Experiment 354: The Mössbauer Effect

Aim

To study the resonance absorption (Mössbauer effect) of the 14.4 keV gamma ray from an excited ^{57}Fe atom.

References

1. A. Melissinos, "Experiments in Modern Physics", Academic Press
2. G.K. Wertheim, "The Mössbauer Effect", Academic Press
3. Jenkins & White, "Fundamentals of Optics", McGraw-Hill

Refs. 1 and 3 are available in the laboratory and Ref. 2 is in the Science Library.

Introduction

This experiment is aimed at providing you with an introduction to the Mössbauer effect, which is the recoilless emission and resonant reabsorption of nuclear gamma rays. The detailed nature of this process, the history of its relatively recent (1958) discovery, and the reasons for its rapidly becoming an important tool for research in a wide variety of fields, are discussed in Ref. 2.

Manuals describing the modular electronic equipment are available from the laboratory technician if they are not supplied with the equipment. The operation of the MPII MCA unit is described in the Appendix. Some details of the proportional counter used are included in the appendix to the bench copy of this pamphlet.

Do not proceed with the experiment until you have discussed it with a demonstrator.

Procedure

In this experiment you will be attempting to observe two effects:

(i) The recoilless emission and resonant reabsorption of 14.4 keV gamma rays emitted in the decay of the first excited state of ^{57}Fe nuclei to their ground state. This is a typical example of the Mössbauer effect as discussed in Chapter 1 of Ref. 2. Fig. 5 on page 14 of Ref. 2 gives the decay scheme for ^{57}Fe.

(ii) The Zeeman splitting of the ^{57}Fe ground and first excited states which occurs when ^{57}Fe atoms are embedded in a ferromagnetic material (natural iron in this case).

The associated energy level scheme and the possible transitions are shown in Fig. 1 on page 73 of Ref. 2, and Chapter 7 discusses the situation.

The basic points you should appreciate while making these measurements are:

(i) You will be measuring an absorption line of extreme sharpness – $\Delta E/E$ for these lines is typically 10^{-12} to 10^{-13}.

(ii) The nuclear Zeeman effect requires magnetic fields about 1000 times as large as those required to observe Zeeman splitting of atomic states since nuclear magnetic moments are smaller than electronic ones by this order. Fields of the order of several tens of Tesla are therefore needed so that to observe this effect on nuclear states through a splitting of the associated gamma transitions is not normally possible. The great sensitivity of the Mössbauer effect to energy changes such as occur in the nuclear Zeeman effect, together with the very high fields experienced by nuclei in ferromagnetic materials ($\sim$ 30 T in your experiment), do make such observations possible.

In this section of the experiment you will then measure the effective field at the sites of ^{57}Fe nuclei in natural iron and the magnetic moment of the ^{57}Fe first excited state. Such a moment for excited states is also not easily measured, yet in your experiment you will obtain it absolutely from quite simple observations.

Part 1: Selection of the 14.4 keV Gamma Ray

(1) Connect the apparatus as in Fig. 1. Before turning on the 478 high voltage bias supply, make sure that the helipot is set at zero and the kV switch to zero. The input circuit of the preamplifier contains a field-effect transistor (FET) which could be destroyed by the sudden application of a large amount of charge. Switch to 0.5 kV, pause for a few seconds and then switch to 1 kV. Turn the helipot slowly until the total voltage reaches 1900. When switching off, reduce the voltage slowly to zero in the same way.

