THE SCINTILLATION DETECTION OF GAMMA RAYS

Objectives

In this experiment, you will use a NaI scintillation detector and a multichannel analyzer (MCA) to observe and measure the energy spectrum of a gamma ray source. The MCA will be calibrated from known gamma sources, then used to identify an unknown gamma source from its spectrum.

Background

1) Review radioactive decay in your modern physics textbook and the Background Notes at the end of Experiment 5.
2) Read pages 333-344 in Melissinos on scintillation detectors.

Theory and Apparatus

A.   Gamma Ray Scintillations

As a gamma photon travels through a scintillation crystal, there are two major processes by which it can interact with the atoms in the crystal (see page 4):

Photoelectric effect: The gamma photon can be absorbed by an atom, thus ionizing the atom and kicking out a fast electron. The electron's escape energy is
$$E_{\text{elec}} = E_{\text{gamma}} - E_{\text{binding}},$$
where E_{binding} is the binding energy of the electron in the atom. But E_{binding} is only a few eV, whereas $E_{\text{gamma}} > 100$ keV. So for all practical purposes, $E_{\text{elec}} = E_{\text{gamma}}$. In other words, the gamma essentially gives its entire energy to the electron.

Compton scattering: The gamma photon can scatter from an atomic electron. The scattered gamma photon has energy E'_{gamma} given by the Compton formula:

$$E'_{\text{gamma}} = \frac{E_{\text{gamma}}}{1 + \left(\dfrac{E_{\text{gamma}}}{mc^2}\right)(1 - \cos\theta)} \tag{1}$$

where E_{gamma} is the incident energy, $mc^2 = 511$ keV is the electron rest mass energy, and θ is the scattering angle. The electron receives sufficient momentum to be kicked out of the atom, but now with energy

$$E_{\text{elec}} = E_{\text{gamma}} - E'_{\text{gamma}} \tag{2}$$

In this case, $E_{\text{elec}} < E_{\text{gamma}}$ because of the existence of the scattered photon.

Regardless of how it's produced, the fast electron, as it shoots through the crystal, collides with and excites atomic electrons. These excited atoms decay back to their ground state within a microsecond, and in doing so they emit visible light. This pulse of visible light that follows a gamma ray interaction is called a **scintillation**. Our goal is to detect and measure the scintillation - the pulse of visible light - in such a way that we can infer the energy of the gamma ray that caused the scintillation. We will do so by detecting the scintillation with a photomultiplier tube (PMT).

As an example, if a 200 keV gamma gives all its energy to a fast electron, the fast electron can excite $\approx$ 100,000 atoms by $\approx$ 2 eV each. Each atom decays and emits a $\approx$ 2 eV photon (visible light). Thus a typical scintillation pulse produced by 1 gamma photon then consists of $\approx$ 100,000 visible light photons. Some fraction of these visible photons will strike the PMT and be detected.

B.   Photomultiplier Tubes

A photomultiplier tube is a device used to detect and amplify low-level light. Figure 1 shows the basic construction of a PMT. It consists of a light-sensitive cathode, several electrodes called "dynodes," and an anode from which the

