

# Mössbauer Spectroscopy

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## Abstract

This paper is a review article on the principles and applications of Mossbauer Spectroscopy. Rudolph Mossbauer, while working on his thesis paper, discovered the recoil-less absorption of  $\gamma$  rays. This phenomenon developed into a spectroscopic technique known as Mossbauer spectroscopy. This technique is used to measure hyperfine interaction in the nucleus. These hyperfine interactions are strongly dependent on the nucleus's neighbouring environment. Thus, this technique has been used in various fields to study the electric and magnetic structure of given sample.

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# 1 Introduction

Mossbauer Spectroscopy is a versatile technique that is based on the quantum mechanical 'Mossbauer Effect'. It is a method that records the spectrum of energies at which specific nuclei absorb  $\gamma$  rays. It is mainly used to get unique measurements of electronic, magnetic and structural properties within the material. The success of this technique is credited to Rudolph Ludwig Mossbauer who discovered the Mossbauer Effect in 1958 by observing the efficient  $\gamma$  ray absorption and emission process in  $^{191}\text{Ir}$ . He explained why the nuclei must be embedded in solids for recoil-free emission and absorption of  $\gamma$  rays.

Most applications of this technique utilizes hyperfine interactions in the nucleus by perturbing the energies of nuclear states. These perturbations are very low in energy ( $10^{-7}$  eV) compared to typical  $\gamma$  rays ( $10^4$  eV). Therefore, Mossbauer spectroscopy requires high resolution energy spectrometers (few parts in  $10^{11}$ ) to record these perturbations. In this technique, the typical hyperfine interactions observed are due to difference in nearby electron densities (Isomer Shift), atomic scale electric field gradients (Electric Quadrupole Splitting), or unpaired electron spins (Magnetic Nuclear Zeeman Splitting).

The Mossbauer effect is very sensitive to the arrangement of its surrounding atoms due to which there has been a lot of research in the past few decades to understand the nuclear hyperfine interactions in different environments. From these studies it is found that Mossbauer spectroscopy is best for identifying electronic/magnetic structure of the atom itself. At present, these studies are performed using  $^{57}\text{Fe}$ ,  $^{119}\text{Sn}$ ,  $^{151}\text{Eu}$ ,  $^{121}\text{Sb}$ ,  $^{161}\text{Dy}$ . Other elements can be used if one can tackle problems such as the short lifetimes of radioactive isotopes, and the temperatures required for the study of the sample. Recently, Mossbauer spectroscopy has been used to study oxides, metals and alloys, and organometallics.

## 2 Working Principle

### 2.1 Nuclear States

To understand the working of a Mossbauer spectrometer it is essential that we understand some basic nuclear properties. It is a well-known fact that electron can excite and de-excite between different states by absorption or emission of a photon. Similarly, a nucleus can undergo transition between different quantum states. But, unlike an electronic transition that is in the order of a few eV's, nuclear excitations are of much higher energy (few 100 keV's). Therefore, the excite and de-excite through  $\gamma$  rays which are high energy photons ( $\sim 10^5$  eV). The Mossbauer effect is also called the Nuclear Resonant Gamma Ray Scattering because of the stated reason.

Also, an excited state can never be assigned a sharp energy value, but only a value within a range  $\Delta E$  due to the Heisenberg's Uncertainty Principle  $\Delta E \cdot \Delta t \geq \hbar$ . In general, it has been shown that  $\Gamma \tau = \hbar$ , where  $\Gamma$  is the natural line width and  $\tau$  is the lifetime of the state. In such a case, the energy distribution about energy  $E_o$  is given by the Lorentz distribution.

$$I(E) = \frac{(\Gamma/2)^2}{(E - E_o)^2 + (\Gamma/2)^2}$$

A Mossbauer spectrometer uses a highly monochromatic  $\gamma$  ray from one nucleus to excite the nucleus that we wish to study. The spectrum of the subsequent de-excitation in the nucleus is recorded and studied to get the Mossbauer spectrum. However, the de-excitation does not always occur by emission of  $\gamma$  particles. For example in  $^{57}\text{Fe}$  only 10.9% of the decay occurs this way. Other times, the energy is distributed among the surrounding electrons which de-excite by emitting X-rays. These X-rays can also be recorded and used to study the Mossbauer Spectrum.