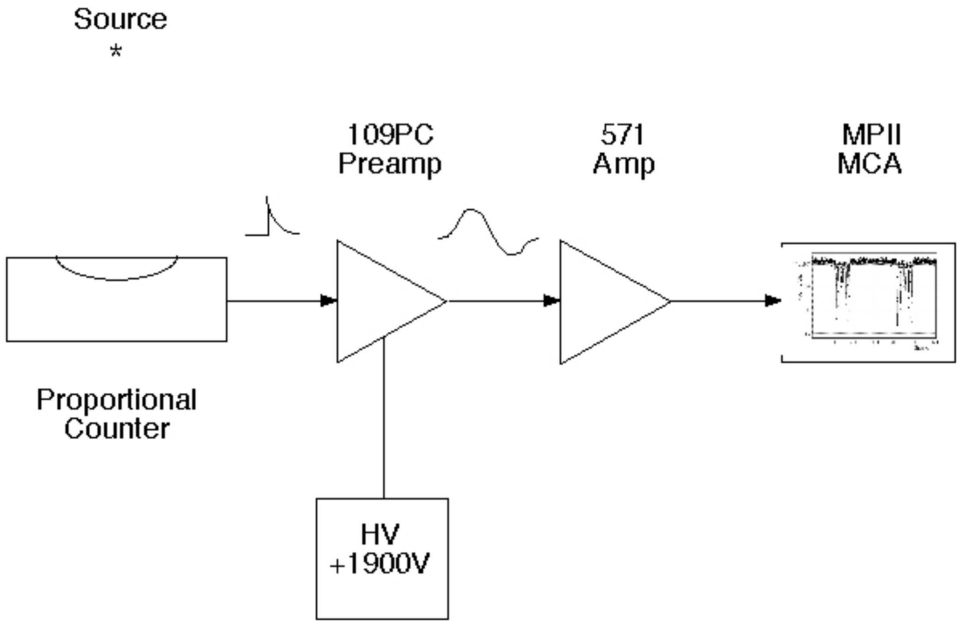

Figure 1: Experimental setup.

(2) Set the preamp gain to $\times$10. Its output pulses should be positive, with risetime < 1 μs and falltime several tens of μs. Set the shaping time of the 571 amp to 2 μs, and initially set its gain so that, using the bipolar output, all the output pulses are seen in the spectrum accumulated in the MCA. The gain of the spectrum in the MCA should be 1024 channels. The pulses, when viewed with the oscilloscope (the CRO) should show positive and negative lobes, roughly gaussian in shape, of total length around 5 μs. They should not be clipping.
Ask a demonstrator to help you understand the details of the MCA spectrum.
Now turn up the gain of the 571 until the 14.4 keV gamma ray and the 6.4 keV X-ray peaks are the main features of the MCA spectrum. It is the Mössbauer effect for the 14.4 keV gamma rays which will be demonstrated in this experiment.

Use the MCA menu, as described in the Appendix, to adjust the LLD and ULD settings so that only that part of the spectrum which is the 14.4 keV peak is accumulated. Make the limits in the flat parts,

either side of the peak. Note the LLD and ULD settings. Now the MCA generates an internal logic pulse whenever a 14.4 keV gamma ray is detected.

Part 2: Observation of Resonant Absorption - Single Line Mössbauer Spectrum

The aim here is to demonstrate the resonant absorption of the 14.4 keV radiation by ^{57}Fe nuclei and the extreme sensitivity of this process to small energy changes. This is done by measuring the variation in intensity of the 14.4 keV radiation transmitted through a thin (12.5 or 25 microns) foil of stainless steel as the source velocity (and therefore the gamma ray energy) is varied. Resonant absorption should occur at zero relative velocity. Only about 2 % of the iron atoms in the foil are ^{57}Fe but this is adequate to give an increase of about 10 % in absorption at zero velocity.

Motion of the source is produced by mounting it on a small transducer which is driven by an AC signal just like the voice coil of a loudspeaker. The sinusoidal driving signal is derived from the control box. To display the drop in transmission of the 14.4 keV radiation at zero velocity the MCA is used in the Multiscaling (MCS) mode as follows.

Change the mode of the MPII operation from MCA to MCS (see Appendix). In this mode, make sure the number of MCA channels is 1024 and set the upper and lower level discriminators (LLD and ULD) to the settings previously noted. Set the MCS channels to 1024, the dwell time to, say, 40 μs, and the MCS input to LLD/ULD so that the logic pulse generated by the MCA is used as input by the MCS. In the MCS mode, the MPII stores all the logic pulses in one channel for a length of time equal to the dwell time. It then switches the input to the next channel and so on.

