NES 409000

Radiation Measurement Laboratory and Reactor Experiments

Lecture Notes 2016

<table>
<tr><td colspan="3">課程名稱：（中文）輻射度量與反應器實驗</td><td colspan="2">開課單位</td><td>核工所</td></tr>
<tr><td colspan="3">（英文）Radiation Measurement Laboratory and Reactor Experiments</td><td colspan="2">科號
Course Number</td><td>NES409000</td></tr>
<tr><td colspan="6">任課教師: 李志浩/林明緯/李進得</td></tr>
<tr><td>學分</td><td>1</td><td>必/選修</td><td>選修</td><td>開課年級</td><td>大四課程</td></tr>
<tr><td colspan="6">先修科目或先備能力：無</td></tr>
<tr><td colspan="6">課程說明(Course Description)：
本暑期實驗課程目的為啟發學生對於輻射度量與反應器實驗的興趣並加強實作能力所開設，訓練學生熟悉各種輻射偵檢系統，實際操作進行輻射量測實驗，以及了解研究用反應器的特性與應用。輻射量測實驗包括熟悉核儀基本電子設備(示波器, 放大器, 鑑別器, 以及多頻道脈高分析儀等)的操作，課程內容涵蓋數種基本的輻射偵檢器，例如蓋格-米勒(GM)計數器、NaI(Tl)碘化鈉閃爍偵檢系統與純鍺偵檢器(HPGe)，學生實際操作儀器進行計數度量與加馬能譜分析，了解計數統計與誤差傳遞等基本數據處理技巧。課程內容亦涵蓋反應器實驗，讓學生實際至清華水池式反應器進行實驗觀察，以瞭解核子反應器的運作特性以及可能的應用。</td></tr>
<tr><td>指定用書(Text Books)</td><td colspan="5">實驗講義</td></tr>
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教學要點概述：

1. 教學方式(Teaching Method):上課講解(投影片教學)與實驗操作

2. 成績考核(Evaluation) : 實作評估(60%)及報告(40%)

3. 教學進度(Syllabus) : 4 個輻射度量實驗(14 小時)與 6 個反應器實驗(21 小時) + 總結與討論 (1 小時)， 共 36 小時。

	上午 08:30~12:00	下午 13:30~17:00
6/20(Mon)	Rad Exp#1: Introduction & oscilloscope and nuclear electronics	Rad Exp#2: Geiger-Mueller counters and basic nuclear statistics
6/21(Tue)	Rad Exp#3: NaI(Tl) Scintillation and multichannel analyzer	Rad Exp#4: High resolution gamma spectroscopy with HPGe
6/22(Wed)	Rx Exp#1: THOR introduction and applications	Rx Exp#2: Start-up check and THOR operation practice
6/23(Thu)	Rx Exp#3: Reactor period and control blade worth calibration (I)	Rx Exp#4: Reactor period and control blade worth calibration (II)
6/24(Fri)	參訪核一廠演習	參訪核一廠演習
6/27(Mon)	Rx Exp#5: Reactor power measurement and calibration	Rx Exp#6: Effect of fuel temperature on reactivity Conclusion & Discussion (17:00~18:00)

Contents

註：Experiments 5,7,8 講義提供學生參考，課程時間有限，實際操作內容參考 p.4 教學進度。

Introduction to Radiation Measurement Laboratory

Date: 2016/06/20 (Mon), 2016/06/21(Tue)

Advisors: Profs. Chih-Hao Lee, Ming-Wei Lin

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  Cellular phone: 0912-090253 E-mail: chlee@mx.nthu.edu.tw
- M.W. Lin: Office: 綠能大樓 609 Extension number: 35555;

  Cellular phone: 0953-583732 E-mail: mwlin@mx.nthu.edu.tw

Teaching assistants (TA):

- To be assigned
- To be assigned

Purpose of this course:

For students to have a **hands-on experience** on the nuclear radiation measurements

Reference book:

G.F. Knoll "Radiation Detection and Measurement" (Always bring this book with you)

Course Outline:

Introduction and Radiation Safety

Exp1: Introduction and Operation of Oscilloscope

Exp2: Nuclear Electronics

Exp3: Geiger-Mueller Counters and Basic Nuclear Statistics

Exp4: NaI(Tl) Scintillation Counting System and Multichannel Analyzer

Exp5: Proportional Counter and Slow Neutron Detection

Exp6: High Resolution Gamma Spectroscopy with High-Purity Germanium Detector

Exp7: Surface Barrier Detector and Alpha Particle Measurement

Exp8: Neutron Activation Analysis

註：課程時間有限，實際操作內容參考 p. 4 教學進度。

Scores:

(Performance on experiments: 50%, Experimental report: 50%)

1. Performance on experiments: Usually, two-three persons formed a group. The original data (in each group) should be plotted out on a mesh paper and signed by the advisor or teaching assistant (TA) before you finished your experiment. The approval depends on your knowledge learned in this experiment and the comprehensive reporting of your experimental data. In other words, you should be able to answer all the questions that Advisor/TA asked and the writing of the experimental result can be understood by others. The TA and I won't sign it off for you, if you don't understand the meaning of experiment.

2. Experimental Report: The report should include: Objective, experimental procedure, results and discussion. The report should be in electronic format and submitted by E-mail. Each person has to submit your report within one month after finishing the course. This original data should be attached to the experimental report.

Safety rules:

1. Personal safety

    - You must have a license to do radiation-related works, or you have to attend the radiation safety training held in each semester for a legal operation of radiation source by yourself. Otherwise, the TAs or your advisor has to accompany you all the time. Safety training course will be held periodically by NSTDC (Nuclear Science & Technology Development Center) of NTHU. If you need a personal radiation badge from NSTDC, to attend the training course is a must.

    - Recommended limit of dose rate: 10 Sv/h (for professional person), about 0.5 Sv/h for ordinary person. (The ICRP suggested 20 mSv/y for professional person and 1 mSv/y for an ordinary person.)

    - Natural radiation background in Taiwan is 0.05-0.2 Sv/h.

    - Keep the source in the lead can whenever you can. Do not touch the source by your hands if possible (e.g. using tweezers or gloves). In particular, the source is usually an open source. Do not touch the source with your finger.

    - Don't eat and drink anything in the radiation lab. In case some radioactive or contaminated materials were ingested or inhaled. Please remember to wash your hands before leaving the lab.

    - You may apply a radiation badge, either TLD or OSL, for your personal record if you want. The cost of the radiation badge is around NT$2000 each. The radiation badge should put at the designated badge shelf every time you leave the lab.

    - Many high voltage sources are around. For electrical safety, be careful and don't touch the high voltage ends by hands.

2. Equipment safety

   - Read the manual before operation any instrument.
   - Don’t pull the NIM modules out of NIM power bin without shut the power switch of the power bin off. It may cause a spark across the junctions and damage the electronic components.
   - Different kinds of detector use different kinds of preamplifier and high voltage suppliers in order to optimize their performance. For a high voltage supplied preamplifier, some of preamplifiers are not self-protected during the rapid increase or decrease of applied high voltage. Please tune the high voltage up and down by hand slowly. The high voltage (DC) applied for the detector is usually isolated from the preamplifier by an isolated capacitor which becomes short circuit if a rapid change of voltage applied, resulting in a breakdown of first stage of transistor in the preamplifier.
   - Please switch off high voltage supplier to zero volt before power-off and leaving the lab. Otherwise, in the next experiment, an immediate power-on may cause an excessive high voltage feed into the detector and preamplifier directly.
   - For all the knots, adjust screws, or switches, don’t use brute force. You must be wrong if you have to use the extra force to do the job because a good engineering design of a product will not use excessive force to operate it. It must be due to your wrong procedure. For example, the switch might be locked. You have to unlock it before tuning it.
   - Most of the detectors are very expansive. Some of them consist of fragile window (e.g. GM counter), very narrow wire (e.g. proportional counter), or a vacuum tube inside (e.g. scintillation counter and Ge detector). Handle it with care please.
   - In order to prolong the lifetime of electronics, please keep the lab clean and dry. For instance, put the umbrella outside during the raining season.
   - Don’t put the high voltage connector into signal I/O. The connector looks differently, but it is so easy to get confused between MHV connector and BNC connector.

Some useful data:

1. Connectors: For high voltage connectors, we have SHV, MHV, HN. For signals, we have BNC, Lemo connectors. Most of instrument are with female connectors, and cable with male connectors.
2. Coaxial Cables: 93 Ohm (RG-62/U; for pulse voltage signal) and 50 Ohm (RG-58/U; for fast logic timing). Impedance match for signal transfer should be noticed. (Ref. Knoll’s book, Appendix B)
3. NIM: Nuclear Instrument Modules: A nuclear instrument standard issued in July 1964. (Ref. Knoll’s book, Appendix A). The NIM power crate fit the 19” standard instrument rack. See Fig.1.
4. TLD: Thermal Luminescence Detector (Usually LiF:Eu), see Fig.2.
5. OSL: Optically stimulated Luminescence (Al2O3:C)

Fig. 1: Examples of NIM bin and NIM modules.

Fig. 2: TLD dosimeter 8814.

Operation of NIM bin:

Before starting your first experiment, check the power bin with +/- 24 V, +/- 12V and +/- 6 V power source. Please check the voltage out of your NIM power using either with either oscilloscopes or multimeters.

The operation of survey meter:

Most survey meters are designed to be self-instructive. The following provides you an example of survey meter operation for your own interest and radiation safety.

Instrument: PM1405 (Polimaster Ltd, Republic of Belarus)

The PM1405 is capable of measuring the and rays. When is measured, the cover of survey meter should be opened. Don’t touch the window (140 m mica) because it is very thin and fragile.

Procedure:

Press “ON” for a few seconds the power of PM1405 will be on. Wait for few second, the survey meter will finish the TEST cycle. You can see measurement mode, the value Sv/h and statistical errors. Usually, when the counting rate is small, the statistical error is large. A long time counting is needed in order to reduce the statistical error. Wait for a few seconds to get the statistical errors down to a smaller number.

Take the survey meter and walk around the lab or go outside to see the values of survey meter change. The background should be around 0.05-0.2 Sv/h.

To shutdown the survey meter:

1. Push SELECT
2. Choice the menu to “ power off” then “ SELECT”.
3. Press “ Yes” to shut the survey meter down.
   Note: If you want to measure the paricles, please go to the MENU to select measurement of . In counting mode, the unit of the measurement value will be in Hz only in this survey meter (PM1405)

Experiment 1: Operation of Oscilloscope

Purpose

The purpose of this experiment is to familiarize the student with an oscilloscope and a pulser that we will use in the later experiments to test counting systems, especially, to learn the triggering technique of an oscilloscope in order to capture the pulse shape of a random nuclear pulse.

Fig. 1-1: An analog and a digital oscilloscopes used in our lab.

Description

Almost all nuclear radiation measurements involve the use of electronic equipment. Some systems will be complete instruments such as the survey instruments used in the first experiment. More general, especially in the laboratory, a system for a particular measurement will be assembled using standard instrument packages. For nuclear counting measurements, most of the instrumentation conforms to the **Nuclear Instrument Module (NIM)** Standard that was established in the early 1960's to standardize the equipment used in low energy nuclear physics. The NIM Standard specifies the size of the modules, the power supply voltages and currents, the signal shapes and levels, the input and output characteristics of the modules and the connectors, please refer to G.F. Knoll textbook for more details.

When interconnecting the instrument modules, particular care must be exercised that the output of one module is compatible with the input of the next module. It is also important to know when a module is malfunctioning or not adjusted properly. Although tests can be devised to test a system's operation, the fastest way to insure the proper adjustment and operation is to observe the shapes of the electric pulses going into and out of each module. An oscilloscope is used for this purpose.

An oscilloscope is a device that permits one to examine the time dependence of electric signals. Its vertical axis (y) corresponds to the amplitude of a signal and the horizontal axis (x) corresponds to time. Thus using an oscilloscope while assembling a radiation detection system will permit us to insure that the individual modules are working properly and the signals from the modules agree with the specifications stated by the manufacturer.

The typical laboratory oscilloscope is a versatile instrument with several tens of controls. However, the various controls can generally be grouped into four main functions, those governing the focusing and intensity of the beam, those governing the scale of y axis, those governing the scale of x axis (called time base), and those responsible for creating stable CRT (Cathode Ray Tube) displays (called triggering). Refer to the manual of oscilloscopes for detailed descriptions of each control. Today, two kinds of oscilloscopes, namely, analog type and digital type, are available in the market. The digital type prevails right now. An LCD (Liquid Crystal Display) is used to replace the bulky CRT in a digital type oscilloscope. The vertical deflection of electron beam was replaced by an ADC (Analogy to Digital Converter) also in a digital oscilloscope. However, to learn the analog type oscilloscope is better for understanding the operation principle of an oscilloscope.

A pulesr is designed to simulate the output signal of a nuclear particle reaction in a nuclear detector and is used to check the performance (linearity, electronic resolution, etc.) of a radiation counting system. The pulser (ORTEC 480 or Canberra 807) provides pulses characterized by a fast rise time, (usually < 10 ns 10-90%) and a slow exponential decay time (several hundred micro-seconds). The output amplitude is adjustable by attenuation switches or a potentiometer.

Nuclear decay is a random process. We cannot predict the exact time that a nuclear reaction induced by radiation occurs in the detector. Therefore, to capture a nuclear pulse on an oscilloscope strongly relies on the triggering technique of the oscilloscope. In this experiment, to learn the triggering technique is the most important issue. The trigger system of the oscilloscope decides when to start displaying the signal. The moment of triggering is the beginning of the trace in the left side. Usually, the trigger system in analog oscilloscopes can be seen as a simple comparator which compares the input signal from one of the channels with the trigger level provided by user through an adjustable knob.

Apparatus

Oscilloscope: ____________

Pulser: ____________

Procedures

I. Oscilloscope Turn-On Procedure

1. Turn on the power and set the controls/switches as follows:

   - Vertical controls

     - ✓ VERT MODE channel 1
     - ✓ INPUT COUPLING GND
     - ✓ VOLTS/DIV 5

   - Time base and triggering

     - ✓ TRIG SOURCE channel 1

✓	TRIG SRC COUPLING	DC
✓	TRIG LEVEL	0
✓	TRIG MODE	AUTO
✓	SLOPE	(+)
✓	TIME/DIV	1 msec

2. Note that the INPUT COUPLING switch AC/DC/GND means: GND → check position of zero volt; AC → block any DC signal and only pass AC signal component; DC → usually normal setting for this switch that allows all signals including AC.

3. There is no need to have a signal connected to the scope at this moment to see a trace displayed on the screen of the CRT (Cathode ray tube). Now, adjust the CH 1 POSITION and horizontal POSITION to center the trace on the screen; adjust INTENSITY and FOCUS to get a sharply focused and bright enough display (too much brightness will shorten the lifetime of the screen). You now have the most basic display: a free running trace with a voltage level zero volt (any DC level will be referred to this GND level).

4. Turn the TIME/DIV knob to 20 ms and 0.2 s. What do you observe? ___________ What you have just done is to change the horizontal sweep speed. We usually use a fast sweep to observe a fast varying signal and a slow sweep to observe a slowly varying signal.

5. Now, using a probe that comes with the package to do the self-calibration procedure of the oscilloscope. You should observe a square wave. Write down the frequency _______________ and amplitude __________ of the square wave. Is it the same values as those in manual of oscilloscope? If not, an adjustment of the oscilloscope is needed.

