MASS-SEPARATION PROCESSES IN A ROTATING WEAKLY IONIZED PLASMA

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ABSTRACT

The various separation processes for neutrals with different masses in a weakly ionized plasma rotating in crossed fields are considered. The expressions for the separation factors are obtained.

I. INTRODUCTION

In the investigations of a mass-separation in a plasma rotating in crossed radial electric and axial magnetic fields the main attention paid was usually to the mechanism caused by a rotation of plasma components. However, as that followed from the experiments with a rotating plasma, the separation degrees obtained may not always be explained by processes caused by a rotation of components [1] . In a steady-state weakly ionized plasma in crossed E and B fields we must take into account the separation mechanisms caused by a temperature gradient of a neutral gas (a thermal diffusion and separation due to a difference in a heating of neutrals with different masses [2]). In a plasma with unmagnetized ions we must take into account the separation due to both cataphoresis and transfering of a radial momentum from ions to neutrals.

2. SEPARATION DUE TO NEUTRAL ROTATION

In crossed E and B fields the magnetized charged particles move with azimuthal drift velocities $\approx E_r/B$ and transfer their momentum to neutrals by elastic and charge-exchange collisions. If the radius dependence of a neutral velocity is of the form $v_\varphi \approx v_{\varphi 0} r_0/r$ (that dependence corresponds to a radial pattern of ion drift velocities for the case when $E_r = E_0 r_0/r$) the separation factor takes the form

$$\alpha = \frac{(n_1/n_2)_{r_0}}{(n_1/n_2)_{r_1}} \approx \exp\left\{\frac{m_2 - m_1}{2kT} v_{\varphi 0}^2\left(1 - \frac{r_0^2}{r_1^2}\right)\right\}, \quad (1)$$

where T is the temperature of neutrals.

If the mean free path of neutrals is less than the cross dimensions of a device ($\lambda_{nn} < R$) the average azimuthal velocity of neutrals may be estimated from the azimuthal component of the equation of motion for neutrals:

$$m_n n_n v_r\left(\frac{\partial v_\varphi}{\partial r} + \frac{v_\varphi}{r}\right) = -\tilde{m} n_n \nu_0 \left(v_\varphi - v_{i\varphi}\right) + \eta\left(\frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial v_\varphi}{\partial r} - \frac{v_\varphi}{r^2}\right), \quad (2)$$

where $\eta \approx \frac{1}{3} n_n \lambda_{nn} m_n v_T$, $\tilde{m} = m_n m_i/(m_n + m_i)$, ν_0 is the frequency of charge-exchange collisions of neutrals with ions. Approximately eq. (2) is reduced to

$$v_\varphi \approx v_{i\varphi}\left\{1 + \frac{\eta}{R^2 \tilde{m} n_n \nu_0}\right\}^{-1} \quad (3)$$

Thus, the neutrals have to rotate more slowly when the neutral density and the ionization degree are decreased. On the other hand, the value of the ion azimuthal drift velocity may be less than cE_r/B if the neutral density is much greater than a critical value $n_n = \omega_i / \langle \sigma_{in} v_i \rangle$. Therefore the separation caused by a rotation of neutrals may be ineffective if the inequality $\omega_i > \nu_{in}$ is incompatible with a neglect of viscous forces for devices with cross dimensions $R \lesssim 10$ cm.

3. THERMAL DIFFUSION

If the neutral temperature varies in a radial direction we must take into account a thermal diffusion. In that case the temperature dependence of the neutral collision frequency causes the appearance of forces retaining the light particles in the region with the greater temperature. If the masses of neutrals differ considerably ($m_1 \ll m_2$), in the equilibrium state the light neutrals act on the unit volume of heavy neutrals with the force

$$F \approx -\tilde{m} n_1 n_2 v_{T1} \lambda \, \frac{\partial \langle \delta v \rangle}{\partial T} \cdot \frac{dT}{dr} \quad , \tag{4}$$

where λ is the mean free path of light neutrals, δ is the transport cross-section. From the momentum conservation law we can find the force acting on the light neutrals:

$$f \approx \frac{\tilde{m} v_{T1}}{\delta} \cdot \frac{\partial \langle \delta v \rangle}{\partial T} \cdot \frac{dT}{dr} \tag{5}$$

If the temperature gradient is small and the separation degree is not great, the use of the Boltzmann formula for the field of forces (5) leads to the expression for the separation factor [2] :

$$\alpha \approx \exp\left(1 + {}^{n_1}\!/_{n_2}\right) \frac{\nu - 5}{2(\nu - 1)} \left(\frac{T(r_0)}{T(r_1)} - 1 \right), \tag{6}$$

where ν is the exponent in the expression for the interaction force F_* acting between two different neutrals, located at the distance x $\left(F_* \propto x^{-\nu} \right)$ [3] . The usual expression for the ratio

$$k_T \equiv \frac{D_T}{D} = \frac{n_1}{(n_1 + n_2)} \cdot \frac{\nu - 5}{2(\nu - 1)} \tag{7}$$

may be obtained from eq. (5) and from the Einstein relation $D = kTB_0$ (D_T is the coefficient of a thermal diffusion, D is the diffusion coefficient, B_0 is the mobility).
In the case when $m_1 \lesssim m_2$, the separation factor can be ex-

pressed by the "constant of the thermal diffusion"

$$\alpha_T = k_T (n_1+n_2)^2 / n_1 n_2 \; . \tag{8}$$

In this case we obtain [4]