## 2.2 Mossbauer Effect

In the previous section, it was stated that the  $\gamma$  ray emission from one nucleus is used to excite another one. But, in general, a energy precision for a nuclear excitation could be in the order of  $10^{-8}\text{eV}$ , which is extremely small. At room temperature, the vibrational energy of the nuclear center of mass is in the order of  $10^{-2}\text{eV}$ . So, if a  $\gamma$  that is incident on the target nucleus changes its vibrational state, then it would be far too imprecise to cause nuclear excitation. This seems extremely likely due to momentum conservation. When a high energy photon is incident on the nucleus, the photon loses its energy, thereby, loses some momentum. Due to the principle momentum conservation, the nucleus gains momentum and a kinetic energy ( $E_{recoil}$ ) is transferred from the  $\gamma$  ray to the nucleus.

$$p_{\gamma} = \frac{E_{\gamma}}{c}$$

$$E_{recoil} = \frac{p_{\gamma}^2}{2m} = \frac{E_{\gamma}^2}{2mc^2}$$

For a  $^{57}\text{Fe}$ , this energy is in the order of  $10^{-3}\text{eV}$ . This energy is much higher than the order of precision required for nuclear transitions. Because of this, such experiments were far less in number before the discovery by Mossbauer.

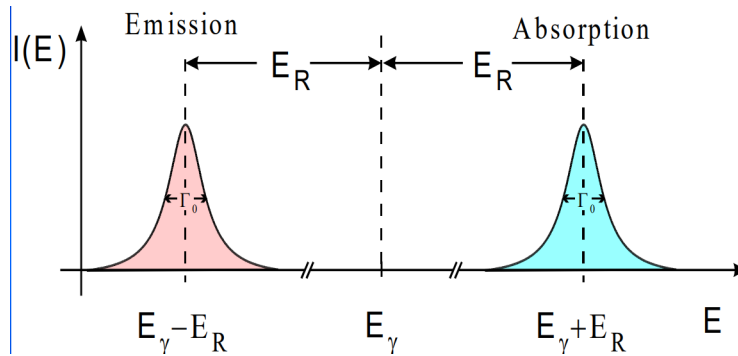


Figure 1: Energy Change due to Recoil Effect

For his thesis project, Rudolph Mossbauer had to record the emission spectrum of  $^{191}\text{Ir}$ . He used various methods such as reducing thermal excitation using a cryogenic bath, thermal Doppler broadening the emission line to compensate the recoil energy for increasing the number of resonant absorption. He also thought of using small mechanical movements on the sample or source to Doppler shift the  $\gamma$  ray to produce the appropriate wavelength necessary. During this he discovered that when the nuclear

sample is attached to crystal lattice, under appropriate conditions, the whole crystal system acts as a cushion to the recoil. This reduces the energy to the order of  $10^{-9}eV$ . This is true in the case that the nucleus is rigidly attached to the crystal lattice. But it is well-known that, a more realistic model is that of a Einstein's Solid.

In this model, the nucleus is attached to the lattice through a spring and acts as a simple harmonic oscillator with Einstein's frequency  $\omega_E$ . Here, it is possible that the energy of the incident photon is absorbed and dissipated by changing the simple harmonic oscillator's energy,  $\hbar\omega_E$ , (i.e. through phonons) which is in the order of  $10^{-2}eV$ . But, there is also a finite probability of the whole system acting as a cushion thus reducing the recoil energy significantly and the emitted  $\gamma$  ray has appropriate energy and resonance can occur. The fraction in which the body acts as such and we get an almost recoil free absorption is given by the Lamb-Mossbauer fraction.

To calculate the Lamb-Mossbauer fraction, one has to find the probability of the nuclear state going from initial state,  $|i\rangle$  to final state,  $|f\rangle$ . Here the nuclear states are given by,

$$|i\rangle = \left(\frac{m\omega_E}{\pi\hbar}\right)^{1/4} \exp\left(-\frac{m\omega_E X^2}{2\hbar}\right)$$

$$|f\rangle = \exp\frac{ip_\gamma X}{\hbar} |i\rangle$$

Then the final probability (Lamb-Mossbauer fraction) is given by,

$$f = |\langle i|f\rangle|^2 = \exp\left(-\frac{\hbar^2 k_\gamma^2}{2m\hbar\omega_E}\right) = \exp(-k_\gamma^2 \langle X^2 \rangle) = \exp\left(-\frac{E_{recoil}}{\hbar\omega_E}\right)$$