II. Observing the output signal of a pulser

1. Turn the NIM bin power switch on and set the pulser controls as follows:

➢	PULSE HEIGHT	fully clockwise
➢	All ATTEN switches	x1
➢	OFF/ON	ON
➢	Polarity POS/NEG	POS
➢	TIME/DIV	2 ms
➢	DIR/NORM OUPUT	without Terminator

2. Connect the pulser ATTEN OUTPUT to the scope CHANNEL 1 with a BNC ended coaxial cable.

3. Turn the channel 1 input coupling switch to AC. Now, you should see the pulses output from the pulser on the screen. Adjust the time base to 0.02 ms and horizontal position so that only the first pulse can be seen. Plot it out! ____________ These pulses have a fast leading edge (less than 10 ns)

with a slow trailing edge to simulate the typical output pulse from a radiation detector. In order to see the leading edge clearly, you may need to change the time base, increase intensity and shield the strayed light around.

4. Do you see a stable display when you turn the TRIGGER LEVEL knob fully clockwise and counter-clockwise? __________ If not, explain your reason? __________ .
5. Try to get a stable display with TRIG MODE by adjusting the TRIGGER LEVEL and measure the amplitude of the pulse: __________ (use proper VOLT/DIV setting).
6. Turn the channel 1 input coupling switch to DC. Is any measurable DC level in the pulse? __________ . Increase the VOLT/DIV to see the small difference.
7. Play the horizontal sweep speed by changing the TIME/DIV knob to determine the repetition rate of the pulse __________ . Write it down and explain why? __________ .
8. Measure the time that takes for the pulse falling to 9/10, 1/2, 1/10 of the peak amplitude using proper TIME/DIV settings. Does the tail of the pulse follow exponential decay? __________ . What is the decay time constant? __________ . Is it correct? __________ (Please check the manual of pulser for its specification)
9. Turn the TRIG LEVEL knob to slightly less than zero. Set the polarity switch of the pulser to NEGative. What happened to the first pulse? __________ .
10. Set the SLOPE (+/-) switch to (-) and compare the display with the one you just observed. Is the pulse amplitude smaller or larger? ___________ . Now, turn the triggering level up and down. Do you see the pulse amplitude change with the trigger level? ___________ . If you change the slope to +, and turn the trigger level up and down, can you observe the pulse amplitude change? ___________ . Do you understand the function of the SLOPE (+/-) switch?
11. Set the attenuation of the pulser to x2 and measure the peak amplitude: __________ . You probably need to change the VOLT/DIV setting. Measure the peak amplitude when the attenuation is at X5, X10, and X50 ___________ . You may need to adjust trigger level for a stable display. Once the input signal is properly triggered, the TRIG light will be on. What is the function of the TRIG LEVEL switch?

Questions

1. Please state the major components and working principle of an oscilloscope using block diagram. (remark: analog oscilloscope is different from digital one in display part)
2. Can you explain why the frequency of the pulser is around 60 Hz?
3. What is the difference between AC and DC coupling of your oscilloscope?
4. What is the maximum bandwidth of your oscilloscope? How fast you need to measure the leading edge of the pulser output?

Experiment 2: Nuclear Electronics

Purpose

The purpose of this experiment is to introduce the basic pulse counting concepts and familiarize the student with the commonly used NIM modules.

Description

The signal chain shown in Fig.2-1 represents a basic measurement scheme in which only the number or rate of pulses from a detector is to be recorded.

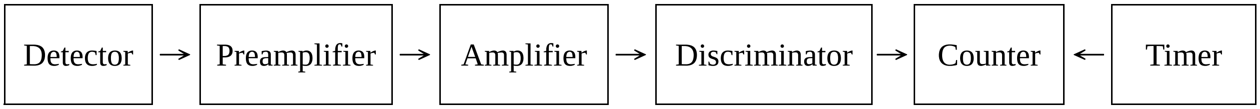


Fig. 2-1: Basic pulse counting system.

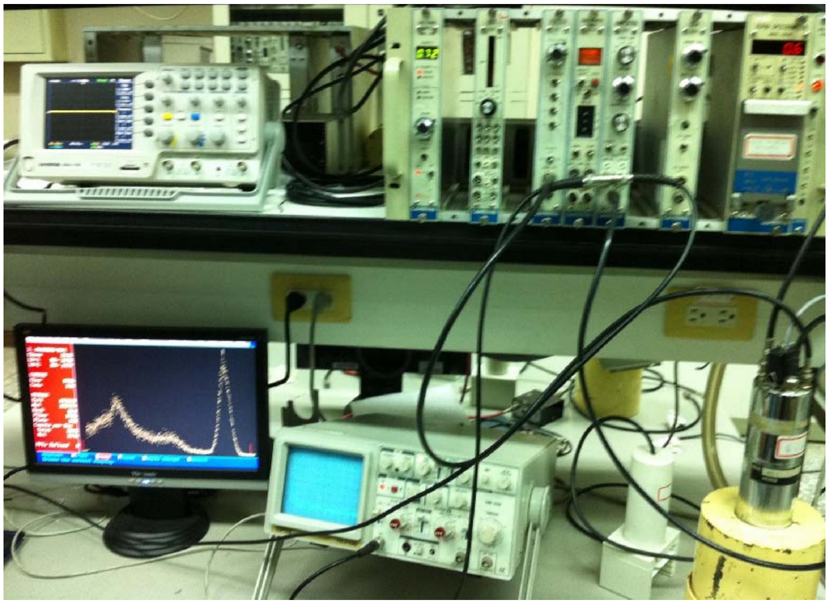


Fig. 2-2: Typical layout of a nuclear detection system in our lab.

The fundamental output of all pulse type radiation detectors is **a burst of charge Q** (V=Q/C) that is liberated by the incident radiation. In this experiment, a pulser is used to simulate the output of a detector. Using ORTEC 480 as an example, it features an exponential pulse shape with < 10 ns rise time and 200~400 µs decay time. A preamplifier has two main functions. It is usually located next to a detector to serve as an impedance matcher, presenting a high impedance to the detector to minimize loading, while providing a low impedance output to drive succeeding components. It also minimizes the capacitance loading on the detector and thus maximizes signal to noise ratio. The output of a preamplifier is a linear tail pulse with a fast rise time (< 1 s) and a slow fall time (> 50 s). The function of a linear amplifier is to amplify and shape the pulses from the preamplifier for pulse height analyzing. Most amplifiers use CR-RC network to provide output pulses with Gaussian shaping. The differentiation and integration time constant are on the order of s. A Gaussian shaping amplifier requires an input pulse with a fast rise time (< 1 sec) and a decay time (> 50 s) with either a positive or negative polarity. The output of the amplifier is a positive unipolar or bipolar pulse with a positive leading edge. Bipolar pulses are used for high counting rate experiments or timing experiments. More details on pulse shaping are given in chapter 16 of the Knoll's textbook.

In order to count properly, the shaped linear pulses must to convert into logic pulses. A single channel analyzer (SCA) or an integral, discriminator can be used for this purpose. If the linear pulses meet the conditions imposed by the SCA or integral discriminator, logic pulses are generated. The integral discrimination mode of operation is the simplest method for converting shaped linear pulses into logic pulses. When the linear pulse exceeds the discrimination level (or called threshold), a logic pulse is produced and then can be sent to the next stage (timer/counter) for counting. A more common method of analyzing pulse height is using an SCA in the differential discriminator mode (or window mode). In this mode, two discriminators, a lower level discriminator (LLD) and an upper level discriminator (ULD), are used together to select the desired pulse height. If the input pulse amplitude exceeds the LLD level but not the ULD level, logic pulse is then generated. Therefore, a differential pulse height spectrum can be obtained directly by adjusting the LLD and ULD settings sequentially. In modern pulse height analyzing system, a multichannel analyzer (MCA) is used to obtain the differential pulse height spectrum in a parallel operation. The working principle of an MCA will be discussed in a later lab session.

Apparatus

Pulser: e.g. ORTEC 480 or Canberra 807

Preamplifier: e.g. ORTEC 113 or Canberra 2007P

Amplifier: e.g. ORTEC 485, 575 or Canberra 2012

Single Channel Analyzer: e.g. Canberra 2030

Counter: e.g. ORTEC 775, 875 or Canberra 2071A

Timer: e.g. ORTEC 719 or Canberra 2071A

T-shape BNC connectors

Oscilloscope:

Procedures

I. Check the performance of the preamplifier

1. The ORTEC 113 (or Canberra 2007P) preamplifier is designed for use with scintillation counting systems which will be used in later experiments. The ORTEC 113 is a voltage sensitive non-inverting preamplifier (Canberra 2007P is an inverting preamplifier) with no provision for pulse shaping except the variation of fall time. This model of preamplifier is intended to operate into a shaping linear amplifier such as ORTEC 485.

2. Turn on the pulser and feed the ATTN output to Ch1 of the scope. Adjust the attenuation switch and/or pulse height knob of the pulser so that the pulser produces 0.2 V negative pulses (for Canberra 2007P, use positive pulses). Record the settings and plot the output of your pulser __________ .

3. Connect the power cable of the preamplifier to a power source located on the rear of a linear amplifier module. Set the input capacitance switch of the preamplifier to 100 pf (Canberra 2007P does not have input capacitance selection). Feed the pulser ATTN output to both the scope Ch1 and the preamplifier TEST input with a "T" shaped BNC connector.

4. Feed the output of the preamplifier to Ch2 of the scope. Set the VERT mode of the scope to Ch2. Sketch the preamplifier output pulse amplitude versus time ____________ . Determine the fall time constant according to the plot __________ . (Please notice that the pulse shape is usually overshot or undershot)

5. Change the input capacitance of the preamp from 0 to 1000 pf step by step and record pulse amplitude versus the input capacitance setting. (Canberra 2007P does not have input capacitance selection, skip this step) Explain your data __________ .

6. Set the preamplifier input capacitance back to 100 pf. Set the scope VERT mode to ALT. You should observe two traces: one is the output of the pulser and the other is the output of preamplifier. Compare the shape and amplitude of the two signals __________ .

II. Observing the output of a linear shaping amplifier

1. Set the controls of the amplifier as follows:

   - Fine Gain: minimum (fully counter-clockwise)
   - Coarse Gain: 2

- Polarity: UNIPOLAR, POS (because preamp output is positive)

2. Connect the preamplifier output to the amplifier input. Connect the amplifier output to Ch1 of the scope.

3. Sketch the amplifier output waveform with proper VOLT/DIV and TIME/DIV settings __________ .

4. Compare the amplifier output with the preamplifier output. Describe the differences of the two waveforms __________ .

5. Set the amplifier polarity to BIPLOAR with the preamp input capacitance at 100 pf. Sketch the pulse using same VOLTS/DIV and TIME/DIV settings as in step 3. (Canberra 2012 amplifier does not have bipolar output, skip this) Compare the pulse shape of the unipolar and bipolar outputs __________ . Measure the zero-crossing time of the bipolar pulse and the peaking time of the unipolar pulse, are there any differences? __________ .

6. Set the amplifier controls back to UNIPOLAR. Adjust the coarse gain (leave the fine gain at fully counter-clockwise) so that the amplifier output is about +6 volts. Record the actual pulse amplitude for later use. Now, increase the amplifier gain by more than two times to observe the saturation of pulse. Record the maximum saturated pulse height ___________ . Now, put the pulse height back to +6 V. You are ready for pulse counting.

III. Pulse counting with an integral discriminator

1. Set the discriminator knob at 10 volts; set COUNT/STOP to COUNT. (Use Canberra 2030 SCA LLD as discriminator to give a better adjustment ability) Connect the amplifier output to the counter input. Set the timer in long time counting situation.

2. Reduce (counter-clockwise) discriminator level gradually until the counter starts to count. Is the discriminator setting close to what you have recorded (+6 V) in step II-6? __________ .

3. Connect the timer output to the GATE INPUT of the counter (Canberra 2071A already connects internally). Set the time interval to 10 s. Take ten 10 s counting. Calculate the average and the standard deviation of the ten readings __________ .

$$\text{Average or Mean} \quad \bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$$

$$\text{Standard deviation} \quad \sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2}$$

Questions:

1. What are the functions of preamplifier and amplifier?
2. Why the preamplifier and amplifier are usually separated as two nuclear instrument modules?
3. In which nuclear instrument modules, the logic output is provided?

Experiment 3: Geiger-Mueller Counters and Basic Nuclear Statistics

Purpose

The purpose of this experiment is twofold. First, the experiment demonstrates the setup, use, and characteristics of GM counters; second, it demonstrates the statistical phenomena involved in nuclear radiation measurements. An understanding of these statistical effects is necessary for a meaningful interpretation of the measured data.

Theory of GM counters

The three basic gas-filled detectors are ionization chambers (IC), proportional counters (PC), and Geiger-Mueller counters (GM). The gas-filled chamber has two electrodes, consisting of an outer cylinder and a thin wire along the cylinder axis as shown in Fig. 3-1. The wire is maintained at a high positive voltage with respect to the cylinder. Various gases may be used in the chamber; the most common gases are the noble gases, particularly argon. A large range of pressures can be used, usually varying from 7 to 20 cm Hg. The electric field between the two electrodes is highly non-homogeneous, being very large near the central wire. All gas-filled detectors operate on the following principles: a) charge particles ionize some of the gas molecules within the chambers; b) the electric field pulls the electrons and ions to the electrodes producing a current pulse in the circuit; c) the current pulses are measured or counted either in current mode or pulse mode operations.

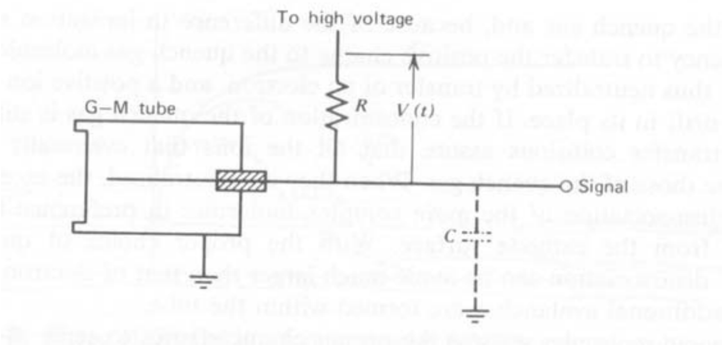


Fig. 3-1: Configuration of gas-filled detectors.

Fig. 3-2: A GM counter used in our lab.

The various types of gas-filled detectors can best be understood by considering each of the four regions in Fig. 3-3. In region A, the charge collection is difficult due to the small electric field; thus the detector cannot operate efficiently. In region B, practically all ion pairs formed by the radiation are collected before recombination can take place. The current from the ionization chamber is a direct measure of the energy transferred from the radiation to the detector. In region C, when an ion pair is formed, the electron can gain enough kinetic energy as it is accelerated towards the central wire to produce further ion pairs in its collision with gas molecules. This process is called charge multiplication because an electron from one of the primary electron-ion pairs can produce more ionization and thereby increase the charge collected on the electrodes. In this region, total charge collected by the electrodes is proportional to the energy deposited in the detector by the nuclear radiation; therefore called proportional region and a detector operated in this region is called the proportional counter. In region D, the applied voltage and thus the electric field are so high that any nuclear particle producing a single ion pair within the detector can initiate an avalanche of electrons by charge multiplication process. The multiplication process continues until the density of the ion pairs is sufficient to disrupt the electric field between the electrodes. Note that the pile up of positive ion concentration around the anode from a space charge effect which creates a counter electric field to limit the electrons for more multiply gain. Since the ion pair density required to stop the multiplication process is a function of only the electrode configuration and the applied voltage, the output pulse from the GM counter is independent of the energy deposited by the nuclear radiation.