$$\alpha \approx \left(T(r_0) / T(r_1) \right)^{\alpha_T} \; . \tag{9}$$

4. SEPARATION DUE TO A DIFFERENCE IN A NEUTRAL HEATING

In some experiments on a separation there were used gases with different ionization cross-sections. In a mixture of rare gases [1] or in a mixture H_2-Ar [5] the neutrals with larger masses have larger ionization cross-sections. In a such weakly ionized plasma the ion current has to heat heavy neutrals, because the resonant charge-exchange cross-section is much greater than another cross-sections of the energy transfering from ions to neutrals [3] . If the diffusion time for the light neutrals is less than the time of the energy transfering from the heavy neutrals, the temperature of latters has to be greater than the temperature of light neutrals. In a quasi-steady state ($\partial P / \partial r \approx 0$) the separation factor is reduced to

$$\alpha \approx \frac{(T_2/T_1)_{r_0}}{(T_2/T_1)_{r_1}} \; , \quad r_0 < r_1 \; . \tag{10}$$

5. CATAPHORESIS

In this case the separation appears when the partial ion currents differ essentialy [6] . The ion current is equivalent to the neutral flow and is balanced by the diffusion due to the density gradient. When $E_r > 0$ we obtain from the balance condition:

$$\alpha \approx 1 + \frac{3(r_2 - r_1)}{e} \left(\frac{\bar{j}_2 \sigma_2}{v_{T2}} - \frac{\bar{j}_1 \sigma_1}{v_{T1}} \right) , \tag{11}$$

where $\bar{j}_{1,2}$ are the average ion current densities, $v_{T1,2}$ are the thermal velocities of neutrals. For the case of $\omega_i \gtrsim \nu_{in}$, $cE_r / B > v_{T1,2}$ the ion current density is

$$j_{kr} \approx n_{ik} n_k \sigma_{ex}^{(k)} c^3 E^2 m_k / B^3 , \qquad (12)$$

where $\sigma_{ex}^{(k)}$ is the charge-exchange cross-section for particles of species k, $k=1,2$. Neglecting the separation caused by the difference of ionization degrees, when $n_1 \approx n_2$, $n_{i1} \approx n_{i2}$, we obtain

$$\alpha \approx 1 + \frac{3(r_2 - r_1)}{\lambda_{nn} \lambda_{ni}} \rho_2 \left(1 - (m_1/m_2)^{3/2}\right), \qquad (13)$$

where ρ_2 is the ion Larmor radius, λ_{ni} is the mean free path for neutral-ion collisions.

6. TRANSFERING OF A RADIAL MOMENTUM FROM IONS TO NEUTRALS

The ions accelerated by a radial electric field transfer their momentum to neutrals mainly by the charge-exchange collisions. For the unmagnetized ions ($\omega_i < \nu_{in}$) the probability of a momentum transfering in a radial direction corresponds to a value ~ 1. In this case there exist the radial forces $F_n(r)$ acting on neutrals. In a steady-state plasma the radial flow of fast neutrals has to be balanced by the back flow due to a density gradient of neutrals. In that case which is similar to the case of a thermal diffusion, the forces acting between neutrals are proportional to $\partial \langle \sigma v \rangle / \partial v$. For a constant temperature the separation factor may be obtained from the Boltzmann distribution for the neutrals:

$$\alpha \approx \exp\left\{ \frac{1}{kT_2} \int_{r_1}^{r_2} F_2(r)\,dr - \frac{1}{kT_1} \int_{r_1}^{r_2} F_1(r)\,dr \right\} \qquad (14)$$

For the small separation degrees, when $n_1 \approx n_2$, if the electric field varies inversely with r, we obtain:

$$\alpha \approx \left(\frac{r_2}{r_1}\right)^{\gamma} ; \ \gamma = \xi_2 \frac{eE_0 r_0}{kT_2} \left[1 - \frac{m_1}{m_2} \cdot \frac{2^{\frac{4}{\nu-1}}}{\varkappa^2} \left(\frac{\nu - 5}{\nu - 1}\right)\right], \qquad (15)$$

where ν has the same meaning that in eq.(6); $\varkappa$ varies from 1/2($m_1 \ll m_2$) to 1 ($m_1 \sim m_2$); $\xi = n_i/n_n$, $\xi_1 \ll \xi_2$, $T_1 \approx T_2$.

When $m_1 \ll m_2$ the difference of the forces $F_2 - F_1 \approx \xi_2 e E_r$ is not dependent on n_1/n_2. In this case the separation factor is

$$\alpha \approx \left(\frac{r_2}{r_1}\right)^{\xi_2 \frac{eE_0 r_0}{kT_2}} \approx \exp\left\{\xi_2 \frac{eU_{12}}{kT_2}\right\}, \qquad (16)$$

where U_{12} is the radial voltage. When $\xi_1 \sim \xi_2$, neglecting the interaction between different neutrals we obtain the more general relation instead of eq.(16)

$$\alpha \approx \exp\left\{\left(\xi_1 - \xi_2 \frac{T_2}{T_1}\right) \frac{eU_{12}}{kT_2}\right\}. \qquad (17)$$

If the relation $\omega_i > \nu_{in}$ is valid only for one gas component the radial force from ions has to act only on the neutrals of another component (for example, if $\omega_1 > \nu_{in}^{(1)}, \omega_2 < \nu_{in}^{(2)}$, in the exponent of eq.(17) the term with ξ_1 vanishes).

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