Figure 1 - A photomultiplier tube

signal is extracted. In moving from the cathode toward the anode, each dynode is $\approx$100 volts more positive than the one preceding it.
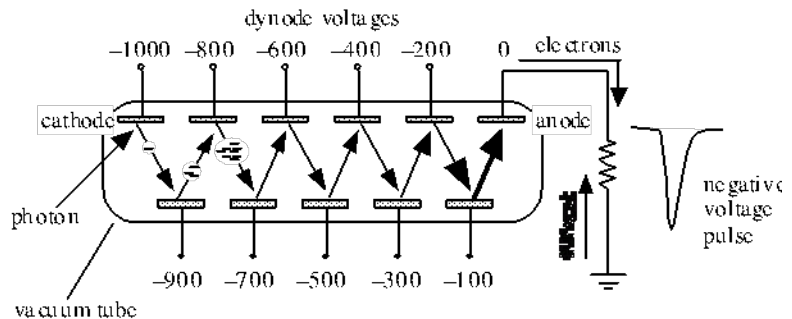
When a photon strikes the cathode, it ejects an electron via the photoelectric effect (assuming the photon's frequency is higher than the threshold frequency of the cathode). This electron is attracted toward the first dynode and, because of the potential difference, will crash into the dynode with $\approx$ 100 eV of kinetic energy. When an electron hits a piece of metal at this speed, it usually knocks several electrons out of the metal. These are called "secondary electrons." This is a random process, but on average each electron generates $\approx$ 3 secondary electrons upon impact. So while there was 1 electron heading toward the first dynode, there are 3 leaving it. Each of these is accelerated toward the second dynode, crash into it at $\approx$ 100 eV, and generate (for each) 3 more secondary electrons. Now there are 9. Each of these is accelerated toward the third dynode, and so on, causing a chain-reaction buildup of electrons. After the nth dynode, the number of electrons is 3^n, or $\approx 10^5$ electrons for a typical value n = 10. These all started from a single photon hitting the cathode, so the gain of a PMT is $\approx 10^5$.

This pulse of electrons is collected by the anode as a current, passes through a resistor to create a voltage, and we can then observe and measure the voltage pulse. The output pulse is negative, due to the charge of electrons, but we use an inverting amplifier to change it to a positive pulse. If N photons hit the cathode simultaneously, as is the case with a scintillation detector, the output current pulse consists of $N \cdot 10^5$ electrons. That is, the output is directly proportional to the number of photons from the scintillator, which makes the output directly proportional to the energy deposited in the crystal by the fast electron. This proportionality is essential for understanding our measurement technique.

It's important to understand that the PMT measures the energy deposited in the crystal by the fast electron and subsequently emitted as visible light. The PMT does not measure the gamma ray directly. If the gamma gives all its energy to a single electron (photoelectric effect), then the intensity of the pulse of light will be directly proportional to the gamma's energy. The light pulses that correspond to the full gamma energy will produce a peak in the energy spectrum called the **photopeak**. However, Compton scattering will produce fast electrons with less than full energy. These electrons, in turn, will produce light pulses having a broad spread in pulse heights below the photo-peak (see Fig. 2).
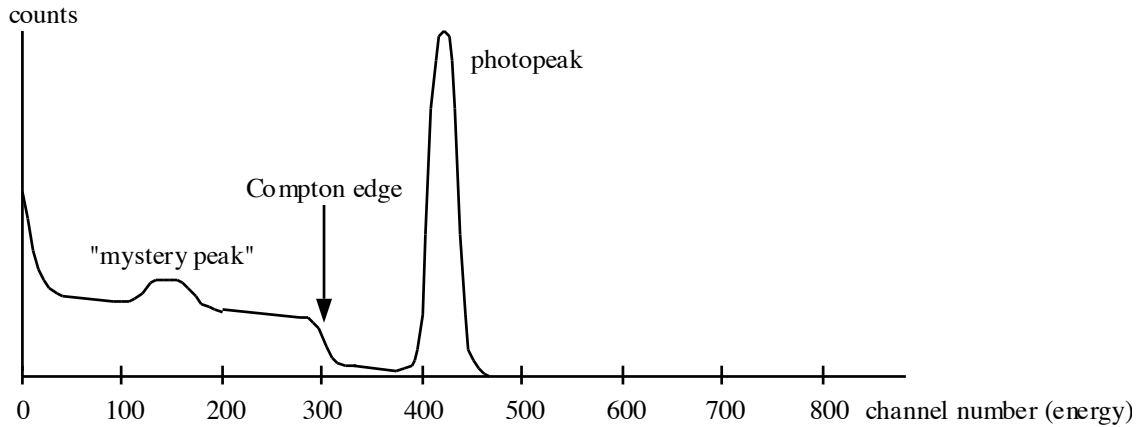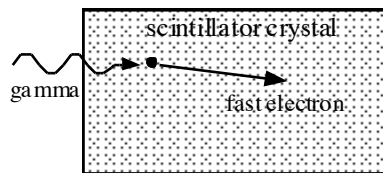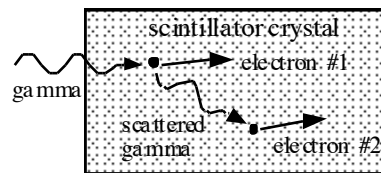
counts