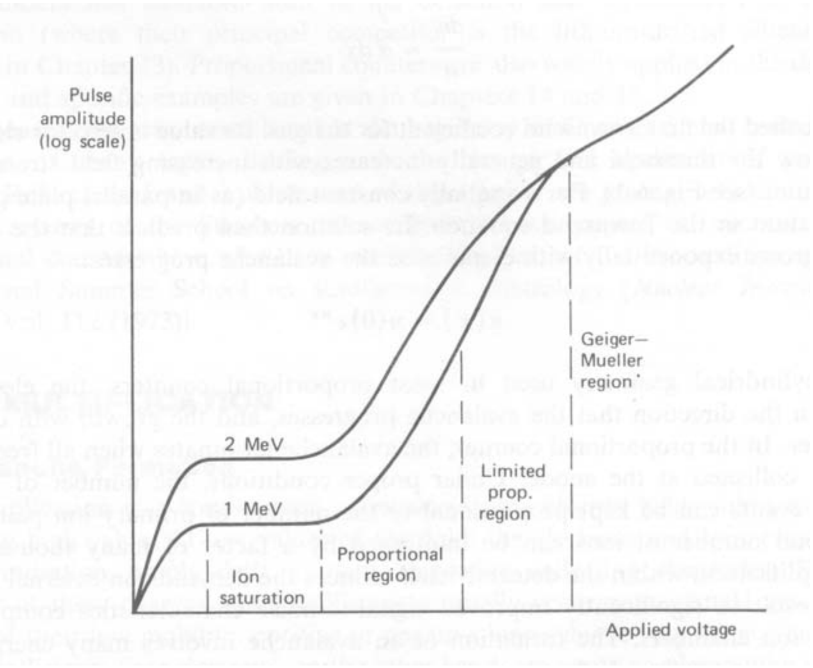


Fig. 3-3: The different region of operation of gas-filled detectors. As the applied voltage increases, the following regions are observed: A) recombination before collection, B) ionization chamber region, C) proportional region, D) GM region, E) continuous discharge.

Gas-filled type detectors using charge multiplication must have some means of quenching the discharge. Without quenching, electrons would be released when the positive ions struck the negative electrode and these electrons could start the multiplication process again and thus produces multiple pulses. Good GM tubes often use a small amount of halogens to quench the discharge and prevent multiple pulses from occurring. When the counting rate of the GM tube is plotted as a function of applied voltage, a curve similar to Fig. 3-4 is obtained. In general, the counting rate starts slowly at V1, and then increases rapidly while the applied voltage is increased. Beyond a point, called the threshold voltage V2, the counting rate of increase is slow over a "Plateau" which may extend for several hundred volts. The plateau in the counting-rate curve between V2 and V3 is called GM plateau. The slope of the plateau for a good GM tube will be no more than 2 or 3% per hundred volts. Beyond the voltage V3, the counting rate starts to rise sharply again when multiple discharges start to occur. If the tube is operated above V3, it will soon be destroyed. Each time a detector system is turned on, whether for the first time or for any subsequent operation, the high voltage should be started at zero volt and increased gradually to the point where counting starts. The best operating high voltage should be near the center of the plateau.

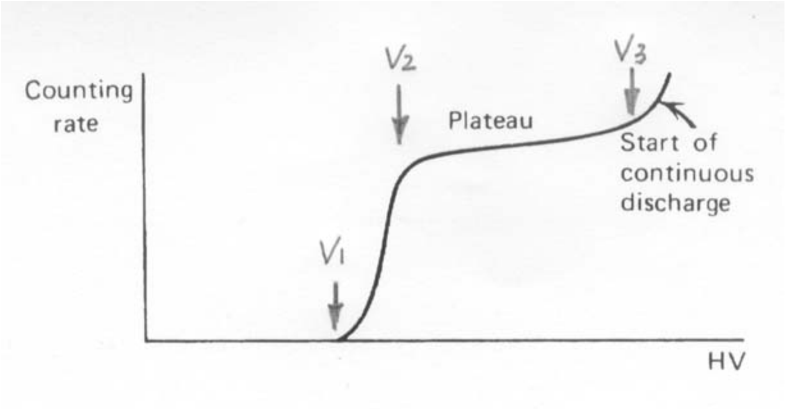


Fig. 3-4: Illustration of a counting curve.

Nuclear Statistics

Nuclear radiation measurements are statistical in nature. When speaking of a finite number of measurements, one can not in effect determine the true mean; rather one can only estimate. For the binomial, normal (Gaussian), Poisson, and interval distribution, it can be shown that our best estimation to the true mean is simply the arithmetic average $\bar{x}$;

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{3.1}$$

When the number of measurements N approaches infinity, $\bar{x}$ approaches to the true mean of the distribution. Our best estimation to the standard deviation of a distribution in terms of our finite number of observations (N) is σ ;

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{3.2}$$

The (N-1) in the denominator is correlated with the number of "degree of freedom". From N independent observations of x_i (the number of counts for the i^th observation), there are originally N independent equations. This number is reduced by one when $\bar{x}$ is computed from Eq.(3-1); thus there are only (N-1) independent data from which to compute the standard deviation. The quantity ^{2} is called the sample variance. The physical meaning of the standard deviation is to specify the degree of dispersion in a data set. For a Gaussian distribution, 68% of all measurements will lie in the band of + and - In other words, it is expected that one out of three of the measurements will fall outside of the band ± .

It can also be shown that for a Poisson distribution, the result of a single observation is to be reported as:

$$x_i \pm \sigma_i \quad \text{where} \quad \sigma_\text{i} = \sqrt{x_i} \tag{3.3}$$

The result of a single series of N observations is to be reported as: $\bar{x} \pm \sigma_{\bar{x}}$, where

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{N}} \tag{3.4}$$

or

$$\sigma_{\bar{x}} = \sqrt{\frac{\bar{x}}{N}} \tag{3.5}$$

A repetition of the series of N measurements would, in general, give a different mean value, but the chance that the new mean value would lie within $\bar{x} \pm \sigma_{\bar{x}}$ is 68%. For another single observation, the observed value would lie within $\bar{x} \pm \sigma$ is 68%, instead where $\sigma = \sqrt{N} \times \sigma_{\bar{x}}$.

Apparatus

The counting system used in this experiment is shown in Fig. 3-5. The output signal of the GM is usually quite large. Therefore, no preamplifier or amplifier is required. The function of the GM preamplifier (Canberra 148A) is to pass through the high voltage to the GM tube, to provide impedance matching and to invert the GM output to positive polarity for counting.

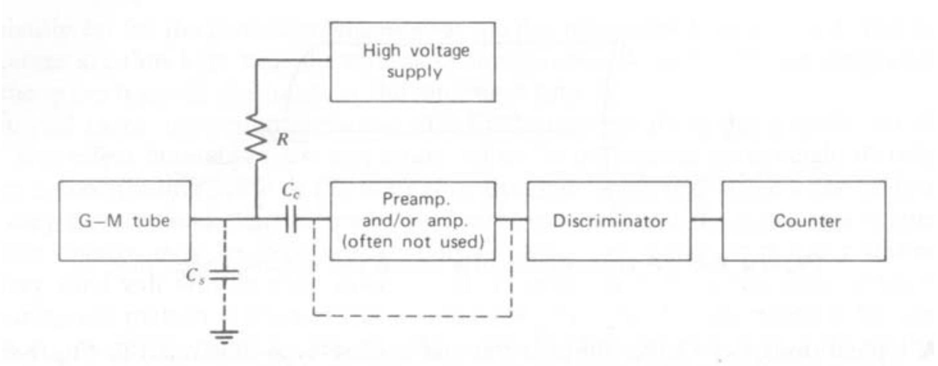


Fig. 3-5: A GM counting system.

Procedures

1. Set up the system shown in Fig. 3-5 with preamplifier (Canberra 148A) but without amplifier. Remove the window cover from the GM-tube. CAUTION: DO NOT TOUCH THE MICA LAYER. It is thin and breaks easily! (The Oxford GM-counter set already installed with window cover removed)

2. Make sure the high voltage setting is at zero volt and positive. Connect the GM output on the converter (or preamplifier) to the oscilloscope. Get a beta source (^{90}Sr) from the instructor, put into the second shelf of the sample house, and face it to the GM tube.

3. Turn on the NIM power bin and the power of the high voltage supplier. Gradually increase the high voltage setting until you see negative pulses on the scope (may be very small, use small VOLT/DIV). (If you use Canberra preamplifier 148A, the polarity already inverted into positive pulses). The voltage setting, at this moment may be around 750 V. (Please use mutlimeter to make sure the output from the voltage supplier is correct) If you further increase the H.V. about 50 to 70 V, you should observe the pulse amplitude increases. Make sure that the pulse is due to the source not noise (pulses should disappear by removing the source). Yes? _________ .

4. Determine the counting curve shown in Fig. 3-4. Set the discrimination level on the counter to 0.5 V (or use SCA). Record the high voltage setting V1 _________ , where the counter starts to count. This voltage V1 is dependent on the discrimination level setting, why? _________ .

5. Measure the counting rate as a function of H.V. setting by increasing the voltage in steps of 25 V starting from V1. Counting rates can be measured by using the provided timer/counter in time interval 30 s or 1 min.

6. For each data you record in the last step, immediately plot that point on a graph of counting rate versus high voltage setting _____________ . Use this graph to determine V3, the voltage at which multiple discharges begin affecting the counting rate. (Please keep the applied high voltage below 900V) IMPORTANT: Do not exceed V3 more than 900 V.

7. The operation voltage of the GM tube is approximately at the center of the GM plateau, i.e. (V2 + V3)/2 __________ . Refer to Fig. 3-4, assumed V3 = 900 V if you cannot go above it to see the drastic rise of counting rate. Set the high voltage at this value. Sketch the waveforms from the connectors (labeled GM OUT). If the output peak height still larger than saturation, try to reduce the H.V. furthermore until the pulse height is far from saturation. Take 30 times of 20 s counting data.

8. Get a gamma source ^{60}Co to replace the beta-source ^{90}Sr. Put it at the same position as before. Record the pulse height of both sources _________ .

9. Repeat the experiment of last step using ^{137}Cs instead of ^{60}Co __________ . Note that the gamma-ray energy of ^{137}Cs is 0.662 MeV; and ^{60}Co is 1.173 and 1.332 MeV.

10. Put a piece of stainless steel sheet before the window of the GM tube. Take a 30 s counting with the ^{137}Cs, ^{60}Co, ^{90}Sr. Record the counting rate before and after putting the attenuation sheets. What are the attenuation factors of this shielding material for each radiation? _________ .

Questions

1. Determine the slope of the GM plateau (percent change in count rate per 100 V change in high voltage). A good GM tube will have a plateau with a slope of no more than 2% or 3% per 100 V. A bad GM tube may have plateau with slope of about 10% per 100 V. How good is yours?

2. Why the counting rate increases with the applied high voltage in the range between V1 and V2 but not so sensitive in the range between V2 and V3?

3. Calculate the estimated true mean, standard deviation, and the standard deviation of the mean (Take the root-square of the mean directly) based on the data measured in step 7. (please notice the significant digitals of the numbers) Any difference between the standard deviation of the mean calculated from Eqs. (3-4) and (3-5)? Which formula is more suitable?

4. What percentage of the individual readings in step 7 lies outside the band $\overline{x} \pm \sigma$? How many lies outside the band $\overline{x} \pm 2\sigma$? Are these percentages consistent with the proceeding description on statistics?

5. Based on your analysis of 20 s runs, what would be the number of counts expected in 5 minutes? What would be the standard deviation of a 5-minute long count?

6. What conclusions can you make from this experiment concerning the radiation energy dependence of the GM output signal? (by comparing the pulse height of the ^{137}Cs, ^{60}Co, ^{90}Sr).

Experiment 4: NaI(Tl) Scintillation Counting System and Multichannel Analyzer

Purpose

The purpose of this experiment is to demonstrate the use of NaI(Tl) scintillation detectors in the detection and spectrum measurement of gamma rays and to demonstrate the function of a multichannel analyzer (MCA) and its use for gamma spectroscopy.

Theory of scintillation detector

Scintillation detectors detect the presence of radiations by converting some of the energy deposited in the detector into light. The process of converting the energy to light involves the raising of atoms or molecules to excited levels by the radiation and the de-excitation to the ground state with a low energy photon emitted. Some scintillators have a very high probability of reabsorbing their emitted light, so a small amount of secondary material is added to shift the wavelength of the light and to enhance the light emitting efficiency. Such an additive, called activator, is thallium (Tl) in sodium iodine (NaI). Imperfections in the crystalline structure of the scintillation detector also offer a mechanism for re-absorption of the light. For this reason all inorganic detectors such as NaI(Tl) are made from single crystals.

In most modern scintillation detectors (e.g. in Fig. 4-1), the light from the scintillators is collected, transformed to electrons, and then amplified to electric signals by a photomultiplier tube (PMT). The PMT has a photocathode which serves to convert the incoming light to low energy electrons by the photoelectric process. The amount of light from the scintillator can only produce a few hundred photoelectrons which are too few to serve as a detectable electrical signal. The PMT, therefore, has an electron multiplier section which consists of 3 to 10 electrodes (called dynodes). The dynodes provide an efficient collection geometry for the photoelectrons as well as serving as a near-ideal amplifier to greatly increase the number of electrons. After the electron multiplier section, a typical scintillation pulse will give 10^7-10^{10} electrons. This charge is then collected at the anode of the PMT and output to the external signal processing circuit.

Since the processes of scintillation, light collection, conversion to electrons, electron multiplication, and charge integration to give a voltage pulse are linear processes, the amplitude of voltage is proportional to the energy deposited in the scintillator. The voltage pulse is usually fed to a multi-channel analyzer (single channel analyzer will be used first in this experiment) to measure the energy spectrum or activity of radioactive sources.

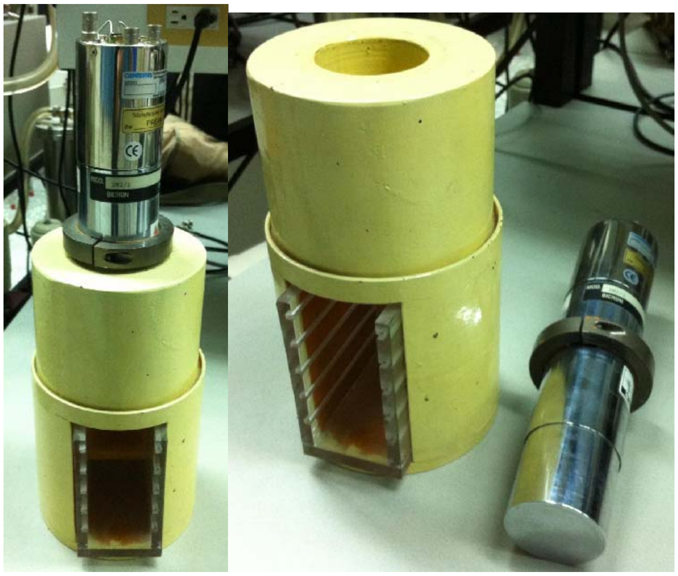


Fig. 4-1: NaI(Tl)+PMT detector and its sample holder used in our lab.

Multichannel analyzer (MCA)

A modern MCA is composed of four basic functional blocks: a) analog signal processing and digitizing; b) memory storage; c) image display; d) data acquisition and digitized data input/output. The basic block diagram of an MCA is illustrated in Fig. 4-2.

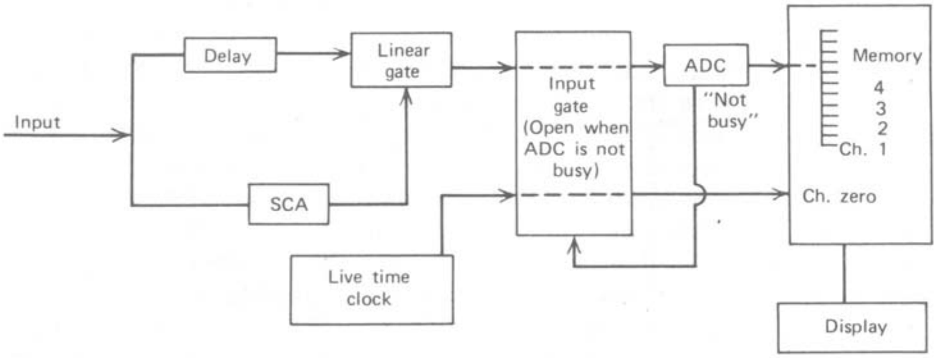


Figure 18-8 Functional block diagram of a typical MCA.

