A first-principles model for the long-standing plasma thermal conductivity puzzle

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Abstract

Suppressed electron thermal conductivity in plasmas remains unexplained from first principles for over half a century, challenging inertial confinement fusion, astrophysics, and laboratory plasma physics. We introduce semi-free electrons in a locally neutral plasma: electrons retain velocity freedom but lack independent positional freedom, being enslaved to ions. This principle yields a reformulation of the electron Fokker-Planck equation and a closed-form, parameter-free model for plasma thermal conductivity and the heat-flux limiter. The model quantitatively reproduces long- and short-pulse laser-plasma measurements. It predicts that effective electron thermal conductivity scales with ion mobility rather than electron mobility, naturally explaining strong flux suppression. The model applies to collisional, quasi-neutral transport and excludes high-frequency processes such as Langmuir waves.

keywords: plasma thermal conductivity; Fokker-Planck equation; heat-flux limiter

1. INTRODUCTION

The long-standing suppression of heat transport in plasmas presents a fundamental challenge across disciplines, from inertial confinement fusion (ICF) to astrophysics [1, 2]. In ICF, achieving ignition requires precisely controlled heat flow, yet the discrepancy with classical Spitzer-Härm (SH) theory [3-6] has hindered predictive capability for decades. This gap has spurred numerous explanations, including nonlocal transport [7-11] and non-Maxwell electron distributions [12-19]. However, while these models have provided valuable insights, many incorporate empirical parameters, which can limit their predictive capability under extrapolative conditions [2]. Thus, despite decades of effort, a first-principles, predictive theory rooted in a corrected microscopic picture has remained elusive. In practice, large-scale simulations rely on an empirical heat-flux limiter to match data [1, 6, 10, 20, 21], yet this approach fails to capture key spatial features of plasma emission [11]. Thus, the physical root of suppressed conductivity remains an open question [1, 2], suggesting that the standard microscopic description may lack a key constraint of plasma electrons.

Here, we identify this missing ingredient by refining a foundational assumption: electrons in a local charge-neutral plasma are not free, but semi-free. This principle mandates a first-principles reformulation of the electron Fokker-Planck equation. From this foundation, we derive a closed-form analytical model for thermal conductivity that quantitatively captures the widely recognized suppression and simultaneously explains the empirical heat-flux limiter without invoking arbitrary parameters. This reformulation may shed light on heat transport in magnetically confined plasmas, where

the interplay between neoclassical transport and turbulence remains a central challenge.

2. THEORETICAL METHODS

2.1. Semi-free electrons

The canonical model of plasma transport is built upon the assumption of free electrons. Microscopically, the ionized electrons are unbounded by the nucleus and are therefore free, exhibiting both the positional and velocity degrees of freedom. However, this picture is fundamentally at odds with a key physical constraint of charge neutrality on a larger length and time scale. On timescales longer than the electric relaxation time ($\tau=\varepsilon_0\varepsilon/\sigma_e$), the local charge neutrality forces the light electrons to follow the massive ions within the plasma element. Their positional freedom is effectively locked in the slow processes such as thermal transport, while their velocity freedom in momentum space remains intact. Mathematically, the electron and ion positions are indistinguishable within a macroscopic fluid element and the element's location is defined by the position of ions due to their heavier masses than electron masses, as shown in Fig. 1. Consequently, the electrons in a neutral plasma are not free but semi-free, demonstrating that they possess stochastic velocities but are denied independent macroscopic trajectories within the scale of fluid element, as shown in Fig.1. Just as the internal electron degrees of freedom in a neutral atom are subsumed into the atom’s effective transport properties, the independent positional degrees of freedom of electrons in a quasi-neutral plasma are subsumed into the ion fluid’s description. Electrons retain velocity-space freedom but their macroscopic position is enslaved to the ions via neutrality. This is the

central insight of our work.