using normalization condition  $\langle i|i\rangle = 1$

From this equation, the condition for obtaining a significant number of recoil-free absorptions is achieved when the  $E_{recoil}$  is much smaller than the phonon excitation energy ( $\hbar\omega_E$ ) which is of the order of  $10^{-2}eV$ . For a free  $^{57}\text{Fe}$ , we have seen that  $E_{recoil}$  is of the order of  $10^{-3}$  and the condition is satisfied. But for other nuclei, the  $E_\gamma$  is much higher, thereby increasing  $E_{recoil}$  which makes it difficult for it to be used for Mossbauer spectroscopy.

### 3 Measurable Phenomenon

As hinted in the previous sections, the phenomenon that are mainly observed in Mossbauer spectroscopy are the three hyperfine interactions - Isomer Shift, Electric Quadrupole Splitting, Hyperfine Magnetic Splitting. Some other quantities such as the recoil free fraction can also be studied using this technique. There are also some other phenomenon such as phonon DOS, relaxation time, diffraction that have been studied in recent years.

#### 3.1 Isomer Shift

Isomer shift is a phenomenon that arises due to the finite radius of the nucleus and the s-electron density at the same nucleus. This leads to an Electric monopole (Coulombic interaction) between

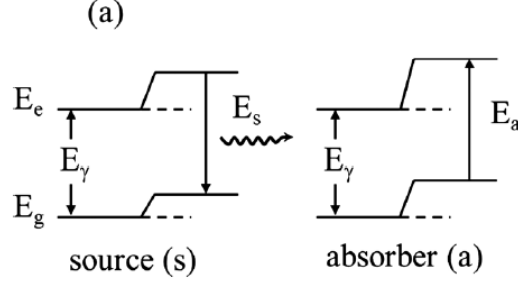


Figure 2: Isomer Shift

the atomic electrons and the nucleus. This causes perturbations in the nuclear energy levels. If this change in energy was same for all excited states of the nucleus, the emitted  $\gamma$  ray would have the same frequency. However, different excited states of the nucleus have different radii compared to the ground state. For example, in  $^{57}\text{Fe}$ , the 1st excited state nuclei is smaller where as for  $^{119}\text{Sn}$ , the ground state is smaller compared to the first excited state. Due to this change in the radii, the perturbation in the nuclear energy level may be more or less. Thus this change in energy causes a shift in the peaks in the Massbauer Spectrum.

The energy shift due to this effect is given by,

$$\Delta E_{IS} = CZe^2(R_{ex}^2 - R_g^2)(|\Psi_{sample}|^2 - |\Psi_{source}|^2)$$

Thus if the excited state radius is smaller than the ground state radius, there is a shift in peaks towards the left (negative shift) and in the complimentary case, there is a positive shift.

Depending on how the electronic shells are filled, the number of electrons in the d or f orbitals may change. When there are more electrons in these orbitals, the shielding effect is more, which reduces the s-electron density. Therefore, studying this shift in the Mossbauer spectrum allows us to glean information about the valence electron configuration of the given sample. More d/f orbital electrons, lesser the s-electron density, thus causing a more positive shift in the spectrum. Thus the isomer shift can be used for determining the oxidation states, valency states, electron shielding and electron drawing power of electronegative groups.

### 3.2 Electric Quadrupole Splitting

When the nucleus has a non-spherical charge distribution (when  $I \geq 1/2$ ), it has a non zero electric quadrupole moment that is given by

$$Q_{ij} = \int_{\tau_N} \rho_n(\vec{r})(3x_i x_j - r^2 \delta_{ij})$$

In presence of a uniform electric field, the nuclear charge distribution has no effect on the Coulomb energy. However, in presence of an electric field gradient, the interaction energies will be different on

