# LAB 2: Experiments in Nuclear Physics

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## Purpose

Introduce the student to some of the basic techniques and approaches used in nuclear physics.

## Reading Assignment

Reading required as per references in text of experiment.

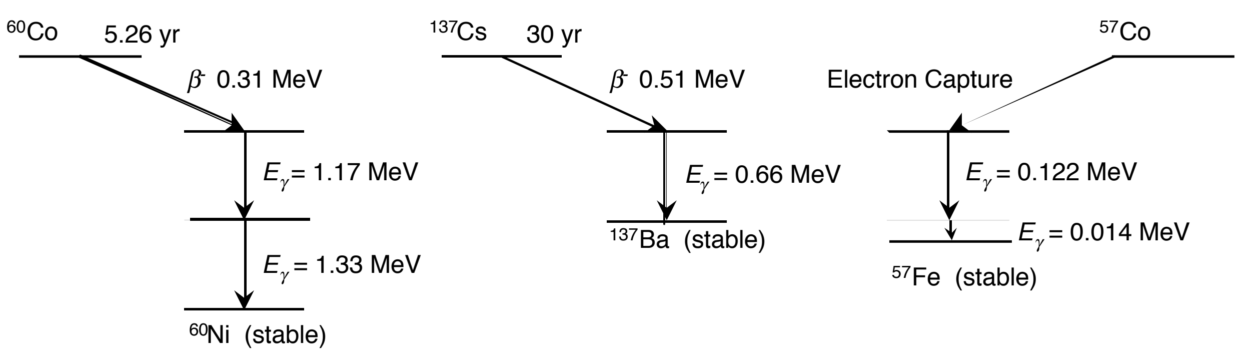
## Preface

This laboratory is divided into two sections. The first section is an introduction to gamma-ray spectroscopy. $\gamma$-ray spectroscopy is of both fundamental and applied interest. The techniques introduced in $\gamma$-ray spectroscopy will be expanded upon and used in the second section to measure the mean-life of the muon. The mean life of the muon is directly related to the fundamental strength of the Weak Nuclear Force; one of the four fundamental forces in nature.

### Part 1: Gamma-Ray Spectroscopy

## Introduction

The decay of many radionuclides involves the emission of $\gamma$-rays. Processes that leave the daughter in an excited state can lead to gamma emission. Alpha emission and beta emission precede gamma decay in the natural radionuclides. For example, there can be a large difference between the nuclear spin of the ground states of the parent and the daughter. Then the beta transition directly to the ground state of the daughter is forbidden and therefore most of the transitions leave the daughter in an excited state. Decay schemes for some radionuclides are shown below.




Often the half-life of the parent is very long relative to the half-life of the daughter. In this case gamma decay is in transient equilibrium with the decay of the parent and the $\gamma$-ray intensity falls off with the half-life of the parent. This is the reason it is customary to name the parent as the $\gamma$-ray source.

$\gamma$-ray spectroscopy has a number of important uses in the applied sciences. For example, it can be used to identifying much of the elemental composition of an unknown sample. To do this the unknown sample is irradiated with neutrons which makes the sample radio active. This is so-called 'neutron-activation". One can then measure the $\gamma$-rays (and $\beta$-rays) and sample half-life to determine the constituents and their relative concentrations. This technique is used in the petroleum industry and areas of geology, medicine, and criminology, to name a few.

To learn about $\gamma$-ray spectroscopy and standard instrumentation used in nuclear physics you will:

1. Observe $\gamma$-ray energy spectra,[1]
2. Identify the processes taking place,[2-8]
3. Complete an energy calibration of the apparatus. [9, 10]
4. Determine the identity of an unknown isotope.
5. Determine the attenuation coefficients of $\gamma$-rays as a function of $\gamma$-ray energy.[2, 10, 11]

**Procedure:**

A radioactive $\gamma$-ray source is placed near a NaI(Tl) scintillation detector. The NaI(Tl) absorbs the $\gamma$-ray and gives a light burst proportional to the amount of energy absorbed. The light is converted into electrons by a photocathode mounted on the input of a photomultiplier tube (PMT). The PMT is interfaced by the PMT base to a high voltage power supply and amplifier (or preamplifier plus amplifier). The PMT outputs a current pulse which is proportional to, and much greater than, the initial photoelectron current. Finally a multichannel analyzer (MCA) digitizes the pulses and stores a histogram of the number of pulses versus pulse amplitude. This is shown schematically in Fig. 1.

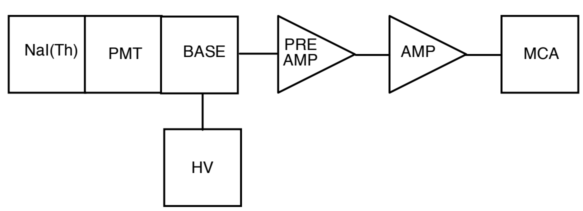



Fig. 1: Schematic drawing of the electronics for $\gamma$-ray spectroscopy. The NaI(Th) scintillator crystal, PMT, and PMT Base are a single unit. The high voltage applied to the base is negative and less than 1500 V. The preamp and amplifier are typically Nuclear Instrumentation Modules (NIM) powered by a NIM crate. The MCA is a special purpose electronics plug-in board in a PC.

**1. Observe $\gamma$-ray energy spectra, identify the processes taking place, energy calibration the apparatus, and determine the identity of an unknown isotope.**

Using the $^{137}$Cs source, observe the output from the anode output of the PMT base on an oscilloscope using 50Ω termination. The pulse will be negative. Set the high voltage on the PMT so that the pulses are > 50-100 mV. Typically ~ *positive* 1000 V is adequate high voltage; **do not exceed +1500V**. If you use a preamplifier (before the amplifier) then connect the anode output to the input of the preamp. If you do not use a preamplifier, then change from the *anode* to the *dynode* output of the PMT base. The pulse will now be positive and about one-half the size of the anode signal. This pulse can go directly into the amplifier (which typically want positive polarity signals). Before continuing it is instructive to see the $\gamma$-ray line(s) directly on the oscilloscope. Each line will appear as a brighter *band*. To see this you will need to get the correct trigger polarity: negative if you take the signal from the anode output of the PMT base or positive if you take the signal from the dynode output of the PMT base. You will also need a sweep rate that is matched to the time response of the NaI(Tl) detector. Once you find the signal, vary the high voltage (modestly) to see how the signal magnitude varies with applied high voltage. At this point you may want to determine what voltage change will cause a doubling of the signal amplitude!

A preamplifier-amplifier combination, or simply an amplifier, is used to shape the pulse. Pulse shaping is important for high rate applications and/or for minimizing electronic noise. These units also provide additional amplification if needed. Generally these modules perform best at or below the midrange of their settings. To see how the amplifier changes the pulse, pass the signal (from the PMT base) through channel 1 of the oscilloscope and into the input of the amplifier (check that you have the polarity correct). Look at the output of the amplifier in channel 2 of the oscilloscope to check that it is not clipped, i.e. limited in amplitude, and that it meets the input specifications of the MCA. For example for the PCA-3 card the input signal specifications are:

- 0 to +10 volts,
- unipolar or positive edge leading bipolar,
- pulse rise times from 0.5 to 30 $\mu$s.

Finally look at the signal on the MCA. For simple applications you should set the MCA to accumulate/display the maximum number of channels. The final choice of high voltage and amplifier gain settings should place the highest energy $\gamma$-ray line near the upper end of the MCA range. As different combinations of high voltage and amplifier gain will result in the same amplitude signal you may want to investigate which combination gives you the sharpest signal: i.e. the narrowest line for a fixed signal amplitude. At this point you should also accumulate $\gamma$-ray spectra from the $^{60}$Co source to learn the range of $\gamma$-ray energies and the number of distinct lines. Then you should consider building a cave, from lead bricks, to shield the NaI(Tl) detector from extraneous (i.e. background) $\gamma$-rays. Where does this background come from? You should also experiment with the distance between the source and the front of the NaI(Tl) detector. Does this make any discernable difference other than count rate? A good rule of thumb is to place the source at least 2 detector diameters from the detector. Why? The effective solid angle of the detector is then $(\pi r^2)/4\pi d^2$, where $r$ is the detector radius and $d$ is the source-to-detector distance. With your optimal setup you should accumulate a spectrum from each of the $\gamma$-ray sources. Do the spectra look different from your first spectra? How and why? Do the spectra look like the text book spectra? Identify as many of the features and lines as you can. Now take individual spectra for a couple sources such as the $^{137}$Cs and $^{60}$Co. You may also want to try the $^{57}$Co source if it is not too old. Do this in as short a time period as is possible. Repeat to be sure that your peaks have not drifted! Fit the peaks with the PCA3 program on the PC to determine the channel numbers for the center of each $\gamma$-ray line. If the DAQ electronics and the MCA are linear there should be a linear relation between peak channel number and $\gamma$-ray energy. To check this make a plot of channel number versus energy. Are the points in a line? Does the curve go through (0,0) or is there an offset? To what energy does channel 1 correspond? Now get an unknown $\gamma$ source from the instructor. Using references[2, 10] identify the unknown source.

Other issues you should consider include:

Do you have a circuit diagram including all equipment device types/numbers, SETTINGS, etc so that you could easily rebuild your setup. Have you sketched pulse shapes at different places in the circuit? What should you check for when looking at pulse shapes? What change in phototube high voltage results in a 100% increase in the observed $\gamma$-ray pulse heights (i.e. channel number in MCA)?

To a first approximation the gamma ray line width, that is its Full-Width at Half-Maximum (FWHM) is $2.35\sigma$, and related to the statistical fluctuations in the number of photo-electrons, $N_e$, that are collected from the photocathode of the phototube. In turn $N_e \propto E_\gamma$, thus:

$$\sigma/E_\gamma = 1/\sqrt{N_e} \propto 1/\sqrt{E_\gamma}$$

Thus this ratio measures $N_e$. Check this by plotting $(E_\gamma/\sigma)^2$ versus $E_\gamma$. If the plot is linear then our approximation was valid; that is there should be an essentially constant $\gamma$-ray energy required per observed photo-electron. What is the average $\gamma$-ray energy/photo-electron in your experiment? The inverse question is how many photoelectrons result from a 1 MeV $\gamma$-ray?[12] Does this number make sense?

$\gamma$-ray (i.e. photon) cross sections for interacting with the NaI(Tl) are rather small in the energy range of a few hundred keV to ~MeV. The photon interaction processes include the photoelectric effect, Compton scattering and pair production. What photon cross section is most directly related to the total conversion of the $\gamma$-ray to visible light in the energy range of this experiment? Is this the dominant cross section at these energies? What is the dominant photon interaction? Does this dominant process result in events in the observed $\gamma$-peaks? If not how do events get to be in the peak?

**2. Measure $\gamma$-ray attenuation coefficients:**

Just as $\gamma$-rays interact with the NaI(Tl) to be detected or with lead shielding to reduce background counts, $\gamma$-rays interact with all matter. The physical processes include the photoelectric effect, Compton scattering and pair production as noted above. These cross sections are combined (in a variety of ways depending on the precise definition) into an absorption or attenuation coefficient, $\mu$. Thus following a distance, $X$, an initial number of $\gamma$-rays, $N(0)$, is attenuated to a final number, $N(X)$:

$$N(X) = N(0)\, e^{-\mu X}$$

Because the photon cross sections change rapidly with energy and depend on the absorber material's nuclear charge, it is interesting to measure $\mu$ at different energies and for more than one absorber material.

To measure the energy dependence of $\mu$, start with the $^{137}Cs$ source and the MCA. To know $N(0)$ for each $\gamma$-ray line, you need to take (and fit) a MCA spectra with no absorber and for a known "live-time" interval. Then take additional spectra with different thickness of absorber and for different types of absorber. Copper and lead are available. Plot $N(X,E_\gamma)$ versus absorber thickness, $X$, as you accumulate the data. Remember to include the statistical uncertainty in each measurement, $\delta N$, in your plot:[13]

$$\delta N = \sqrt{N}$$

Are your statistics sufficient such that $\delta N << N$ ? If not, accumulate spectra for longer periods of time. If spectra are accumulated for different time intervals how do you record them in one plot? Have you taken spectra for enough absorber thicknesses to measure the $X$-dependence of $N(X)$ at small-$X$ where $N(X) \sim N(0)$, and also at large $X$ where $N(X) << N(0)$. Why is this important? Now try the $^{60}Co$ source. Should your steps in absorber thickness be the same at different $\gamma$-ray energies and/or for different absorbing materials? Why or why not?