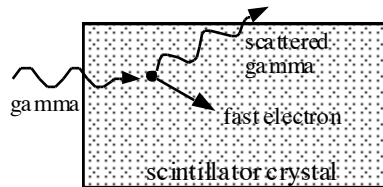Figure 2: A typical gamma ray pulse height spectrum (^{137}Cs)

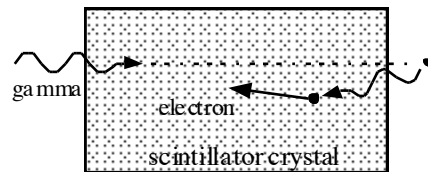There are four situations of interest when using a scintillation detector:

Situation 1: photoelectric

Situation 2: Compton plus photelectric

Situation 3: Compton, gamma exits crystal

Situation 4: external Compton scatter into crystal

1. Photoelectric effect, $E_{elec} = E_{gamma}$. This produces the photopeak, which is the signal of interest since it measures the gamma ray energy.

2. Compton scattering, $E_{elec\ 1} < E_{gamma}$, followed by the photoelectric effect. Here the gamma scatters from the first atom and is absorbed by a second atom, generating a second electron. But $E_{elec\ 1} + E_{elec\ 2} = E_{gamma}$, so all of the gamma energy is deposited in the crystal and used to generate visible photons. This produces a PMT pulse of exactly the same height as situation #1, so this situation contributes to the photopeak.

3. Compton scattering, $E_{elec} < E_{gamma}$, followed by the scattered gamma leaving the crystal. The energy deposited in the crystal is less than E_{gamma}, so the PMT will produce a smaller pulse. Note, from Eq. 2, that E_{elec} ranges in energy from zero (when $E'_{gamma} = E_{gamma}$ at $\theta \approx 0$) up to a maximum $E_{elec\ max}$ (when E'_{gamma} reaches its minimum value at $\theta = 180°$). So Compton scattering causes the PMT to generate pulses ranging in height from zero up to a

well-defined maximum height that is *less* than the photopeak height. This maximum pulse height from Compton scattering causes the **Compton edge** seen in Fig. 2. The energy of the Compton edge is $E_{edge} = E_{elec\ max} = E_{gamma} - E'_{gamma}$ at $\theta = 180°$.

4. Compton backscattering into the crystal. Sometimes, gammas from the source pass all the way through the crystal, Compton scatter from an electron further downstream in the PMT, travel back into the crystal, and then are absorbed to create a photoelectron. This photoelectron will have the energy of the backscattered gamma, which is considerably less then the initial gamma energy. We'll leave it to you to think about the consequences of this situation.