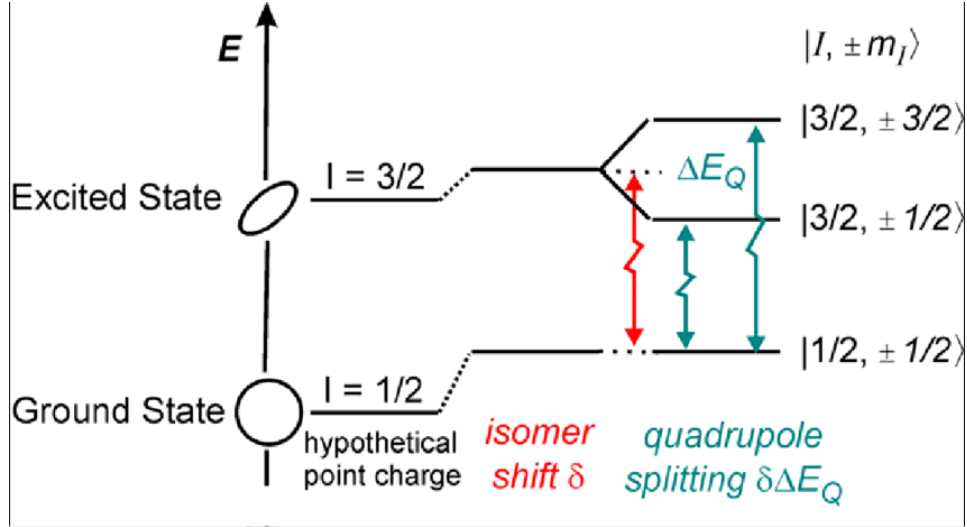


Figure 3: Nuclear states due to Quadrupole Splitting

each axis due to the asymmetry of the quadrupole moment. While specifying an electric field gradient, it is necessary to know how it changes in different directions (x,y,z generally). By convention, it is set that  $|V_{zz}| > |V_{yy}| > |V_{xx}|$ . Also the Laplacian requires that  $V_{xx} + V_{yy} + V_{zz} = 0$ . Therefore an electric field gradient can be characterized by only 2 quantities  $V_{zz}$  and asymmetry parameter  $\eta = \frac{V_{xx} - V_{yy}}{V_{zz}}$ .

The energy of the state due to this asymmetry is given by,

$$E_q = \frac{eQV_{zz}}{4I(2I-1)}(3M^2 - I(I+1))(1 + \frac{\eta^2}{3})^{1/2}$$

where I is the nuclear spin and M is the magnetic quantum number. In case of  $I = 1/2$ , there is only one level. But as we go to higher spins, the degeneracy in the nuclear energy is partially lifted. The number of levels the nuclear energy level splits into in presence of EFG for  $I = \frac{2n-1}{2}$  is given by n with each M state having a degeneracy of 2.

When an Mossbauer active isotope goes to an excited state (where  $I \neq 1/2$ ), in presence of EFG, the one line corresponding to de-excitation from excited state to ground state in the Mossbauer spectrum splits into multiple different lines. These transitions are subject to the selection rule  $\Delta M = 0, +1, -1$ . The change in the corresponding energy can be calculated by the above expression. The  $V_{zz}$  in the above expression is given by,

$$V_{zz} = (1 - \gamma_\infty)V_{zz}^{lat} + (1 - R)V_{zz}^{val}$$

here,  $\gamma_\infty$  and R are the Sternheimer anti-shielding and shielding factors. Depending on the valence electron configuration, these factors change thus changing the  $V_{zz}$ . This can be found from the energy difference in the split peaks in the Mossbauer spectrum. Thus, the quadrupole splitting can be used for determining oxidation state, spin state, site symmetry, and the arrangement of ligands.

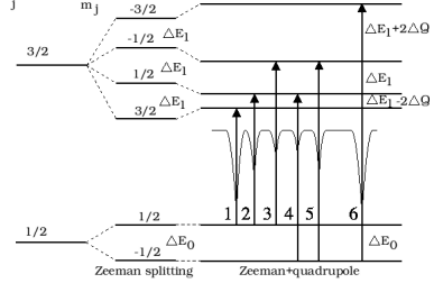


Figure 4: Nuclear states due to Hyperfine Magnetic Splitting

### 3.3 Hyperfine Magnetic Splitting

Nuclear states have spin and therefore have a corresponding magnetic dipole moment. These spins can be oriented along different directions. So, when a magnetic field is applied, the energies are split into a multitude of levels depending on  $I$  ranging from  $+I$  to  $-I$ . The energy perturbations by this are called the Nuclear Zeeman splitting which is analogous to that of Zeeman effect in atomic physics. Because of this splitting, the allowed transition lines increases pertaining to the condition the  $\Delta M = 0, +1, -1$ . The hamiltonian for this hyperfine interaction is given as,