Do you need to correct for the NaI(Tl) efficiency, $\varepsilon$? Why or why not? Because you expect an exponential decrease with absorber thickness you should plot your data on semi-log paper (or use a log scale on the y-axis in your computer graphing program). Do your results agree with the exponential dependence on absorber thickness? Do your results agree with smaller values for $\mu$ at larger $\gamma$-ray energies? If the answer to either of the last two questions is no, then you may want to reconsider the *geometry* of your experimental setup. Can the absorber provide a scattering path for $\gamma$-rays not initially directed at the NaI(Tl) detector to scatter into the detector? How can you minimize this experimental problem? Once you have a reliable experimental geometry and analysis procedures, take sufficient spectra to measure $\mu$ at several energies and for at least two absorber materials. How do your results compare with tabulated values for $\mu$?

## Part 2: Measurement of the Mean Life of the Muon

### Introduction

The muon[14] is an elementary particle indistinguishable from the electron except that its mass is ~ 200 times greater. Muons are produced primarily from the decays of charged pions, $\pi^{\pm}$, which are themselves produced (copiously) in extensive air showers caused by cosmic rays. Primary cosmic rays cover the spectrum from protons to intermediate mass nuclei (< iron). The primary cosmic rays interact with nuclei in the atmosphere creating large numbers of charged and neutral $\pi$ mesons. These subsequently interact or decay. Depending on the energy of the initial cosmic ray, millions or billions of secondary particles can be produced. This is called an extensive air shower.

Generally the neutral mesons, $\pi^{o}$, decay before interacting. Depending on their energy, the charged pions may interact with nuclei in the atmosphere or may decay, $\pi^{\pm} \rightarrow \mu^{\pm} + \nu$, to charged muons and neutrinos. To understand this behavior look up the lifetimes, $\tau_{\pi}$, and masses, $m_{\pi}$, of charged and neutral pions. The average distance they travel (before decaying) depends on their energy, $E_{\pi}$, and is given by:

$$Distance \sim (E_{\pi}/m_{\pi}c^2)\ c\ t$$

where $c$ is the speed of light. What are typical distances if $E_{\pi} = 10^9$ eV or if $E_{\pi} = 10^9$ eV? If this distance is large then it is likely the $\pi$ interacts before it decays.

Unlike pions, muons do not interact strongly. Thus to first order they will decay before they interact. The distance a *typical* $E_{\mu} = 10^9 - 10^{10}$ eV muon travels is thus:

$$Distance = (10^9 \sim 10^{10}\ [eV])/(105.7\ [MeV])(3 \times 10^8\ [m/s])(2.197 \times 10^{-6}\ [s]) =$$

$$6.24 \sim 62.4\ [km].$$

Where the muon mass $m_{\mu} = 105.7$ MeV. This distance is sufficiently great that many muons reach the earth surface. In fact at the earth's surface muons are the dominant component of secondary particles from cosmic ray showers. Most of the muons are of modest energy by the time they reach ground level. Thus some will range out, i.e. stop, in a tank of liquid scintillator. The study of the decay of these stopped muons is the basis of this experiment.

Muons decay via the weak interaction similar to the $\beta$-decay of free neutrons and nucleons in nuclei:

$$\mu^{\pm} \rightarrow \nu_{\mu} + e^{\pm} + \nu_{e}$$

Because neutrinos only interact via the weak nuclear force, muon decay is one of very few natural processes that only involves the weak interaction. The decay rate is actually a measure of the strength of the weak interaction, much like the electronic charge is a measure of the strength of the electromagnetic interaction.

As with nuclear $\beta$-decay the energy ($E_e$) spectrum of the resultant $e^{\pm}$ is that for a typical three body weak decay:[1]

$$d\Gamma( E_e)/dE_e = (G_F^2/12\pi^3)\ m_{\mu}^2\ E_e^{\ 2}\ (3 - 4\ E_e\ /m_{\mu}).$$

where $d\Gamma$ is the muon decay rate. If this is integrated over possible electron energies:

$$\Gamma = 1/\tau_{\mu} = G_F^2\ m_{\mu}^5/192\pi^3$$

where $\tau_{\mu}$ is the muon lifetime and $G_F$ is the Fermi coupling constant. The Fermi coupling constant is the fundamental coupling constant of the charge changing weak interaction. Thus a measurement of the muon lifetime provides a measurement of $G_F$ once the muon mass is known!

A fraction of the muons that reach the earth's surface have just the correct energy to stop in a block or tank of scintillator. As the muons stop they deposit ~ 2 MeV/(gm/cm$^2$) in the scintillator. Because the density of scintillator is ~1 (gm/cm$^3$), muons deposit ~ 2 MeV/cm of path length. This is much greater than the ~ 1 MeV/cm of typical $\gamma$-rays in Part 1 of this lab. Thus these stopping muons result in a pulse of light (in the scintillator) which is easily detected.

Roughly 5% of the $\mu^-$ will be captured into low Bohr orbits and then interact with the nucleus of the scintillator atoms before decaying. Thus the majority of $\mu^-$ and virtually all the stopped $\mu^+$ decay before interacting with electrons or nuclei in the scintillator. Each muon decay results in an electron with a energy up to $m_{\mu}/2$ ~ 53 MeV (i.e. neutrinos are essentially massless). These electrons also can result in a pulse of light (in the scintillator) which is also easily detected.

If one starts a clock each time a muon stops, i.e. this defines $t = 0$, then for a total of $N_{stop}$ stopped muons the number of muons remaining at a time t later is:

$$N(t) = N_{stop}\ exp\ (-t\ /\tau_{\mu}).$$

Note: clearly this assumes that muons are not lost due to interactions with the scintillator (see comments above). Process other than weak decays that remove muons will result in a low value for $\tau_{\mu}$. Random accidentals will be flat in time and will result in a high value for $\tau_{\mu}$, unless you analyze your data properly.

The number of muon decays in the time interval from $t_1$ and $t_2$ is:

$$\Delta N(<t>) = N(t_1) - N(t_2) = N_{stop}\ \{exp\ (-t_1/\tau_{\mu}) - exp\ (-t_2/\tau_{\mu})\} \sim N_{stop}\ (\Delta t/\tau_{\mu})\ exp\ (-<t>/\tau_{\mu}).$$

where $\Delta t = t_2 - t_1$ and $<t> = (t_2 + t_1)/2$, and the approximate relation is valid when $\Delta\square << \tau_{\mu}$. Thus a histogram of the number of the observed decays, $\Delta N(<t>)$, binned in time bins of width $\Delta t$, is predicted to be a simple exponential in $<t>/\tau_{\mu}$. A semi-log plot of $\Delta N(<t>)$ versus $<t>$ will have a slope $-1/\tau_{\mu}$.

**Procedure**

The muon decay experiment starts with a large tank of liquid scintillator viewed by two phototubes (PMTs). If one PMT is sufficient to trigger on cosmic ray muons and on the electrons from muon decay, why use two PMTs? The basic setup is shown schematically in Fig. 1. As depicted in Fig. 1, the difference between a through going muon and a stopped muon followed by a $\beta$-decay, is one pulse versus two pulses.

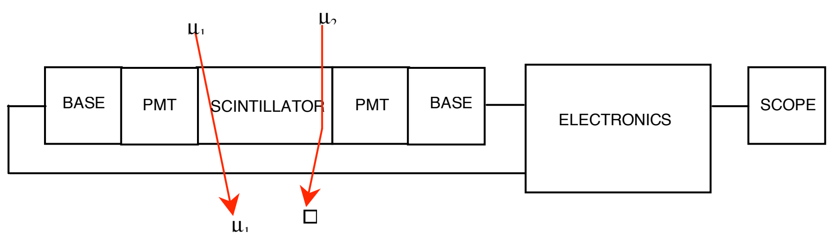



Fig. 1. Schematic setup for muon lifetime experiment. $\mu_1$ passes through the scintillator losing some energy: A single voltage pulse appears on the scope. $\mu_2$ stops in the scintillator and decays after time t to an electron: Two voltage pulses appear on the scope.

A sketch of a realistic experimental setup is shown in Fig. 2. The PMTs require *negative* HV and ~ -1500 V or less should provide adequate output signals. In practice you need to adjust the HV for each PMT to get approximately the same output signals. Typically the PMT output signals are discriminated with $V_{threshold}$ = 30 mV. Set the discriminator output pulse length to ~ 20 ns. Are the pulse lengths sufficient to allow for the variation in pulse timing between the 2 PMTs and still give a coincidence? Have you adjusted the relative time delay between the two scintillator signals so the signals are in time on average? Set the coincidence unit to require a 2-fold coincidence. The coincidence requires that both PMTs are above threshold to avoid noise triggers or triggers from cosmic ray muons that are clippers.

To monitor and set up your experiment pass signals of interest through the scope; i.e. put the oscilloscope between outputs of interest and the next device in the logic/signal chain.

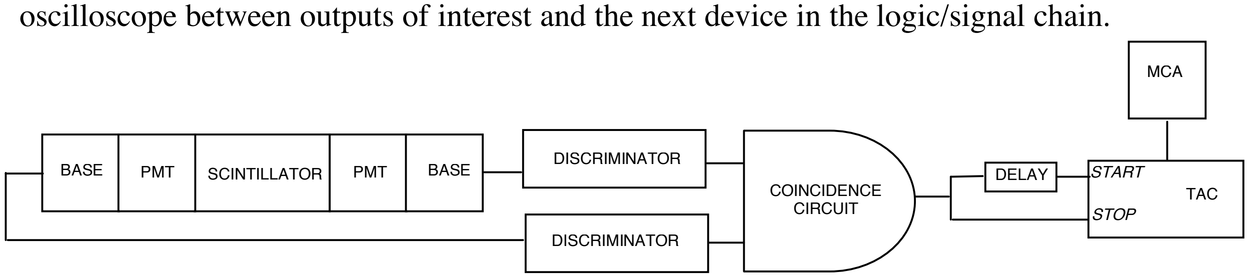



Fig. 2. A practical experimental arrangement for the muon lifetime experiment.

Two outputs are taken from the coincidence unit. One is delayed and used to START the TAC. The other is used to *STOP* the TAC. For details on how a TAC works see Appendix 2. At first this order appears to be counter intuitive. This is explained by Fig. 3 and by the fact that only when the TAC receives a good *START-STOP* combination will it produce an output pulse. To delay the signal to the TAC *START*, use the delay cable supplied with the experiment. How much delay does this cable introduce and why was this length chosen?

Thus all the events that have a *START* but no *STOP* within the TAC time window will result in no TAC output. For events with a good START-STOP combination the TAC output pulse has an amplitude proportional to the difference in time between the *START* and *STOP*. The TAC output signal is analyzed in the MCA. This is the good news. The bad news is that if a second muon passes through the scintillator close in time to first, then the second muon is indistinguishable from a decay electron. This results in a random accidental signal that should be uniform in time and thus produce a flat background. Start to think how you will analyze the data to accommodate this background!

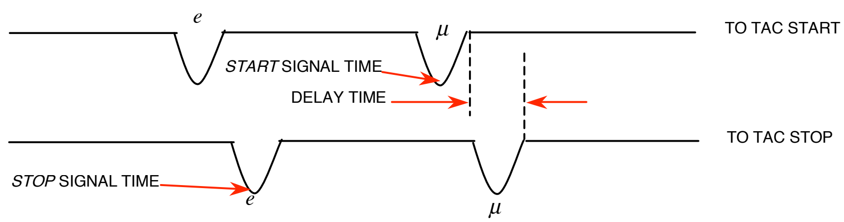



FIG. 3. Sketch of the signals entering the TAC (not to scale in time). The effect of the delay is to cut off the first part of the histogram stored in the MCA. It does not change the exponential nature of the histogram.