C.   Experimental System and the MCA

The system necessary to observe and measure gamma rays consists of a **NaI scintillation crystal**, a **photomultiplier tube (PMT)** to detect and amplify the light pulses, **high voltag**e to operate it, a **preamplifier**, a **linear amplifier**, an oscilloscope, and a **multichannel analyzer (MCA)**. These are shown in Fig. 3.
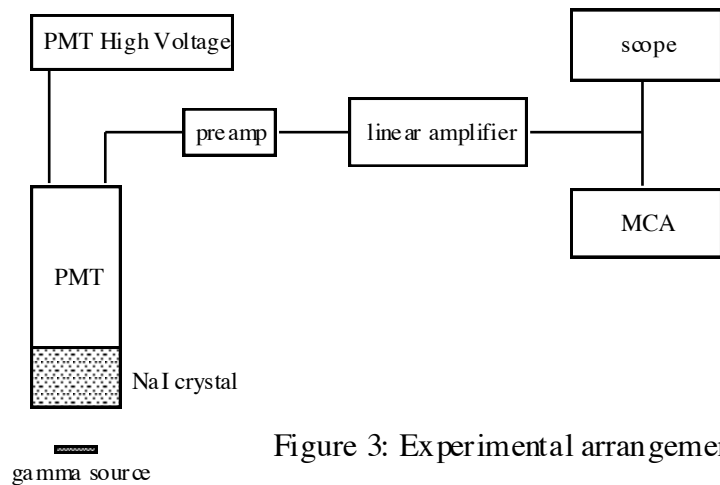
Figure 3: Experimental arrangemer

The MCA consists of a large number of "channels" (typically 1024 or 2048 or adjustable). Each channel is simply a counter. The output display of the MCA, such as seen in Fig. 2, shows the channels horizontally and the number of counts in each channel vertically. For this experiment, the MCA is operated as a **pulse height analyzer**. In this mode, the MCA counts the number of pulses at each of 1024 possible voltages (actually small "bins" of voltage) and plots a histogram of the results. To do this, the MCA measures the height of each incoming voltage pulse and assigns that pulse to the corresponding channel. Roughly speaking, a pulse of height V is assigned to channel number 100 x V. For example, a 3.00 V pulse is assigned to channel 300 and a pulse of height 5.67 V is assigned to channel 567. Once the voltage of an incoming pulse is measured, the accumulated count in the corresponding channel is incremented by 1. So if there are sixty-five 3.00 V pulses and twenty-two 5.67 V pulses,

channel 300 will contain the value 65 and channel 567 will contain the value 22. This simple idea makes for a very powerful and versatile measuring instrument.

Figure 2 showed a pulse height spectrum obtained with the MCA for a source such as ^{137}Cs that emits gammas of only a single energy. Note that the horizontal axis of the plot shows channel numbers, not energy values. We know, from the way the crystal, the PMT, and the MCA work, that the channel number is directly proportional to energy. But to have energy values on the horizontal axis, we will have to *calibrate* it by using photopeaks of *known energy*.

In looking at Fig. 2, you should note the photopeak (the signal of interest), the broad continuum of lower energy peaks due to Compton scattering when the scattered gamma ray leaves the crystal, and the "Compton edge". At the very lowest energies there is a rising count rate due to "noise" – random voltage fluctuations that are an inevitable aspect of any experiment. In addition to the photopeak, notice the smaller but distinct "mystery peak" at lower energy. Finally, note that the photopeak is not perfectly sharp, even though all the gammas that contributed to this peak had exactly the same energy. This "broadening" of the peak is an inherent part of the detection system. It is due to random fluctuations in the number of atoms excited, random fluctuations in the number of scintillation photons that reach the PMT, electronic fluctuations, and other factors. We can measure the full width at half maximum (FWHM) of the photopeak, and this serves as a measurement of the **resolution** of the detection system.

Procedure

Part 1: Learn to use the MCA with a pulsed source.

1. The Appendix for this experiment has a summary of basic commands for using the computer-based MCA multichannel analyzer (Amptek MCA 8000D). Follow those instructions to set the **mode** to m̲ulti c̲hannel a̲nalyzer (MCA) and the number of channels to 1024. Also set the vertical scale initially to LOG.

2. In order to create pulses with which to test the MCA, we will use the WAVEGEN capability of the Agilent DSO-X 2002A oscilloscope that allows us to generate voltage signals. Set the waveform to pulse with a frequency of 10 kHz, low-level: 0V, high level: 2V, pulse width: 50 μs, and make sure you can see this on the oscilloscope.

Start the MCA acquiring data. You should see one channel racing upward in counts and perhaps a few nearby channels gaining counts. This is the channel corresponding to 2 V.