The control box generates a crystal-controlled driving signal at a frequency of 41.67 Hz (24 ms period). The transducer driver unit allows adjustment of the amplitude of the driving signal. The actual motion of the transducer may be inferred from the signal from a pickup coil. The phase of the start pulse relative to the sinusoidal motion may be adjusted by looking at both on an oscilloscope, and altering the phase of the start pulses to be at the maximum velocity positions of the pickup signal.

If these pulses are then connected to the MPII "XMCSSTART" input, and the MCS operation initiated, data collection will proceed, starting at channel 1 and continuing in 40 μs increments to higher channels until the next start pulse is received (after 24 ms = 600 ch) at which point the address will return to the first channel. Thus time spectra of many sequential source oscillations may be accumulated with constant relative phase, and therefore no consequent blurring due to time jitter.

Run a stainless steel absorption spectrum. After 15 – 30 minutes, dips should become apparent (at roughly channels 150 and 450 in a spectrum 600 channels wide; why?). The dips should be defined by at least 5 or 6 channels. If they are too narrow, reduce the transducer amplitude and/or the MCS dwell time. Within reason. Readjust the phase of the start pulse. You may need to run overnight to obtain a spectrum with good enough statistics. A typical spectrum is shown in fig. A1. The operating conditions for this were:

source - absorber distance = 14 cm	transducer driver gain = about 2
absorber - detector distance = 15 cm	transducer driver phase = about 8

Measurement of Vibrator Amplitude

This is necessary in order to determine the velocity and hence the Doppler shift. The best method of doing this is with a laser interferometer. As the amplitude of vibration of the source is only a few hundredths of a millimeter it is very difficult to measure accurately simply by the use of a stroboscopic flash and travelling microscope. However, great precision may be obtained if the source has an attached mirror which then forms part of a Michelson interferometer. As the mirror moves, the path length of one arm of the interferometer changes and interference fringes appear at a rate proportional to the velocity. These intensity changes are detected by a photodiode and counted by means of a scaler. From this the amplitude of vibration may be determined.

For information on the principle of the Michelson interferometer refer to Ref.3, or the pamphlet for experiment 322 "The Michelson Interferometer".