Set the time window on the TAC to ~ 5-10 muon lifetimes. Thus the data at large times will be essentially all accidentals. But don't set the time window too long or you will only be studying accidentals. If you have time you should accumulate and analyze data taken with different TAC time windows.

To obtain adequate statistics you will need to run for at least 24 hours. Remember to leave a big **DANGER HIGH VOLTAGE** sign on you apparatus.

The raw data from the MCA is a histogram of counts versus channel number. You need to calibrate the system.. That is, you supply a well defined time signal into the TAC/MCA combination to obtain the conversion from channel number to time. This is shown schematically in Fig. 4. Use a pulse generator followed by a discriminator (or simple splitter) to create two *in-time* signals. Put one through a precision delay, e.g. BNC model 7020 digital delay NIM module. Run with various values of delay to calibrate the full scale of the TAC/MCA. If you take data sets with different TAC time windows you will need to calibrate for each TAC setting. Remember to calibrate the TAC/MCA immediately before or after your data run, i.e. before you inadvertently change something.

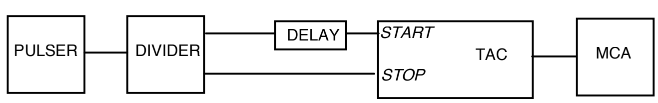



FIG. 4. Arrangement for time calibration of the TAC-MCA.

The recommended technique to analyze the data is to extract an *ASCII* file from the MCA and transfer this to a PC or workstation to manipulate and fit the data. You will need to correct for background counts. Remember if your time bins become too wide then the simple 1-exponential form is no longer correct. How does your measurement compare with the world average of $\tau_\mu$ = 2.197 $\mu$s?[15] If you agree within 5-10 % you are measuring the Fermi coupling constant to that same precision!

## REFERENCES

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3. W.R. Leo, Ch. 7, *Scintillation Detectors*.

4. W.R. Leo, Ch. 8, *PMTs*.

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6. W.R. Leo, Ch. 11, *Pulse Signals*.

7. W.R. Leo, Ch. 12, *NIM Electronics*.

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10. See Appendix 2, *AN34 - Experiments in Nuclear Science*, 3rd Ed.(EG&G ORTEC, 1984).

11. G.F. Knoll, *Radiation Detection and Measurement*, Ch. 2, 2nd Ed. (Wiley, New York, 1989).

12. *Harshaw Radiation Detectors*, Harshaw/Filtrol, 6801 Cochran Rd., Solon, Ohio report FWHM/$E\gamma \sim$ 7-9 % at 662 KeV for NaI(Tl) detectors.

13. W.R. Leo, Ch. 4, *Statistics and Error Analysis*.

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15. Particle Data Group, Phys Rev. D **54**, 1 (1996)

**APPENDIX 1: Time-to-Amplitude Converters**

**Bill Miller, edited by Paul Schwoebel**

A Time-to-Amplitude Converter (TAC) is a device that accepts a start pulse and waits for a stop pulse. Circuitry inside the TAC determines how much time has elapsed between the two pulses. The TAC produces a voltage pulse with an amplitude that is proportional to the elapsed time.

To use the TAC:

1. Check if there are any special power requirements like ±6 V. This can usually be found on the front panel. Some units have a rear panel switch that allows for either ±12 V of ±6 V. Make sure that your NIM bin has correct voltages available.

2) Check to see what logic family the unit uses, NIM logic (a "V" looking character) or TTL (a representation of a positive going pulse). Some units can be switched between the logics.

3) Set up the TAC for the proper time scale. If you set it up for a 1 µs scale and give it a signal with 2 µs between start and stop you will not get an output from the TAC. Similarly, If you select 1 µs and deliver only 1 ns the TAC will provide no output.

4) There can be a number of extra functions on the front panel. For *COINC* and *ANTICOINC* select *ANTICOINC*. *GATE* should be *OPEN*. The SCA is not important for this experiment. Leave the ULD at 10 and the LLD at 0. Buttons or switches associated with the SCA should be set to *OFF* or *OUT*. Anything that says *DELAY* is not important. This adjusts the time between the accepted *STOP* signal and the TAC output pulse. For slow count rates, 10 µs is nothing to worry about.

**APPENDIX 2: Gamma-Ray Spectroscopy**
**EG&G ORTEC**
**and**
**EQUIPMENT MANUALS**

**EXPERIMENT 3**

# Gamma-Ray Spectroscopy Using NaI(Tl)

**EQUIPMENT NEEDED FROM EG&G ORTEC FOR EXPERIMENTS 3.1 THROUGH 3.7, 3.9, and 3.10**

Bin and Power Supply
905-3 NaI(Tl) Crystal and Phototube Assembly
266 Photomultiplier Tube Base
556 High Voltage Power Supply
113 Scintillation Preamplifier
575A Amplifier
$^{137}$Cs gamma source, 5 $\mu$Ci ±5%
SK-1G Source Kit (see Appendix)
Absorber Kit Model 3-Z2
Absorber Kit PbAl-23
M-NaI-3 Stand for Sodium Iodide Detector
ACE-2K MCA System including suitable IBM PC (other EG&G ORTEC MCAs may be used)
Oscilloscope

**ADDITIONAL EQUIPMENT NEEDED FROM EG&G ORTEC FOR EXPERIMENT 3.8**

427A Delay Amplifier
551 Timing Single-Channel Analyzer
426 Linear Gate
875 Counter

## Purpose

The purpose of this experiment is to acquaint the student with some of the basic techniques used for measuring gamma rays. It is based on the use of a sodium iodide (NaI) detector that is thallium (Tl) activated.

## Gamma Emission

Most isotopes that are used for gamma measurements also have betas in their decay schemes. The typical decay scheme for the isotope will include a beta decay to a particular level followed by gamma emission to the ground state of the final isotope. The beta particles will usually be absorbed in the surrounding material and not enter the scintillator at all. This absorption is normally assured with aluminum absorbers (ref. 10). For this experiment the betas offer no real problem, and so absorbers are not specified. There will be some beta absorption by the light shield over the phototube. The gammas, however, are quite penetrating and will pass easily through the aluminum light shield.

Generally there are two unknowns that we would like to investigate about a gamma source. One is the energies of the gammas from the source; the other is the number of gammas that leave the source per unit of time. In this experiment the student will become familiar with some of the basic NaI(Tl) measurements associated with gamma-emitting unknowns.

A total time of ~6 h is required to complete all the parts of Experiment 3 (3.1 through 3.10). The complete series can be done in two 3-h lab periods, since each is written to be fairly independent of the others.

**EXPERIMENT 3.1**

# Energy Calibration

## Setup of Equipment

Set up the electronics in the arrangement shown in Fig. 3.1. There are two parameters that ultimately determine the overall gain of the system: the high voltage that is furnished to the phototube and the gain of the linear amplifier. The gain of the photomultiplier tube is quite dependent upon its high voltage. A rule of thumb for most phototubes is that a 10% change of the high voltage will change the gain by a factor of 2. The high-voltage value depends on the phototube being

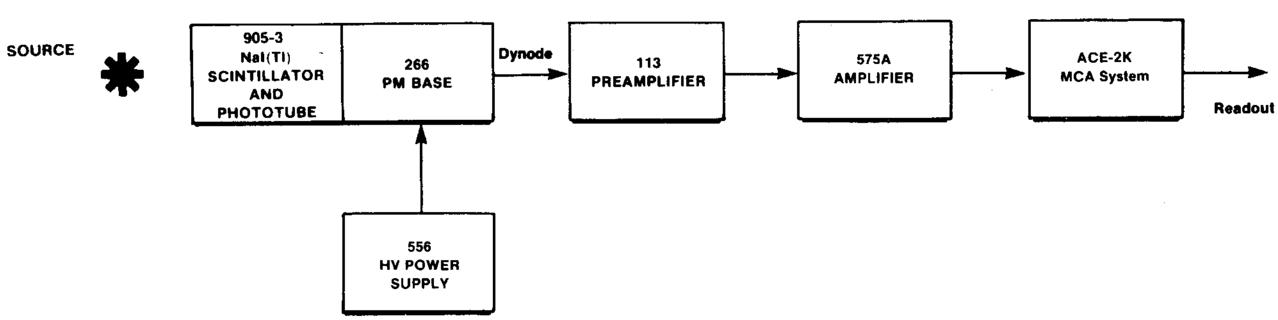


**Fig. 3.1. Electronic Block Diagram for Gamma-Ray Spectroscopy System with NaI(Tl) Detector.**

used; consult your instruction manual for the phototube and select a value in the middle of its normal operating range. (The instructor may wish to recommend a value.)

Set the indicated modules as follows:

556 High Voltage: See phototube instructions and set the level at about the middle of the acceptable operating range (normally about +1000 V).

113 Scintillation Preamplifier: Set the Input Capacity switch at 200 pF. The output pulses will be positive.

575A Amplifier: Positive input and Bipolar output. Shaping time set to 0.5 $\mu$sec. The gain will be adjusted during the experiment.

Multichannel Analyzer: PHA Analysis mode; 1000 channels are adequate for this experiment.

## Procedure

**1.** Place the $^{137}$Cs source from SK-1G ($E_\gamma$ = 0.662 MeV) ~2 cm in front of the NaI(Tl) crystal.

**2.** Adjust the coarse and fine gain controls of the linear amplifier so that the 0.662-MeV photopeak for $^{137}$Cs falls at approximately channel 280. For the illustrations shown in Figs. 3.2 and 3.3, the gain of the system has been set so that 1 MeV falls at about channel 420 to 425. Since the system is linear, 2 MeV would therefore fall at approximately channel 840 to 850.

**3.** Accumulate the $^{137}$Cs spectrum for a time period long enough to determine the peak position. Figure 3.2 shows a typical $^{137}$Cs spectrum that has been plotted. Although these spectra are usually plotted on semilog graph paper, the figures shown in this experiment are plotted on linear paper to point out some of the features of the spectra.

**4.** After the $^{137}$Cs spectrum has been read out of the MCA, erase it and replace the $^{137}$Cs source with a $^{60}$Co source from SK-1G.

**5.** Accumulate the spectrum for a period of time long enough for the spectrum to be similar to that in Fig. 3.3.

**6.** Read out the MCA.

## EXERCISES

**a.** Plot both the $^{137}$Cs and $^{60}$Co spectra and fill in items 1, 2, and 3 in Table 3.1.

**b.** From items 1, 2, and 3 in Table 3.1 make a plot of energy of the photopeaks vs channel number. Figure 3.4 shows this calibration for the data taken from Figs. 3.2 and 3.3. If other calibration sources are available, additional data points can be added to Fig. 3.4. The other entries in Table 3.1 will be filled out in Experiment 3.3.

