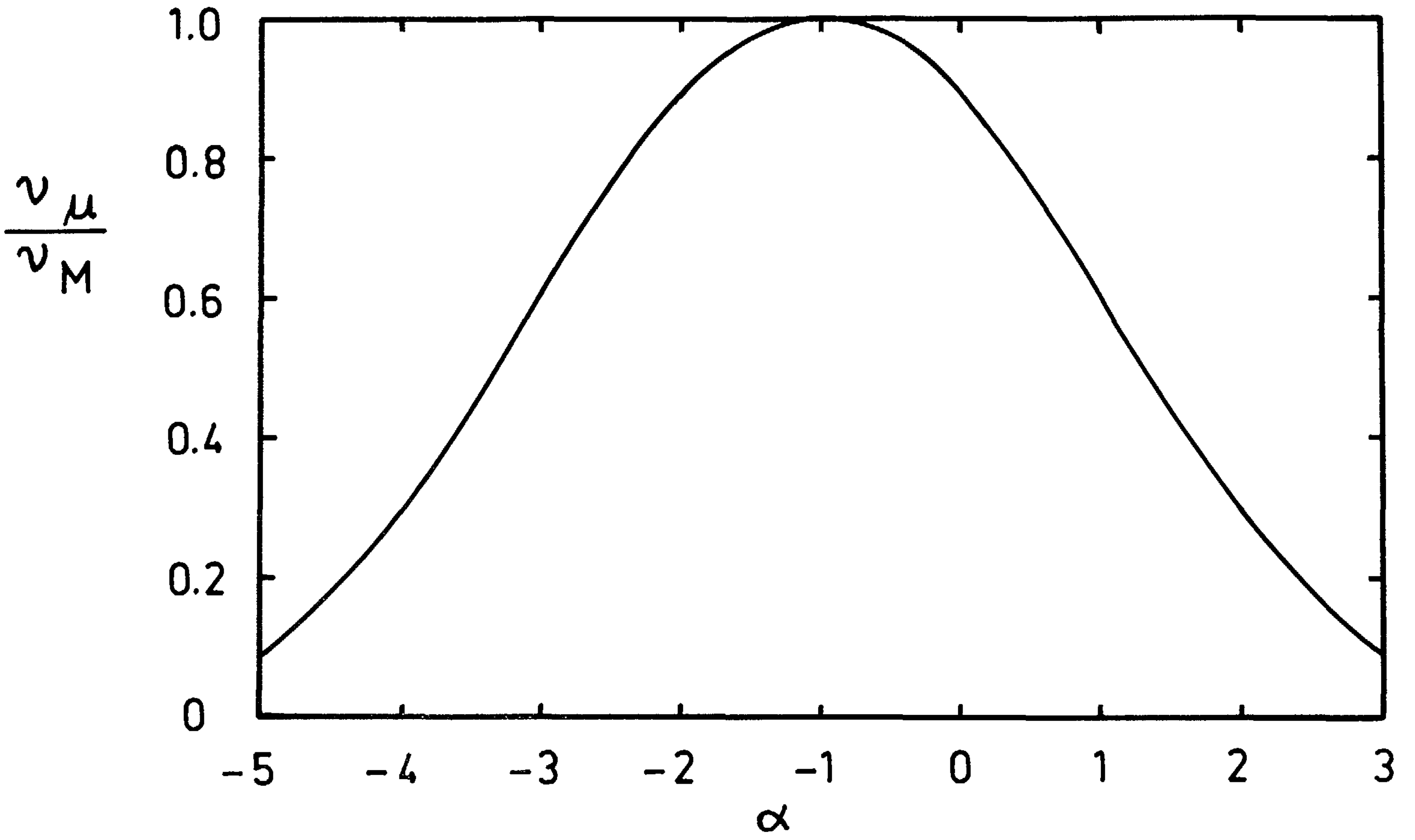
Fig. 1



The mean collision frequency for mobility, ν_μ (in the Lorentz approximation), divided by the mean collision frequency for momentum transfer ν_M, plotted as a function of α. α is the exponent in the velocity dependence of the momentum transfer cross section.

