- The interaction of the conduction electrons with phonons. An electron tends to polarize or distort the lattice in its neighborhood, so that the moving electron tries to drag nearby ions along, thereby increasing the effective mass of the electron.
- The interaction of the conduction electrons with themselves. A moving electron causes an inertial reaction in the surrounding electron gas, thereby increasing the effective mass of the electron.

Heavy Fermions. Several metallic compounds have been discovered that have enormous values, two or three orders of magnitude higher than usual, of the electronic heat capacity constant γ. The heavy fermion compounds include UBe_{13}, $CeAl_3$, and $CeCu_2Si_2$. It has been suggested that f electrons in these compounds may have inertial masses as high as 1000 m, because of the weak overlap of wavefunctions of f electrons on neighboring ions (see Chapter 9, "tight binding").

ELECTRICAL CONDUCTIVITY AND OHM'S LAW

The momentum of a free electron is related to the wavevector by $m\mathbf{v} = \hbar\mathbf{k}$. In an electric field $\mathbf{E}$ and magnetic field $\mathbf{B}$ the force $\mathbf{F}$ on an electron of charge $-e$ is $-e[\mathbf{E} + (1/c)\mathbf{v} \times \mathbf{B}]$, so that Newton's second law of motion becomes

(CGS) $$\boxed{\mathbf{F} = m\frac{d\mathbf{v}}{dt} = \hbar\frac{d\mathbf{k}}{dt} = -e\left(\mathbf{E} + \frac{1}{c}\mathbf{v}\times\mathbf{B}\right)\ .} \qquad (39)$$

In the absence of collisions the Fermi sphere (Fig. 10) moves in $\mathbf{k}$ space at a uniform rate by a constant applied electric field. We integrate (39) with $\mathbf{B} = 0$ to obtain

$$\mathbf{k}(t) - \mathbf{k}(0) = -e\mathbf{E}t/\hbar\ . \qquad (40)$$

If the force $\mathbf{F} = -e\mathbf{E}$ is applied at time $t = 0$ to an electron gas that fills the Fermi sphere centered at the origin of $\mathbf{k}$ space, then at a later time t the sphere will be displaced to a new center at

$$\delta\mathbf{k} = -e\mathbf{E}t/\hbar\ . \qquad (41)$$

Notice that the Fermi sphere is displaced as a whole because every electron is displaced by the same $\delta\mathbf{k}$.

Because of collisions of electrons with impurities, lattice imperfections, and phonons, the displaced sphere may be maintained in a steady state in an electric field. If the collision time is τ, the displacement of the Fermi sphere in the steady state is given by (41) with $t = \tau$. The incremental velocity is $\mathbf{v} = \hbar\delta\mathbf{k}/m = -e\mathbf{E}\tau/m$. If in a constant electric field $\mathbf{E}$ there are n electrons of charge $q = -e$ per unit volume, the electric current density is

$$\mathbf{j} = nq\mathbf{v} = ne^2\tau\mathbf{E}/m\ . \qquad (42)$$

This is **Ohm's law**.

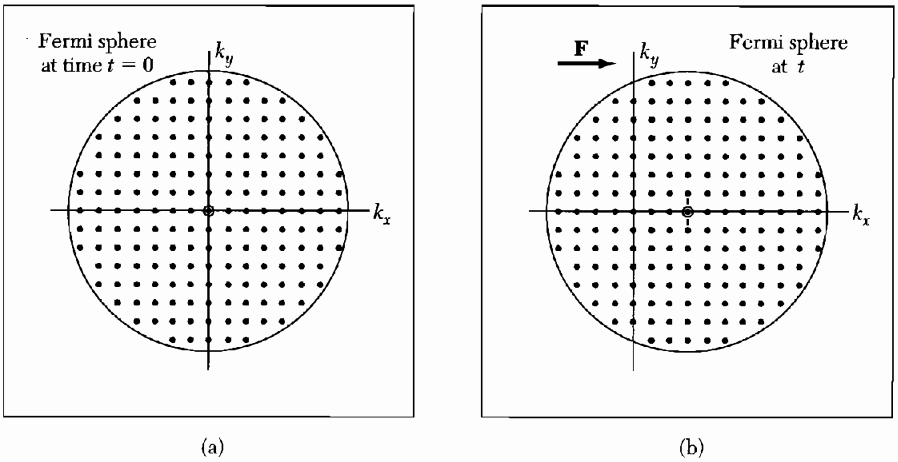

Figure 10 (a) The Fermi sphere encloses the occupied electron orbitals in **k** space in the ground state of the electron gas. The net momentum is zero, because for every orbital **k** there is an occupied orbital at $-\mathbf{k}$. (b) Under the influence of a constant force **F** acting for a time interval t every orbital has its **k** vector increased by $\delta\mathbf{k} = \mathbf{F}t/\hbar$. This is equivalent to a displacement of the whole Fermi sphere by $\delta\mathbf{k}$. The total momentum is $N\hbar\delta\mathbf{k}$, if there are N electrons present. The application of the force increases the energy of the system by $N(\hbar\delta\mathbf{k})^2/2m$.

The electrical conductivity σ is defined by $\mathbf{j} = \sigma\mathbf{E}$, so by (42)

$$\boxed{\sigma = \frac{ne^2\tau}{m}} \; . \tag{43}$$

The electrical resistivity ρ is defined as the reciprocal of the conductivity, so that

$$\rho = m/ne^2\tau \; . \tag{44}$$

Values of the electrical conductivity and resistivity of the elements are given in Table 3. In Gaussian units σ has the dimensions of frequency.

It is easy to understand the result (43) for the conductivity of a Fermi gas. We expect the charge transported to be proportional to the charge density ne; the factor e/m enters (43) because the acceleration in a given electric field is proportional to e and inversely proportional to the mass m. The time τ describes the free time during which the field acts on the carrier. Closely the same result for the electrical conductivity is obtained for a classical (Maxwellian) gas of electrons, as realized at low carrier concentration in many semiconductor problems.

Experimental Electrical Resistivity of Metals

The electrical resistivity of most metals is dominated at room temperature (300 K) by collisions of the conduction electrons with lattice phonons and at