**c.** Use the energy calibration feature of the MCA and compare the results with those found in Exercise **b**.

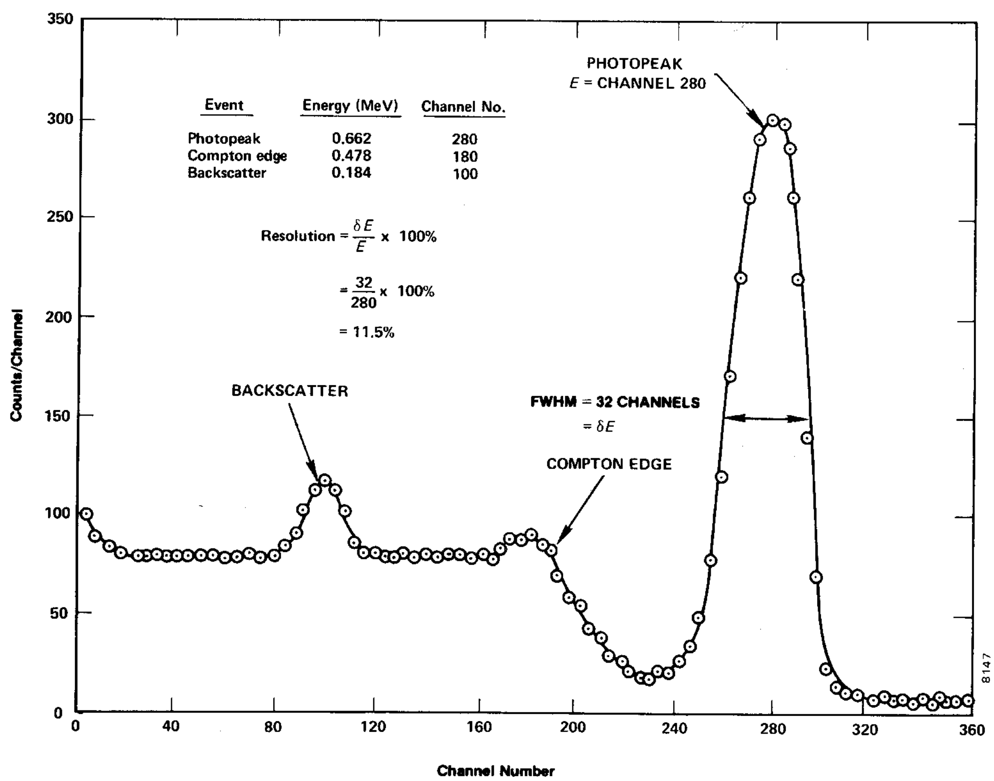


**Fig. 3.2. NaI(Tl) Spectrum for $^{137}$Cs.**

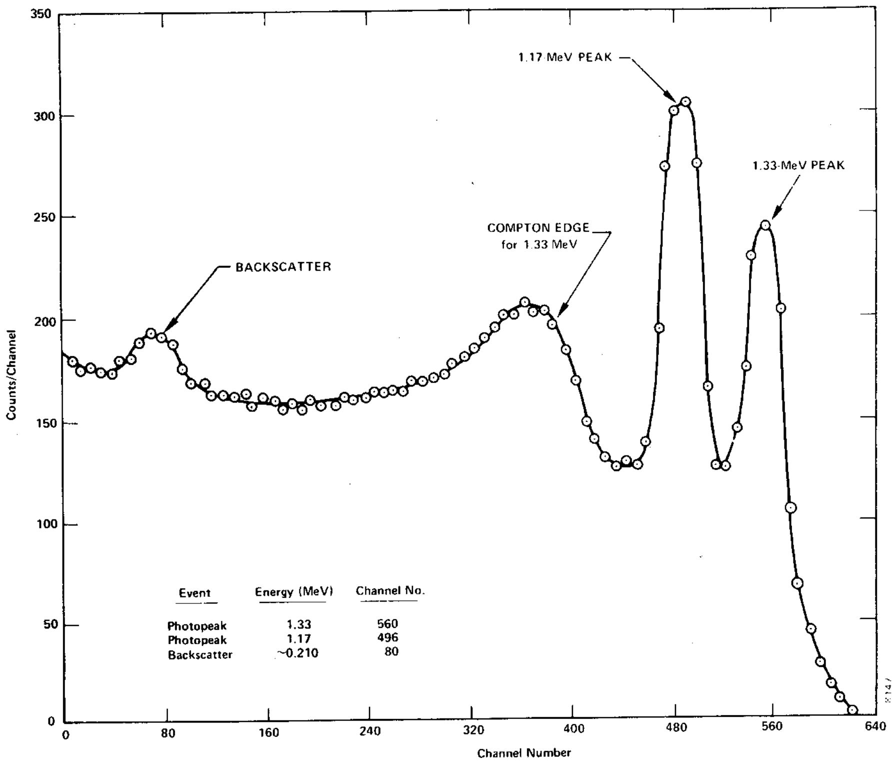


**Fig. 3.3. NaI(Tl) Spectrum for $^{60}Co$.**

**Table 3.1**

| | Event | Energy (MeV) | Channel Number |
|---|---|---|---|
| 1. | 0.662-MeV photopeak | 0.662 | |
| 2. | 1.17-MeV photopeak | 1.17 | |
| 3. | 1.33-MeV photopeak | 1.33 | |
| 4. | Compton edge $^{137}Cs$ | | |
| 5. | Backscatter $^{137}Cs$ | | |
| 6. | Backscatter $^{60}Co$ | | |

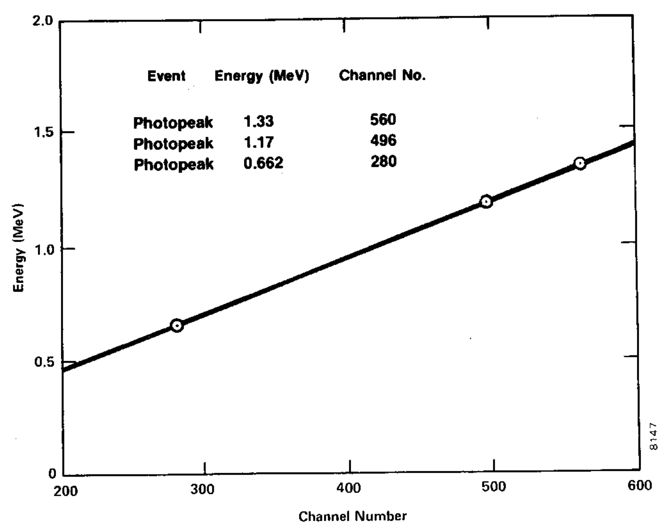


**Fig. 3.4. Energy Calibration Curve for NaI(Tl) Detector.**

**EXPERIMENT 3.2**

# Energy Analysis of an Unknown Gamma Source

## Purpose

The purpose here is to use the calibrated system of Experiment 3.1 to measure the photopeak energies of an unknown gamma emitter and to identify the unknown isotope.

## Procedure

**1.** Erase the $^{60}Co$ spectrum from the MCA, but do not change any of the gain calibration settings of the system.

**2.** Obtain an unknown gamma source from the instructor. Accumulate a spectrum for the unknown source for a period of time long enough to clearly identify the photopeak(s) of the source. From the calibration curve, determine the energy for each photopeak.

**EXERCISE**

Use refs. 7 and 8 to identify the unknown isotope.

**EXPERIMENT 3.3**

# Spectrum Analysis of $^{60}$Co and $^{137}$Cs

## Purpose

The purpose of this experiment is to explain some of the features, other than the photopeaks, that are usually present in a pulse-height spectrum. These are the Compton edge and the backscatter peak.

The Compton interaction is a pure kinematic collision between a gamma photon and what might be termed a free electron in the NaI(Tl) crystal. By this process the incident gamma gives up only part of its energy to the electron. The amount given to the recoil electron (and the intensity of the light flash) depends on whether the collision is head-on or glancing. For a head-on collision the gamma imparts the maximum allowable energy for the Compton interaction. The energy of the scattered gamma can be determined by solving the energy and momentum equations for this billiard ball collision. The solution for these equations in terms of the scattered gamma can be written approximately as

$$E_{\gamma'} \cong \frac{E_\gamma}{1 + 2E_\gamma (1 - \cos\theta)} , \qquad (1)$$

where

$E_{\gamma'}$ = energy of the scattered gamma in MeV,
$\theta$ = the scattering angle for $\gamma'$,
$E_\gamma$ = the incident gamma-ray energy in MeV.

If $\theta = 180°$ due to a head-on collision in which $\gamma'$ is scattered directly back, Eq. (1) becomes

$$E_{\gamma'} \cong \frac{E_\gamma}{1 + 4E_\gamma} . \qquad (2)$$

As an example, we will calculate $E_{\gamma'}$ for an incident gamma energy of 1 MeV:

$$E_{\gamma'} = \frac{1 \text{ MeV}}{1 + 4} = 0.20 \text{ MeV}. \qquad (3)$$

The energy of the recoil electron, $E_e$, for this collision would be 0.80 MeV. This is true since

$$E_e = E_\gamma - E_{\gamma'} . \qquad (4)$$

Then the position of the Compton edge, which is the maximum energy that can be imparted to an electron by the Compton interaction, can be calculated by Eq. (4).

### EXERCISES

**a.** Calculate the energy of the Compton edge for the 0.662-MeV gammas from $^{137}$Cs. Enter this value in Table 3.1. From your plot and calibration curve, does this calculation agree with your measured value?

**b.** Backscatter occurs when gammas make Compton interactions in the material that surrounds the detector. Figure 3.5 was taken from ref. 10 and is a good illustration of the various events that can take place in a typical source–NaI(Tl) detector–lead shield arrangement. Backscattered gammas from these interactions ($E_{\gamma'}$) make photoelectric interactions in the NaI(Tl) when they enter the crystal. The energy of the backscattered peak can be found by solving Eq. (2).

Solve Eq. (2) for the background gammas from $^{137}$Cs and for the 1.33-MeV gammas from $^{60}$Co. Fill in the rest of Table 3.1. How do your measured energies compare with the theoretical energies from Eq. (2)? If the backscatter peak is not very pronounced in your spectrum, it can be improved by accumulating a spectrum with a sheet of lead absorber placed slightly to the left of the source in Fig. 3.1.

**EXPERIMENT 3.4**

# Energy Resolution

## Purpose

The resolution of a spectrometer is a measure of its ability to resolve two peaks that are fairly close together in energy. Figure 3.2 shows the gamma spectrum that was plotted for the $^{137}$Cs source. The resolution of the photopeak is found by solving the following equation:

$$R = \frac{\delta E}{E} \times 100, \qquad (5)$$

where

R = the resolution in percent,
$\delta E$ = the full width of the peak at half of the maximum count level (FWHM) measured in number of channels,
E = the channel number at the centroid of the photopeak.

In Fig. 3.2 the photopeak is in channel 280 and its FWHM = 32 channels. From Eq. (5) the resolution is calculated to be 11.5%.

### EXERCISE

Calculate the resolution of the system from your $^{137}$Cs spectrum. Record this value for later reference.

**EXPERIMENT 3.5**

# Activity of a Gamma Emitter (Relative Method)

## Purpose

In Experiments 3.1 and 3.3, procedures were given for determining the energy of an unknown gamma source. Another