Fig. 4-2: Functional diagram of a multichannel analyzer. (Reference: Knoll's textbook)

The operation of an MCA is based on the principle of converting an analog signal to an equivalent digital number, then store and display the digital number in an array. Therefore, the basic function of an MCA involves only the analogy to digital converter (ADC) and the memory. There are two basic modes of operations in an MCA: one for pulse height analysis (PHA) and the other for timing analysis or called multiscaling (MCS). In the PHA mode, the amplitude of each coming pulse is digitized and stored in a memory location that corresponds most closely to its amplitude. The result is similar to obtain a differential pulse height spectrum by using many single channel analyzers in parallel as illustrated in Fig. 4-3.

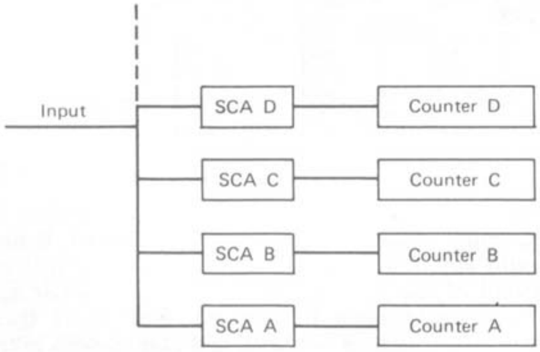


Figure 18-2 An array of stacked single-channel analyzers. Windows $A, B, C, \ldots$ are assumed to be contiguous and of equal width ΔH, with A at the bottom of the pulse height scale.

Fig. 4-3: An array of stacked SCA in parallel operation (Reference: Knoll's textbook)

In the PHA mode, the ADC is the key element. The performance of an ADC can be characterized by a) conversion speed, b) linearity of conversion, c) resolution of conversion. The resolution of an ADC is conventionally quoted in the number of channels; e.g. a 1024 channel ADC can subdivide the full amplitude span into 1024 channels. There are two main controls in an ADC, CONVERSION GAIN and OFFSET (in some MCA, the offset is called ZERO). The GAIN specifies the number of channels divided over the full amplitude span. The OFFSET specifies the difference between the memory channel zero and the ADC zero (see Fig. 4-4). For example, if the GAIN is set to 1024 and the OFFSET is set to 0, a 5 volts pulse falls into channel 512; the pulse will then fall into channel 510 if the OFFSET changes to 2. Usually, the channel corresponds to the 0 V in pulse height, while the maximum channel corresponds to 10 V (some of your Canberra Accuspec card, the maximum channel at 8 V).

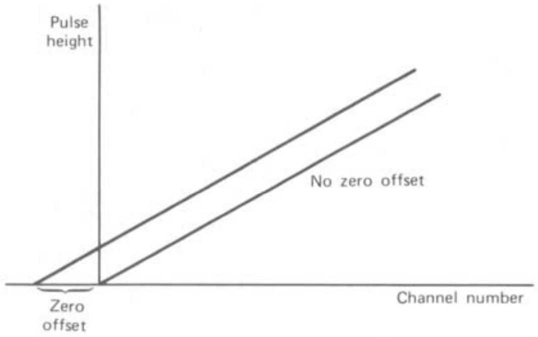


Figure 18-5 Typical calibration plot for a linear MCA with and without zero offset.

Fig. 4-4: The zero offset of a MCA.

In the MCS mode, each incoming pulse is stored sequentially in the memory locations according to the arriving time regardless of its amplitude. In other words, each memory location is simply treated as a counter. Those pulses arrive at the start of the analysis period are stored in the first channel; those arriving in the next period are stored in the second channel, etc. The period is called dwell time which can be preset by the user. Therefore, the MCS mode gives a curve of counts versus time. In this mode of operation, the ADC is not applied to digitize the pulse amplitude. Some MCAs also have an MCSR mode which is repetitive multiscaling, i.e. accumulate several MCS spectra and add them together.

There are some additional components and controls in the signal processing and digitizing block. A built-in amplifier can be switched on to amplify the input analog signal. There is an ULD and LLD to select analog pulses with proper amplitude. There is also a dead time meter to indicate the percentage time that the ADC is busy.

In the memory block, a memory control can be used to subdivide the memory into halves for independent data acquisition and comparison. The display block consists of controls for vertical and horizontal scale adjustment. A cursor is equipped to readout the counts in each memory location.

In the input/output block, the input section controls the conditions for data acquisition, i.e. PHA/MCS modes, counting time/dwell time, ADD/SUB background and digital data read in. The output section specifies where the store spectrum to be sent, e.g. printer, plotter or recorder. There is a "region of interest (ROI)" function to select a segment of the spectrum which can be printed out or simply be integrated to get the total counts of that region. Fig. 4-5 shows a detection system with MCA where a pulse height spectrum is shown on the screen monitor.

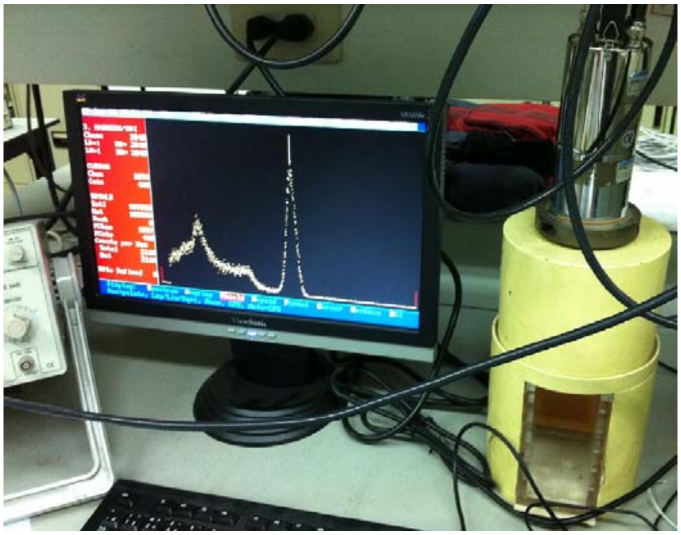


Fig. 4-5: Pulse height counting application using a NaI(Tl) detector with MCA.

NaI(Tl) Counting System

The counting system used in this experiment is shown in Fig. 4-6

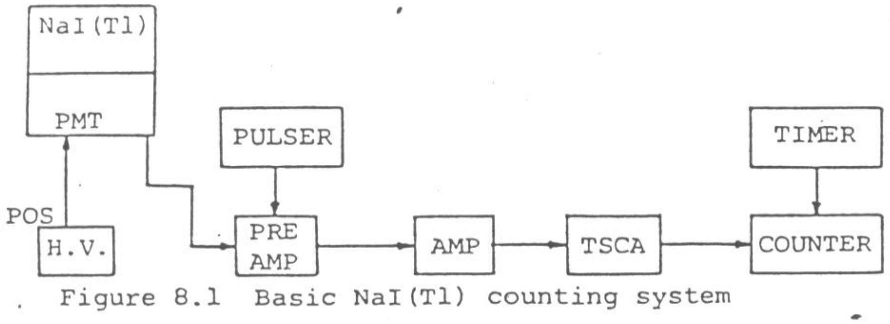


Fig. 4-6: Basic NaI(Tl) counting system.

In the above equipments, only the detector portion and the Timing Single Channel Analyzer are new to you. The NaI(Tl) crystal and the PMT are connected together as a light-tight package. CAUTION: the crystal is brittle, and the PMT is a vacuum tube sealed in a glass. Please handle it carefully. Don't drop it. The package costs about US$5000. The PMT base contains a voltage-divider string and two connectors: one is the high voltage input and the other is the anode output signal with negative polarity. The gain of the PMT can be adjusted by changing the voltage across the photocathode and the first dynode. The gain or focus should be adjusted to give the maximum output signal at the anode or after a linear amplifier. Some PMT bases have a third connector called DYNODE which is the output signal from the last dynode with positive polarity. If we do not use this output, the output should be terminate by a 100 ohms terminator.

The Single Channel Analyzer (SCA) or Timing Single Channel Analyzer (TSCA) is designed for timing experiments as well as energy analysis. In this experiment, we only use the part for energy (or pulse height) analysis. The part for timing analysis will be used in experiments for coincidence measurements in the advanced radiation measurement course in the future. Basically, there are two modes for pulse height analysis in a TSCA: integral and differential (or window) discrimination. (In the Canberra 2030 SCA, only WINDOW mode is provided and no delay time adjustment.) In the integral mode, the mode switch is set to INT or E. The "Lower Level" or "E" knob determines the threshold setting. The TSCA produces an output whenever the input pulse amplitude is larger than the "Lower Level" setting. In this experiment we will use the differential or window mode to measure differential pulse height spectra. In the differential mode, the TSCA mode switch is set to WINDOW or DIFF. The window width is determined by the setting of the knob "WINDOW" or " E" which indicates the amount of difference between the lower discrimination level and the upper discrimination level. The TSCA produces an output whenever the input pulses with amplitudes lie between the "Lower Level" setting and "Lower Level" + "Window or E" setting. There are two outputs from TSCA: one is positive and the other is negative; we use positive output. Refer to the TSCA manual for detailed descriptions of various controls.

The counting system with a multichannel analyzer used in this experiment is depicted as follows:

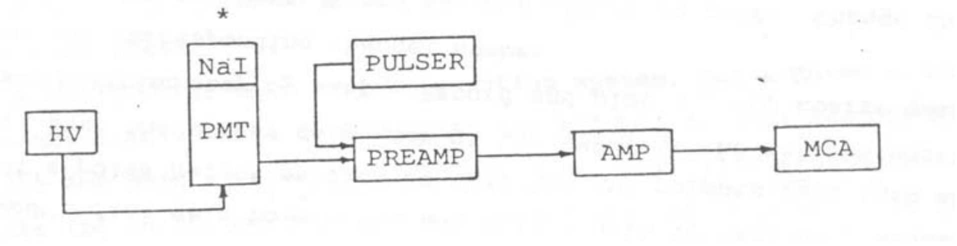


Fig. 4-7: Counting system with a multichannel analyzer.

Gamma Energy Spectrum with NaI(Tl)

Detailed descriptions of the response function for NaI(Tl) scintillators can be found in Knoll's textbook. For a 2" x 2" intermediate size NaI(Tl) crystal, the spectrum from source with single gamma energy such as ^{137}Cs is illustrated in Fig. 4-8.

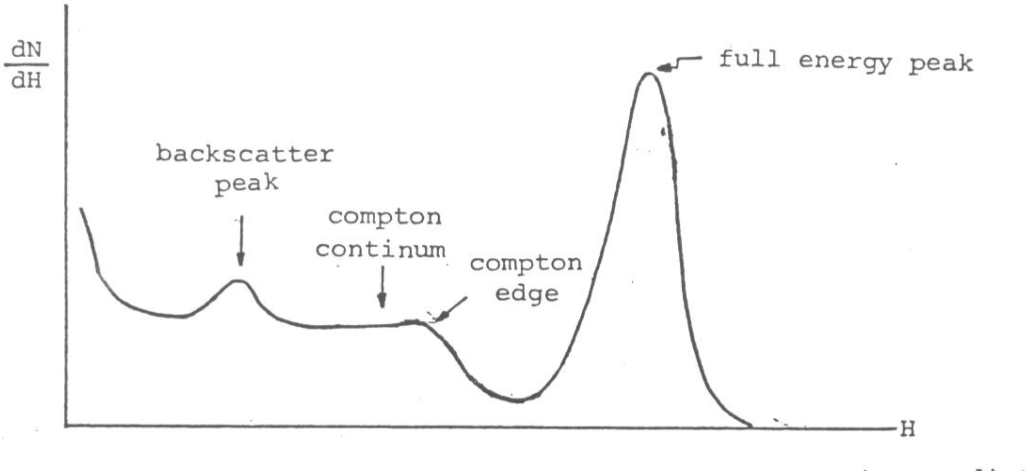


Fig. 4-8: Illustration of a typical response of an intermediate size NaI(Tl) system.

The quality of a NaI(Tl) may be checked by the FWHM of the ^{137}Cs 0.662 MeV photopeak and the peak to vally ratio, the ratio of the height of the 1.17 MeV photopeak to the height of the valley between the two photopeaks of a ^{60}Co source. A good NaI(Tl) system will give a ^{137}Cs photopeak resolution of 7-8% and a ^{60}Co peak-to-valley ratio of larger then seven.

Procedures (Part I: NaI + SCA)

1. Use pulser to set up the system shown in Fig. 4-6. Don't connect the detector and the high voltage at present. Set the pulser polarity to NEG and 1 V output. While setting up the system, use the

oscilloscope to monitor the output of each module and make sure it is properly working before connecting to the next module.

2. Set the delay of the TSCA to the minimum value and the mode switch to DIFF or WIN (In the Canberra 2030 SCA, only WINDOW mode is provided). Adjust the amplifier gain to get a slightly >6 V positive unipolar pulse. Set the LLD to 6 V (i.e. 600 on the knob) and the window width to 0.5 V (i.e. 500 or 50 on the knob depending on the SCA you used).

3. Use the oscilloscope to monitor the SCA positive output, plot the output of the SCA? ___________ . Slowly increases the LLD setting until the SCA output just disappears and record this setting ___________ . Then slowly decrease the LLD setting until the TSCA output disappears again. Also, record this setting ___________ . Do the two settings differ by 0.5V? Why does the SCA output disappear at the two LLD settings? __________ .

4. Turn off the pulser. Connect the NaI(Tl) detector and the H.V. supplier. Get a gamma source ^{137}Cs and put the source about 3 cm away from the detector. Slowly increase the H.V. to 750 V, monitor and record the amplifier output at the same time? __________ .

5. Adjust the amplifier gain such that amplifier output is about 4 V for ^{137}Cs photopeak.

6. Increase and decrease the H.V. 50 V to see the change of amplifier output? _____________ . Don't increase the H.V. beyond 950 V. Adjust the H.V. so that amplifier output is about 4 V for ^{137}Cs photopeak again. Plot the amplifier output and the anode output on the PMT base?

7. Measure the differential pulse height spectrum using the SCA. Set the window width as 0.2 V. LLD start from 0.1 V, and increase 0.2 V after each measurement until the LLD reaches 5 V to include the photopeak. Each measurement takes 5 s.

8. Plot the spectrum? ____________ . Do you note the special feature of photopeak, Compton edge, a Compton continum? __________ . The plot should be in a histogram form.

9. Measure the total counts under the photopeak of ^{137}Cs source by setting window width wide-open to cover the entire peak region _____________ . On the other hand, calculate counts under the full energy peak of the differential pulse height spectrum that obtained in step 7 ___________ . Are two counts the same? ________________ . What is counting ratio of the full energy peak to the total counts? __________ .

10. Replace the ^{137}Cs source with a ^{60}Co source, and repeat the differential pulse height spectrum measurement. Don't change any gain and high voltage setting. The window setting of the SCA is 0.2 V for the LLD from 0.1-1.5 V and 5.5-9.5 V; the window is 0.5 V for the LLD from 1.5 V to 5.5 V. Plot the differential spectrum ____________ . Calculate the ratio of peak (1.173 MeV) to valley (between two full energy peaks) of ^{60}Co source __________ .

11. Plot the photopeak energy calibration curve, i.e. pulse height of the photopeak versus photopeak energy __________ .

Questions

1. What is the total efficiency for these two sources at 3 cm away from the detector (consider pulse height above 0.1V only)? Please notice that the noise of your detection system might higher than 0.1 V. Is the efficiency of the NaI(Tl) larger than that of the GM tube?