Practice using the various MCA commands to acquire and erase data, change the vertical scale, move the cursor, expand the viewing region, and so on. Vary the pulse height (the high level) and watch how the MCA responds.

3. Stop acquiring and erase the MCA. Using the output from the oscilloscope, set the pulse height back to 2.00 V. Acquire 5 s of data. (Use the preset time under MCA->Acq. Setup->MCA->Preset Real Time). Find the total counts by setting a *region of interest* (ROI) to span all channels with counts. Since you recorded a 10 kHz pulse rate for 5 s, the total counts for all channels should be near 50,000. If not, check with your instructor.

4. You will notice in the information panel to the right of the spectrum that there is a "Live Time" and you will see that with the settings given above it is reading about 2.5 seconds. This is because the instrument records the time for which the pulse level is above some threshold (which the lab instructors have set to around 200 mV) and is unable to record another pulse during that time. So the time that the instrument is actually "live" is half of the real time of 5 seconds. Change the pulse width to, say, 10 μs and record again for 5 seconds. You should get the same number of overall counts but now the live time should be 4.5 seconds. Does that make sense?

5. Since we have the signal generator plugged into the MCA we can do a quick check of the linearity of the MCA. Set the pulse height to 1 V and after clearing the MCA record for 5 seconds. The 10 μs pulse width you used before is fine. Use the ROI tool to find the centroid of the peak. Repeat this process for pulse heights of 2 V, 3 V, 4 V, and 5 V. You should find that the difference in channels at which the centroids occur is pretty close to constant (and pretty close to 100). This means that the channel number is directly proportional to the size of the incoming pulse voltage. So if that voltage itself is proportional to the energy of the gamma rays, then we have an energy spectrometer!

Part 2: Measure the ^{137}Cs gamma ray spectrum.

1. ^{137}Cs is a source we will use many times this year to set up the detector and MCA. Place the source on or under the detector, depending on how it's set up.

CAUTION: Do not exceed 600 V to the scintillation tube.

- Turn the PMT high voltage to 500 V, and observe the PMT pulses on the scope.
- Adjust the gain on the amplifier and/or the high-voltage to the PMT so that the pulses are $\approx$ 4 V high. (You'll do a more precise adjustment in the next step.) The pulse widths should be $\approx$ 2 μs.

Each pulse is from one gamma ray photon interacting with the NaI crystal. Most of the pulses are due to photoelectric absorption of the 662 keV gamma of the ^{137}Cs decay, although there will be some smaller pulses from Compton scattering.

Note: The amplifier gain is the <u>product</u> of the coarse gain setting and the fine gain setting. The numbers on the fine gain control range from 5 to 15, but these actually mean 0.5 to 1.5. So the fine gain changes the total gain from 50% to 150% of the coarse gain setting.

2. Start acquiring data with the MCA and set the vertical scale to 1000 counts max. Within just a few seconds you should begin to see an energy spectrum looking similar to Fig. 2. Now adjust the amplifier gain/HV to place the ^{137}Cs photopeak somewhere between channels 400 and 425. This will make all the peaks we look at later stay within the range of channels 1 to 1024. Then run the Cs source for long enough to record a smooth spectrum. *Print* out the spectrum (one for each lab partner). The following data should be right on your spectrum:

a) Find the *centroid* of the photopeak by setting the ROI *symmetrically* on the peak, down to near the baseline on both sides.

b) Determine, in channels, the FWHM of the photopeak.

c) Locate the channel number of the Compton edge. The edge isn't too well defined, but it makes most sense to measure the "half max," where the counts have dropped to about half their value on the relatively flat region of Compton-scattered pulses. Most of the width of the Compton edge can be attributed to the same mechanisms that are broadening the photopeak.

d) Determine the channel number corresponding to the center and the left and right end of the "mystery peak."