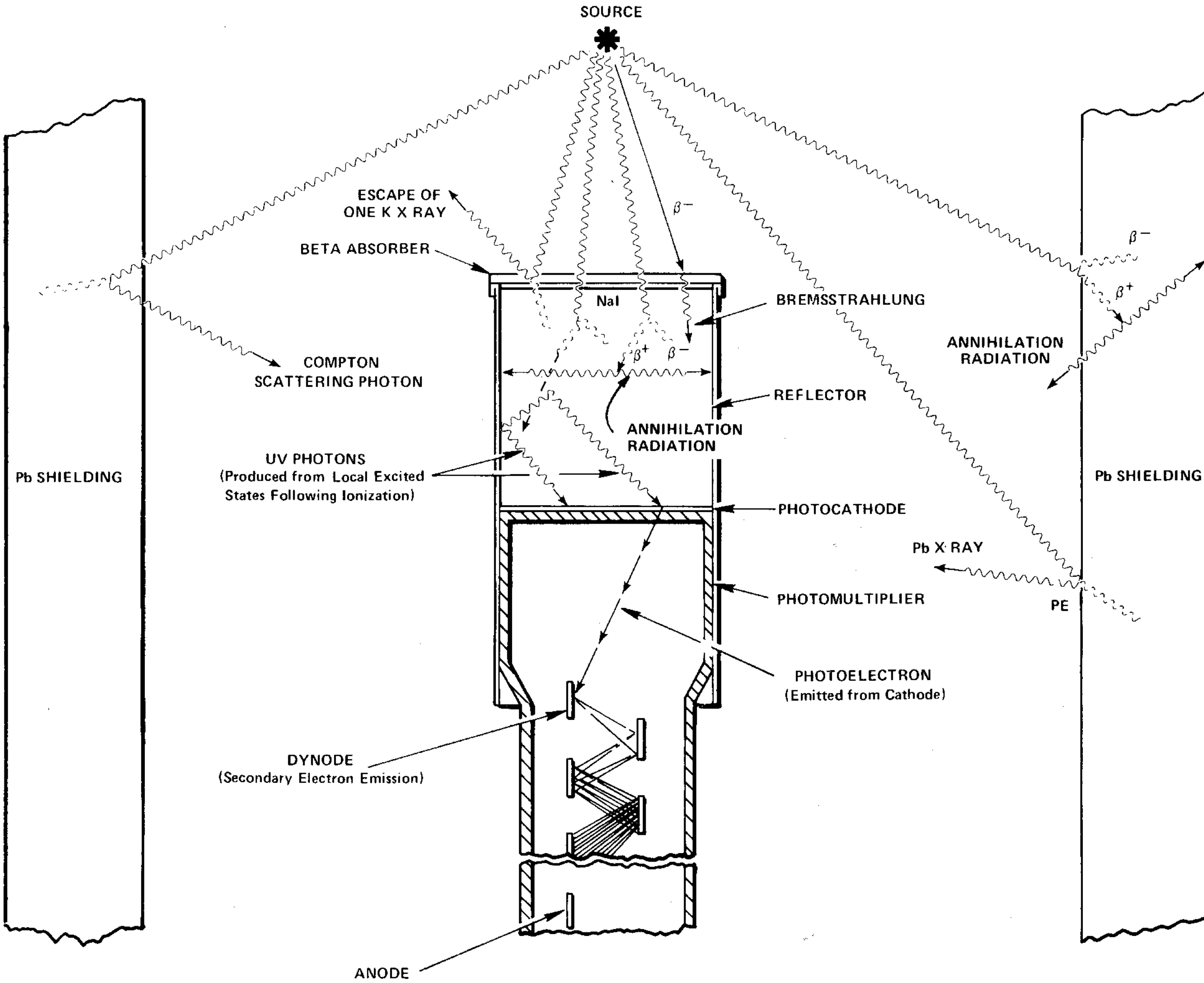


**Fig. 3.5. Various Events in the Vicinity of a Typical Source–Crystal Detector–Shield Configuration.**

unknown associated with the gamma source is the activity of the source, which is usually measured in curies (Ci); 1 Ci = $3.7 \times 10^{10}$ disintegrations/s. Most of the sources that are used in nuclear laboratory experiments have activities of the order of microcuries ($\mu$Ci). The purpose of this experiment is to outline one procedure by which the activity of a source can be determined, called the relative method.

In using the relative method, it is assumed that the unknown source has already been identified from its gamma energies. For this example, assume that the source has been found to be $^{137}$Cs. Then all that is necessary is to compare the activity of the unknown source to the activity of a standard $^{137}$Cs source that will be supplied by the laboratory instructor. For convenience, call the standard source S1 and the unknown source U1.

## Procedure

**1.** Place the S1 source about 4 cm from the face of the detector (or closer if necessary to get reasonable statistics) and accumulate a spectrum for a period of live time, selectable on the analyzer, long enough to produce a spectrum similar to Fig. 3.2.

**2.** Use the cursor to determine the sum under the photopeak. In the example shown in Fig. 3.2, this would correspond to adding up all counts in channels 240 through 320. Define this sum to be $\Sigma_{S1}$.

**3.** Erase the MCA spectrum. Remove source S1 and replace it with source U1, positioned **exactly** the same distance from the crystal as the S1 source was. Accumulate a spectrum for the same period of live time that was used in step **1**. Sum the peak as in step **2**.

**4.** Erase the spectrum from the MCA. Remove the U1 source and accumulate background counts for the same period of live time that was used in steps **1** and **3** above.

**5.** Sum the background counts in the same channels that were used for the photopeaks in steps **2** and **3** above. Call this sum $\Sigma_b$.

## EXERCISE

Solve for the activity of the U1 by using the following ratio:

$$\frac{\text{activity of U1}}{\text{activity of S1}} = \frac{\Sigma_{U1} - \Sigma_b}{\Sigma_{S1} - \Sigma_b} \qquad (6)$$

Since the efficiency of the detector is only energy dependent, the standard and unknown sources do not have to be the same isotope. It is only necessary that their gamma energies be approximately the same (±10%) in order to get a fairly good estimate of the absolute gamma activity of the unknown.

### EXPERIMENT 3.6

# Activity of a Gamma Emitter (Absolute Method)

## Purpose

The activity of the standard used in Experiment 3.5 can be determined by the absolute method. The purpose of this experiment is to outline the procedure for this method. Here the source that is to be measured will be called U1.

## Procedure

**1.** Place the U1 source 9.3 cm away from the face of the detector.

**2.** Accumulate a spectrum and note the live time that is used.

**3.** Use the cursor to determine the sum under the photopeak, $\Sigma_{U1}$. Then erase the spectrum, remove the source, and accumulate background for the same live time and calculate $\Sigma_b$.

**4.** Use the following formula to calculate the activity of U1:

$$\text{activity of U1} = \left(\frac{\Sigma_{U1} - \Sigma_b}{t}\right) \frac{1}{G\epsilon_p f}, \qquad (7)$$

where

t = live time in seconds,

$\epsilon_p$ = intrinsic peak efficiency for the gamma energy and detector size used (Fig. 3.6 and ref. 10),

f = the decay fraction of the unknown activity which is the fraction of the total disintegrations in which the measured gamma is emitted (refs. 7 and 8 and Table 3.2),

G = area of detector $(cm^2)/4\pi s^2$,

s = source-to-detector distance in cm.

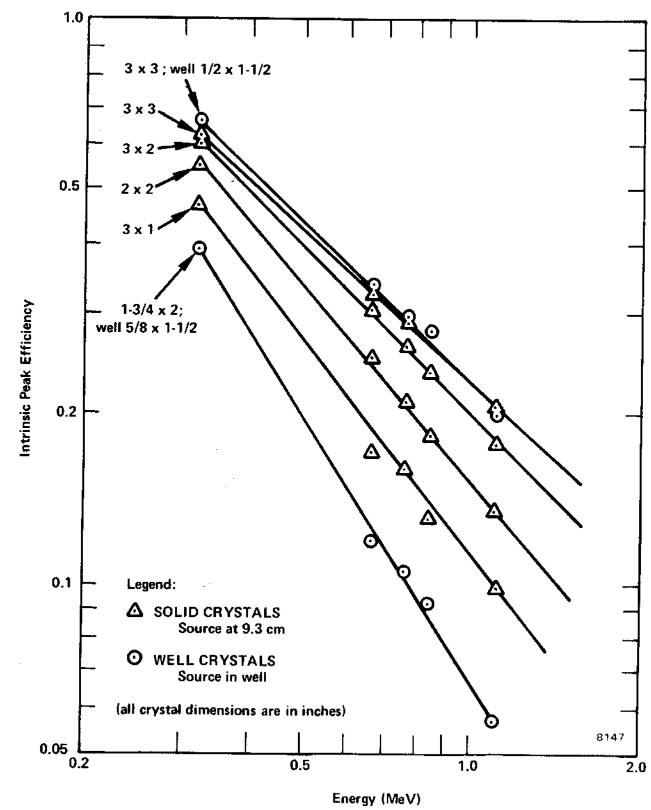


**Fig. 3.6. Intrinsic Peak Efficiency of Various NaI(Tl) Crystals vs Gamma Energy.**

**Table 3.2. Gamma Decay Fraction, (f), for Some Common Isotopes.**

| Isotope | Gamma Energy (MeV) | *f* |
|---|---|---|
| $^{137}Cs$ | 0.662 | 0.92 |
| $^{51}Cr$ | 0.323 | 0.09 |
| $^{60}Co$ | 1.17 | 0.99 |
| $^{60}Co$ | 1.33 | 0.99 |
| $^{22}Na$ | 1.276 | 0.99 |
| $^{22}Na$ | 0.511 | 0.99 |
| $^{54}Mn$ | 0.842 | 1.00 |
| $^{65}Zn$ | 1.14 | 0.44 |

### EXPERIMENT 3.7

# Mass Absorption Coefficient

## Purpose

The purpose of the experiment is to measure experimentally the mass absorption coefficient in lead for 662-keV gamma rays.

References 2, 3, and 5 point out that gammas interact in matter primarily by photoelectric, Compton, or pair-production interactions. The total-mass absorption coefficient can be measured easily with a gamma-ray spectrometer. In this experiment we will measure the number of gammas that are removed from the photopeak by photoelectric or Compton interactions that occur in a lead absorber placed between the source and the phototube.

From Lambert's law (ref. 1) the decrease of intensity of radiation as it passes through an absorber is given by

$$I = I_0 e^{-\mu x}, \quad (8)$$

where

$I$ = intensity after the absorber,
$I_0$ = intensity before the absorber,
$\mu$ = total-mass absorption coefficient in $cm^2/g$,
$x$ = density thickness in $g/cm^2$.

The density thickness is the product of the density in $g/cm^3$ times the thickness in cm.

The half-value layer (HVL) is defined as the density thickness of the absorbing material that will reduce the original intensity by one-half. From Eq. (8):

$$\ln I/I_0 = -\mu x. \quad (9)$$

If $I/I_0 = 0.5$ and $x$ = HVL, $\ln 0.5 = -\mu(\text{HVL})$ and hence

$$\text{HVL} = \frac{0.693}{\mu} \quad (10)$$

In this experiment we will measure $\mu$ in lead for the 0.662-MeV gammas from $^{137}Cs$. The accepted value is 0.105 $cm^2/g$. Values for other materials can be found in ref. 8.

## Procedure

**1.** Place the $^{137}Cs$ source about 5.0 cm from the NaI(Tl) detector and accumulate the spectrum long enough for the sum under the 0.662-MeV peak $(\Sigma_{Cs} - \Sigma_b)$ to be at least 6000 counts. Determine $(\Sigma_{Cs} - \Sigma_b)$.

**2.** Erase the MCA and insert a piece of lead from the absorber kit between the source and the detector. Accumulate the spectrum for the same period of live time as in step **1** above. Determine $(\Sigma_{Cs} - \Sigma_b)$.

**3.** Erase the MCA and insert another piece of lead. Determine $(\Sigma_{Cs} - \Sigma_b)$. Repeat with additional thicknesses of lead until the count-sum is >1000. Fill in the data in Table 3.3.

**Table 3.3. Data for Mass Absorption Coefficient.**

| Absorber | Absorber Thickness ($mg/cm^2$) | $\Sigma_{Cs} - \Sigma_b$ |
|---|---|---|
| 1 | 0 | |
| 2 | | |
| 3 | | |
| 4 | | |
| 5 | | |
| 6 | | |
| 7 | | |

## EXERCISES

**a.** Using semilog graph paper, plot I vs absorber thickness in $mg/cm^2$, where $I = (\Sigma_{Cs} - \Sigma_b)$/live time. Determine the HVL from this curve and calculate $\mu$ from Eq. (10). How does your value compare with the accepted value of 0.105 $cm^2/g$?

**b.** Repeat the above experiment for the aluminum absorbers in the Absorber Kit. The $\mu$ for aluminum is 0.074 $cm^2/g$.

EXPERIMENT 3.8

# The Linear Gate in Gamma-Ray Spectroscopy

## Purpose

The purpose of this experiment is to show how a linear gate can be used with an MCA in gamma-ray spectroscopy. The linear gate will limit the analysis of input pulse amplitudes to those that will be included within the photopeak.

The measurement of the mass absorption coefficient in Experiment 3.7 required the accumulation of several complete spectra, although the data of interest were included within only a fraction of the total number of channels that were used. The normal time for completing Experiment 3.7 is approximately 45 min. By using a linear gate, the same information can be obtained in about 1/3 of the time. An equivalent saving of time can also be made in Experiments 3.5 and 3.6 (Source Activity Determinations). Since the procedures are about the same as for Experiment 3.7, the student should repeat these experiments with the linear gate to see how much time will be saved.

See equipment list at beginning of Experiment 3 for additional equipment required for Experiment 3.8.

Connect the system components as shown in Fig. 3.7. Connect the bipolar output of the 575A Amplifier to both the 427A Delay and the 551 Timing Single-Channel Analyzer. Connect the Delay output to the linear Input of the 426 Linear Gate and connect the gate output to the analyzer input. Connect the SCA output to both the 875 Counter input and the Enable input of the Linear Gate.