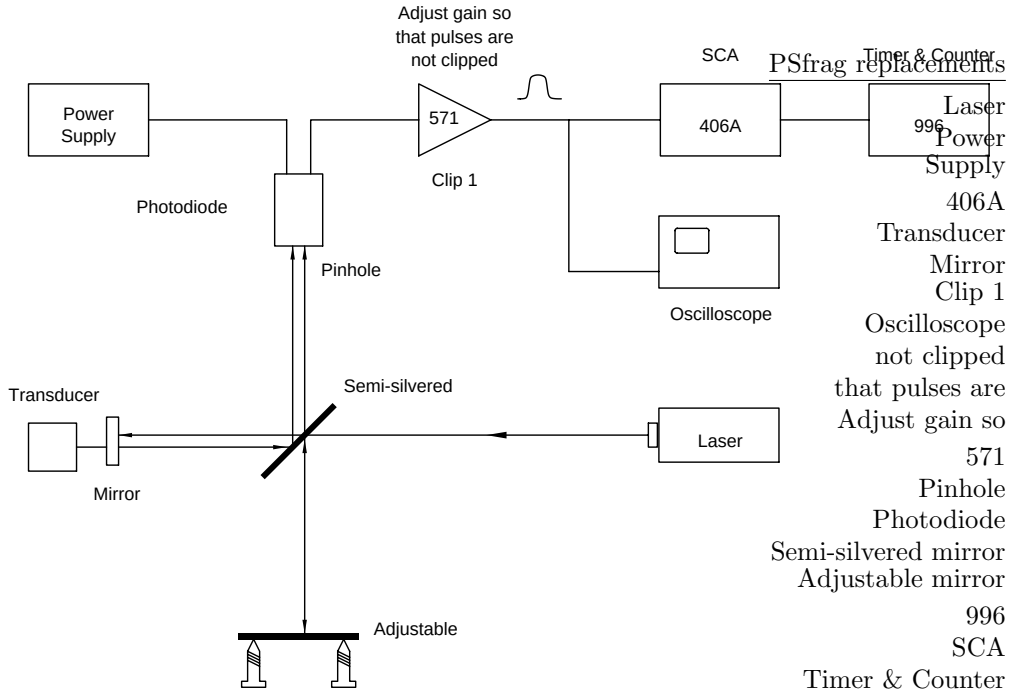

Figure 2: Michelson interferometer.

Fig. 2 indicates the physical and electrical arrangement of the apparatus.

(3) Carry out the following steps to measure the vibrator amplitude:

(a) Screw the half-silvered mirror stand firmly to the baseplate. Adjust it to approximately 45°. **Do not touch the mirror surface**.

(b) Turn on the laser and the oscilloscope. Turn the external transducer multiscaling pulses on and waveform on.

(c) Check that the laser beam is parallel and produces a spot with a diameter of about 5 mm.

(d) Align the laser beam to pass through the half-silvered mirror and to hit the vibrating mirror just above the source.

(e) A sheet of white paper should be used for tracing the position of the laser beam. There are three beams incident on the half-silvered mirror. It is sound practice to adjust its angle so that they are incident (nearly) on the same part of the half-silvered mirror. **Do not look into the laser beam either directly or via the mirrors**.

(f) Move the photodiode out of the way and set up a screen (or have someone hold a sheet of paper about 2 m away from the half-silvered mirror. You should see two beams. Use the adjustable mirror to make them coincide.

(g) Now replace the photodiode and adjust it so that the light from the combined beams enters the pinhole.

(h) You should find that a shaping time of 2 μs on the 571 amplifier with a gain of 500 and UNIPOLAR output will give you signals approximating those sketched in Figs. 6 and 7. You may need to make further adjustments until a p-p amplitude of at least 5 V is achieved. Reproducible results are unlikely to be achieved if the p-p amplitude is below 1 V. If you have problems consult a demonstrator. At a high sweep speed (say 10 μs) the oscilloscope trace should look like that in Fig. 3.

Because of the sinusoidal motion of the transducer, the frequency of the signal varies with time, hence the blurring of the trace on the right hand side of the screen. At a low sweep speed

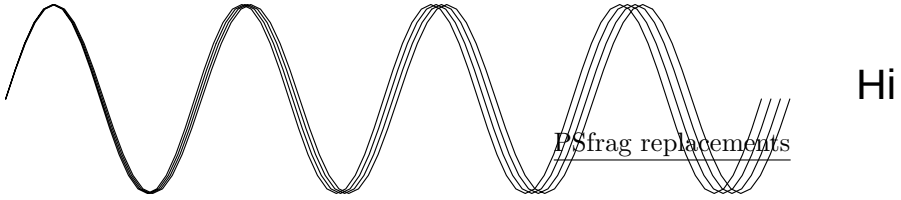

Figure 3: Oscilloscope trace: high sweep speed.

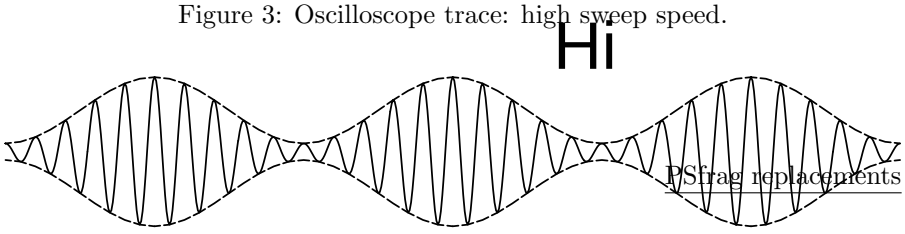

Figure 4: Oscilloscope trace: low sweep speed.

comparable with the period of oscillation of the source (say 2 ms) the trace looks like that in Fig. 4.