2. Is the obtained energy calibration curve reasonable linear? Please linear fitting your result using a least squared curve fitting (assume you can include the 0 MeV point). Based on your curve, what would be the pulse height of ^{198}Au photopeak? The main gamma ray energy of ^{198}Au is 0.4118 MeV.

3. What is the energy resolution (FWHM) in keV of ^{137}Cs photopeak based on your measurement?

Notice: Note that, in order to estimate detection efficiency, please remember to check the package of the source that you use in your experiment and keep a record of its production date and strength. For example, the standard source of ^{60}Co is 1.039 Ci produced at Feb 15, 2000. Our home-made source is about 3 Ci produced in March 14, 1995. The standard ^{137}Cs source is 1.036 Ci produced at March 1, 1999. Our home-made ^{137}Cs is about 1.5 Ci, production date is around 1992. Check the package of the source that you used in your experiment for sure!

Procedures (Part II: NaI + MCA)

1. Turn the MCA power on. Set the conversion gain to 2048, offset (or zero) to 0 V, ULD to 10.0 V and LLD to 0.1 V. Some of the MCA may not allow adjusting the LLD in hardware. Read the above write-up and the manual of your MCA (or consult with your TA) to set up the MCA for PHA operation. Find out the functions of the switches.

2. Set the pulse height knob to 10.0 in your pulser, adjust the attenuation switch to make the output of the amplifier to 6 V, set pulse height knob of the pulser from 10.0 to 9.0, 8.0, 7.0, …, 0.0. Plot the channel number versus the reading of the knob ___________ . Is it a straight line? ___________ . Will the line go through (0,0) point on your plot? __________ . Should you adjust the OFFSET (or ZERO) of your MCA? __________ .

3. Set the fine gain of amplifier to minimum and coarse gain to maximum. Adjust the pulse height setting of the pulser so that the amplifier outputs fall into about channel 2000. Turn the coarse gain knob of the amplifier from the maximum position to the minimum position step by step. Record and plot the amplifier coarse gain setting versus the corresponding channel number. Plot it out ___________ . Check the pulse height of each coarse gain setting from the oscilloscope. Plot out the relation of pulse height versus channel number __________ . Estimate the maximum pulse height the MCA can recorded at 2048 channels __________ .

4. Set amplifier output to about 2V and the MCA OFFSET (or ZERO) to zero. Change the conversion gain setting step by step from the minimum to the maximum position. Record the conversion gain setting versus the corresponding channel number of the MCA __________ .

5. Set amplifier output to about 0.4 V and the MCA gain to 2048 and the OFFSET to zero. Increase the LLD setting until the pulses disappear from the MCA. Record the LLD setting ____________ . If your MCA cannot adjust the LLD, then lower the pulse height by adjusting the gain of pulser until the pulses disappear from the MCA. Write down the LLD now __________ .

6. Connect a NaI(Tl) with PMT unit to your counting system (see Fig. 4-7). Get a ^{60}Co source and increase the high voltage to 750 V. Set the MCA GAIN to 2048 and OFFSET to 0. Adjust the amplifier gain so that the 1.332 MeV photopeak falls around channel 1400. Get a ^{60}Co pulse height spectrum in MCA __________ .

7. Change the LLD setting to 0.01 V and recount again. Determine the proper LLD setting to discriminate the electronic noise. Does the dead-time meter give a high reading when the LLD approaches to zero? __________ .

8. Record the channel number where the two ^{60}Co photopeaks located __________ .

9. Accumulate a ^{137}Cs pulse height spectrum with exact the same setting as you did in the previous step. Record the channel number where the peak locates __________ .

10. Learn to use the "region of interest" to integrate only the peak area (full energy peak). Show the counts in the region of interest and total counts __________ .

11. What does the spectrum of ^{60}Co look like if we change the gain to 256 channel __________ ?

Questions

1. How good is the linearity of your MCA in terms of a) the pulse height knob of the pulser, b) amplifier gain, and c) the ADC gain?

2. What are the functions of the conversion gain and the offset of an MCA?

3. Plot the channel versus energy curve derived from this experiment. Determine the channel width in terms keV from the above plot. Determine the resolution of the ^{137}Cs peak in percentage and the FWHM of the full energy peak in keV. Determine the peak to valley ratio based on the measured ^{60}Co spectrum.

4. What is the relation between Live Time, Real Time and Dead Time of an MCA?

Experiment 5: Proportional Counter and Slow Neutron Detection

Purpose

The purpose of this experiment is to demonstrate the setup and characteristics of boron-10 contained proportional counters as well as their use for slow neutron detection.

Description

Two types of boron-10 detectors, i.e. BF_3 counter and boron-lined counter, will be used in this experiment, as shown in Fig. 5-1.

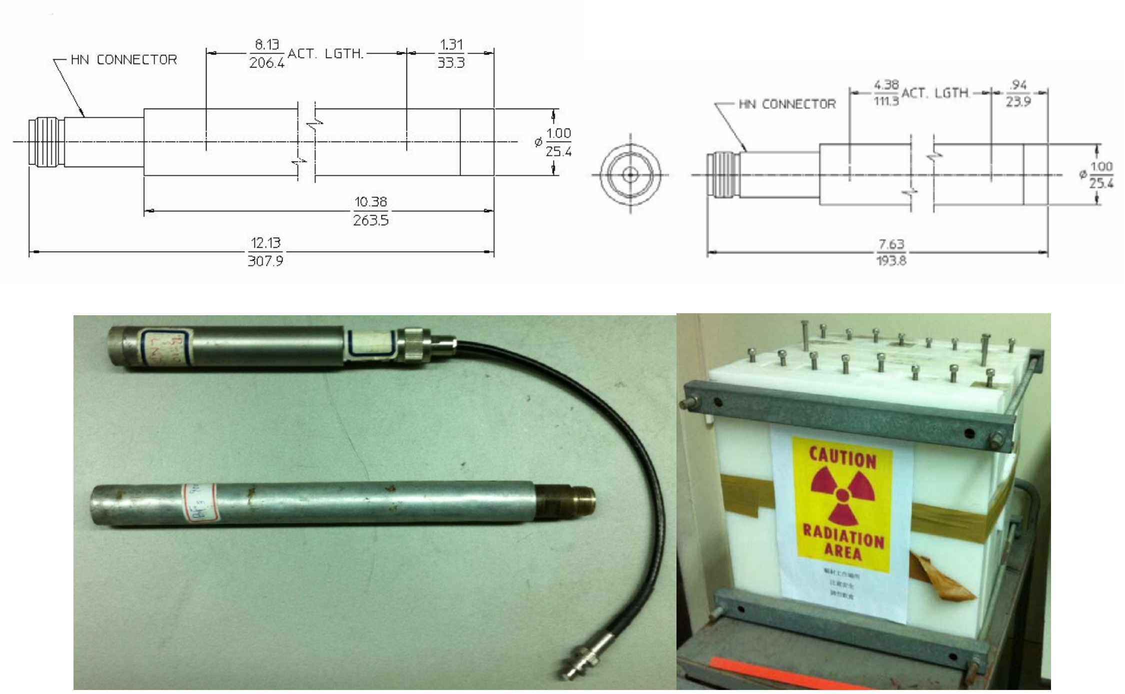


Fig. 5-1: Neutron detectors: Model LND-202 (BF_3) and LND-232 (Boron-lined) and neutron source.

The two types of detectors are both gas-filled proportional counters and are based on the following reaction for slow neutron detection:

$^{10}B + n \rightarrow {}^{7}Li +$ + 2.79 MeV (ground state, 6%)

$^{10}B + n \rightarrow {}^{7}Li^{*} +$ +2.31 MeV (excited state, 94%)

The BF_3 counter use enriched $^{10}BF_3$ as the filling gas. Boron-lined counter is, however, coated with ^{10}B on its interior wall. This configuration, therefore, has the advantage that a more suitable proportional gas (such as Ar and CH_4) than BF_3 can be used. The boron-lined counter used in this experiment is filled with Ar-CO_2 gas with a pressure of 200 torr. The thickness of the coated ^{10}B is about the range of created alpha particles in boron, approximately 1 mg/cm^2.

A significant difference in the pulse height spectrum between the two types of detectors is due to the different wall effect. For a large BF_3 detector, nearly all the (n,) reaction occurs far from the wall of the tube. Therefore, the alpha and the recoil ^{7}Li produced in the reaction can deposit their full energy to the filling gas. The resulting pulse height spectrum is then look like that shown in Fig. 5-2. Once the diameter of the tube is not large compared with the range of the alpha particle, some events no longer deposit the full reaction energy in the gas and the spectrum is look like that shown in Fig. 5-3. The two steps in the continuum are rather interesting and are well explained in Knoll's textbook.

In boron-lined counters, the (n,) reaction occurs in the wall of the tube and the alpha and ^{7}Li are moved in opposite directions. Therefore, only one reaction product can deposit its energy in the filling gas. Because the thickness of the coated boron is about the range of these alpha particles and the location or reactions can be varied from the coating surface to the tube wall, the amount of energy deposited by the alphas or the ^{7}Li particles can vary from its maximum kinetic energy to zero with equal probability. Therefore, an ideal pulse height spectrum from a boron-lined counter would be look like Fig. 5-4.

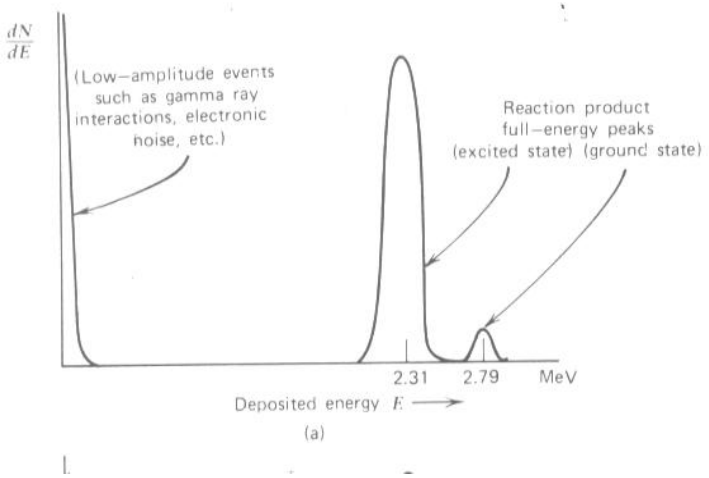


Fig. 5-2: Pulse height spectrum from a large BF_3 counter without wall effect.

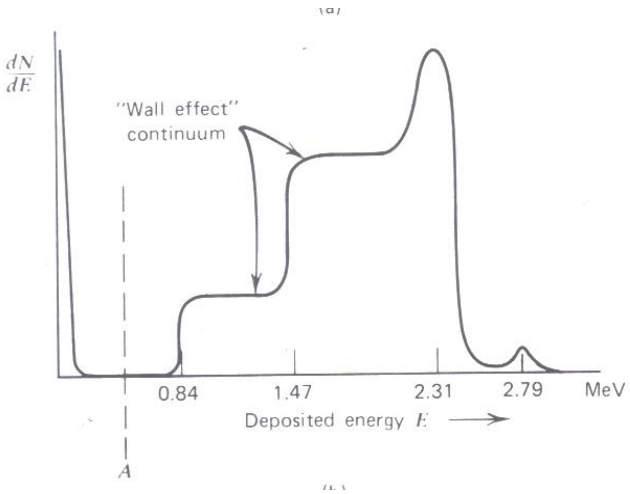


Fig. 5-3: Pulse height spectrum from a small BF_3 counter with a significant wall effect.

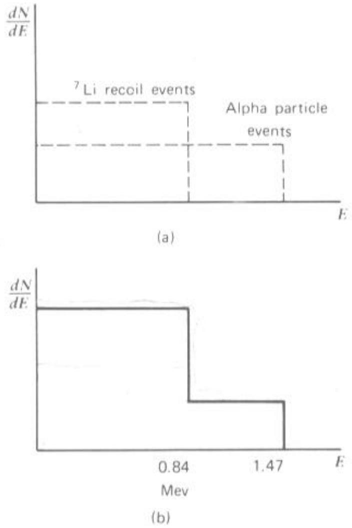


Figure 14-4 Idealized pulse height spectra from a boron-lined proportional tube. (a) Separate contributions of alpha particles and lithium recoil nuclei, which add to give the spectrum shown in plot (b).

Fig. 5-4: Idealized pulse height spectra from a boron-lined proportional tube. Plot (a) shows the separate contributions of alpha particles and lithium recoil nuclei, which add to give the spectrum shown in plot (b).

Counting system

The counting system used in this experiment is shown as Fig. 5-5. The detector requires a POSITIVE high voltage and produces negative current pulses. The neutron source used in this experiment is a Ra-Be source. The preamplifier (ORTEC 142PC or Canberra 2008) is a charge sensitive unit designed for use with proportional counters. There are two outputs from the preamplifier (ORTEC 142PC only); one is the E output for energy measurement and the other is the T output for timing measurement. Both outputs have opposite polarity to the input pulse polarity. The H.V. is fed through the preamplifier to the detector.

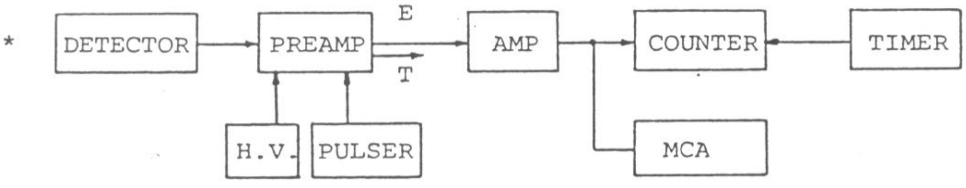


Fig. 5-5: Counting system using boron-contained proportional counters.

The proportional counter consists of a very thin wire (20mm diameter) as the anode. It is very sensitive to the acoustic motion or vibration which will produce extra noisy pulses. Usually, the neutron proportional counters come with a HN connector. Please use the HV cable with HN connector in one end and SHV connector in other end. The first stage of preamplifier consists of an isolated capacitor to avoid the DC high voltage bias on the first stage of FET, only the AC signal (the radiation pulse signal) can go through the isolated capacitor to the first stage of preamplifier. When you want to decouple the bias voltage from the detector, be sure to shut down the high voltage first. Otherwise, the spark occurred during the disconnection might burn out the anode wire, or the signal might pass through the isolated capacitor and damage the first FET of the preamplifier.

Procedures

1. Set up the pulser to get 0.2V negative pulses. Feed the pulser output to the TEST input of the preamplifier (a charge sensitive preamplifier, usually, the ORTEC 142PC or Canberra 2008). Plot the waveforms from the E output __________ .

2. Feed the E output of the preamplifier to a linear amplifier. Adjust the amplifier gain so that the output signal is about positive 4V.

3. Place a BF_3 counter close to the neutron source and connect the detector output to the preamplifier. Slowly increase the high voltage from 0 volt to several hundred volts. Monitor the amplifier output with a scope. Record the voltage when the detector starts to produce pulses __________ .

4. Increase the high voltage to 1500 V (It depends on the operation voltage of your detector. Please check with TA before applying the voltage.) in steps of 100 volts and record the counting rate. Plot the counting curve while you increase the voltage ___________ . Determine the range and the slope of the counting plateau ______________ . Determine your operating voltage based on the counting curve ____________________ . Plot the amplifier output waveform with the HV at the operating voltage ____________ . What are the pulse heights due to the gamma ray and neutron events at the operating voltage? __________ .

5. Set HV to the operating voltage. Do 5 min background counting __________ . Do 5 min counting with neutron source __________ . Remember that the threshold of the counter should be set higher than the gamma pulse height.

6. Ask the instructor for a cadmium sheet. Cover the BF_3 detector with the Cd sheet and do a 5 minutes counting with a counter. What is the difference compared to step 5? __________ .

