Mossbauer Effect and Spectroscopy

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Emission

$E_{transition}$

$\gamma$-photon

$hv = E_{transition} - E_R$

Photon does not carry the full transition energy

**Conservation of momentum**  $\rightarrow$  **Energy loss in the form of recoil of the source atom**

Higher the energy of transition, the greater the photon energy ($hv$) and hence, its momentum ($hv/c$)

Higher is the energy loss to the recoil

$hv = E_{transition} - E_R$

Actual energy of the emitted photon.
\[ E_\gamma = E_{\text{transition}} - E_R \]

\[ E_\gamma' = E_{\text{transition}} + E_R \]

Thus, there is an energy mismatch of \(2E_R\).

**Is absorption possible?**

It depends on the **lifetime of the excited state** and **recoil energy**.

- **Natural energy width**
  \[ \Gamma = \frac{1}{T} \]

- **Recoil energy**
  \[ E_R = \frac{E_\gamma^2}{2m_a^2} \]

**Condition for absorption**

\[ \Gamma > 2E_R \]
Atomic transitions

\( E_{\text{transition}} = \text{few eV (in visible region)} \)

\( m_a = \text{atomic mass} = A \times 1000 \text{MeV (} A \text{ is atomic number)} \)

\[
E_R = \frac{(1 \rightarrow 10 \text{eV})^2}{(10 \rightarrow 100)1000 \text{MeV}} = 10^{-12} - 10^{-10} \text{eV}
\]

*For atomic transitions, the typical lifetime is \(~10^{-8} \text{ sec}\)*

The energy uncertainty \( \Gamma = 10^{-7} \text{eV} \)

\[ \Gamma \gg 2E_R \]

Thus, recoil does not affect the absorption
Nuclear transitions

$E_{\text{transition}} = \text{few MeV (for } \gamma\text{-emission)}$

$m_a = \text{atomic mass} = A \times 1000 \text{MeV (} A \text{ is atomic number)}$

$$E_R = \frac{(0.1 \rightarrow 10 \text{MeV})^2}{(10 \rightarrow 100)1000 \text{MeV}} = 0.1 - 10^4 \text{ eV}$$

*For atomic transitions, the typical lifetime is* $\sim 10^{-10} \text{ sec}$

The energy uncertainty $\Gamma = 10^{-5} \text{ eV}$

$\Gamma \ll 2E_R$

Magnitude of recoil in a free atom is much larger than the natural linewidth.
Resonance Fluorescence in a free-standing nucleus is impossible
**Iridium 191**

Transition energy \((h\nu) = 129\ \text{keV}\)
Recoil velocity on emission of a \(\gamma\)-photon emission \((v) = 202\ \text{m/s}\)
Actual energy of the emitted \(\gamma\)-photon \((h\nu') = 128.999912874\ \text{keV}\)

Energy difference \(\Delta E = 8.71 \times 10^{-5}\ \text{keV}\)

Natural linewidth \(\Gamma = 3.22 \times 10^{-8}\ \text{keV}\)

\(\Delta E \gg \Gamma \rightarrow \text{Transition not possible}\)

Resonance fluorescence in a gas in visible region (atomic transitions) is readily observed. This is not true for nuclear transitions in a gas.
In 1958, Rudolf Mossbauer, a German physicist demonstrated recoil-less emission and resonant absorption of $\gamma$-radiation.

**Mossbauer’s Scheme**

Embed the emitting and absorbing nuclei in crystals and cool them down

Nuclei tightly held in place

Negligible momentum transfer during emission due to much larger mass (virtually stationary)

Resonant absorption *IF* the absorber nucleus is in the same state as the source nucleus.

What if the source and the absorber are not in identical environment?
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Fe$^{3+}$ nuclei are placed in different environments

Shift in nuclear transition energies

These *signature* shifts can experimentally determined using **Mossbauer effect** and **Doppler effect**

**Mossbauer Spectroscopy**

*What if the source and the absorber are not in identical environment?*
**Mossbauer Spectroscopy**

**Absorber** consists of atoms whose spectra is to be studied is embedded in a crystal.

**Source** consists of identical (radioactive) atoms that emit $\gamma$-photons and is back and forth with variable speeds.

**Detector** collects $\gamma$-photons and records dips in intensity corresponding to resonant absorptions.
Moving the source introduces Doppler shift in the emitted photons

\[ h\nu_{\text{observed}} = h\nu_{\text{source}} \sqrt{\frac{1 + \frac{v}{c}}{1 - \frac{v}{c}}} \]

If \( \frac{v}{c} \ll 1 \) this simplifies to

\[ h\nu_{o} \approx h\nu_{s} (1 \pm \frac{v}{c}) \]

Source of continuous energy over a small range about a central frequency

Suitable for probing nuclear transition energies which are very closely spaced
Nuclear Zeeman effect

Mössbauer effect in $^{57}$Fe

Note that the splittings are 11 orders of magnitude smaller than the nuclear transition energy!

Chemical information in Mossbauer Spectra

Spectra reveal splittings of nuclear levels, determined by the electronic environment

- **Isomer shift**: Interaction of the nuclear charge distribution with the electron cloud surrounding the nuclei in both the absorber and source. Information about position of the centroid of the line, oxidation state, covalency of the bondings

- **Quadrupole splitting**: Interaction of the nuclear electric quadrupole moment with the EFG (electric field gradient) and the nucleus. Multiple asymmetry in the electronic environment, chemical spin state, strength of ligand field

- **Magnetic splitting** (Zeeman or Dipole interaction): Interaction of the nuclear magnetic dipole moment with the external applied magnetic field on the nucleus.
Effect of a) Isomer shift, and b) Quadrupole splitting on nuclear energy levels of $^{57}\text{Fe}$
Criteria for observing Mossbauer Effect are:

1.
Thank you!