

Quantum Plasma And Its Applications

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- Classical Plasma
- Breakdown of Classical Description
- Quantum Plasma Conditions
- Fermi energy and Degeneracy
- Quantum Effects in Plasma Models
- Quantum Tunneling
- Quantum Diffraction
- Wave–Particle Duality
- Stellar Evolution and Degeneracy Pressure
- Applications of Quantum Plasma

Classical Plasma

- Ionized gas of electrons and ions
- Quasi-neutral and collective behavior

A system behaves as a classical plasma if:

1.

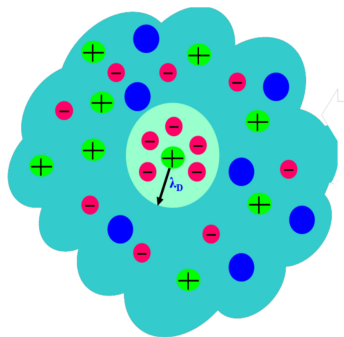
$$L \gg \lambda_D$$

2.

$$N_D \gg 1$$

3.

$$\omega_p \tau \gg 1$$



Debye length vs de Broglie wavelength

1. Debye length

$$\lambda_D = 69 \left(\frac{T}{n} \right)^{1/2} m$$

2. de Broglie wavelength

$$\lambda_{dB} = \frac{\hbar}{p}$$

- High density \rightarrow wavefunction overlap
- Low temperature \rightarrow quantum effects appear

A plasma behaves as a quantum plasma when

1. de Broglie Wavelength Condition

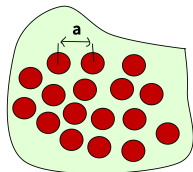
$$\lambda_{dB} \sim a$$

2. High Density Condition

$$n \gtrsim 10^{26} \text{ m}^{-3}$$

3. Degeneracy Condition

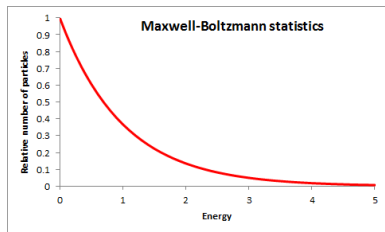
$$T \leq T_F$$



Fermi vs Boltzmann

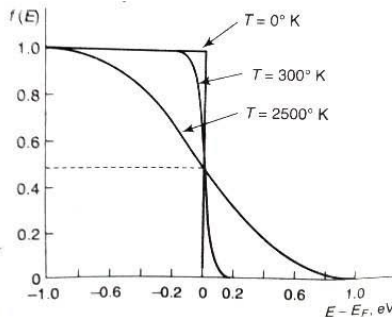
- Maxwell-Boltzmann statistics

$$f(E) \propto e^{-E/kT}$$

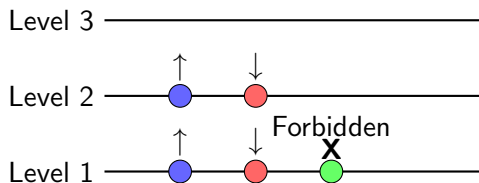


- Fermi-Dirac statistics

$$f(E) = \frac{1}{e^{(E-E_F)/kT} + 1}$$

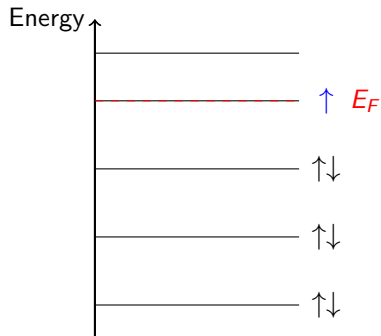


Pauli Exclusion Principle



Fermi Energy and Degeneracy

- **Fermi energy E_F** : highest occupied state at $T = 0$
- **Degeneracy**: filling low-energy states forces electrons upward
- **Degeneracy pressure** $\propto n$



- Classical fluid equations modified by:

① **Bohm potential** $V_B = -\frac{\hbar^2}{2m} \frac{\nabla^2 \sqrt{n}}{\sqrt{n}}$

② **Quantum force** $F_Q = -\nabla V_B$

③ **Fermi pressure** $P_F \sim n^{5/3}$

$$V_B = \frac{\hbar^2}{2m} \frac{\nabla^2 \sqrt{n}}{\sqrt{n}}$$

- Quantum hydrodynamic effect
- Appears due to wave nature of particles
- Derived from Schrödinger equation

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \psi + V\psi$$

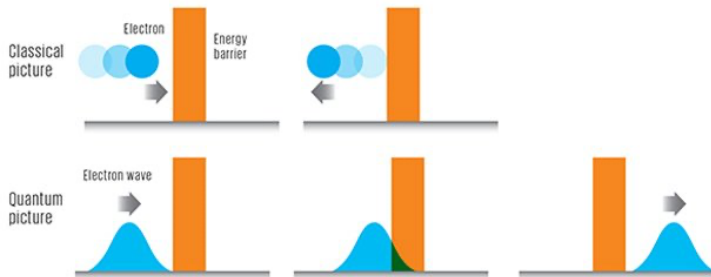
Continuity:

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\vec{u}) = 0$$

Momentum:

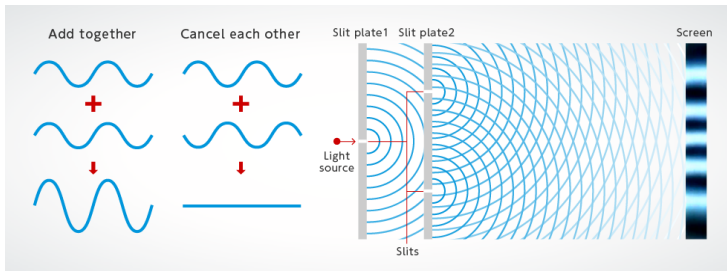
$$mn \left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} \right) = -\nabla V_C - \nabla V_B$$

Quantum Tunneling



$$E = V_C + V_B$$

Quantum Diffraction

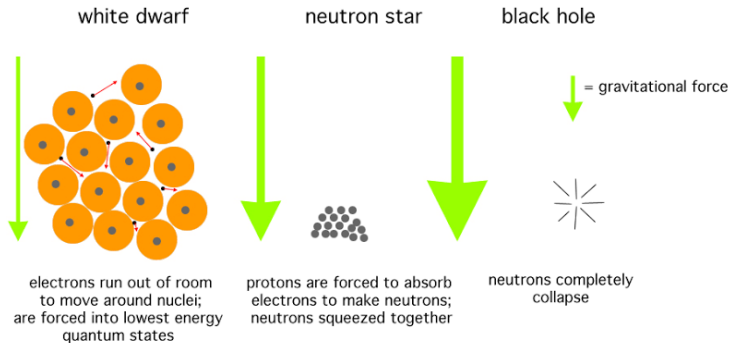


Wave-Particle Duality

$$n = |\psi|^2$$

- Density linked to wave function
- Represents probability

Stellar Evolution and Degeneracy Pressure



Degeneracy Pressure

- Arises from Pauli exclusion principle, independent of temperature, supports dense objects.

Chandrasekhar Limit

- If $M \leq 1.4M_{\odot}$ → White Dwarf (stable)
- If $M > 1.4M_{\odot}$ → Neutron Star

Tolman-Oppenheimer-Volkoff (TOV) limit

- If $M > 2.5M_{\odot}$ → Black Hole

Competition of Forces

- Gravity \rightarrow compresses the star
- Degeneracy pressure \rightarrow resists compression

Outcomes

- Thermal $>$ Gravity \rightarrow Explosion
- Gravity $>$ Pressure \rightarrow Collapse

Key Message

- Quantum effects determine the fate of stars

Summary Table: Classical vs Quantum Plasma

| Property | Classical Plasma | Quantum Plasma |
|---------------------|--------------------------------|---|
| Length scale | Large ($L \gg \lambda_{dB}$) | Small ($L \sim \lambda_{dB}$) |
| Statistics | Maxwell-Boltzmann | Fermi-Dirac |
| Exclusion Principle | Not applicable | Pauli exclusion principle |
| Pressure | Thermal | Fermi pressure (even $T = 0$) |
| Control Parameter | Temperature | Density |
| Tunneling | Not possible | Possible |
| Typical Systems | Lab plasmas | White dwarfs, neutron stars, nanostructures |

Applications of Quantum Plasma

- **Astrophysical Systems:** White dwarfs

After the star exhaust the nuclear fuel it becomes white dwarf

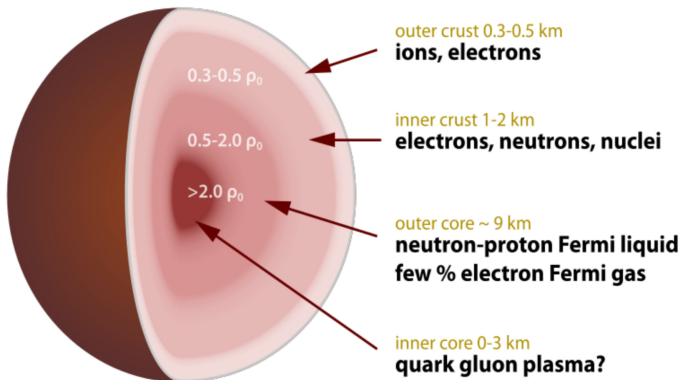


Figure: White dwarfs

Applications of Quantum Plasma Con...

- **Astrophysical Systems:** Neutron stars

Neutron stars are created when giant stars die in supernovas and their cores collapse, with the protons and electrons essentially melting into each other to form neutrons.



- Ultracold Plasmas
- Laser Fusion and Laser-Produced Plasmas
- Plasmonics and High-Intensity Light Sources
- Nanoscale Systems and Quantum Wells
- Nanowires and Nanoelectronics
- High-Density Semiconductors

Thank You