$$H_m = -\mu \cdot B_{eff} = -g\mu_N I \cdot B_{eff}$$

and the energy corresponding to each level is given as,

$$E_m = \frac{-\mu B}{I} M = -g\mu_N B_{eff} M$$

The  $B_{eff}$  is the total magnetic hyperfine internal field acting on the nucleus which arises primarily due to the atoms own electron.  $B_{eff}$  can be split in different contributions such as,

$$B_{eff} = B_c + B_{orb} + B_{dip}$$

Here,  $B_c$  is the fermi contact field which is caused by the core polarization of s-electron density at the nucleus. It has the largest contribution to the effective magnetic field. In the non-relativistic approximation, it can be regarded as being due to the difference between spin up and spin down densities at the nucleus. This difference is due to unpaired electron in the f orbital which causes the polarization. It is expressed as,

$$B_F = \frac{-8\pi}{3} \mu_B \sum (|\Psi_{\uparrow}^s(0)|^2 - |\Psi_{\downarrow}^s(0)|^2)$$

$B_{dip}$  is the interaction of the magnetic dipole with the moment of electron spin.  $B_{orb}$  is the contribution from conduction electron spin magnetisation produced by the orbitals electron from the same and neighbouring atoms.

### 3.4 Other Phenomenons

Fluctuations in the line width of the spectra gives us more information about the sample. From the broadening of the spectra, we can know about the lifetime of the states as given by the relation previously. Atomic diffusion also causes a distortion in the line shape function of the spectra. Phonon partial DOS can be found by analysing the inelastic Mossbauer scattering through Synchrotron sources. We can also study more about the sample using diffraction and other interference phenomenon to understand about the multiple transfers of energy between the excited and ground state.

## 4 Experimental Setup

As seen earlier, a Mossbauer spectrometer contains a  $\gamma$  ray source and a sample that can absorb  $\gamma$  rays. Generally, either the source or the sample is connected to drive. This drive is used to provide the small mechanical movements that are used to Doppler shift the  $\gamma$  ray. Between the source and the sample, there is a collimator that is used to streamline the  $\gamma$  rays into thin beams. The detector can be kept in various places for different modes. In transmission mode, the detector is kept behind the sample to capture the transmitter rays. Whereas in back-scatter mode, the detector is kept all around the sample to capture the back-scattered rays.

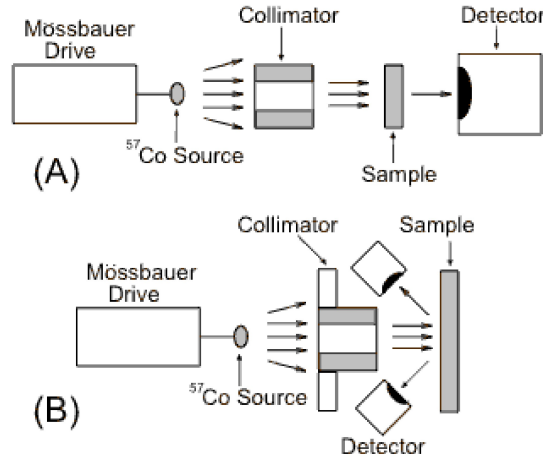


Figure 5: Schematic Diagram of Mossbauer Spectrometer

Suitable sources for Mossbauer spectroscopy include radioactive parent that decays to desired daughter isotopes. The parent isotope also needs to have a convenient life time for proper study of the sample. The energy of the  $\gamma$  ray produced by the source also needs to be low such that the recoil free fraction is high and we have a good signal to noise ratio.

Another factor to make note of while sample selection is to make sure that the natural line width of the sample and source are not too narrow or too broad. In such a case, the spectra may be lost as noise. Sharpness of resonance is given by

$$\text{Sharpness} = \frac{\Gamma}{E_{\gamma}}$$





shift, EFG, and HMF based on present values of model isotope. But sometimes, it is hard to distinguish between if it is an EFG or HMF. When these splits are too close, they may even be fit in an IS curve. Thus sorting out these parameters is a separate topic of research by itself.