You should convince yourself of why these oscilloscope traces have the appearance they do. A full understanding depends on a knowledge of the frequency response of the preamplifier and amplifier.

(i) Now connect the 571 amplifier output to the 406A SCA. Check that the scaler is set to normal and that the upper level is at its maximum (1000). Set the lower level at about 10.

(j) Connect the 406A SCA to the POS input of the 996 timer and counter. Set the preset and time base so that you can count for a few seconds. Now by varying the lower level on the 406A SCA check that the discriminator is high enough so low amplitude noise is excluded. A rate of the order ten thousand per second should be observed.

(k) The amplitude A of transducer vibration is given by:

$$A = \frac{n\lambda}{8f}$$

where n is the count rate per second (averaged over many cycles of vibration), f is the frequency of transducer (= 41.67 Hz) and λ is the wavelength of the laser light (= 632.8 nm for the laser provided).
Check the above equation. Use it to determine the amplitude of the transducer vibration.

(4) From these results deduce the energy width of the absorption line. The relationship of your result to the natural width is discussed in Refs. 1 and 2. Compare your result with the natural width (see, e.g. Table I, p.13 of Ref. 2). Discuss any differences you observe.

Part 3: The Zeeman splitting of the ^{57}Fe Nuclear States

The Zeeman effect is dealt with in Ref. 1 and other texts, and chapter 7 of Ref. 2 discusses the particular measurement to be made here.

When embedded in natural iron, the ^{57}Fe nuclei experience strong magnetic fields which Zeeman-split the nuclear states and associated spectral lines. The 14.4 keV transition becomes split into six possible transitions.

As the source velocity sweeps over a cycle from $+v_{\max}$ to $+v_{\max}$, there will be six velocities in the first half cycle and six velocities in the second half cycle at which resonant absorption occurs. In the MCS display, resonant absorptions will appear as dips, six in channels corresponding to absorption velocities in the first half cycle and six in channels corresponding to absorption velocities in the second half cycle. To observe this pattern, proceed as before but use a natural iron absorber. A typical spectrum is shown in fig. A2.

Note: These absorbers rust so keep them in the desiccator when not in use.

(5) From the positions of the two pairs of six dips, deduce the magnetic moment of the ^{57}Fe first excited state assuming that the ground state magnetic moment is +0.0903 nuclear magnetons. Using a velocity calibration, determine the effective magnetic field at the ^{57}Fe nucleus site. Deduce the relative intensities of the six lines and compare with the expected ratios (see p.74–75 of Ref.2).
Note: The value of the excited state magnetic moment is obtained without knowledge of the internal field.

Questions

All of these questions are to be answered as part of the write-up.

1. When the MCA is used with this apparatus in the multiscaling mode the spectrum observed can be regarded as a graph of number of gamma rays detected per energy interval against energy, but with a non-linear energy scale. Explain this and show that when the correct phase relationship exists between the source motion and the train of channel advance pulses the energy corresponding to channel N is given by:
$$E(N) = E_\gamma \left[1 + \frac{u_0}{c} \cos\left(\frac{\pi N}{300}\right)\right]$$
where $E_\gamma = 14.4$ keV and u_0 is the maximum source velocity.
2. Is the source – absorber distance critical in any way?
3. Is the foil thickness important?
4. Why does the Zeeman splitting result in only six lines when there are eight energy differences between a quartet and a doublet state in a magnetic field?