7. Lower the HV to zero and replace the BF_3 tube with the boron-lined detector. The location of the detector should be kept as close as possible to the previous detector position. Repeat steps 3, 4 and 5. Do not increase the HV beyond 650 volts for the boron-lined detector.

8. Set up an MCA and accumulate a pulse height spectrum from each detector __________ .

Questions

1. Which neutron detector has a higher efficiency? Please think about the principle of slow neutron detection, and considering the gas pressure inside the BF_3 tube and the thickness of the coating layer of the boron lined detector.

2. Plot the spectra obtained in step 8. Compare and explain the differences. Do you observe their wall effects?

3. Compare the counting curves obtained in both detectors. Which one has a larger slope near the operation bias? Why?

Experiment 6: High Resolution Gamma Spectroscopy with High-Purity Germanium Detector

Purpose

The purpose of this experiment is to demonstrate the characteristics and operation of a high purity germanium detector (HPGe) system for gamma spectroscopy.

Fig. 6-1: HPGe detection system and its sample holder inside the lead chamber.

Description

Semiconductor detectors are good for particle Spectroscopy. The surface barrier detectors used in the last experiment are only useful for alpha and heavily charged particles due to the small depletion depth. Lithium-drifted germanium detectors Ge(Li), and HPGe detectors due to the high atomic number of Ge and their much greater active volume are widely used for gamma spectroscopy. Ge(Li) detectors have to be stored and operated at low temperature to prevent the re-distribution of Li from the perfectly compensated situation. The different manufacturing process permits the HPGe detectors stored at room temperature but operated under low temperature to reduce thermally generated leakage current. However, the HPGe cannot be operated at room temperature with high voltage bias on. It will develop a high leakage current resulting in a burn-out of the very expensive detector (Cost >NT$500,000 each).

In the measurement of gamma-ray energies above several hundred keV, there are only two detector categories of major importance: inorganic scintillators NaI(Tl) and germanium semiconductor detectors. NaI(Tl) has the advantage of high photopeak efficiency but suffering from poor energy resolution. Germanium semiconductor detectors, in contrast, have excellent energy resolution but an order of magnitude lower photopeak efficiency. Therefore, germanium detectors are preferred for the analysis of complex gamma-ray spectra involving many energies and peaks. Fig. 6-2 illustrates a comparison of the spectra obtained from an NaI(Tl) system and a Ge(Li) system.

Fig. 6-3 depicts a typical HPGe counting system. The connection from the detector to the preamplifier is made automatically through its cryostat mounting. There are two output connectors from the preamplifier: E output for pulse height analysis and T output for timing measurement. These outputs have negative polarity. The amplifier unit is ORTEC 572 (or Canberra 2011) spectroscopy amplifier designed for high resolution spectroscopy. The high voltage power supplier used in this experiment should have continuous voltage dialing to prevent voltage spikes and don't forget to connect the inhibit interlock between Ge detector and HV power supply.

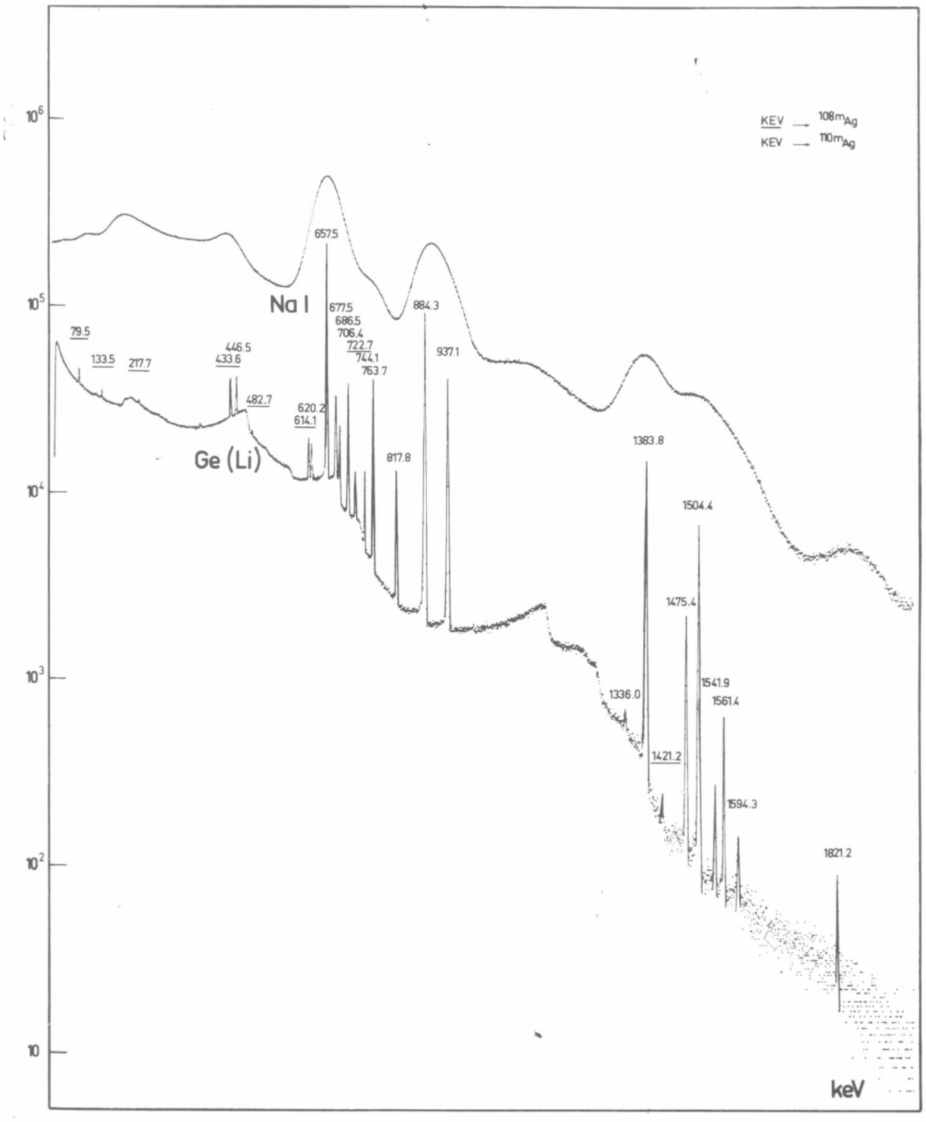


Fig. 6-2: Comparison of spectra obtained from NaI and Ge(Li) apparatus (see Knoll's textbook).

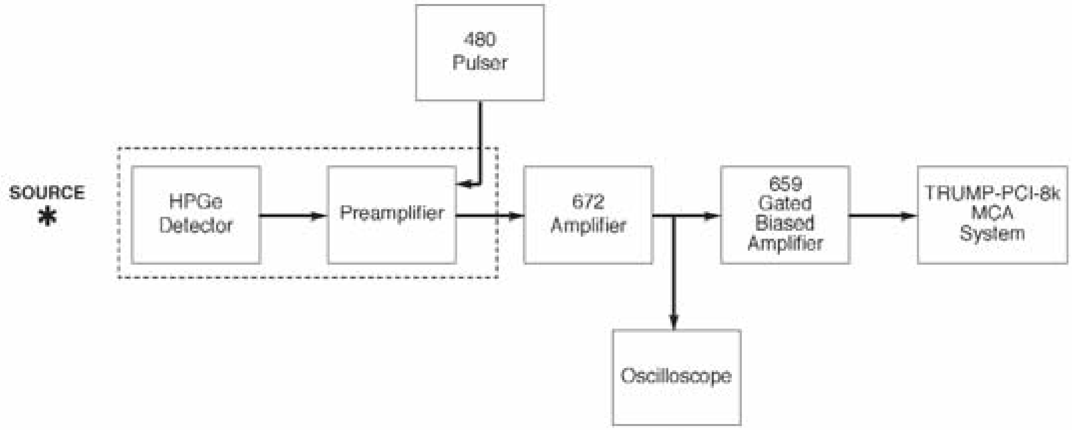


Fig. 6-3: HPGe counting system (ORTEC659 will not use in this experiment).

Procedures

✓ **When you connect or disconnect the detector, be sure the applied voltage should be reduce to zero. Otherwise, the preamplifier (cost NT$60000) might be damaged!**

✓ **When you increase or decrease the applied voltage, it should be done slowly by the ten-turn potentiometer. Don't just turn the high voltage on and off. Otherwise it might damage the preamplifier.**

✓ **When the detector is not cold enough, don't applied high voltage. The large current will damage the Ge crystal.**

✓ **When you finish the experiment, be sure the high voltage was reduced to zero.**

1. First of all, ask your instructor about the information of operation voltage. Each Ge detector is different. Some of them are negative bias, always check the manual first __________ . Adjust your high voltage supplier to either positive or negative depending on your detector. Make sure the high voltage is at zero volt. Set up the system as shown in Fig. 6-3 (bypass the biased amplifier) using the pulser as input. Set pulser polarity to NEG (or POS depending on the preamplifier of your detector) ______________ . Feed E output to the amplifier. Set amplifier shaping time to 3 μs, UNIPOLAR, BLR AUTO, delay OUT, and gain 100. (Some of the amplifier does not have BLR/AUTO and Unipolar/Bipolar, skip these!) Adjust pulser so that the amplifier output is about 6V and plot the AMP output waveform _________ .

2. Turn off the pulser. Connect the preamplifier output to AC coupling of the oscilloscope. Increase the vertical sensitivity of the oscilloscope. You should observe the "grass" that is caused by noise in the system. Slowly increase the bias. You can see the output baseline is shifting because of the change of bias as function of time is an AC signal which is possible to pass through the isolation capacitor between the high voltage connected to detector and first stage of field effect transistor

(FET) of the preamplifier. Increase the bias slowly to avoid an overload on the FET. The FET usually will sustain a voltage of a few tens of applied voltage. If the bias increases too fast, the over-voltage might burn the FET of the preamplifier. Since this FET is operated in low temperature inside the vacuum chamber. To repair the FET will be a big job. Slowly increase the bias to POSITIVE (or NEGATIVE depends on your detector) 300 V. Resting a minute or two, you should observe that the noise amplitude is decreased due to the reduction of detector capacitance.

3. Increase the bias voltage slowly to operation voltage of the detector. Monitor the amplifier output while increasing the voltage. The noise amplitude should normally continue to decrease. A large increase in noise amplitude indicates a defect somewhere in the system. Notify the instructor immediately.

4. Place a ^{60}Co source near the detector. The counting rate should be less than 1000/sec. Adjust the gain of the amplifier so that the 1.332 MeV gamma rays is around 7 V. Accumulate the ^{60}Co spectrum with an MCA __________ . Record the peak location, FWHM, FWTM, Peak/Compton ratio, and peak area __________ .

5. Change the shaping time of the amplifier. Did you see any change? ____________ . Which shaping time is the best one? ____________ . Adjust the P/Z (pole/zero) of the amplifier to make the pulse shape with no overshot or undershot, plot your best waveform __________ .

6. Turn on the pulser. Adjust the pulser amplitude to place the pulser peak between the 1.173 MeV and the 1.332 MeV peaks. Remove the source. Accumulate a pulser peak to several thousand counts maximum. Record the peak location and the FWHM of the pulser peak. Why the FWHM is smaller for the pulser only? __________ .

7. Turn off the pulser. Place gamma sources of ^{137}Cs, ^{22}Na, or ^{152}Eu one at a time and place them at the same position as that of the ^{60}Co source. Record the peak locations and peak areas for detector efficiency calibration. Plot the energy calibration curve __________ .

8. Remove gamma sources, reduce the amplifier gain to half, and make a 20 minutes background measurement. Save the spectrum. Using the energy calibration curve (Note that the amplifier gamin has been reduced to half) to identify the radioisotopes you found in the background __________ .

Questions

1. Determine the FWHM of ^{60}Co peaks in keV and in percentage. Is the value the same as the specification reported in the catalog or manufacture test report before delivery? __________ .

2. Is the peak to Compton ratio of your detector the same as the specification reported in the catalog or manufacture test report before delivery? __________ .

3. Calculate the efficiency of the measured sources in this experiment. Plot the detector efficiency versus energy curve _____________ . You have to derive the source intensity from source strength recorded at the manufacturing date.

Experiment 7: Surface Barrier Detector and Alpha Particle Measurement

Purpose

The purpose of this experiment is to demonstrate the setup, operation, and characteristics of a surface barrier detector system and its application for alpha spectroscopy.

Theory

Surface barrier detectors (SBD) are one type of semiconductor diode detectors. The name of "surface barrier" comes from the fabrication process of the detector: a layer of p-type material is formed on the surface of an n-type silicon crystal; a thin gold film is then coated on top of the p-type material to provide electrical contact (40 g/cm^2). The simplified cross section of a silicon surface barrier semiconductor detector is illustrated in Fig. 7-1. The coated gold layer is extremely delicate. Please DON'T use fingers to touch the surface.

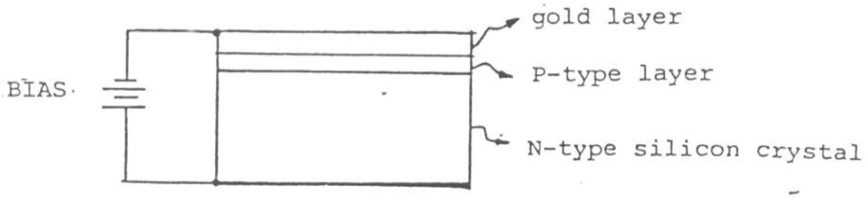


Fig. 7-1: Basic configuration of a surface barrier silicon detector.

When a radiation particle passes through the semiconductor, its deposited energy produces many electron-hole pairs. In normal operation, the PN-junction is reversely biased by a low voltage (less than 100 volts), to reduce electron-hole recombination and to improve the electron collection efficiency. The collected electrons then produce a current pulse in the external circuit. Because the ionization energy in a typical semiconductor is only about several eV, which is much less than that of a typical gas-filled detector (about 30 eV), the number of electrons created is thus much greater. In addition, the number of electrons created in a semiconductor detector is proportional to the energy deposited in the detector by the particle. Therefore, semiconductor detectors are commonly used for particle spectroscopy. Surface barrier detectors are commonly used for heavy charged particle spectroscopy because of its relatively thin depletion depth. There are three main parameters that define a silicon SBD: resolution, active area, and depletion depth. The ORTEC model numbers reflect each of these three parameters in that order, e.g. A-016-050-100 stands for series A (partially depleted) detector with a total system resolution of 16 keV FWHM for 5.477 MeV alphas from ^{241}Am, an area of 50 mm^2, and a depletion depth of 100 pm. If you use CANBERRA SBD, it will be a PIPS (Passivated Implanted Planar Silicon) detector. Fig. 7-2 shows some of SBDs. Surface barrier detectors are sensitive to room light. In addition, charged particles are subject to attenuation in air. Therefore, the detectors are usually placed inside a vacuum chamber. If the detector is stored in air, it is better to pump down the vacuum until all the water moisture is evaporated before applied the bias to avoid the surface breakdown of the SBD.

Fig. 7-2: Surface barrier detectors used in our lab.

Counting system

The counting system used in this experiment is as follows:

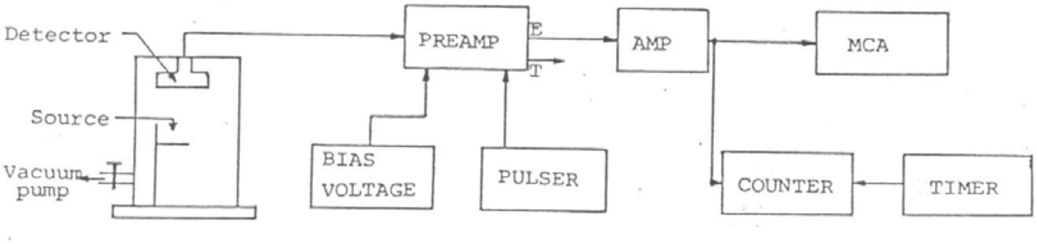


Fig. 7-3: Counting system of a surface barrier silicon detector.

