The Mössbauer Effect

An interesting feature of γ decay is the Mössbauer effect. The photons emitted by nuclei making a transition from an excited state to the ground state are not monoenergetic but have a distribution of energies because of the energy width of the excited state. The natural width of the energy distribution of photons Γ is related to the mean lifetime τ of the excited state by $\Gamma = \hbar/\tau$, consistent with the uncertainty principle. The width and thus the lifetime can, in principle, be determined by the technique of *resonance fluorescence*, the absorption and reemission of a photon emitted by an atom or a nucleus of the same type. If the excited state has energy centered at E_0 with width Γ, the cross section for the absorption of photons has a sharp maximum at the excitation energy E_0 and drops to half the maximum value at $E_0 \pm (1/2)\Gamma$. The integral of the cross section over energy is proportional to Γ, so a measurement of absorption cross section versus energy can be used to determine Γ and therefore the lifetime τ. Resonance fluorescence is observed for atomic transitions but generally not for nuclear transitions because of the difference in the recoil energy between the two cases. The recoil energy is negligible compared with Γ for atomic transitions because of their low energy ($\approx$1 eV), which can be seen as follows: The typical lifetime of atomic states is about 10^{-8} s; therefore

$$\Gamma = \frac{\hbar}{\tau} \approx 10^{-7}\ \text{eV}$$

while the recoil energy E_r, also given by Equation 11-47 with M equal to the atomic mass, is

$$E_r = \frac{(1\ \text{eV})^2}{10^{11}\ \text{eV}} \approx 10^{-11}\ \text{eV}$$

for an atom with $A = 50$. Thus, the natural width of the photon emitted in the atomic transition is of the order of 10^4 larger than the recoil energy (see Figure 11-24*a*). In the nuclear case, however, the photon energy is 10^5 to 10^6 times larger. For a nuclear state with the same lifetime and mass number as above, the recoil energy is

$$E_r = \frac{(10^5\ \text{eV})^2}{10^{11}\ \text{eV}} \approx 10^{-1}\ \text{eV}$$

Hence, the recoil energy is roughly a million times larger than the line width, and the resonance absorption rendered possible by the overlap of emitted and absorbed photons illustrated in Figure 11-24*a* for atomic transitions does not exist for nuclear gamma transitions, as Figure 11-24*b* illustrates. Therefore, in general, if the width of

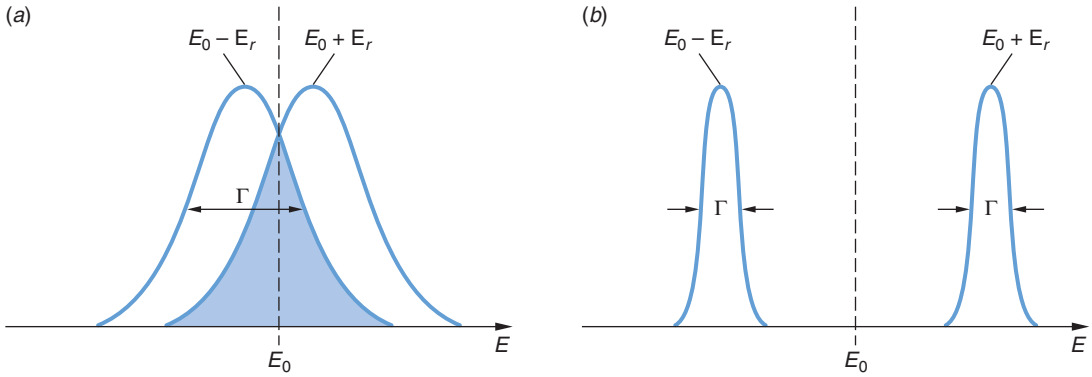

FIGURE 11-24 Schematic diagram of the photons emitted (left) and absorbed (right) by (*a*) an atomic state and (*b*) a nuclear state. In the atomic case the large energy overlap (shaded area) between the photon emitted by a state E_0 and that which the atom must absorb to excite the state E_0 allows the phenomenon of resonance absorption. In the corresponding nuclear case shown in (*b*), the magnitude of the recoil energy relative to the natural line width eliminates the overlap and with it the resonance absorption of gamma rays. (The energy axes of the two diagrams are different.)

the excited state Γ is less than $2E_r = E_0/Mc^2$, no photons will be emitted by a nucleus with energy great enough to be absorbed by another nucleus of the same kind and resonance fluorescence of gamma radiation cannot take place, *unless* the lines are greatly broadened by the Doppler effect so that at least a small overlap of the lines in Figure 11-24*b* occurs.

The thermal motion of atoms gives a Doppler broadening of the lines but does not shift the central energy because the motion is random and the chances of increase or decrease of energy are equal. At ordinary room temperatures, the Doppler energy width is of the order of $D = 10^{-6}E_0$, which is about 10 times the natural width for atomic transitions and much larger that the natural width for nuclear transitions. Because the Doppler width D is of the order of magnitude of the recoil energy E_r for nuclear transitions, the emission and absorption lines do have some overlap, and some resonance fluorescence is possible (see Figure 11-25).

In 1950, P. Moon successfully observed nuclear resonance fluorescence by placing a source on the rim of an ultracentrifuge rotor that revolved such that the rim had a speed of about 800 m/s, introducing an external Doppler shift compensating for the recoil loss. By varying the speed, he was able to measure the absorption cross section as a function of energy and determine a mean life of the order of 10^{-11} s for his source.