List of Equipment

1. Lead box with ^{57}Co (5 mCi)
2. Reuter-Stokes proportional counter
3. Transducer amplifier
4. Pulse shaper
5. ORTEC 478 0 – 2 kV HV supply
6. ORTEC 109PC preamplifier
7. ORTEC 571 amplifier
8. ORTEC 420 Single Channel Analyser (SCA)
9. ORTEC 996 Timer and Counter
10. He-Ne laser (1 mW)
11. Optical bench
12. Hitachi 1065A oscilloscope
13. MCA (MPII)

A. Poletti

P. Barker

June, 2006.

APPENDIX A

Use of the Multiport-II MCA-MCS

The MPII unit will be used in two modes: to histogram energy amplitude pulses (MCA); to display the time dependence of incoming logic pulses (MCS)

To Change from MCS to MCA

In "Genie 2000" open MCA Input Definition Editor (MIDE).

```
          Database - Unload from - MOSSMCS - Unload - Done
          Database - Load to - MOSS - Load - Done
Exit MIDE
Open Gamma Acquisition and Analysis (GAA)
          File - Open Datasource - Detector - MP2_MCA1 - Open
          MCA - Adjust - [1024ch, LLD 1%, ULD 100%, Zero 0%] - Exit
          Start
          Stop
```

To store a spectrum in Text Mode (for Matlab etc):

```
          File - Save As - Toolkit File [Stud01.TKA] - Save
Exit GAA
```

To Change from MCA to MCS

Open MIDE

```
          Database - Unload from - MOSS - Unload - Done
          Database - Load to - MOSSMCS - Load - Done
Exit MIDE
Open GAA
          File - Open Datasource - Detector - MP2_MCA1 - Open
          MCA - Adjust - [ADC 1024ch, LLD = ?, ULD = ?],
          [MCS ?us, MCS Input LLD/ULD - Exit
          Start
          Stop
```