Despite making much progress in the data processing of Mossbauer data, it is always important to look at difference in the experimental data by themselves. For such reasons it is always preferred to look at the experimental data without process for ourselves to judge if there is any difference in the Mossbauer spectra. For the general hyperfine interactions, the plots look as follows:

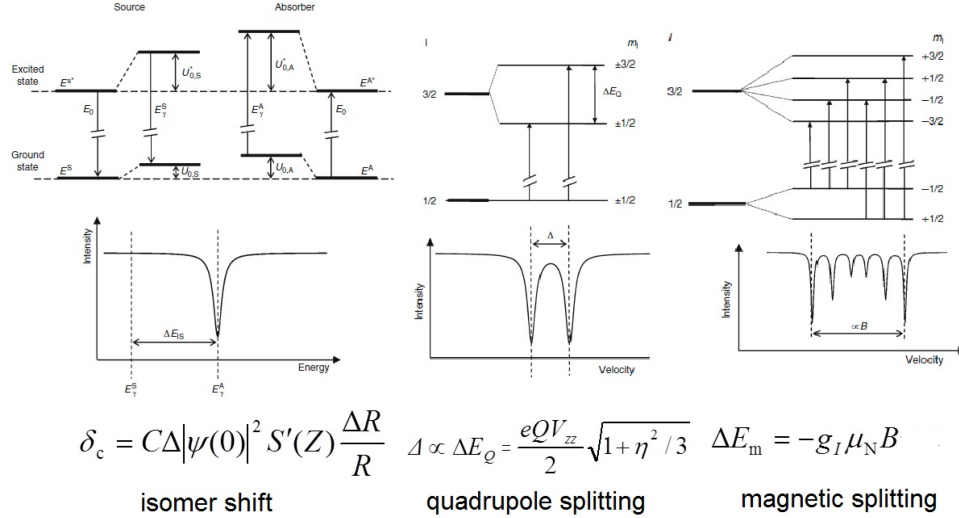


Figure 7: General change in Mossbauer Plot due to Hyperfine Interactions

## 6 Applications

Due to the very strict requirements from a Mossbauer sample and source, there are very little specimens that can be studied using this technique. Hence, this technique is mainly used for studying Iron (A=57) and Tin (A=119). Other exotic elements such as Lutetium and Europium are also studied using this technique. From the section on the working principle, we see that this technique is most useful in studying the electronic and magnetic properties of a given sample. In this section, we will see the applications in detail.

### 6.1 Chemical Bond Properties

Looking for the number of peaks and the shifts/splits in the peaks in a Mossbauer spectrum allows us to glean information about the chemical bonds of the specimen and some of its properties. One well-known property that we can gain info about is the strength of the specimen to pull electrons (i.e. electronegativity of the bond). As the electronegativity of the ion increases, the s-electron density at the specimen ions center decreases which causes a more positive isomer shift. One such example from literature is using Iron salts. The electronegativity increases from Iodine to Fluorine, thus the Isomer shift increases from  $\text{FeI}_2$  to  $\text{FeF}_2$ .

Another application of it has been in determining the structure of a compound. Based on the number of peaks in the spectrum and their positions, one can understand the different type of central atoms and their valency, which will help them in understanding the structure of the compound. The structure of  $\text{Fe}_3(\text{CO})_{12}$  was determined using this technique. From the analysis of X-ray diffraction, the structure of this compound was narrowed down to 3 possible structures. Two of the structures had a symmetry in the sense that all 3 Fe atoms has same type of ions surrounding them, whereas one of the structures has 2 different types of Fe atoms. The Mossbauer spectrum of this compound showed 2 different peaks implying there were 2 different types of Iron centres. Hence, the structure of  $\text{Fe}_3(\text{CO})_{12}$  was confirmed.