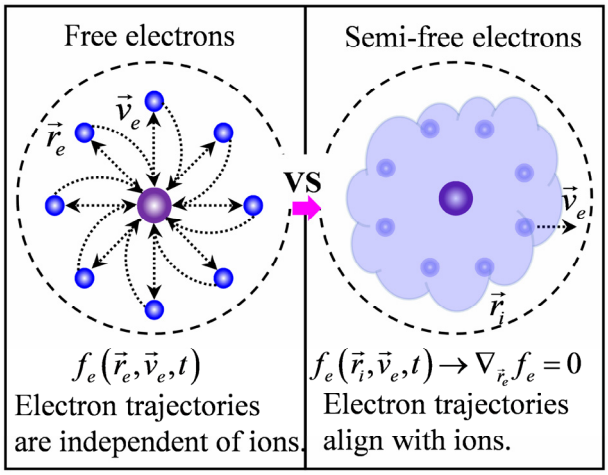


FIG. 1. Schematic of the semi-free electron concept. Dashed black lines enclose locally neutral plasma elements with ions (large purple circles) and electrons (small blue circles). In the conventional free-electron picture (left), electrons possess both spatial and velocity degrees of freedom, described by the distribution function $f_e = f_e(\vec{r}_e, \vec{v}_e, t)$. In the semi-free electron paradigm (right), electrons retain velocity freedom but are spatially enslaved to ions due to charge neutrality, leading to $f_e = f_e(\vec{r}_i, \vec{v}_e, t)$ and the constraint $\nabla_{r_e} f_e(\vec{r}_i, \vec{v}_e, t) = 0$.

Based on this picture, the description of a neutral plasma in slow processes collapses onto a reduced phase space. The macroscopically continuous electron distribution function f_e depends on the plasma element's location defined by the ion position $\vec{r}_i$, the velocity of electrons $\vec{v}_e$, and time t, *i.e.*, $f_e = f_e(\vec{r}_i, \vec{v}_e, t)$. Here $\vec{r}_i$ denotes the position of a plasma element containing many ions, not a specific ion. The spatial gradient of the electron distribution function with respect to the electron vanishes

$$\nabla_{r_e} f_e = 0 \tag{1}$$

Eq. (1) is fundamental to our reformulation. It arises naturally from the semi-free electron picture under the quasi-neutrality condition. This suggests a necessary refinement of the standard Fokker-Planck framework for electrons in neutral plasmas, pointing toward a new kinetic equation built from this constrained phase-space geometry. Such a reformulation has the potential to refine our understanding of transport, heating, and instability thresholds in regimes governed by charge neutrality.

However, the scope of this refinement is limited. The semi-free electron picture is derived from the conditions, i.e., local charge neutrality holds on timescales longer than the electric relaxation time ($\tau=\varepsilon_0\varepsilon/\sigma_e$). Under the condition, the positional degrees of freedom of electrons are enslaved to the ions within each quasi-neutral fluid element.

Consequently, the model does not apply to high-frequency phenomena where charge separation and electron inertia play essential roles. A paradigmatic example is the Langmuir wave, which relies on: (a) electron inertia as the reactive element, (b) charge separation as the restoring force, and (c) dynamics on the timescale of the electron plasma frequency. The semi-free electron constraint would incorrectly suppress the very charge separation that sustains Langmuir oscillations. Therefore, the present model is explicitly limited to the locally quasi-neutral heat transport and does not purport to describe high-frequency collective modes.

3. RESULTS AND DISCUSSION

3.1. Plasma thermal conductivities

For a non-degenerate plasma, the ions and electrons are described by Maxwell distributions. The key departure from standard SH theory is the treatment of the electron number density n_e and the electron temperature T_e. In our framework, they are evaluated at the position of plasma element defined by position of ions $\vec{r}_i$, rather than the position of electrons $\vec{r}_e$. The relationships can be expressed as n_e=n_e ($\vec{r}_i$,t) and T_e=T_e ($\vec{r}_i$,t).

