magnetic moment $m = MV$, where M is the **magnetization** and V is the volume. The **magnetic susceptibility** χ is given by

$$\chi = \lim_{H\to 0} \frac{M}{H}. \tag{17.27}$$

For most paramagnets $\chi \ll 1$, so that $M \ll H$ and hence $B = \mu_0(H + M) \approx \mu_0 H$. This implies that we can write the magnetic susceptibility χ as

$$\chi \approx \frac{\mu_0 M}{B}. \tag{17.28}$$

Paramagnetic systems obey **Curie's law** which states that

$$\chi \propto \frac{1}{T}, \tag{17.29}$$

as shown in Fig. 17.6, and hence

$$\left(\frac{\partial \chi}{\partial T}\right)_B < 0, \tag{17.30}$$

a fact that we will use below.

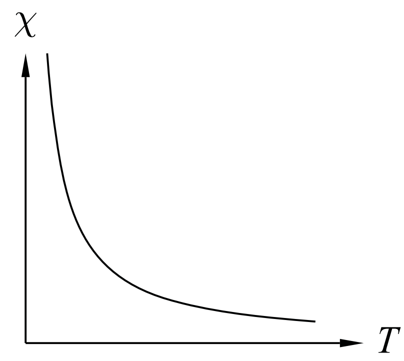

Fig. 17.6 The magnetic susceptibility for a paramagnet follows Curie's law which states that $\chi \propto 1/T$.

Example 17.4

Show that heat is emitted in an isothermal increase in B (a process known as **isothermal magnetization**) but that temperature is reduced for an adiabatic reduction in B (a process known as **adiabatic demagnetization**).

Solution: For this problem, it is useful to include the magnetic energy $-mB$ into the Helmholtz function, so we write it as

$$F = U - TS - mB. \tag{17.31}$$

This implies that (assuming V is constant)

$$\mathrm{d}F = -S\,\mathrm{d}T - m\,\mathrm{d}B, \tag{17.32}$$

which yields the Maxwell relation

$$\left(\frac{\partial S}{\partial B}\right)_T = \left(\frac{\partial m}{\partial T}\right)_B \approx \frac{VB}{\mu_0}\left(\frac{\partial \chi}{\partial T}\right)_B, \tag{17.33}$$

which relates the isothermal change of entropy with field at constant temperature to a differential of the susceptibility χ.

This coupling between thermal and magnetic properties is known as the **magnetocaloric effect**.

The heat absorbed in an isothermal change of B is

$$\Delta Q = T\left(\frac{\partial S}{\partial B}\right)_T \Delta B = \frac{TVB}{\mu_0}\left(\frac{\partial \chi}{\partial T}\right)_B \Delta B < 0, \tag{17.34}$$

and since it is negative it implies that heat is actually emitted. The change in temperature in an adiabatic change of B is

$$\left(\frac{\partial T}{\partial B}\right)_S = -\left(\frac{\partial T}{\partial S}\right)_B \left(\frac{\partial S}{\partial B}\right)_T. \tag{17.35}$$