Electron Thermionic Emission and Tunneling Transport in Spherically Symmetric Charged Grains in Dusty Plasmas

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Abstract

Electron emission from charged spherical dusty grains plays a crucial role in plasma environments, influencing charge dynamics and transport properties. This presentation explores thermionic emission and substantial tunneling currents for electrons. Based on the Richardson-Dushman equation, we analyze the feasibility of quantum tunneling, incorporating Debye shielding effects to assess barrier modifications and electron transmission probabilities.

Thermionic Emission

Thermionic emission from a spherical charged particle/grain can be analyzed by the Richardson-Dushman theory and the presence of charge on the grain. The Richardson-Dushman equation describes mobile electron transport over potential barriers: its complete form is as follows:

$$J = A^{*}T^{2}\exp\left(-\frac{q\phi_b}{kT}\right)$$

Where J stands for thermionic current density, A* is Richardson's constant, T is the temperature, while the exponential term includes the potential barrier f_b. For a spherical (radius R) charged dusty grain with charge Q_d, the electrostatic potential, at the surface of the sphere, is $\phi = Q_d/4\pi\varepsilon R$. Therefore, an electron (charge q) leaving the surface must overcome an additional potential barrier $q\phi(eV) = qQ_d/4\pi\varepsilon R$. Electrons leaving a spherically charged particle generate thermionic current:

$$I = 4\pi R^{2}A^{*}T^{2}exp\left[-\frac{q\phi_b + \frac{qQ_d}{4\pi\epsilon_o}}{kT}\right]$$

Space Charge

If emitted electrons accumulate near the grain, they form a space charge region (SCR) that can further suppress emission (Child-Lagmuir) space charge limit). In such a case, the Debye length l_D is a crucial factor in treating thermionic emissions from a charged dusty grain in a plasma environment. The Debye length depends on several quantities: plasma temperature kT_e, electron density n_e and electron charge:

$$\lambda_D = \sqrt{\frac{\epsilon_o kT_e}{n_e q^2}}$$

It describes a distance beyond which a charged particle's electrostatic field is significantly shielded by surrounding free electrons and ions.

The Debye Length Affects Thermionic Currents

For a thermionically emitting dust grain in a plasma, the surrounding electrons and ions modify the electrostatic potential due to Debye shielding. Charge accumulation and shielding: the grain's charge Q_d creates an electrostatic potential barrier that modifies the work function:

$$q\Phi' = q\Phi + \frac{qQ_d}{4\pi\epsilon_o R}$$

However, in a plasma, this potential is screened over the Debye length, which means that the effective potential at the distance l_D reduces due to Debye shielding. If R >> λ_D, the grain behaves like a macroscopic object with a well- defined electrostatic potential. If R << λ_D, the charge distribution of the plasma significantly affects the potential near the grain.

Space-Charge Effects and Plasma Sheath

Electrons emitted by the grain do not travel freely in vacuum, they interact with plasma. A sheath forms around the grain affecting escaping electron flux. In the R << λ_D case, emitted electrons experience less immediate recombination with ions nearby, thus enhancing thermionic emission.in the opposite case (λ_D << R) shielding suppresses the barrier with limited electron escape. With Debye shielding: the spherical electrostatic potential is

$$q\Phi' = q\Phi + \frac{qQ_d}{4\pi\epsilon_o R}e^{-R/\lambda_D}$$

and the final thermionic current will be

$$I = 4\pi R^{2}A^{*}T^{2}exp\left[-\frac{q\Phi_b + \frac{qQ_d}{4\pi\epsilon R}e^{-R/\lambda_D}}{kT}\right]$$

Feasibility of Tunneling

So far, we have seen that for a charged dust grain (R, Q_d) the electrostatic potential generates an energy potential barrier E_b in the plasma environment, however, this energy barrier is screened by the surrounding electrons and ions due to Debye shielding as described earlier:

$\frac{qQ_d}{4\pi\epsilon_o R}e^{-R/\lambda_D}$. Electrons with energy below E_b may escape via tunneling with probability $|t| \cong e^{-2\gamma}$, where

$$\gamma = \int_{R}^{R+L_b}\sqrt{\frac{2m^{*}}{\hbar^{2}}(V_{eff} - E\ )}dr$$

m* is the electronic effective mass, E is the electronic energy ~kT_e, and L_b is the barrier width of the "quantum well" formation around the dusty grain. Typically, for a thin barrier width, the exponent 2γ in the tunneling probability is of the order of unity, which requires that $\frac{qQ_d}{4\pi\epsilon_o R}e^{-R/\lambda_D} \cong kT_e$, so that if the screening effect (Debye effect) weakens the barrier, tunneling would be possible. For strong plasma screening, λ_D << R implies energy barrier weakening and tunneling becoming significant. At λ_D >> R conditions, barrier remains large and tunneling weakens. With tunneling conditions, one may arrive at an improved version for total current that includes tunneling probability as follows:

$$I = 4\pi R^{2}A^{*}T^{2}|t|exp\left[-\frac{q\Phi_b + \frac{qQ_d}{4\pi\epsilon R}e^{-R/\lambda_D}}{kT}\right]$$

High-T and high-density plasmas

At high T's more electrons can escape. At $T = 10^6$ K (hot astrophysical plasma), with $n_e = 10^{20}\ m^{-3}$, the Debye length is $\lambda_D = 23nm$. In this case, $E = kT_e = 86eV$. $V_{eff} = V \exp(-R/\lambda_D) = 25V$. Repeating the calculation for the barrier width we find $L_b = 71nm$. Tunneling probability $|t| = 4x10^{-4}$. Current calculated: $J = 4.6 \times 10^7\ (A/m^2)$. For a grain with R = 100nm, total current becomes **$I = 4\pi R^2 J = 6\mu A$**.

Conclusion

At hot plasma regions (10^6 K), electrons may escape from the grain via a combined thermionic/tunneling process developing currents near 6 μA, with a 71nm thick quantum barrier. Along thermionic emission dominating at elevated temperatures, tunneling contributes substantial current in dense plasma conditions, influencing overall charge equilibrium. A promising direction for future probing is the impact of dynamic charge fluctuations on tunneling probabilities.

References

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