The equilibrium distributions are [22] $f_\alpha^0 = n_\alpha(\vec{r}_i, t)exp(-v_\alpha^2/v_{\alpha T}^2)/\pi^{3/2}v_{\alpha T}^3$, where α=i, e for ions and electrons, $v_{\alpha T} = \sqrt{2k_B T_\alpha/m_\alpha}$ is the thermal speed, and temperatures T_α may be position-dependent.

Following the SH formalism [3, 22], the non-equilibrium distribution functions are written as $f_\alpha = f_\alpha^0 + f_\alpha^1$, with f_α^1 representing the anisotropic perturbation. For electrons, the linearized Boltzmann equation under the relaxation-time approximation yields [22, 23] $f_e^1 = -\tau_{ei}\left(\vec{v}_e \cdot \nabla_{r_e} f_e^0 + e\vec{E} \cdot \nabla_{v_e} f_e^0/m_e\right)$ where τ_{ei} denotes the electron-ion collision time. Using Eq. (1) and evaluating the velocity gradient, we obtain the compact form $f_e^1 = \tau_{ei} e\vec{E} \cdot \vec{v}_e f_e^0/k_B\, T_e$. Thereby the electron current density [22] $j_e = e\int d\vec{v}_e\, \vec{v}_e f_e^1$ then integrates to $j_e = 8\, e^2 n_e \tau_{ei}\vec{E}/\pi^{1/2}m_e$.

For ions, the anisotropic component derived from the transport equation is $f_i^1 = -\tau_i f_i^0 \vec{v}_i \cdot \left[\nabla_{r_i} lnn_i(r_i, t) + (v_i^2/v_{iT}^2 - 3/2)\nabla_{r_i} lnT_i + Ze\vec{E}/k_B T_i\right]$ where τ_i is the ion-ion collision time. Computing the ion current density $j_i = -Ze\int d\vec{v}_i\, \vec{v}_i f_i^1$ gives

$$j_i = 8Zen_i\tau_i k_B T_i \left[\nabla_{r_i} lnn_i(r_i, t) + 5/2\, \nabla_{r_i} lnT_i + Ze\vec{E}/k_B T_i\right]/\pi^{1/2}m_i.$$

In many plasma transport scenarios, the local charge neutrality is a valid approximation, implying the total electrical current vanishes j_i+j_e=0 [3, 8, 12, 22-24].

Applying this condition to the above expressions for j_i and j_e allows us to solve for the self-consistent electric field:

$$e\vec{E} = -\frac{\tau_i}{m_i}\left(\frac{\tau_{ei}}{m_e}+\frac{Z\tau_i}{m_i}\right)^{-1} k_B T_i \left[\nabla_{r_i} lnn_i(r_i,t) + \frac{5}{2}\nabla_{r_i} lnT_i\right] \quad (2)$$

The field points in the direction of the ion temperature gradient ∇T_i, contrary to the conventional Fokker–Planck predictions [22], yet consistent with the negative electric fields commonly observed in tokamaks [25-27]. A detailed analysis of the tokamak plasmas has been presented in a separate work [28]. This agreement lends strong support to our framework, particularly the concept of semi-free electrons. The direction of electric field implies that, within our model, electron motion is effectively dragged by the ion motion. This reverses the standard paradigm, in which ions are typically dragged by faster electrons.

The electron thermal current density is given by [22, 23] $q_e = \int d\vec{v}_e\, m_e v_e^2 \vec{v}_e\, f_e^1/2$. Using the expression for f_e^1 and the derived field in Eq. (2), we find $q_e \approx -32 n_e k_B^2 T_e T_i \tau_i\,(5/2L_T + 1/L_n)/\pi^{1/2} m_i$. Here, $1/L_n = \nabla lnn_i(\vec{r}_i,t)$ and $1/L_T = \nabla lnT_i(\vec{r}_i,t)$ are the inverse scale lengths for density and temperature gradients [12, 22-24, 29] respectively. The approximation $\tau_{ei}/m_e >> Z\tau_i/m_i$ [22], reflecting the higher electron mobility, has been used. Notably, the thermal flux is governed by the ion temperature gradient and scales with the ion collision time τ_i, a direct consequence of the field generation mechanism described above.