Important note: Now that you've measured the ^{137}Cs spectrum, *do not* change the PMT high voltage or the amplifier gain. If you do, you won't be able to analyze this spectrum with the energy calibration you're about to do.

Part 3: Calibrate the MCA.

1. The calibration is to determine as accurately as possible the energy corresponding to channel number *N*. We will do this with several sources that are gamma emitters, all of them known. Place one of the calibration sources on or under the NaI crystal. *Do not adjust your amplifier gain or high voltage.*

Energy (keV)	Source	Half-life (y)
81	Ba-133	10.8
276	Ba-133	10.8
303	Ba-133	10.8
356	Ba-133	10.8
384	Ba-133	10.8
662	Cs-137	30.2
1173	Co-60	5.3
1333	Co-60	5.3

2. Run each calibration spectrum until it looks *very* smooth (i.e., has "good statistics" in each channel), and print one of these spectra for your report. The calibration sources are left at the side of the room. When you are not actively collecting a spectrum, return the calibration source so others may use it. Find the centroid of each peak by setting a *symmetrical* ROI around it.

3. Determine the FWHM for all the high energy peaks. You'll use this later to compare this resolution to that found earlier for the ^{137}Cs photopeak.

Part 4: Measure the gamma spectrum of an unknown source.

1. Move the ^{137}Cs and calibration sources *far away*. *Do not adjust the amplifier gain or high voltage.* Place one of the unknowns under the detector and acquire a high quality gamma spectrum. Be sure to record the code letter that identifies your unknown. Print out the spectrum. Find the centroid and FWHM of each *notable* peak, and again record this information right on your spectrum.

Analysis

1. Recall the table above for the known gamma emitting calibration sources in Part 3.

Use Matlab to plot the calibration data. Plot the energy of the photopeak (vertical) versus channel number (horizontal). Use Matlab to fit a *second-order* polynomial to your data. The result is your *calibration equation* in the form $E = a + bN + cN^2$. This equation converts channel number (N) to the corresponding energy (E). Save your graph to submit with your report.

> **Note**: Make sure you have your **coefficients a, b, and c to 4 significant figures**. (Do this in Excel by highlighting the equation, then selecting "Selected Data Labels" under the **Format** menu.) According to our simple theory of how the scintillation detector works, the channel-energy relationship should be linear. In reality, it is very slightly nonlinear, which is why we include a quadratic term. The coefficient c will be very small, but its inclusion does improve your calibration.

2. How good is your calibration? That is, if you measure a peak in channel N, what is the uncertainty δE in the energy that you calculate? To determine this, use the calibration equation to calculate the energy E_{calc} for each of the peaks of your calibration spectrum. Since you know the actual energies, calculate the deviation $\Delta E = E_{calc} - E_{actual}$ for each peak. Finally, average the *absolute values* of all the deviations. The result is a reasonable estimate of the energy uncertainty δE that you'll obtain for any other channel number N. **Note**: These calculations will be much easier if done in a spreadsheet or in Matlab than if done by hand.

3. Using your calibration equation, detemine the following for your ^{137}Cs spectrum:
    a) The energy of the photopeak. Include an appropriate uncertainty. Compare your result to the known value.
    b) The FWHM of the photopeak (in keV). **Caution**: Plugging the FHWM in channels into your calibration equation will *not* give you the FWHM in keV. Think about it.
    c) The energy of the Compton edge.
    d) The energy of the "mystery peak."

4. Calculate the expected energy of the Compton edge and compare your calculated value with your experimental measurement.

5. Explain the source of the "mystery peak." (Hint: What angle of Compton scattering would produce this peak? Where could such photons be coming from?)

6. The **resolution** at an energy E is defined as $R = $ FWHM$/E$. That is, the resolution is the peak width expressed as a fraction of the peak energy. Smaller values of R are better! Calculate the resolution for all of your peaks. Plot your R vs. E data.