The Linear Gate is a module that permits linear pulses to be passed only during the time interval that follows each Enable input. In normal operation the adjusted time interval will allow only one linear pulse to be furnished into the MCA.

The Timing Single-Channel Analyzer determines whether each input pulse amplitude is within the window and generates a logic output pulse for each input pulse that satisfies the criteria. By adjusting the lower and upper levels of its window, the 551 then can determine what portion of the spectrum is gated through for analysis in the MCA. This is true since it delivers the enable logic pulse to open the linear gate.

From the standpoint of timing, one would like to have the logic pulse arrive at the enable input of the linear gate just prior to the arrival of the corresponding linear pulse that is to be gated. Since the amplifier provides a bipolar output to the SCA, and since the SCA generates an output at 50% of full amplitude on the trailing edge of the positive lobe, the SCA output will occur at about 2 $\mu$s after the onset of the pulse. Thus, if the 427A Delay is set for 3 $\mu$s and the 426 Linear Gate width is adjusted to maximum, 4 $\mu$s, the gate passes the input pulse for a period from 1 $\mu$s before the delayed pulse reaches the 426 until 3 $\mu$s of elapsed pulse time. This passes the positive portion of the bipolar pulse, which is all that affects the MCA measurement; the negative portion of the bipolar pulse is not used.

The inclusion of a counter in Fig. 3.7 permits a direct total of the counts to be observed, and the adjustment of the window width will limit these to the peak area. This simplifies the summing of counts for peak area integrations.

Figure 3.8 shows how Fig. 3.2 might look if the window of the SCA were set properly to just span the $^{137}$Cs photopeak. Since the MCA has a live display while it is accumulating, it is quite simple to adjust the window of the SCA properly.

The single-channel principle and the control of the linear gate are examined here with individual modules. Both functions are also included in the MCA, so the separate modules are not required for other experimental applications.

### Module Settings:

Use the same settings for the high-voltage power supply, preamplifier, and amplifier that were used for Experiment 3.1. Set the 426 Linear Gate for Normal with its Gate Width control fully clockwise for 4 $\mu$s. Set the 875 Counter for count and use the Positive input from one of the Pos Out connectors on the 551 Timing SCA; reset the 875 Counter to zero. Set the 551 Timing SCA for Normal operation, the Lower-Level control at 030, the Upper-Level control fully clockwise

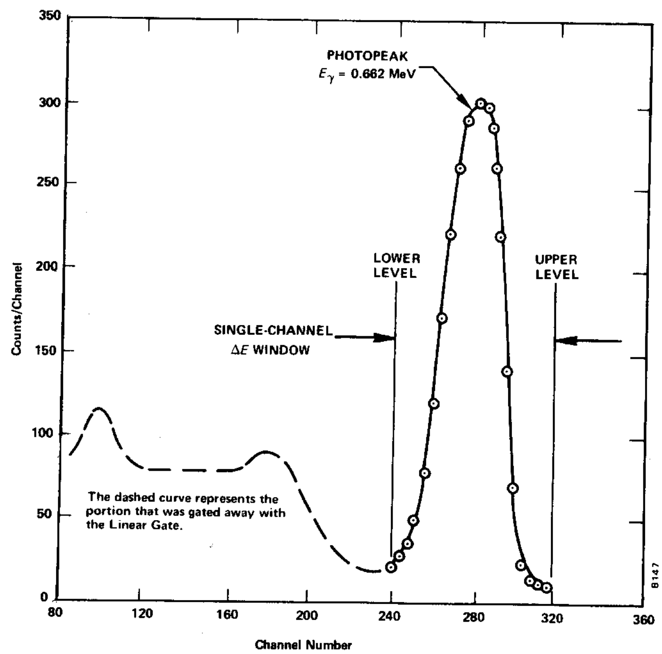


**Fig. 3.8.** $^{137}$**Cs Spectrum with the Linear Gate.**

at 1000 divisions, and Delay at minimum for 0.1 $\mu$s. Set the 427A Delay Amplifier for a 3-$\mu$s delay.

## Procedure

**1.** Place the $^{137}$Cs source from SK-1G about 4 or 5 cm from the crystal face. Accumulate a spectrum in the MCA while adjusting the E and the ΔE window on the 551 Timing SCA. Set the window so that it just brackets the photopeak as in Fig. 3.8. You are now ready to make the first measurements.

**2.** Clear the MCA and reset the counter to zero. Start both at the same time and accumulate for a period of time long enough to obtain about 6000 counts in the counter. Record

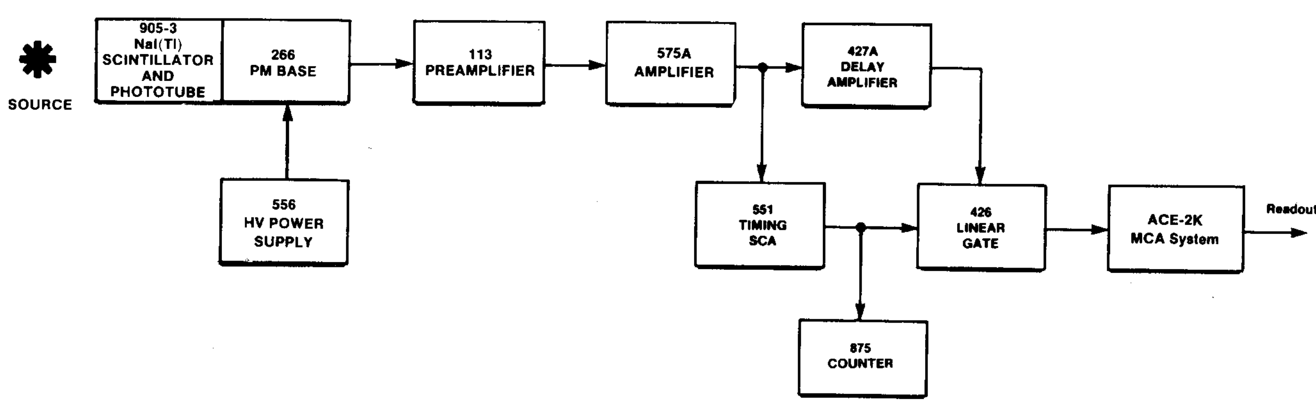


**Fig. 3.7. Block Diagram of Electronics for Gamma-Ray Spectrometry System with a Linear Gate.**

the total elapsed time for the measurement, the average dead time from the MCA, and the count in the counter. Read out the analyzer and then clear both the MCA and the counter.

**3.** Place the first lead absorber between the source and the detector as in Experiment 3.7 and accumulate for the same period of time that was used in step **2** above. Record only the counter counts and the total elapsed time. It is not necessary to read out the MCA for each spectrum since the counter is summing the counts under the photopeak. You should observe the MCA for each spectrum to make sure that the proper spectrum is being stored.

**4.** Repeat step **3** for each added absorber thickness that was used in Experiment 3.7. Make a background run with the source removed, and fill in Table 3.4 as in Experiment 3.7.

**Table 3.4**

| Absorber | Absorber Thickness (mg/cm$^2$) | $\Sigma_{Cs} - \Sigma_b$ |
|---|---|---|
| 1 | 0 | |
| 2 | | |
| 3 | | |
| 4 | | |
| 5 | | |
| 6 | | |
| 7 | | |

**5. Calculate the same data as in Experiment 3.7, Exercises a and b.**

**6.** In step **2** the output of the MCA was read. Sum this output spectrum and compare it with the counter sum that was taken from the same run. The counter sum should be slightly larger since it does not suffer from dead-time corrections at these counting rates. The MCA does suffer, because it requires some amount of time to measure and store each pulse and thus does not actually analyze as many pulses as have been furnished to it. The MCA sum should be equal to the counter count times the percent of live time, which is equal to the live time of the MCA divided by the clock time for the spectrum accumulation.

**EXPERIMENT 3.9**

# Sum Peak Analysis

Figure 3.3 shows the two pronounced peaks in $^{60}$Co. Figure 3.9 shows the decay scheme of $^{60}$Co.

Most of the time the decay occurs by $\beta$ emission to the 2.507-MeV excited state of $^{60}$Ni. Subsequent decay to the ground state always occurs by gamma emission to the 1.3325-MeV level (a 1.174-MeV gamma) followed almost simultaneously by the 1.3325-MeV gamma to the ground state. In Experiment 19 we will show that these two events are in coincidence and have an angular correlation that deviates from an isotropic distribution by only 16%. For the purposes of this experiment we can assume that each of these gammas are isotropically distributed. In other words, if $\gamma_1$ goes in a particular direction, $\gamma_2$ can go in any of the $4\pi$ steradians that it wishes. There is a certain probability that it will go in the same direction as $\gamma_1$. If this occurs within the resolving time of the detector, $\gamma_1$ and $\gamma_2$ will be summed and hence a sum peak will show up in the spectrum. From the definitions in Experiment 3.6, the number of counts, $\Sigma_1$, under the $\gamma_1$ peak is given by:

$$\Sigma_1 = \epsilon_1 G f_1 t A, \tag{11}$$

where A is the activity of the sample and t is the time. In a similar calculation, the sum $\Sigma_2$ for $\gamma_2$ is given by:

$$\Sigma_2 = \epsilon_1 G f_2 t A. \tag{12}$$

From Eqs. (11) and (12) the number of counts in the sum peak, $\Sigma_s$ is given by:

$$\Sigma_s = \epsilon_1\epsilon_2 f_1 f_2 G^2 A t\ [W(0°)], \tag{13}$$

where W(0°) is a term that accounts for the angular correlation function. For the case of $^{60}$Co, Eq. (13) is quite simple. $\Sigma_s$ becomes:

$$(\Sigma_s)_{^{60}Co} \cong \epsilon_1\epsilon_2 G^2 A t, \tag{14}$$

since W(0°) ≅ 1.0.

In this experiment we will show that the sum peak for $^{60}$Co has an energy of 2.507 MeV and that its sum is given by Eq. (14).

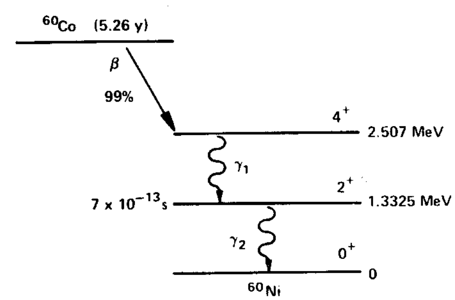


**Fig. 3.9. The Decay Scheme of $^{60}$Co.**

## Procedure

**1.** Set up the electronics as shown in Fig. 3.1.

**2.** Use the gammas from the source kit to calibrate the MCA so that full scale is ~3.0 MeV. For 1024 channels this would put the $^{137}$Cs (0.662 MeV) peak at approximately channel 225.

**3.** Construct a calibration curve as in Experiment 3.1.

**4.** Place the $^{60}$Co source from the source kit at exactly 9.3 cm from the face of the detector. Count for a period of time long enough so that the area under the sum peak is ~1000 counts. This procedure was outlined in Experiment 3.6.

### EXERCISES

**a.** Verify that the energy of the sum peak is 2.507 MeV. Subtract the background from the sum peak and verify its sum from Eq. (14).

**b.** Repeat this sum peak analysis for the $^{22}$Na source. Figure 3.10 shows the decay scheme for $^{22}$Na and a typical spectrum with the sum peak.

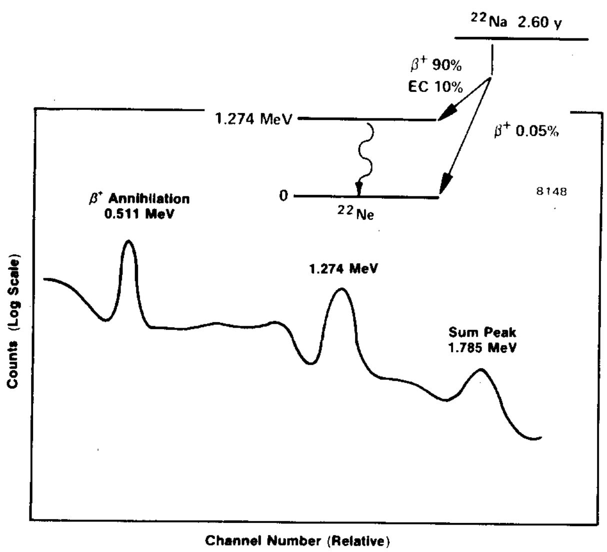


**Fig. 3.10. Sum Peak for the $^{22}$Na Source from Source Kit SK-1G.**

### EXPERIMENT 3.10

# Photoelectric Absorption

## Purpose

The purpose of this experiment is to study the photoelectric absorption of photons and verify the strong dependence of this process on the atomic number of the absorbing material.