The resultant electron thermal conductivity κ_e reads

$$\kappa_e = \frac{32 n_e k_B^2 T_e}{\pi^{1/2}} \frac{\tau_i}{m_i}\left(\frac{5}{2}+\frac{L_T}{L_n}\right). \quad (3)$$

The result indicates a significant difference from the classical theory. The electron thermal conductivity scales with the ion mobility τ_i/m_i, not the electron mobility τ_{ei}/m_e . This inversion of the standard SH dependence stems directly from the core premise that the semi-free electrons are tied to ion positions, forcing both species to move collectively within a plasma fluid element. Thus, the heat-carrying electron flux is governed by the slower ion dynamics, an inversion of the classical picture.

The ion thermal conductivity κ_i is obtained analogously from its thermal flux $\kappa_i = 32n_i k_B^2 T_i \tau_i \,(7/2 + L_T/L_n)/\pi^{1/2} m_i$ [22]. In the regime relevant to inertial confinement fusion and laser-plasma interactions where the temperature gradient is typically much steeper than the density gradient, *i.e.*, $L_T \ll L_n$ [4, 22], the total plasma thermal conductivity simplifies to a revealing form $\kappa_t = \kappa_e + \kappa_i$. Combining the electron and ion thermal conductivities κ_e and κ_i yields

$$\kappa_t = \frac{32 n_e k_B^2 T_e}{\pi^{1/2}} \frac{\tau_i}{m_i} \left(\frac{5}{2} + \frac{7}{2Z} \frac{T_i}{T_e} \right) . \tag{4}$$

The expression highlights that the overall thermal conductivity is controlled by ion mobility τ_i/m_i.

Our model yields thermal conductivities that differ fundamentally from the classical SH result $\kappa_{SH} = 32 n_e k_B^2 T_e \, \tau_{ei}/\pi^{1/2} m_e$ [22]. The ratio of the plasma thermal conductivity in Eq. (4) to the SH value is $\kappa_t/\kappa_{SH} = \left(\sqrt{2}/Z^2\right)\sqrt{m_e/m_i}\,(T_i/T_e)^{3/2}(5/2 + 7T_i/2T_e)$, where the relation $\tau_i/\tau_{ei} = \left(\sqrt{2}/Z^2\right)\sqrt{m_i/m_e}\,(T_i/T_e)^{3/2}$ [22] has been used. The scaling highlights the dominance of ion-scale physics such that the conductivity is suppressed relative to SH by the factor $\sqrt{m_e/m_i}\,(T_i/T_e)^{3/2} \ll 1$ under typical high-energy-density conditions.

The suppression naturally modifies the heat-flux limiter f, a key empirical parameter in simulations designed to bridge the experimental observations and the free-streaming transport. Using the free-streaming flux $q_f = n_e k_B T_e (k_B T_e / m_e)^{1/2}$ [4, 22, 30, 31], the heat-flux limiter becomes

$$f = \frac{32}{\pi^{1/2} Z^2} \sqrt{\frac{m_e}{m_i}} \frac{\lambda_e}{|L_T|} \left(\frac{T_i}{T_e} \right)^{5/2} \left(\frac{5}{2} + \frac{7}{2} \frac{T_i}{T_e} \right) . \quad (5)$$

It indicates that the heat-flux limiter depends on the temperature ratio T_i/T_e and the normalized value $\lambda_e/|L_T|$, where λ_e denotes the electron mean free path.

3.2. Comparison with experimental results

While numerous experimental studies of heat-flux limitation have been reported in recent decades, very few of them simultaneously provide both the electron-to-ion temperature ratio T_i/T_e and the normalized gradient scale length $\lambda_e/|L_T|$ required for a direct quantitative test of Eq. (5). Consequently, we compare our model with the classic experiments of White et al. [5] and Gray et al. [6], which remain among the most complete datasets in this respect.

