

Solutions to the problems in Chapter 6

6.3 Pressure of a Fermi gas at zero temperature

The number of electrons N and the internal energy U , in the volume V , are

$$N = V \int_0^\infty D(\varepsilon) f(\varepsilon) d\varepsilon, \quad U = V \int_0^\infty \varepsilon D(\varepsilon) f(\varepsilon) d\varepsilon, \quad (1)$$

The Fermi distribution function $f(\varepsilon)$ and the density of states (per unit volume) $D(\varepsilon)$ are

$$f(\varepsilon) = \frac{1}{e^{\beta(\varepsilon - \mu)} + 1}, \quad D(\varepsilon) = A\sqrt{\varepsilon}, \quad A = \frac{\sqrt{2m^3}}{\pi^2 \hbar^3}. \quad (2)$$

At zero temperature

$$f(\varepsilon) = \theta(\varepsilon_F - \varepsilon), \quad \varepsilon_F = \frac{\hbar^2 k_F^2}{2m}, \quad k_F = (3\pi^2 n)^{1/3} \quad (3)$$

Introducing the step function and $D(\varepsilon) = A\sqrt{\varepsilon}$ in (1), we may determine $U(0)$ and an alternative expression for A :

$$N = V \int_0^{\varepsilon_F} A\sqrt{\varepsilon} d\varepsilon = \frac{2}{3} V A \varepsilon_F^{3/2} \Rightarrow A = \frac{3n}{2\varepsilon_F^{3/2}}, \quad U(0) = V \frac{2}{5} A \varepsilon_F^{5/2} = \frac{2}{5} N \varepsilon_F \quad (4)$$

i.e. $U \propto \varepsilon_F \propto k_F^2 \propto V^{-2/3}$ and the pressure at zero temperature is

$$P = -\frac{\partial U(0)}{\partial V} = \frac{2}{3} \frac{U}{V} = \frac{2}{3} n \varepsilon_F = \frac{(3\pi^2)^{2/3} n^{5/3} \hbar^2}{5m} \quad (5)$$

in sharp contrast to a classical gas, where the zero-temperature pressure is zero.

6.4 Density of states in low dimensions

The density of states in $\vec{k}$ -space is $D_{\vec{k}} = 2/(2\pi)^d$ in d dimensions (6.34)

$$D(\varepsilon) = \int |\vec{dk}| \delta(\varepsilon - \varepsilon_{\vec{k}}) \equiv \int D_{\vec{k}} \delta(\varepsilon - \varepsilon_{\vec{k}}) d\vec{k} = \frac{2}{(2\pi)^d} \int \delta(\varepsilon - \varepsilon_{\vec{k}}) d\vec{k} \quad (1)$$

Introducing "spherical coordinates" in d dimensions and $k = |\vec{k}|$, then

$$d\vec{k} = \begin{cases} 2 dk & , \quad d = 1 \\ 2\pi k dk & , \quad d = 2 \\ 4\pi k^2 dk & , \quad d = 3 \end{cases} \quad (2)$$

The factor 2 in the one-dimensional case appears because the one-dimensional wave vector may assume both positive and negative values, whereas $k \geq 0$ per definition.

$$\varepsilon_{\vec{k}} = \varepsilon_k = \frac{\hbar^2 k^2}{2m} \Rightarrow k = \frac{\sqrt{2m\varepsilon_k}}{\hbar}, \quad dk = \left(\frac{m}{2\hbar^2 \varepsilon_k} \right)^{1/2} d\varepsilon_k \Rightarrow \quad (3)$$

$$D(\varepsilon) = \begin{cases} \frac{2}{2\pi} \int_0^\infty 2 \delta(\varepsilon - \varepsilon_k) \left(\frac{m}{2\hbar^2 \varepsilon_k} \right)^{1/2} d\varepsilon_k = & \frac{\sqrt{2m}}{\pi \hbar} \varepsilon^{-1/2}, \quad d = 1 \\ \frac{2}{(2\pi)^2} \int_0^\infty 2\pi \frac{\sqrt{2m\varepsilon_k}}{\hbar} \delta(\varepsilon - \varepsilon_k) \left(\frac{m}{2\hbar^2 \varepsilon_k} \right)^{1/2} d\varepsilon_k = & \frac{m}{\pi \hbar^2}, \quad d = 2 \\ \frac{2}{(2\pi)^3} \int_0^\infty 4\pi \frac{2m\varepsilon_k}{\hbar^2} \delta(\varepsilon - \varepsilon_k) \left(\frac{m}{2\hbar^2 \varepsilon_k} \right)^{1/2} d\varepsilon_k = & \frac{\sqrt{2m^3}}{\pi^2 \hbar^3} \varepsilon^{1/2}, \quad d = 3 \end{cases}$$

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