When a gamma of energy <150 keV interacts with matter, the interaction has a high probability of being photoelectric. In the photoelectric interaction, the photon interacts with one of the tightly bound electrons in the material. The electron, in general, is knocked out of the atom with an energy given by:

$$E_e = hf - E_b,$$

where f is the frequency of the photon and $E_b$ is the binding energy of the electron that is involved in the interaction. The probability of photoelectric interaction is dependent on the atomic number of the absorbing material and the energy of the gamma or x-ray photon. Although it is difficult to write out an exact analytic expression for this probability, it can be shown that for low energy photons

$$\mu = \frac{K \cdot Z^n}{E_\gamma^3}, \qquad (15)$$

where K is a constant, Z is the atomic number, and n is usually between 4 and 5.

## Procedure

The set up for this experiment is the same as for Experiment 3.7.

**1.** Place the $^{57}$CO source ~3.8 cm from the NaI detector. Accumulate for a time period long enough to get reasonable statistics in the 122-keV line. As in Experiment 3.7, $\Sigma - \Sigma_b$ should be at least 6000 counts.

**2.** Clear the MCA and place the thinnest aluminum absorber between the source and the detector. Count for the same period of time as in step **1**. Repeat for the other two aluminum absorbers.

**3.** Repeat steps **1** and **2** for the other thin absorbers, Fe, Cu, Mo, Sn, Ta, and Pb, in the Model 3-Z2 source kit. Note: The counting time might have to be increased as the atomic number of the absorber is increased.

### EXERCISES

**a.** For the three measurements made with the thin aluminum foils, calculate and average $\mu$, Eq. (9). Repeat for the other absorbers.

**b.** Make a plot of $\mu$ vs $Z^{4.5}/E_\gamma^3$ from your experimental data. How do your results compare to the theory?

## References

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9. 14th Scintillation and Semiconductor Counter Symposium, *IEEE Trans. Nucl. Sci.* **NS-22**(1) (1975).

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# 567
# Time-to-Amplitude Converter/SCA

The EG&G ORTEC Model 567 Time-to-Amplitude Converter/Single-Channel Analyzer (TAC/SCA), measures the time interval between start and stop input pulses, generates an analog output pulse proportional to the measured time, and provides built-in single-channel analysis of the analog signal. Additional gating modules are not necessary with this unit, and timing experiments requiring time ranges of 10 ns to 2 ms may be performed with single-channel analysis, giving the experimenter unparalleled flexibility in analyzing random nuclear events that occur within a selected time range. Time ranges from 50 ns to 2 ms are provided via the front-panel controls.

Separate gating (anticoincidence or coincidence) of the start and stop inputs eliminates unwanted events from the time spectra via externally imposed energy or timing restrictions. The Model 567 also incorporates a built-in SCA inhibit feature in which a TAC output is available only if the output pulse falls within the window restrictions imposed by the SCA. This feature may be switched in or out by a convenient front-panel switch.

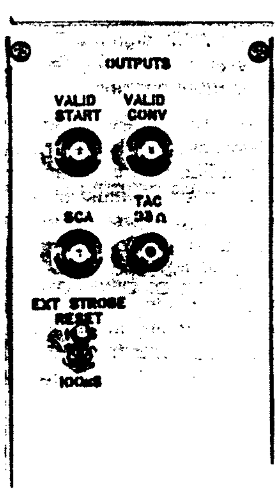
In addition to its start and stop input gating capabilities, the Model 567 provides for a pulsed or dc-level Reset/Inhibit signal via a front-panel input connector. A Reset/Inhibit input signal terminates the conversion cycle and maintains a reset condition, inhibiting further TAC conversions for the duration of the Reset/Inhibit pulse. A TAC output pulse that is in process at the time a Reset/Inhibit input is received will be completed before converter reset is initiated.

Valid Start and Valid Conversion outputs are provided for each accepted start and stop input respectively. The duration of the Valid Start output indicates the interval from the accepted start until the end of reset. Valid Conversion occurs from the end of the internal delay after stop to the end of reset.

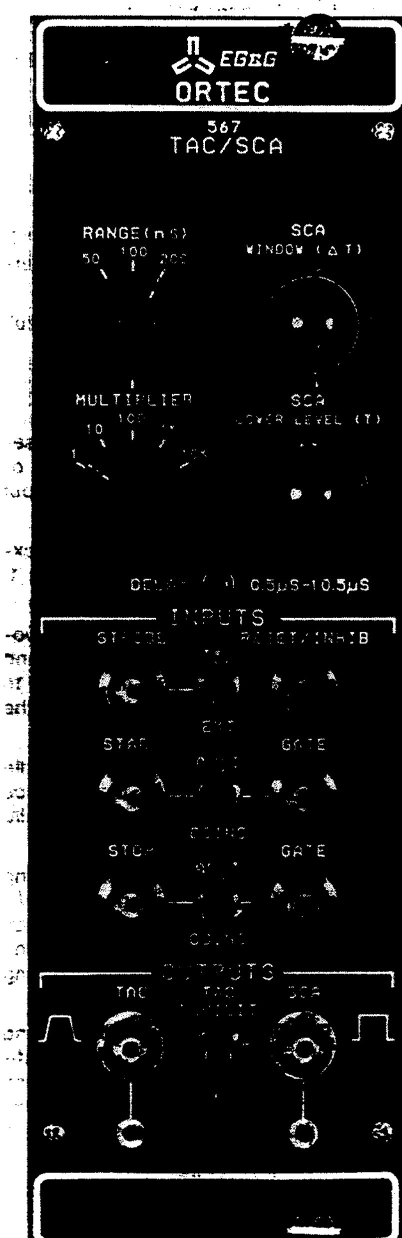
The selectable TAC output width and variable delay, which are easily adjustable, further serve to make the Model 567 a flexible instrument. The output of the TAC may be synchronized with the stop signal or an external strobe signal to further enhance its versatility.

The single-channel analyzer section of the Model 567 allows the experimenter to place very specific time restrictions on the timing spectrum. The SCA is operated in the Window position, where the upper-level discriminator setting is added to that of the lower-level discriminator. The SCA output pulse width is equal to the time from the occurrence of the TAC output until the end of the reset pulse or the end of the TAC output. The synchronization of the SCA output with the stop input virtually eliminates any time walk in the SCA output.

All Model 567 inputs are printed wiring board (PWB) jumper-selectable to accept either negative or positive NIM-standard signals. All inputs and outputs are dc-coupled so that changing input count rates will not hinder normal operation of the Model 567. The TAC output should be connected to the dc-coupled input of a multichannel analyzer (MCA) for optimum high-count-rate performance.




- **For time spectroscopy in the range from 10 ns to 2 ms**
- **Includes SCA to set a time window for coincidence experiments**
- **Valid Start and Valid Conversion outputs**
- **Selectable output delay and width**
- **Output synchronized with a stop or external strobe signal**
- **Provision to reject unwanted start or stop input signals**
- **Positive or negative input signals**



# 567
# Time-to-Amplitude Converter/SCA (continued)

## Specifications

### PERFORMANCE

#### Time-to-Amplitude Converter

**TIME RESOLUTION** FWHM ≤0.01% of full scale plus 5 ps for all ranges.

**TEMPERATURE INSTABILITY** ≤±0.01%/°C (±100 ppm/°C) of full scale plus 10 ps/°C, 0 to 50°C.

**DIFFERENTIAL NONLINEARITY** Typically <1% from 10 ns or 2% of full scale (whichever is greater) to 100% of full scale.

**INTEGRAL NONLINEARITY** ≤±0.1% from 10 ns or 2% of full scale (whichever is greater) to 100% of full scale.

**RESET CYCLE** Fixed 1.0 μs for X1 and X10 Multipliers, fixed 5 μs for X100 Multiplier, and fixed 50 μs for X1K and X10K Multipliers. Occurs after Over Range, Strobe cycle, or Ext Strobe Reset cycle.

**START-to-STOP CONVERSION TIME** Minimum ≤5 ns.

#### Single-Channel Analyzer

**THRESHOLD INSTABILITY** ≤±0.01%/°C (±100 ppm/°C) of full scale, 0 to 50°C (referenced to +12 V NIM bin).

**THRESHOLD NONLINEARITY** ≤±0.5% of full scale.

### CONTROLS (Front Panel)

**RANGE (ns)** Three-position rotary switch selects full scale time interval of 50, 100, or 200 ns between accepted Start and Stop input signals.

**MULTIPLIER** Five-position rotary switch extends time range by a multiplying factor of 1, 10, 100, 1K, or 10K.

**DELAY** 20-turn screwdriver-adjustable potentiometer varies the delay of the TAC and SCA outputs from 0.5 μs to 10.5 μs, relative to an accepted Stop input signal; operable in the Int Strobe mode only.

**STROBE MODE** Two-position locking toggle switch selects either Internal or External source for initiating the strobe cycle to strobe valid information from the TAC and SCA outputs.

**START GATE MODE** Two-position locking toggle switch selects Coincidence or Anticoincidence mode of operation for the Start circuitry. Start circuitry is enabled in the Coinc position or inhibited in the Anti position during the interval of a Start Gate input signal.

**STOP GATE MODE** Two-position locking toggle switch selects Coincidence or Anticoincidence mode of operation for the Stop circuitry. Stop circuitry is enabled in the Coinc position or inhibited in the Anti position during the interval of a Stop Gate input signal.

**SCA WINDOW (ΔT)** 10-turn precision locking potentiometer sets the SCA upper-level discriminator threshold from 0.05 V to 10.05 V above the Lower Level (T) setting.

**SCA LOWER LEVEL (T)** 10-turn precision locking potentiometer sets the SCA lower-level discriminator threshold from 0.05 V to 10.05 V.

**TAC INHIBIT** Two-position locking toggle switch. In the Inhibit position, the TAC output is available only if the output amplitude is within the SCA window. In the Out position, the SCA has no effect on the TAC output.

### CONTROLS (Rear Panel)

**EXT STROBE RESET** Two-position locking toggle switch allows the converter to be reset nominally 10 μs or 100 μs after an accepted Stop input signal if an Ext Strobe signal has not been received.

### INPUTS

All six front-panel inputs listed below are dc-coupled, edge-triggered, and printed wiring board (PWB) jumper selectable to accept either negative or positive NIM-standard signals. Input impedance is 50 Ω in the negative position and >1K in the positive position. The threshold is nominally −400 mV in the negative position and +2 V in the positive position.

**STROBE** Provides an external means to strobe a valid output signal from the TAC in the Ext Strobe mode. The input signal, exceeding threshold within the Ext Strobe Reset interval after the Stop input, initiates the read cycle for the linear gate to the TAC output. Factory-set in the positive input position. Ext Strobe Reset interval has a minimum value of ~0.5 μs and a maximum value of nominally 10 μs or 100 μs, switch-selectable on rear panel.

**START** Time conversion initiated when Start input signal exceeds threshold. Factory-set in negative input position.

**STOP** Time conversion terminated when Stop input signal exceeds threshold. Factory-set in negative input position.

**RESET/INHIB** Terminates conversion cycle and maintains reset condition, inhibiting further TAC conversions, for the duration of the reset cycle or the Reset/Inhib pulse, whichever is longer. A TAC output pulse in process at the time of a Reset/Inhib signal will be completed before converter reset is initiated. Factory-set in the positive input position.

**START GATE** Provides an external means of gating the Start circuitry in either Coincidence or Anticoincidence with the Start input signal. Start Gate input signal must cross threshold ≥10 ns prior to the Start input signal and overlap the trigger edge of the signal. Factory-set in the positive input position.