To validate the model, we compare the normalized heat-flux limiter $f/(\lambda_e/|L_T|)$ against the key laser-plasma experiments. The concept of semi-free electrons yields results that agree with observations across disparate regimes.

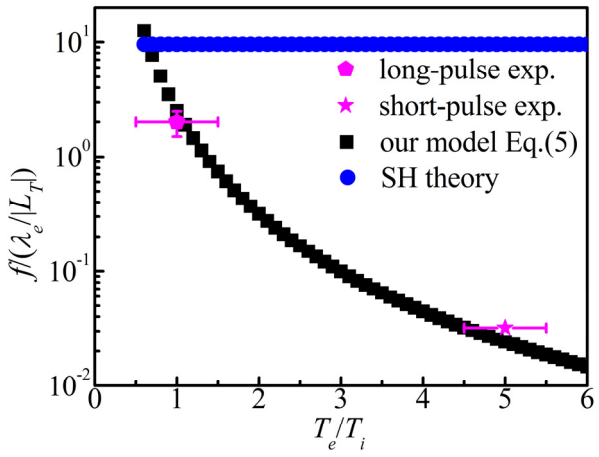


FIG. 2. Comparison of theoretical and experimental normalized heat-flux limiter. The normalized heat-flux limiter $f/(\lambda_e/|L_T|)$ is shown as a function of the temperature ratio T_e/T_i for a fully ionized hydrogen plasma. Theoretical predictions from Eq. (5) (black squares) and from Spitzer-Härm theory (blue circles) are compared with experimental data (magenta pentagram and pentagon) [5, 6]. Error bars are from Ref. [5, 6].

In long-pulse experiments with near-equilibrium hydrogen plasma $T_e \approx (1 \pm 0.5) T_i$, $\lambda_e/|L_T| \approx 0.04$ [5, 6], the model predicts $f \approx 0.1$ and $\kappa_t/\kappa_{SH} \approx 0.2$. As shown in Fig.2, these predictions fall squarely within the experimentally inferred ranges of $0.06 < f < 0.1$ and $\kappa_t/\kappa_{SH} = 0.4 \pm 0.2$ [5].

The model also captures the dynamics of short-pulse experiments, where electron heating is transient. For initial conditions $T_e \sim 5T_i$, $\lambda_e/|L_T| = 0.5$ [6], Eq. (5) gives $f \approx 0.02$, consistent with experimental results based on the definition of free-streaming flux $q_f = n_e k_B T_e (2k_B T_e/\pi m_e)^{1/2}$ [6], as shown in Fig. 2. As the plasma relaxes with $\lambda_e/|L_T|$ decreasing and T_e approaching T_i [31], the predicted heat-flux limiter rises

to $f \approx 0.06$. The temporal evolution, resulting in a range $0.02 < f < 0.06$, matches the experimentally observed range of $0.02 < f < 0.05$ [6].

The consistent agreement across both long and short-pulse regimes provides robust experimental support for the semi-free electron model and the associated transport formulation without any adjustable parameters.

3.3. Model limitations and validity

The model requires small perturbations to the local equilibrium for both species $f_e^1/f_e^0 \ll 1$ and $f_i^1/f_i^0 \ll 1$. From the derived distribution functions, these ratios scale as $f_e^1/f_e^0 \approx -\left(5\sqrt{2}/2Z^2\right)\sqrt{m_e/m_i}\,(T_i/T_e)(\lambda_e/L_T)$ and $f_i^1/f_i^0 \approx -\left(5\sqrt{2}/2Z^2\right)(T_i/T_e)^2(\lambda_e/L_T)$. These expressions clarify the model's domain of applicability. The conditions are readily satisfied in conventional long-pulse experiments where $\lambda_e/|L_T| \ll 1$. Crucially, they also hold in high-power, short-pulse regimes characterized by large temperature gradients ($\lambda_e/|L_T| \sim 1$) and significant electron-ion temperature separation ($T_i \ll T_e$) [6, 32]. In the latter case, the suppressing factors T_i/T_e and $(T_i/T_e)^2$ compensate for the increased gradient, ensuring the perturbation remains small.