The preamplifier is ORTEC 142A which is charge sensitive and is designed for use with room temperature silicon surface barrier detector. The preamplifier has two outputs: E output is for energy measurement with its polarity opposite from input polarity; T output is for timing measurement with polarity same as input polarity. The bias voltage for the detector is applied through the preamp to the PN junction of detector. Positive voltage is required for the SBD used in this experiment. In Canberra 7401VR system, the bias, preamplifier and amplifier were incorporated into the system already. Only an E output for you to directly send to MCA. More about SBD working principle and the counting system is described in Knoll's textbook.

Procedures

1. Set up the pulser to give 0.4 V negative pulse. No bias on the SBD.

2. Feed the pulser output to the TEST input of the preamplifier of ORTEC 142A or the TEST of Canberra 7401VR system.

3. Feed the preamplifier E output to a linear amplifier. (The Canberra 7401 VR system consists of detector, Bias voltage supplier, preamplifier, and amplifier together. The gain of Canberra 7401 VR can be adjusted in the front panel through a jewelry screw driver.) Set the amplifier shaping time constant to 1 μsec (if you use Canberra amplifier 2012, you used don't have shaping time adjustment.) and adjust the amplifier gain to get 5 V positive pulses. Record the FWHM of the peak __________ .

4. Pump down the vacuum in the chamber. Pump the vacuum chamber for at least two minutes before applying the bias voltage on the detector. For CANBERRA 7401 system, pull the valve handle out to the PUMP position and rotate the handle 90 degrees counterclockwise to lock the vacuum chamber, then, wait until the gurgling sound of the pump stop. Notice that, in order to avoid the surface breakdown of the SBD due to the moisture, it is better to pump the vacuum down before you apply the high voltage bias on the detector. It is also suggested that the bias was turned off when you vent the vacuum chamber. Apply POSITIVE bias voltage from 0 to 40 V in steps of 20 V; monitor the amplifier output with an oscilloscope while increasing the bias voltage.

5. With bias voltage at 40 V, measure the output with an MCA. Record the location and the FWHM of the peak __________ .

6. Shut down the bias. Put the home-made ^{241}Am source 1 cm from the SBD in the chamber. **Never touch the surface of the source with your fingers.** Alpha sources offer a potential personal contamination problem. Get an SBD (DON'T touch the gold surface with your fingers) and connect the SBD inside a vacuum chamber. The connector on the detector is called "microdot" connector. Face the source to the detector with a distance about 1 cm. Use a short cable between the detector and the preamplifier. Pump the vacuum down. Adjust the amplifier gain so that the alpha peak

located at around 5 V. Accumulate the alpha spectrum with an MCA (with highest conversion gain). Record the peak locations _________ and the FWHM of the peak _________ .

7. With bias voltage at 40 V, measure the alpha spectrum with an MCA. Record the peak locations and the FWHM of the peak _________ . Any change? _________ .

8. Turn off the bias. Vent the vacuum chamber with air, measure the alpha spectrum with an MCA. Record the peak locations _______________ and the FWHM of the peak _______________ . Any change?_________ .

9. Increase the distance between the source to detector 0.5 cm each time, recorded the intensity until the counting rate drops to zero. Plot the (counting rate x distance squared) versus distance_________ . Determine the mean range of the alpha source in air _________ .

10. Get a standard ^{241}Am source or a mixed alpha source (^{239}Pu, ^{241}Am, and ^{244}Cm). Place 0.5 cm from the SBD, pump the vacuum down, set the bias at 40 V. Measure the alpha spectrum with an MCA. Record the peak locations _______________ and the FWHM of the peak _______________ . Any change? __________ . (The mixed source is very weak, it needs more than 10 min of measurement). There is only one mixed source in the lab. To handle this source be sure don't touch the center of source where the mixed nuclides are electrodeposited. To put source back to the case, please also make sure that the source is suspected and will not touch the case.

Questions

1. Plot the channel number versus alpha peak energy curve based on the measurement of step 10. What are the energies of alpha sources? Is it linear?

2. After determining the total FWHM (in keV) of each energy peak observed and compare to the FWHM of the pulser input alone, what is the electronic noise of the SBD detector system? (Express it in keV).

3. Did you see the peak position shifted with air and/or with bias?

4. Did you observe an energy shift between the home-made ^{241}Am and the one buy from a commercial company. If you do, why?

Experiment 8: Neutron Activation Analysis

Purpose

The purpose of this experiment is to demonstrate the method of neutron activation for neutron flux measurement. Gold foils and NaI(Tl) scintillation counting system or HPGe system will be used.

Description

The saturation activity (A_s) of a foil irradiated in a constant neutron flux (ϕ) is:

$$A_s = N_T \int_E \sigma_a(E)\phi(E)dE \tag{8.1}$$

Where N_T is the atomic density of the irradiated material in [#/cm^3] and σ_a(E) is the neutron energy dependent microscopic absorption cross section in [cm^2].

If the neutron field contains both thermal and epithermal neutrons, it is convenient to divide the activity into two parts according to whether it is produced by thermal neutron or by epithermal neutrons with energy in the resonance absorption region of the foil. For the thermal neutron range, the activation cross section is usually 1/v dependence; for epithermal range, the cross section is the superposition of the 1/v behavior and a resonance contribution. Therefore, Eq. (8.1) can be rewritten as:

$$\begin{gathered} A_s = N_T \left\{ \int_{thermal} \sigma_{0a} \frac{v_0}{v(E)} n(E)v(E)dE + \int_{epithermal} \sigma_a(E)n(E)v(E)dE \right\} \\ or \\ A_s = A_{st} + A_{se} = N_T \sigma_{0a} v_0 n_{th} + A_{se} \end{gathered} \tag{8.2}$$

where A_{st} and A_{se} are the saturation activities due to thermal and epithermal neutrons, respectively.

In most of the neutron activation experiments, the saturation activity is not achievable due to long half life of the nuclei; a correction should be applied by considering the irradiation time. For one group only, the number of product nuclides N, in a foil (with a nuclei density of N_T) irradiated in a constant neutron field is:

$$N = \frac{1}{\lambda} N_T \sigma\phi (1 - e^{-\lambda t_{irr}}) e^{-\lambda t_{cool}} \tag{8.3}$$

Where the is the nuclear reaction cross section, is the decay constant of the product nuclides. t_{irr} is the irradiated time and t_{cool} is the cooling time after irradiation. During the gamma-ray measurement of the product nuclides, the activity you measured is proportional to N. If the neutron field contains both thermal and epithermal neutrons, it is convenient to divide the activity into two parts according to whether it is produced by thermal neutron or by epithermal neutrons with energy in the resonance absorption region of the foil. Two group of neutron flux and two reaction cross sections, both are as functions of neutron energy, are needed to calculate the total activity. The activities due to the two groups of neutrons can be separated experimentally by means of the cadmium difference method. The absorption cross section of cadmium varies with energy in such a way that cadmium absorbs most of the neutrons with energy below 0.4 eV but passes most of epithermal neutrons. Therefore, the activity from a bare foil is due to thermal as well as epithermal neutrons. The activity from a Cd-covered foil is due to epithermal neutrons alone. The difference between the two activities can be used to determine the thermal flux ($\phi_0=n_{th}v_0$) if the weight and the thermal cross section of the foil are known.

Gold foil is very well suited for precision flux measurements, particularly absolute measurements due to its large cross section, reasonable half-life, and simple decay scheme. The decay scheme of ^{198}Au is given in Fig. 8-1. The good mechanic property of gold allows thin foils easily be rolled to minimize the perturbation on the neutron field. Two pieces of gold foils will be used; one was irradiated bare and the other was irradiated with a cadmium cover. The thermal flux is then determined by the cadmium difference method.

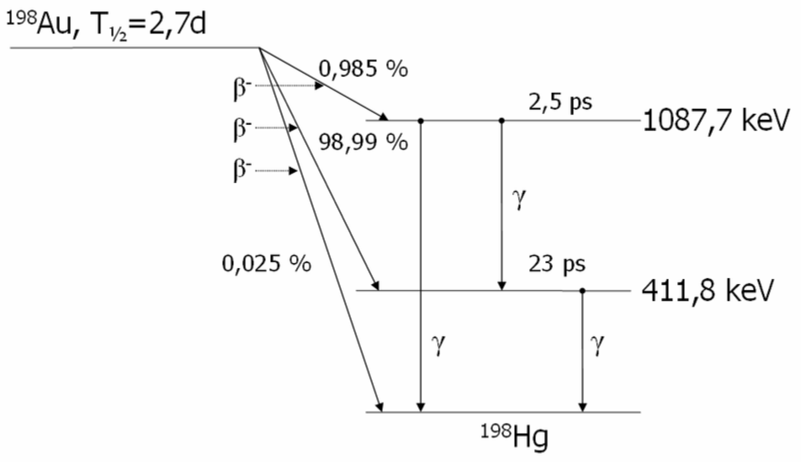


Fig. 8-1: Decay scheme of ^{198}Au (wikipedia.org).

The interested activity from the gold foils is the decay of 0.411 MeV gamma ray. Measurements will be performed with a NaI(Tl) scintillation counting system or HPGe system. In order to determine the activity of the foil, the peak counting efficiency of the system has to be determined at first by using several gamma standard sources. The counting efficiency may be dependent on the gamma energy. Therefore, sources with gamma energy close to 0.411 MeV should be used, e.g. ^{54}Mn, ^{137}Cs, ^{152}Eu and ^{22}Na. (Refer to the supplied document for the gamma energy of these sources). To simplify the efficiency calibration, gold foils and each source should be kept at the same distance from the detector for a consistent counting geometry. The background under the full energy photopeak may be corrected by a straight line approximation as illustrated below.

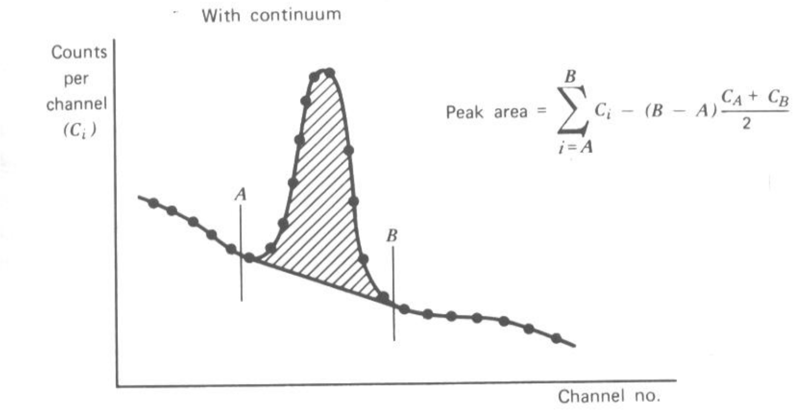


Fig. 8-2: A background subtraction algorithm for the determination of peak area.

Apparatus

- 2" x 2" NaI(Tl) crystal-PMT (or HPGe detector)
- ORTEC 113 Preamplifier (or Canberra 2007A)
- ORTEC 485 Amplifier (or Canberra 2012)
- MCA (with more than 4096 channels if high resolution is needed)

Procedures

I. Determination of neutron flux:

Before the experiments, the gold foils with 0.112% of gold in aluminum, each one weighted 5.55 mg was irradiation at VT6 of THOR for 20 min. Part of the samples are enclosed in Cd to remove the effect of thermal neutrons. Please ask your instructor or TAs to know the exact time of irradiation in order to calculate the flux.

1. Set up the scintillation counting system or HPGe counting system. Calibrate the energy versus channel number with the known radiation sources e.g. ^{54}Mn, ^{137}Cs, ^{152}Eu and ^{22}Na.
2. Plot the energy calibration curve __________ .
3. Measure the differential pulse height spectrum and determine the peak counting efficiency using the gamma sources mentioned in the above at the specific location.
4. Plot the peak efficiency versus gamma-ray energy curve ___________ . Note that the decay time and branch ratio and the percentage of dead time should be taken into consideration.

5. Measure the counting rate of the ^{198}Au 0.411 MeV gamma-ray peak at the same location as standard source calibrated ___________ ? Switch the gold foils (bare vs. Cd-covered) with the other group and repeat the measurement ___________ ? Estimate the activities of ^{198}Au caused by thermal neutrons and by epithermal neutrons ___________________ , respectively? Record the counting interval __________ .

6. Measure the background for a few minutes to see whether any peaks can be found around 0.411 MeV __________ .

7. According to your measurement (after background subtraction), calculate the thermal neutron flux and the cadmium ratio of the neutron irradiation field at VT6 of THOR? ___________ . The cadmium ratio can be obtained by dividing the activity of the uncovered foil by that of the Cd-covered one (i.e., A_s/A_{se}), which is often taken as an indication of the degree to which a given neutron field has been thermalized.

<u>II. Samples of your hairs/fingernails:</u>

1. Set up the HPGe counting system and calibrate the energy versus channel number with the known radiation sources.

2. Measure the pulse height spectrum of the irradiated sample of hairs or fingernails that we collected on the first day of the course.

3. What nuclides can you identified in the sample from your measured spectrum? __________ .

Question

1. What correction factors should be considered to obtain an accurate result of the determined flux? Estimate the magnitude of these correction factors, if possible. Make corresponding corrections on the determined flux.

2. In this experiment, the N_T (i.e. gold) already known, so that we can measure the neutron flux if σ is also known. Now, if we have a rock containing a trace of gold, can we determine the concentration the trace of gold if we knew the neutron flux of the reactor? In this case, if the reactor flux is 10^{12} thermal neutrons per cm^2.s and we get 100 counts per minutes of 0.411 MeV gamma ray (no cadmium covered) , what is concentration of gold atoms per cm^3?

3. What nuclides have you found in the irradiated sample of your hairs/fingernails and what nuclides that you expected in your hair/fingernail sample but cannot identify from your spectrum? Try to explain?

Data:

- The density of Au is 19.3 g/cm^3 and Al is 2.7 g/cm^3. The sample is 0.112% (atomic) Au in Al wire, total weight is 5.55 mg.
- ^{198}Au, 0.4118 MeV (branch ratio 98.99%), half-life =2.7 d, thermal cross section please check Knoll's textbook.