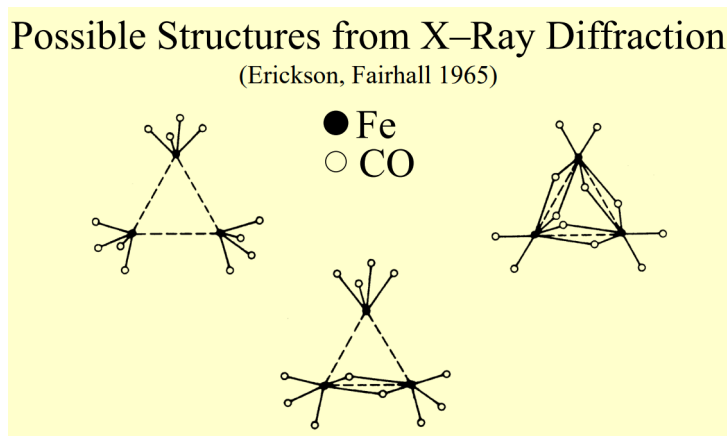


Figure 8: Possible Structures for  $\text{Fe}_3(\text{CO})_{12}$

## 6.2 Oxidation States

One major application of the Mossbauer spectra is in identifying to oxidation of state of the Mossbauer active compound based on the position of the peaks with reference to previous data. This is done using the information from the isomer shift combined with addition info from the Quadrupole splitting. The isomer shift is directly proportional to the electron density at the nucleus. Even if the isomer shift is very close for 2 ions (for eg. Low spin  $\text{Fe(II)}$  and  $\text{Fe(III)}$ ), there is difference in their quadrupole shift. Thus, the electronic state of the compound can be found.

This technique has helped in identifying and differentiating between 2 compounds. As an example, in 1963, a paper by Fluck, Kerler, and Neuwirth was used to distinguish between 2 Fe-Cyano complexes Prussian Blue and Turnbull's Blue. These 2 complexes differed in their preparation. PB was prepared by adding  $\text{Fe(III)}$  salt to a  $[\text{Fe}^{\text{II}}(\text{CN})_6]^{4-}$ , while TB was prepared by adding  $\text{Fe(II)}$  salt to a  $[\text{Fe}^{\text{III}}(\text{CN})_6]^{3-}$ . Before this paper, it was believed that these two compounds were chemically different. But the Mossbauer analysis showed only the presence of  $\text{Fe(III)}$  and  $[\text{Fe}^{\text{II}}(\text{CN})_6]^{4-}$ . The explanation given was that as soon as  $\text{Fe(II)}$  salt was added to a  $[\text{Fe}^{\text{III}}(\text{CN})_6]^{3-}$  solution, electron exchange takes place between the ions and this reaction also gave the same product as PB. This was confirmed by other experiments using Mossbauer Spectroscopy.

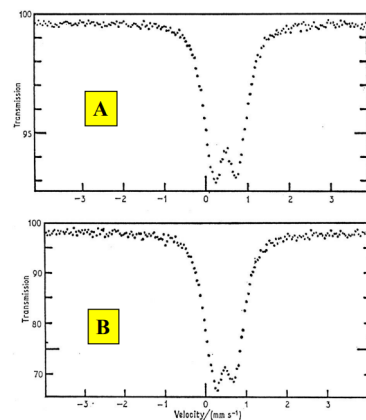


Figure 9: Mossbauer Spectra for A) PB and B) TB

### 6.3 Composition

The Mossbauer spectra can also be used to determine the composition of different compounds present in a given compound. Since this technique detects only Mossbauer active compounds, it is difficult to qualitatively get the exact composition in the specimen. But with some initial information such as the concentration of the active isotope, the composition in the material can be estimated.

Studying the hyperfine magnetic field splitting of a Fe crystal gives us an idea of its composition and purity. In a pure Fe BCC, The HMF for all the Fe atoms is -33.0T. However in ferromagnetic alloys, there is significant perturbations and the HMF value change. Similarly, presence of non-magnetic substances such as Si can also be found by the change in HMF. Since the Mossbauer spectra is measured as an average over the sample, the contributions of random defects cannot be found as they are low in intensity and are lost as noise. However, recent interest in nano-materials has led us to believe the defects/impurities in such a small sample may be found.

In the field of bio-inorganic chemistry, this technique has been used to identify the chemical nature of microorganisms. *Aquaspirillum Magnetotacticum*, is an iron containing microorganism that was studied by Frankel. These are sensitive to geomagnetic fields and act as a kind of bio-magnetic compass. From its spectrum, it was found that it contained  $\text{Fe}_3\text{O}_4$ , with half Fe(III) accommodated in tetrahedral sites and the other half of Fe(III) and all Fe(II) occupying octahedral sites.

### 6.4 Magnetic Properties

Mossbauer spectroscopy has become one of the standard tools that is used in magnetism research. There are many magnetic properties that can be studied using this technique. Some of the major ones are discussed in this section

Studying the Mossbauer spectrum of a sample in various temperature ranges to determine the transition temperature of a sample. One advantage with this is that it does not need any external magnetic field, since HMF due to the intrinsic fields themselves can be used to characterize these transitions. As the transition temperature approaches from a higher temperature, the absorption spectrum splits into multiple different lines. The variation of magnetization around this temperature can also be used

to determine the order of the magnetic transition.