Furthermore, the underlying collision physics, dominated by small-angle scattering processes [22], provides a consistent foundation for the calculated relaxation times across both gradient scales. Therefore, the semi-free electron model and its transport closure are justified across the broad range of temperature gradients relevant to the inertial confinement fusion and laser-plasma experiments.

Finally, we address the interplay between collisions and the fluid element. The semi-free electron is a macroscopic constraint stemming from charge neutrality, which holds on timescales longer than the charge-relaxation time. The collision times τ_{ei} and τ_i used in our derivation describe microscopic momentum exchange. They remain well-defined because the semi-free constraint does not preclude local velocity scattering; it only removes the independent large-scale positional freedom of electrons. Thus, the standard collision physics operates naturally within the reduced phase space dictated by Eq. (1). The present model assumes collisional dominance and a Maxwellian equilibrium. It therefore does not apply to collisionless or weakly collisional regimes where high-frequency electrostatic waves (e.g., Langmuir waves, ion-acoustic waves) or kinetic instabilities prevail. In such regimes, the charge separation and the electron inertia play the key roles, which violate the local charge neutrality. Thus, the semi-free electron picture should be viewed as a complementary description for charge-neutral transport problems, not as a universal replacement for high-frequency kinetic theory.

3.4. Implications and outlook

Our analysis indicates a fundamental hierarchy inversion. The constraint $\nabla_{r_e} f_e = 0$ transfers the agency for heat transport from the fast electrons to the slow ions in a neutral plasma. The constraint compels the thermal conductivity to scale with the ion mobility τ_i/m_i but not the electron mobility τ_{ei}/m_e. A crucial corollary is that this inversion is most pronounced precisely when electrons would classically be most mobile under large temperature difference $T_i \ll T_e$. It provides an explanation for the severe suppression of the heat flux in high-energy-density

experiments. This framework also provides a first-principles origin for the commonly observed, yet classically puzzling, negative radial electric fields in tokamaks, as they arise from the ion-gradient drive within the semi-free electron geometry. The revised kinetic foundation suggests a re-examination of other transport coefficients such as viscosity and instability thresholds in neutral plasmas, where the constraint $\nabla_{r_e} f_e = 0$ may also be important.

This hierarchy inversion distinguishes our model from existing nonlocal transport models [7, 9] which attributed heat-flux suppression to the nonlocal sampling of temperature gradients by free-streaming electrons. While those models introduce adjustable parameters, our first-principles approach traces the suppression to a fundamental constraint $\nabla_{r_e} f_e = 0$ that eliminates the need for adjustable parameters. Thus, our model provides a microscopic foundation that complements and potentially unifies existing phenomenological descriptions.

The framework has immediate, practical consequences. It supplies a first-principles, parameter-free expression for the empirical heat-flux limiter, enabling more predictive simulations. A definitive experimental test lies in the Z-scaling of the thermal conductivity ratio κ_t/κ_{SH}. Our model predicts a relation $\kappa_t/\kappa_{SH} \sim Z^{-2}$ in the semi-free electron regime. Precision measurements across varying Z dopants would provide strong validation.

4. CONCLUSION

We have introduced the concept of semi-free electrons, reformulated the Fokker-Planck equation accordingly, and developed an analytical model that addresses the

long-standing reduction of thermal conductivity in plasmas. The model yields accurate estimates of plasma thermal conductivity and heat-flux limiters across both small and large temperature gradients, consistent with experimental observations. The model is explicitly limited to collisional, quasi-neutral transport phenomena (e.g., heat conduction in ICF and tokamak plasmas) and does not apply to high-frequency processes such as Langmuir waves, plasma oscillations, or collisionless kinetic instabilities. Within this domain, the semi-free electron concept advances our understanding of plasma behavior and may have broad implications for predictive modeling in inertial and magnetic confinement fusion.

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Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Y. J. Huang conceptualized the work and contributed to this work.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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