Appendix

An Example of Neutron Activation Analysis for Hair/Fingernail Samples

Date: 2011.06.07

- Instrument information
  - HPGe
    - Model: CANBERRA GC2520
    - Efficiency: 25%
    - High voltage applied: +2700V

Fig. 1: HPGe and its lead chamber

  - Digital MCA
    - Model: ORTEC DSPEC jr. 2.0

Fig. 2: ORTEC DSPEC jr. 2.0

- Sample Description
  - Some hair and fingernails were collected and fixed with tapes

Fig. 3: Hair and fingernails samples

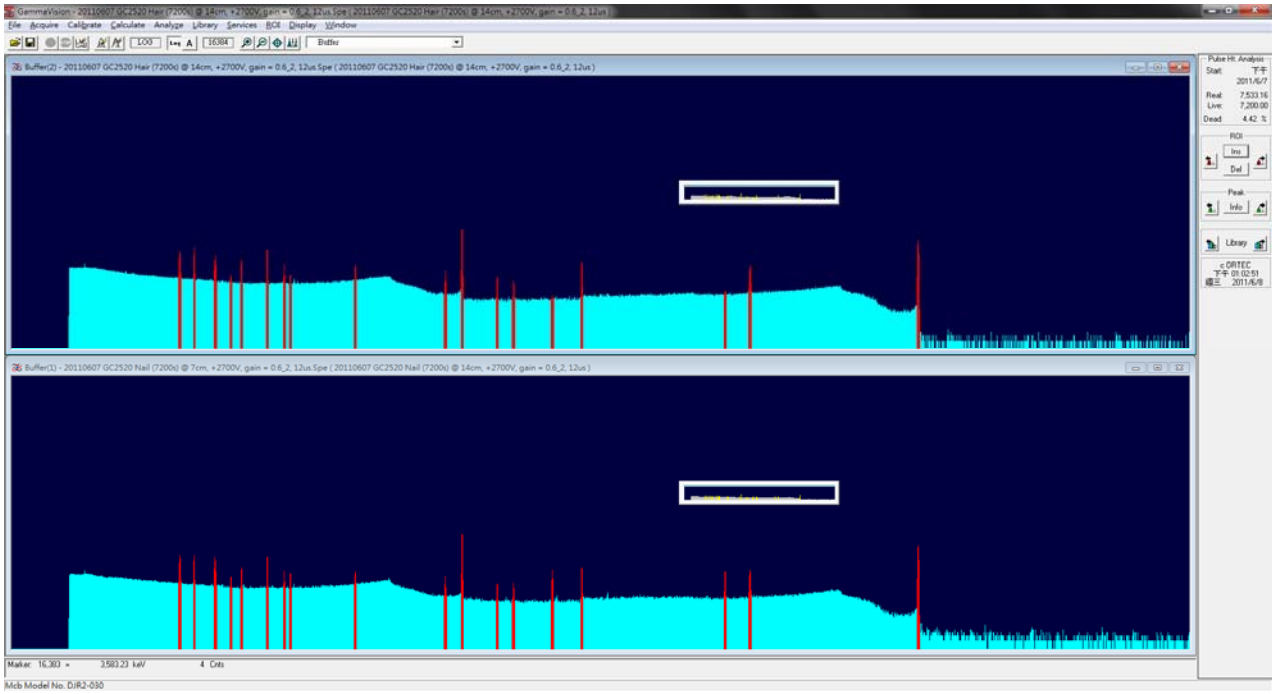
✧ Irradiation and measurement condition

Table 1 Experiment conditions for two sample sets

	Sample Set #1		Sample Set #2	
	Fingernails	Hair	Fingernails	Hair
Irradiation condition	At THOR-VT3*, under 1.2MW reactor power			
Irradiation time	20 min		60 min	
Cooling time	~1 hr	~2.5 hr	~25 hr	~27.5 hr
Counting time	7200 sec			
Measuring position	7 cm from HPGe detector	14 cm from HPGe detector	7 cm from HPGe detector	14 cm from HPGe detector

*Note: Thermal neutron flux at VT3 is 1.07E+12 (#/cm^{2}s^1)
Fast neutron flux at VT3 is 2.56E+11 (#/cm^{2}s^1)

- ✧ Results (I): Sample Set #1
  - ➢ Possible nuclides found
    - ▫ Na-24
    - ▫ Cl-38
    - ▫ K-42
    - ▫ Mn-56
    - ▫ Br-80
    - ▫ Br-82



GammaVision - 20110607 GC2520 Hair (7200s) @ 14cm, +2700V, gain = 0.6_2, 12us.Spe (20110607 GC2520 Hair (7200s) @ 14cm, +2700V, gain = 0.6_2, 12us)

Buffer(2) - 20110607 GC2520 Hair (7200s) @ 14cm, +2700V, gain = 0.6_2, 12us.Spe (20110607 GC2520 Hair (7200s) @ 14cm, +2700V, gain = 0.6_2, 12us)

Buffer(1) - 20110607 GC2520 Nail (7200s) @ 7cm, +2700V, gain = 0.6_2, 12us.Spe (20110607 GC2520 Nail (7200s) @ 14cm, +2700V, gain = 0.6_2, 12us)

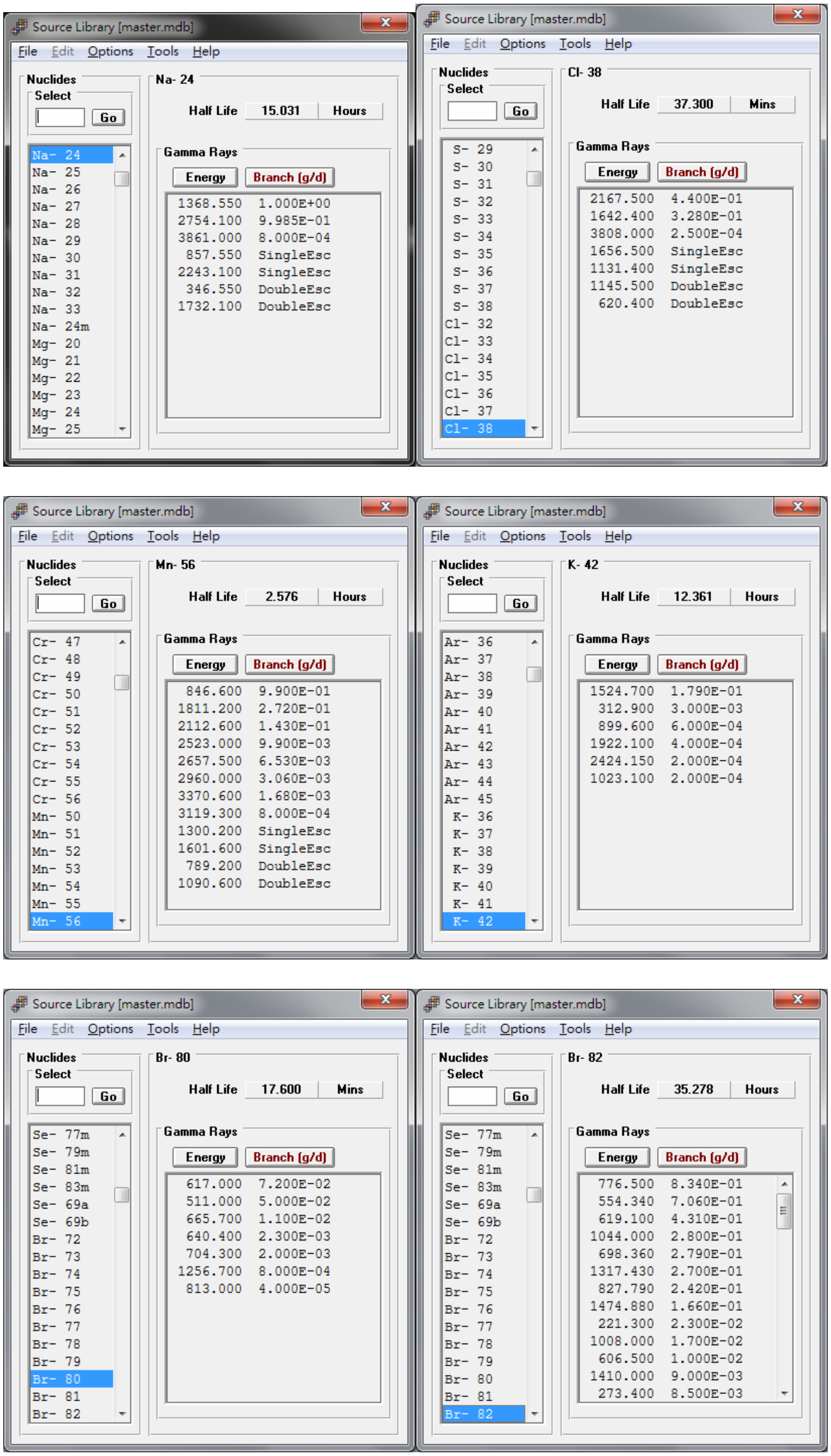
Pulse Ht. Analysis
Start: 下午 2011/6/7
Real: 7,530.16
Live: 7,200.00
Dead: 4.42 %

c ORTEC
下午 01:02:51
週三 2011/6/8

Marker: 16,383 = 3,583.23 keV 4 Cnts

Mcb Model No. DJR2-030

Fig. 4: Gamma spectrums of hair sample (top) and fingernails sample (bottom)



```
Na- 24
Half Life   15.031   Hours
Gamma Rays
 1368.550  1.000E+00
 2754.100  9.985E-01
 3861.000  8.000E-04
  857.550  SingleEsc
 2243.100  SingleEsc
  346.550  DoubleEsc
 1732.100  DoubleEsc
```

```
Cl- 38
Half Life   37.300   Mins
Gamma Rays
 2167.500  4.400E-01
 1642.400  3.280E-01
 3808.000  2.500E-04
 1656.500  SingleEsc
 1131.400  SingleEsc
 1145.500  DoubleEsc
  620.400  DoubleEsc
```

```
Mn- 56
Half Life   2.576   Hours
Gamma Rays
  846.600  9.900E-01
 1811.200  2.720E-01
 2112.600  1.430E-01
 2523.000  9.900E-03
 2657.500  6.530E-03
 2960.000  3.060E-03
 3370.600  1.680E-03
 3119.300  8.000E-04
 1300.200  SingleEsc
 1601.600  SingleEsc
  789.200  DoubleEsc
 1090.600  DoubleEsc
```

```
K- 42
Half Life   12.361   Hours
Gamma Rays
 1524.700  1.790E-01
  312.900  3.000E-03
  899.600  6.000E-04
 1922.100  4.000E-04
 2424.150  2.000E-04
 1023.100  2.000E-04
```

```
Br- 80
Half Life   17.600   Mins
Gamma Rays
  617.000  7.200E-02
  511.000  5.000E-02
  665.700  1.100E-02
  640.400  2.300E-03
  704.300  2.000E-03
 1256.700  8.000E-04
  813.000  4.000E-05
```

```
Br- 82
Half Life   35.278   Hours
Gamma Rays
  776.500  8.340E-01
  554.340  7.060E-01
  619.100  4.310E-01
 1044.000  2.800E-01
  698.360  2.790E-01
 1317.430  2.700E-01
  827.790  2.420E-01
 1474.880  1.660E-01
  221.300  2.300E-02
 1008.000  1.700E-02
  606.500  1.000E-02
 1410.000  9.000E-03
  273.400  8.500E-03
```

Fig. 5: Nuclide database (from NuclideNavigator, ORTEC)

✧ Results (II): Sample Set #2

- Possible nuclides found
  - Na-24
  - K-42
  - Br-82

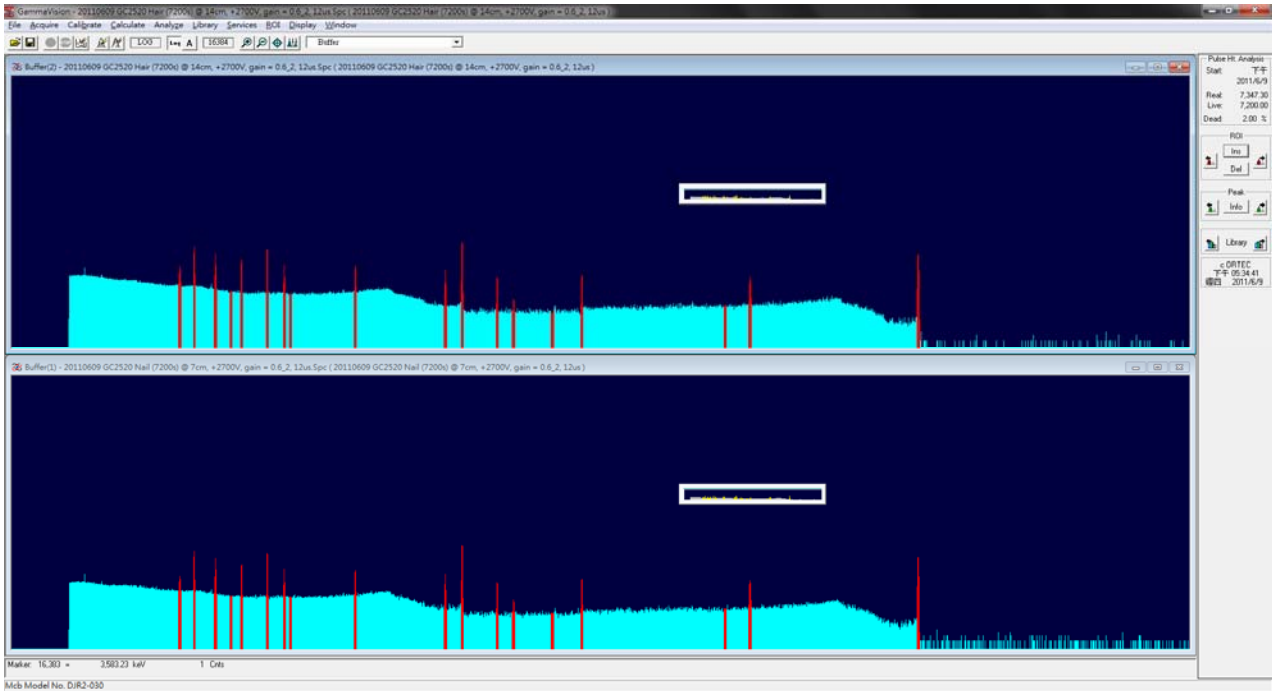
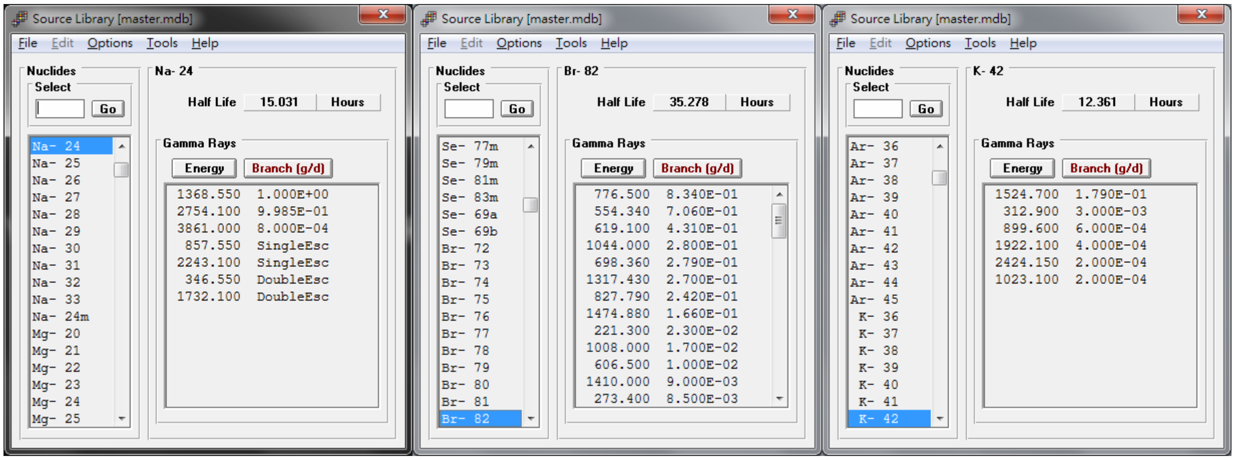


Fig. 6: Gamma spectrums of hair sample (top) and fingernails sample (bottom)



Na- 24

Half Life 15.031 Hours

Energy	Branch (g/d)
1368.550	1.000E+00
2754.100	9.985E-01
3861.000	8.000E-04
857.550	SingleEsc
2243.100	SingleEsc
346.550	DoubleEsc
1732.100	DoubleEsc

Br- 82

Half Life 35.278 Hours

Energy	Branch (g/d)
776.500	8.340E-01
554.340	7.060E-01
619.100	4.310E-01
1044.000	2.800E-01
698.360	2.790E-01
1317.430	2.700E-01
827.790	2.420E-01
1474.880	1.660E-01
221.300	2.300E-02
1008.000	1.700E-02
606.500	1.000E-02
1410.000	9.000E-03
273.400	8.500E-03

K- 42

Half Life 12.361 Hours

Energy	Branch (g/d)
1524.700	1.790E-01
312.900	3.000E-03
899.600	6.000E-04
1922.100	4.000E-04
2424.150	2.000E-04
1023.100	2.000E-04

Fig. 7: Nuclide database (from NuclideNavigator, ORTEC)