Mossbauer spectra can be split into several magnetic sub spectra. This is the consequence of inequivalent atom sites in the crystal structure. Thus by studying the different HMF along with bulk magnetisation data, one can estimate the magnetic structure of a system. In a complex system, some data from neutron scattering may also be required for proper analysis. As seen earlier, this technique can also be used to get specific magnetic phases of the Mossbauer active element present in the crystal lattice.

The magnetic properties of material at the surface level may be different from the atoms in interfaces of the medium. Since the spectrometer works by detecting the  $\gamma$  rays that pass through the sample, this tool can be useful in studying the magnetic properties in the bulk of the sample. Thus, this tool helps us get a 3D overview of the magnetic properties of the sample.

## 7 Other Implementations

### 7.1 Mossbauer Emission Spectroscopy

Generally Mossbauer spectroscopy uses a single line emitter (such as  $^{57}\text{Co}$ ) to study the material under irradiation. The resultant spectra is of the absorber and this is known as Mossbauer Absorption Spectroscopy. Another such technique is the Mossbauer Emission spectroscopy, which is used to study the emitter as the sample. In such a experiment, a single line absorber (such as  $\text{K}_4[\text{Fe}(\text{CN})_6]$ ) is used as reference. Here the recorded spectrum is of the hyperfine interactions of the emitter and it yields information about its physical and chemical properties.

Such experiments are widely used to study the after-effects of nuclear decay in various materials, particularly poorly conducting coordination compounds. For example, radioactive  $^{57}\text{Co}$  nucleus captures an electron and turns into  $^{57}\text{Fe}$ . This transformation may have after-effects such as bond rupture, change of charged state, change in ligand field strength, with a lifetime of about 10 - 500 ns. These after-effects can be recorded and studied using Time Differential MES. Recording the intensity size/areas for the daughter sample at different conditions gives us an idea on the stability of the nucleus.

### 7.2 Mobile Mossbauer Spectroscopy

Around 1990, Prof. E. Kankaleit along with some electronics experts, worked on creating a miniaturised model of the Mossbauer spectrometer (MIMOS). Their goal was reached successfully and they were able to make a spectrometer that was scaled down 100 times. This device has been used in various places to collect data on the content of Iron/other Mossbauer active compounds. In 2003, this device was selected by NASA to be sent on two missions. They landed on Mars in 2007 and were used to collect data on rock and soil samples on Mars to look for presence of water. One of them was active (Spirit) until 2010, while the other (Opportunity) was active till 2018. The most exiting finding of this was the presence of Mineral Jarosite that has 6 OH groups, which shows that it must have been formed in presence of water.

MIMOS has also been used in archaeological findings to find the composition of artifacts and help in its restoration. Other uses for it has been in Iron mineralogy and In-situ air pollution investigations.

## 8 Limitations

After the discovery of the Mossbaouer effect, spectroscopy using this effect has been used quite frequently. But there are also some limitations to this technique that are worth making a note of:

- One major limitation is that it is inherently a bulk technique i.e. it requires a thin spread of the sample across the detector for satisfying results.
- The end spectrum is a result of average over the properties of atoms present in the area over which the sample is spread. Thus it is difficult to analyse local properties such as defects since their spectra may be lost while averaging over the bulk.
- Many of the naturally occurring rocks and minerals have Fe in octahedral coordination. Thus, a lot of them have a similar profile which leads to difficulty in distinguishing minerals.
- The parameters in the spectrum vary with Temperature and other external factors and the variation is distinct for each sample. Thus making a catalogue for reference is difficult. And thus analysis is difficult.
- These spectrum readings are vibration sensitive. Small motions may cause doppler shift which can lead to erroneous results.
- The biggest issue is that very few elements are Mossbauer active and even among those only a handful of elements can be used for analysis due to the requirement of cryogenic temperatures, and accessibility and handling of the sample.

Even with such limitations, this technique has had many successes and is still widely used in various fields (especially material science) to analyse the composition of unknown samples.

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- Mössbauer Spectroscopy on Selected Magnetic Compounds, Beata Kalska Szostko
- Applications of Mössbauer Spectroscopy in Industry, D. C. Cook