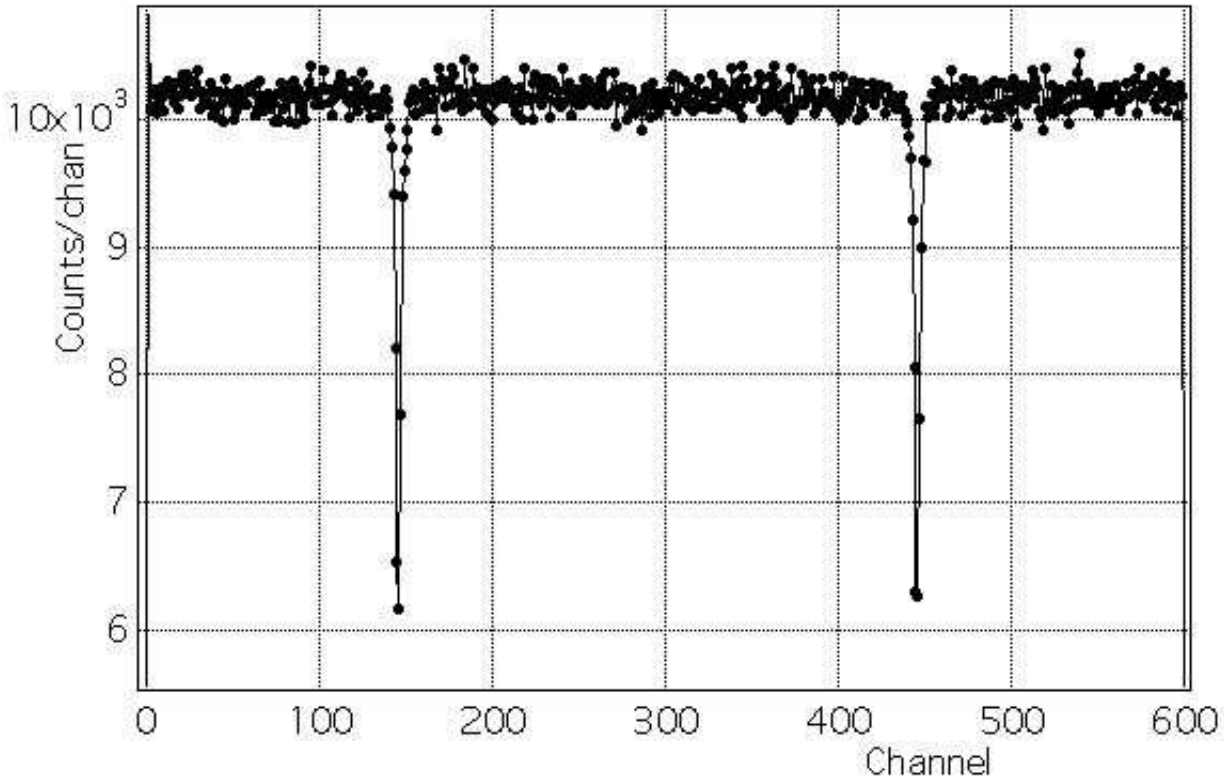

Figure 5: Mössbauer spectrum of ^{57}Fe in stainless steel.

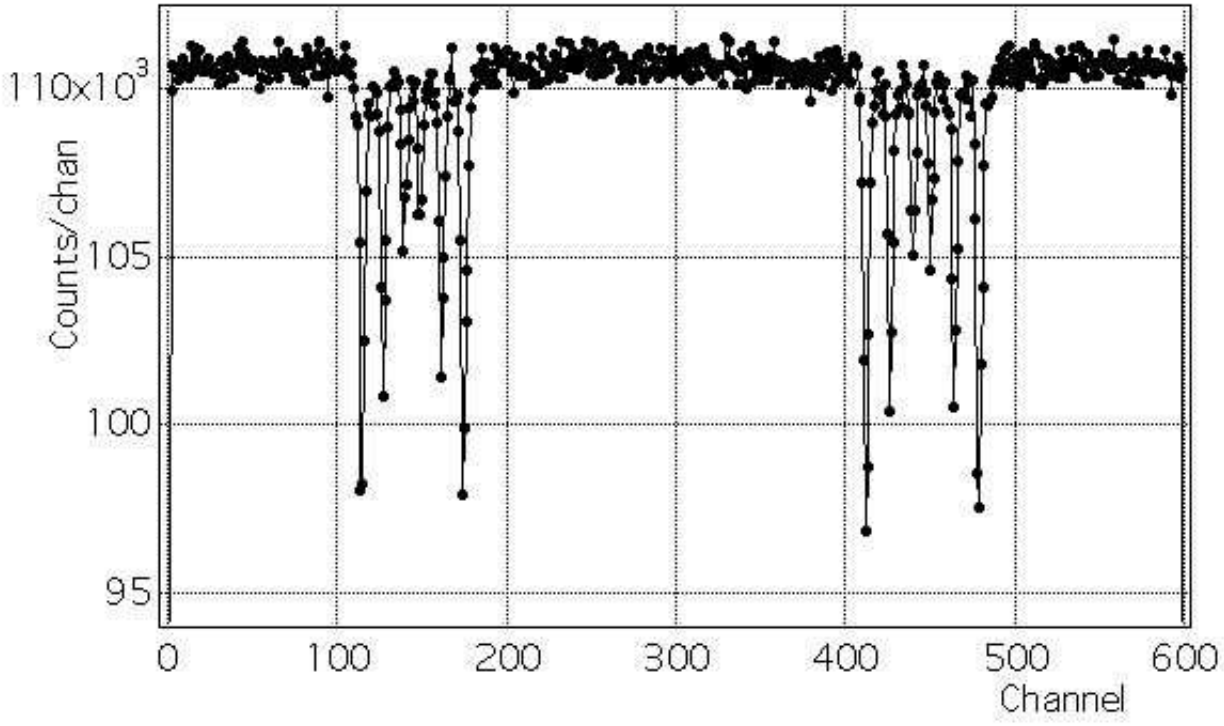

Figure 6: Mössbauer spectrum of ^{57}Fe in mild steel.