In 1958, Rudolf Mössbauer[14] used an ^{191}Ir source of 129 keV photons, for which the Doppler broadening at room temperature is about twice the recoil shift, so that the lines in Figure 11-24*b* overlapped a bit and resonance fluorescence could be observed. When he cooled the source and absorber, he expected to see the absorption decrease because of the decrease in the Doppler width and so in the overlap. Instead, he observed an increase in the absorption. The absorption, in fact, was as much as would be expected if there had been no recoil at all! The qualitative explanation of this effect is that at sufficiently low temperatures, an atom in a solid cannot recoil individually because of the quantization of the vibrational energy states in the lattice. The recoil momentum is absorbed by the crystal as a whole. The effective mass in Equation 11-47 is thus the mass of the crystal, which is so much larger than that of the atom that the recoil energy is completely negligible. The emitted photon, therefore, has energy E_0 that can be absorbed without recoil by another nucleus that is similarly

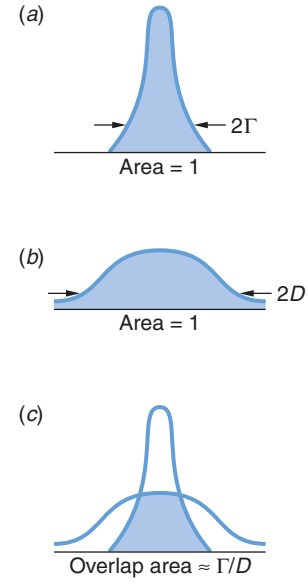

FIGURE 11-25 (*a*) Unbroadened line with natural width Γ. (*b*) Doppler-broadened line with the same area as in (*a*). (*c*) Absorption in resonance fluorescence is proportional to the overlap area, which is approximately Γ/D.

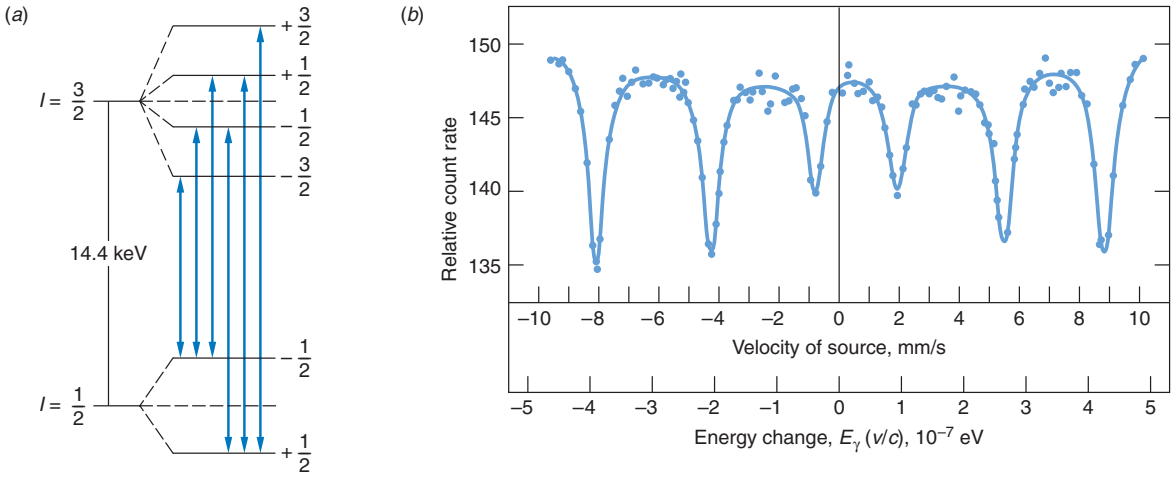

FIGURE 11-26 (*a*) Schematic diagram of the decay of the isomeric state of ^{57}Fe at 14.4 keV for atoms bound in an ordinary iron lattice showing the hyperfine splitting of the levels due to the magnetic field at the nucleus. (*b*) The absorption of the 14.4 keV ^{57}Fe gamma ray by ^{57}Fe bound in a lattice of Fe_2O_3 as a function of the relative source-absorber velocity, showing the nuclear Zeeman effect. *[From O. C. Kistner and A. W. Sunyar, Physical Review Letters, 4, 412 (1960).]*

bound in a lattice. Mössbauer was able to destroy the resonance by moving the source or absorber, thereby introducing an external Doppler shift. However, this shift need be only of the order of Γ, which is 4.6×10^{-6} eV for ^{191}Ir. The velocity needed to obtain a Doppler shift of this energy is only a few centimeters per second. In the event that the excited state is an isomer, then the lines in Figure 11-24*b* are particularly narrow. As a result, a frequently used source for Mössbauer measurements is ^{57}Fe, which has an isomeric state at 14.4 keV with a lifetime of about 10^{-7} second, corresponding to a line width of about 10^{-8} eV, or about $1/10^{12}$ of the transition energy. The ability to "scan" the line from the gamma-emitting source across the line of the gamma-absorbing sample by varying the Doppler velocity of the source or the absorber has enabled scientists to conduct a wide variety of experiments with a precision much higher than had been possible before Mössbauer's discovery. For example, Figure 11-26*a* shows the Zeeman effect in the ^{57}Fe 14.4 keV gamma ray that arises due to the nuclear magnetic field, thus making possible measurement of the magnetic field at the location of the iron nucleus.

Questions

6. Why is the decay series $A = (4n + 1)$ not found in nature?

7. A decay by α emission is often followed by a β decay. When this occurs, it is usually a β^- decay. Why?

8. How can the application of very high pressure affect the lifetime of a sample that decays by electron capture? Why are other types of decay not affected?