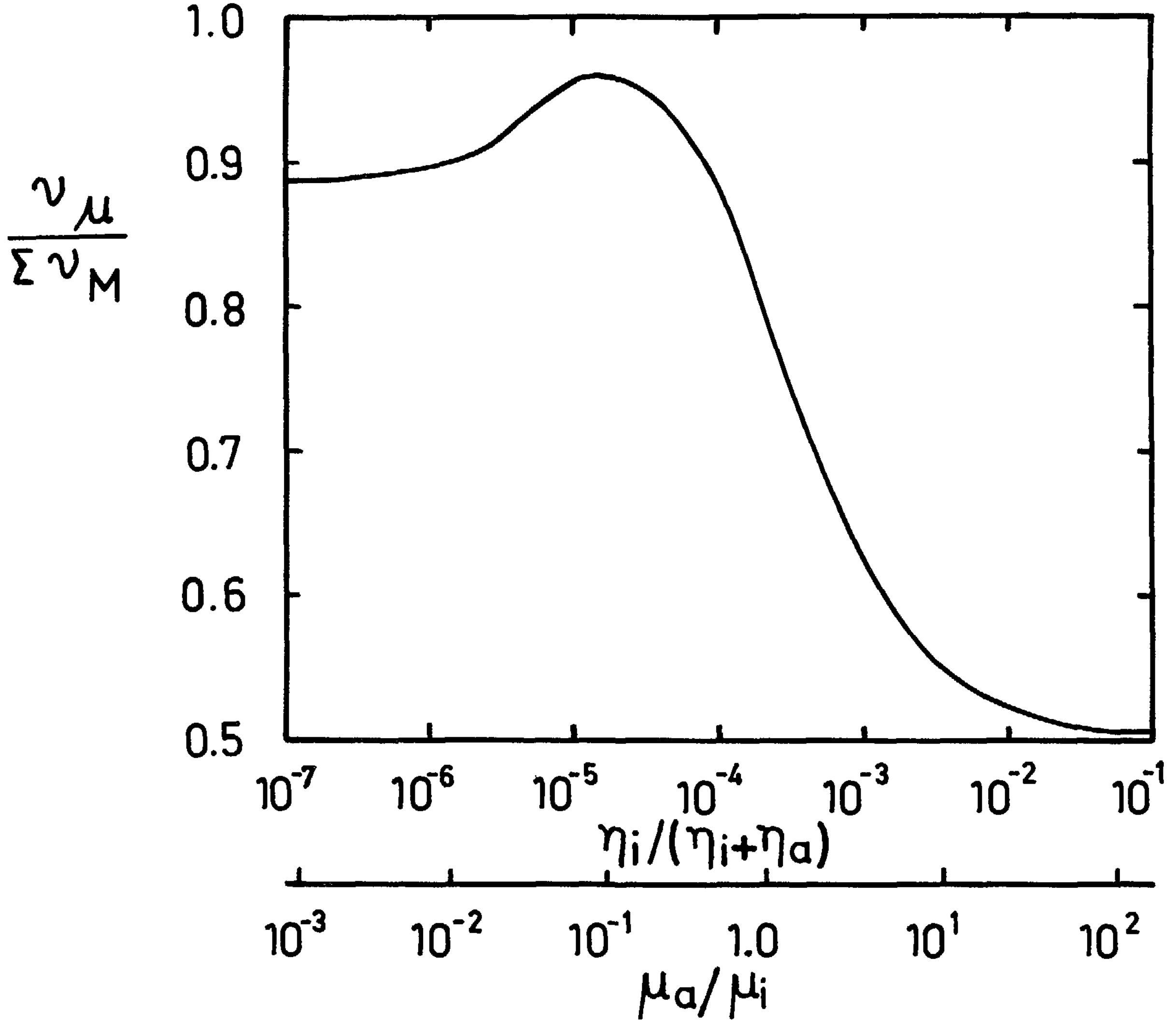


Fig. 2

The mean collision frequency for mobility, ν_μ, divided by the mean collision frequency for momentum transfer $\Sigma \nu_{Ms}$, plotted as a function of the degree of ionization $n_i/(n_i + n_a)$. The values are calculated for helium atoms, assuming a hard sphere cross section of 6.1×10^{-16} cm^2, with T_e = 2000 °K. A scale for the ratio of the mobilities in the helium atoms and ions separately is also given.

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