7. A gamma of energy E creates a fast electron in the crystal that excites N atoms and creates N scintillation photons in a single event. The number N is directly proportional to E. Because N is a count, counting statistics tell us that the fluctuations in N from pulse to pulse should be roughly $\sqrt{N}$. It is these fluctuations in N that cause the photopeak to have a width.

> **a)** Use this information to predict how the resolution R should vary with the photopeak energy E. That is, $R \propto E^x$ for some exponent x. Determine the expected value of x.
>
> **b)** Use your experimental values of R to test your prediction. Do this by fitting the curve $R = aE^x$ through your R vs. E data..

8. Identify your unknown. Look up the candidates in the Appendix D of the *Table of Isotopes* and select the one that most closely matches your spectrum.

a) The unknown *may* be ^{137}Cs plus a second isotope. You should now be able to recognize the ^{137}Cs spectrum, so your task would be to identify the other isotope.

b) All our unknowns have half-lives in the range 200 days $< t_{1/2} < 100$ years. Shorter half-lives would have already decayed, whereas longer half lives make the source too weak for easy use.

c) Some isotopes emit more than one gamma. If you have multiple lines in your spectrum, you need to find an isotope that emits *all* of them. Similarly, if an isotope is listed as having a weak line at 100 keV and a strong line at 200 keV, that can't be the source of a spectrum in which you have a line at 100 keV but no line at 200 keV.

d) Some radioactive sources decay by β^+ emission - emitting a positron, or antielectron. The positron quickly annihilates by colliding with an electron, creating two 511 keV gammas.

These really aren't gammas from the nucleus, so they are *not shown* in the table, but they are present for beta decays in which positron emission occurs.

e) It's extremely unlikely that your photopeak energy, calculated from the calibration equation, is exactly correct. So you'll have to search over some range of energies. How big a range should you search?

f) Even with these constraints, you may not be able to make a unique identification. If that's the case, list all the nuclei you think it could possibly be.

Note: In identifying the unknown (or possible unknowns), state the isotope, the known gamma energy or energies that you used to identify it, and its half life.

Additional Question: The Compton scattering formula in textbooks is usually given in terms of wavelengths. Look up the wavelength version of the formula in a Modern Physics textbook, then use it to derive Eq. 1, the Compton formula in terms of energy.

Appendix: Using the Amptek Pocket MCA (MCA8000D) software

Start the software by clicking on the **DppMCA** icon on the desktop. In most cases the software should come up in MCA mode.

Start/Stop/Scales

Many of the commands you need are under the **MCA tab** in the toolbar. From there you can **Start/Stop Acquisition** and **Delete** acquired data to start afresh. These commands also have icons on the toolbar itself. On the bottom right you will see **LIN** or **LOG** displayed and you can toggle between linear and log scale by typing **L** (or you can go under **Display -> Scale**). The left-right/up-down arrows on the display change the horizontal and vertical scales. The left-right arrows on the keyboard move the **cursor**.

Number of Channels

To set the **number of channels** in the spectrum go to **Acquisition Setup** on the **MCA** tab. There you will find **another MCA tab** on the toolbar and on the screen that follows this you will find a drop down menu under **MCA/MCS channels** where you can set the number of channels.

Mode (MCS vs. MCA)

You can **change the mode** from **MCA to MCS** by again going through the **Acquisition Setup -> MCA** route where you can toggle **MCA Source** from **Norm** to **MCS**.

Print

When you want to print spectra go under **Display -> Plot pane** which will allow you to remove the fill in the spectrum and save some ink.

Regions of interest

Go under **Analyze -> Define ROI…**. The pointer will change to a **vertical double headed arrow**. Place this at the leftmost part of the peak and sweep to the right. The color of the area you sweep out will change. Making sure the cursor is in the region of interest you will see the details of the peak under **Peak Information.** If you print the spectrum and keep the cursor in the ROI then the information in the right panel is also printed. To remove the regions of interest go to **Analyze -> Define ROI….** again where you will have the option to remove some or all of the ROIs.