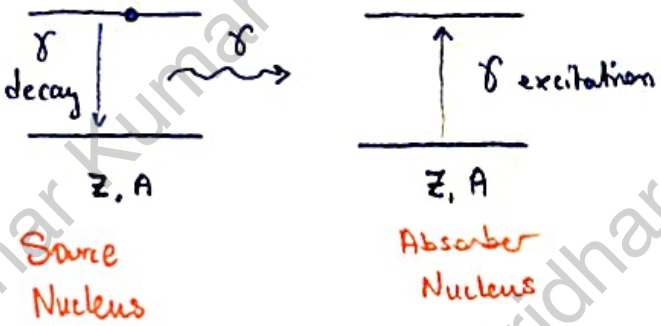
Mössbauer Effect

There are two ingredients in this effect. First one is resonant absorption of a radiated photon by a source (nucleus) captured by an absorber (nucleus)



This emission and resonant absorption had been observed for X-rays (that are produced by electronic transitions) for gases. However, attempts to observe γ-ray resonance in gases failed primarily due to much more significant energy being lost to recoil that down shifts the radiated photon. There is a huge advantage to extend resonant absorption to γ-ray wavelengths as typical width/Energy (Γ/E) ratios lie in 10^{-11} range that has the potentiality as an ultrahigh precision energy spectrometer. So, let's first see the associated recoil energy problem.

Iridium, $^{191}_{77}Ir$ has an energy of 0.129 MeV as its first excited nuclear state, which has a measured lifetime of $T = 1.4 \cdot 10^{-10}$ s

As the mass M of the nucleus is large, we can use classical expression

$P_n = \sqrt{2MK}$ for its recoil momentum

(K: K.E of nuclear recoil)

Cons. of linear momentum: $P_n = P_\gamma = \frac{E_\gamma}{c}$ (E_γ: of the radiated γ-ray)

$$\Rightarrow K = \frac{E_\gamma^2}{2Mc^2}$$

Cons. of energy: $E_{decay} = K + E_\gamma$ (0.129 MeV (transition energy of the source nucleus))

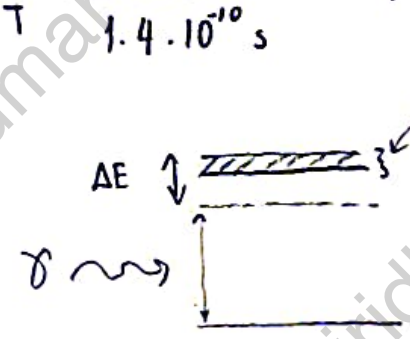
So, the downward shift ΔE in the energy of the γ-ray due to recoil is

$$\Delta E = -K = -\frac{E_\gamma^2}{2Mc^2} \overset{\text{approx.}}{\simeq} -\frac{(0.129)^2\ MeV^2}{2 \times 191 \times 931\ MeV} = -4.7 \cdot 10^{-2}\ eV$$

NB: The same result could be obtained by considering the γ-ray to be emitted from a moving source, the recoiling nucleus, and using the longitudinal Doppler shift formula to evaluate the downward shift in its frequency, or energy.

Now, considering the broadening (width) of the $^{191}_{77}Ir$ first excited state

$$\Gamma = \frac{\hbar}{\tau} = \frac{6.6 \cdot 10^{-16}\ eV \cdot s}{1.4 \cdot 10^{-10}\ s} = 4.7 \cdot 10^{-6}\ eV$$



$\Delta E \gg \Gamma$ ($\exists$ factor of 10^4)

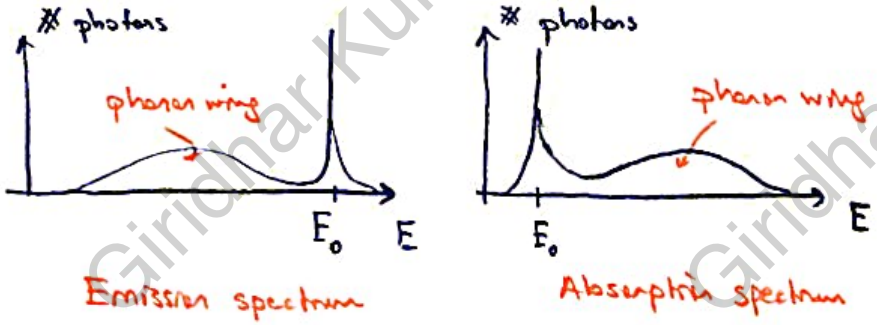
so, due to energy lost to recoil, this γ-ray cannot be reabsorbed by another Ir nucleus!

awarded Nobel prize in 1961

In 1958, a graduate student Rudolf Mössbauer was able to observe resonance in solid iridium, which raised the question of why γ-ray resonance was possible in solids, but not in gases. Mössbauer proposed that, for the case of atoms bound into a solid, under certain circumstances (zero phonon emission) a fraction of the nuclear events could essentially occur w/o recoil. He attributed the observed resonance to this recoil-free fraction of nuclear events.

> The classical analogy for illustrating to lay people is this: imagine jumping from a boat to shore, and imagine that the distance from boat to shore is the largest you can jump (on land). If the boat is floating in water, you will fall short b/c some of your energy goes into pushing the boat back. If the water is frozen solid, however, you will be able to make it!

So, the second ingredient is the recoil-free emission/absorption. In solids, even though the nucleus is bound to a macroscopic body (so that $M_{nuc} \to M_{solid}$ diminishing the recoil momentum/energy), there is the added complication of phonons. During this process no phonons should be involved!



Note that emission and absorption spectra overlap only for the Mössbauer (zero phonon) events and a few events involving low energy phonons. Most Mössbauer effects are performed at cryogenic (liquid He) temp's where zero-phonon processes are enhanced.

Mössbauer Spectroscopy

Mössbauer spectroscopy probes tiny changes in the energy levels (a few parts per 10^{11}) of an atomic nucleus in response to its environment. Typically three types of nuclear interaction may be observed:

1) Chemical Shift (Isomer shift)

The s electrons which have finite probability at $r = 0$ where there is the nucleus. So, MS is sensitive to variations of the s $\bar{e}$ density within the sample (but also, indirectly to p and d $\bar{e}$'s, as they influence s $\bar{e}$ density through screening)

2) Quadrupole Splitting

Nuclei with spin $> 1/2$ have electric quadrupole moments. Due to any electric field gradient at such a nuclear site, the spectra is further split. E.g. For ^{57}Fe with $I = 3/2$, there appear two peaks in MS corresponding to $M_I = \pm 1/2$ and $M_I = \pm 3/2$