**STOP GATE** Provides an external means of gating the Stop circuitry in either Coincidence or Anticoincidence with the Stop input signal. Stop Gate input signal must cross threshold ≥10 ns prior to the Stop input signal and overlap the trigger edge of the signal. Factory-set in the positive input position.

### OUTPUTS

**TAC** Front- and rear-panel BNC connectors provide unipolar pulse.
**Amplitude** 0 to +10 V proportional to Start/Stop input time difference.
**Time** End of delay period in Int Strobe mode; prompt with Strobe input in Ext Strobe mode.
**Width** Adjustable by PWB potentiometer from 1 μs to 3 μs.
**Impedance** Front panel $Z_o$ <10 Ω; rear panel 93 Ω.
**Rise Time** ~250 ns.
**Fall Time** ~250 ns.

**VALID START** Rear-panel BNC connector provides NIM-standard slow positive logic level signal.
**Amplitude** Nominally +5 V. Complement signal selectable by PWB jumper.
**Time and Width** From accepted Start input to end of reset.
**Impedance** $Z_o$ <10 Ω.
**Rise Time** ≤50 ns.
**Fall Time** ≤50 ns.

**VALID CONV** Rear-panel BNC connector provides NIM-standard slow positive logic level signal to indicate a Valid Conversion.
**Amplitude** Nominally +5 V. Complement signal selectable by PWB jumper.
**Time and Width** From end of internal delay after Stop to end of reset.
**Impedance** $Z_o$ ≤10 Ω.
**Rise Time** ≤50 ns.
**Fall Time** ≤50 ns.

**SCA** Front- and rear-panel connectors provide NIM-standard slow positive logic level signals.
**Amplitude** Nominally +5 V. Complement signal selectable by PWB jumper.
**Time and Width** From start of TAC linear output to either end of reset or end of linear output, PWB selectable. Factory-set at end of reset.
**Impedance** $Z_o$ ≤10 Ω.
**Rise Time** ≤50 ns.
**Fall Time** ≤50 ns.

### ELECTRICAL AND MECHANICAL

**POWER REQUIRED** +24 V, 95 mA; +12 V, 210 mA; −24 V, 165 mA; −12 V, 330 mA.

**WEIGHT**
**Net** 1.4 kg (3 lb).
**Shipping** 3.2 kg (7 lb).

**DIMENSIONS** NIM-standard double-wide module 6.90 × 22.13 cm (2.70 × 8.714 in.) per TID-20893 (Rev).

## Ordering Information

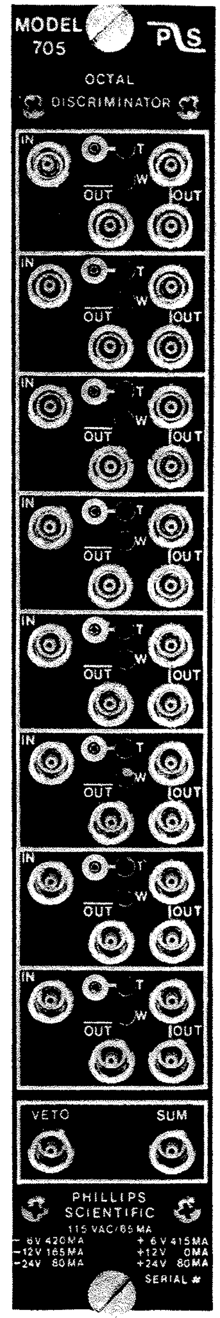
To order, specify:

| Model | Description |
|---|---|
| 567 | Time-to-Amplitude Converter/SCA |

# Phillips Scientific — Octal Discriminator — NIM MODEL 705

## FEATURES

- INDIVIDUAL THRESHOLD AND WIDTH CONTROLS
- LINEAR SUMMED OUTPUT
- BOTH FAST VETO AND BIN GATE
- LOW COST
- EIGHT (8) CHANNELS IN A SINGLE WIDTH NIM MODULE




## DESCRIPTION

The Model 705 was specifically designed for modern experiments with large counter arrays, offering high performance and reliability at a reasonable cost. The 705 features eight (8) totally independent channels with individual threshold and width controls. In addition, a fast veto input and a summed output are common to all channels.

Each channel has a threshold adjustment continuously variable from -10 mV to −1 Volt with a front panel test point providing a DC voltage ten (10) times the actual threshold setting. Likewise, each channel has a non-updating regeneration circuit for adjustable output widths from 6 nSEC to 150 nSEC.

A unique summed output is common to all eight channels providing −1 mA of current for each activated channel, thus allowing a fast decision to be made on the number of channels simultaneously hit. Up to 16 channels can be "OR'D" directly by cable to other summed outputs allowing a versatile scheme to form a trigger.

A fast veto input allows simultaneous inhibiting of all channels to reject unwanted events early in the system. Similarly, a bin gate will inhibit the entire module when applied via the rear connector.

The outputs are the current source type with one pair of negative bridged outputs and one complement for each channel. When only one output of the bridged pair is used, a double-amplitude NIM pulse (-32mA) is generated, when both connectors are used normal NIM levels (-16mA) are produced. The outputs have crisp, clean transitions, and their shapes are unaffected by the loading conditions of the other outputs.

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# INPUT CHARACTERISTICS

## General:

One LEMO connector input per channel; 50 ohms, ±1%, DC coupled; less than ±2% input reflection for a 2.0 nSEC input risetime. Input protection clamps at +.7 Volts and −5 Volts and can withstand ±2 amps for 1 μSEC with no damage to the input.

## Threshold:

-10 mV to −1 Volt; 15-turn screwdriver adjustment; better than ±0.2%/°C stability; front panel test point provides a DC voltage ten (10) times the actual threshold setting.

## Fast Veto:

One LEMO connector input common to all eight (8) channels; accepts normal NIM level pulse (−500 mV), 50 ohms, direct coupled; must precede the negative edge of input pulse by 5 nSEC; 5 nSEC minimum input width.

## Bin Gate:

Rear panel slide switch enables or disables slow bin gate in accordance with TID-20893.

# OUTPUT CHARACTERISTICS

## General:

Three LEMO connector outputs per channel; One negative bridged pair and one complementary output; The bridged outputs deliver -32mA into a single 50 ohm load (-1.6 volts), or -16mA (-800mV) when both outputs 50 ohm terminated. The complement is quiescently -16mA (-800mV) and goes to 0mA during output. The output rise and fall times are less than 1.5 nSEC from 10% to 90% levels.

## Width Control:

One control per channel; 15-turn screwdriver adjustment; outputs continuously variable from 6 nSEC to 150 nSEC non-updating ±.2%/°C stability.

## Summed Output:

One LEMO connector output common to all eight (8) channels; −1 mA output pulse (−50 mV into 50 ohms) for each channel fired. Output duration is equal to the output width setting of the respective channel. Output rise and fall times less than 2.5 nSEC into 50 ohms. Up to 16 channels can be directly "OR'D" by cable.

# GENERAL PERFORMANCE

## Continuous Repetition Rate:

Greater than 75 MHz, with output width set at minimum.

## Pulse-Pair Resolution:

Better than 12 nSEC, with output width set at minimum.

## Input to Output Delay:

Less than 9 nSEC.

## Multiple Pulsing:

One and only one output pulse regardless of input pulse amplitude or duration.

## Power Supply Requirements:

| | |
|---|---|
| − 6 Volts @ 420 mA | + 6 Volts @ 415 mA |
| −12 Volts @ 165 mA | +12 Volts @ 0 mA |
| −24 Volts @ 80 mA | +24 Volts @ 80 mA |

115 Volts AC @ 65 mA

**NOTE: All currents are within NIM specification limits permitting a full powered bin to be operated without overloading.**

## Operating Temperature:

0°C to 70°C ambient.

## Packaging:

Standard single width NIM module in accordance with TID-20893 and section ND-524.

## Quality Control:

Standard 36-hour, cycled burn-in with switched power cycles.

## Options:

Call Phillips Scientific to find out about available options.

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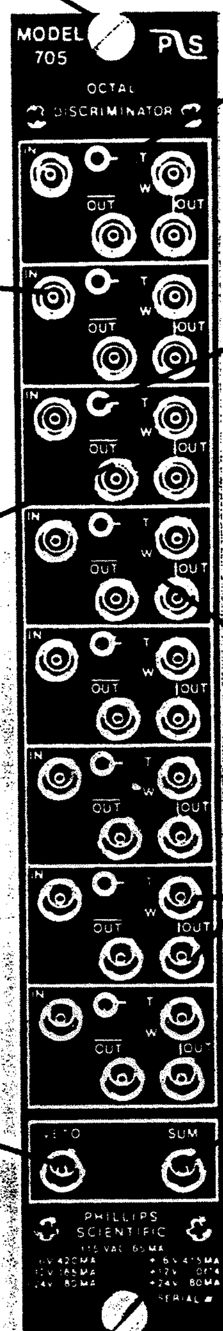
## MODEL 705 OCTAL DISCRIMINATOR

(FRONT PANEL DESCRIPTION)

Standard #1 NIM Packaging in accordance with TID-20893




Threshold Control; 15-turn Screwdriver Adjustment, Variable from -25 mV to -1 Volt

50 Ohm Input

Threshold Monitor; Test Point provides a DC Voltage 10 times the actual Threshold Setting (-250 mV to -10 V)

One Complemented NIM Output. Quiescently -16 mA (-800 mV) Goes to 0 mA (0 Volts) during output.

Output Width Control; 15-turn Screwdriver Adjustment, Variable from 6 nSec to 150 nSec.

Double amplitude bridged output; -32 mA (-1.6 Volts across 50 ohms, -.8 Volt with two 50 ohm terminations)

Fast Inhibit Input accepts normal NIM logic (-500 mV) 50 Ohm Impedance

Linear summed output; -1 mA/step. (-50 mV across 50 ohms)

Voltage and Current Requirements

NOTE: Bin Gate Enable/ Disable Switch on Rear Panel permits Inhibiting via Bin Connector.

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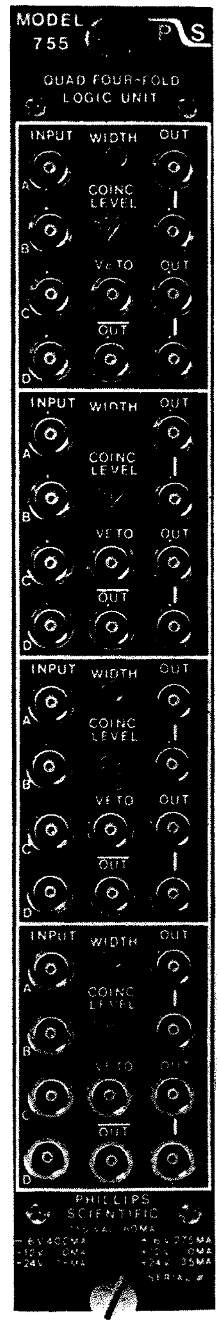
# Phillips Scientific

# Logic Unit

**NIM MODEL 755**

## FEATURES

- VERSATILE LOGIC MODULE WITH MAJORITY LEVEL SELECTION
- FOUR INDEPENDENT CHANNELS
- 125 MHz RATE CAPABILITY
- DEADTIMELESS UPDATING OUTPUTS
- FAST ANTI-COINCIDENCE CAPABILITY




## DESCRIPTION

The model 755 logic unit contains four channels of four input logic with veto in a single width NIM module. Logic AND, OR majority logic, fan-in/fan-out, and anti-coincidence functions can be performed with this versatile module. All functions are direct coupled and operate to over 125 MHz with input overlap times as narrow as 1 nSEC.

Each channel has four logic inputs, an anti-coincidence input, a coincidence level switch, and five outputs with common width control. The inputs are enabled by connecting the input cable to the desired input, eliminating errors often occuring with switched inputs. The setting of the coincidence level switch then determines whether a logic OR, AND, or majority logic function will produce an output.

After the inputs have satisfied the logic function desired, triggering of an updating regenerative stage produces a standardized output pulse, variable from 4 nSEC to 1 uSEC, independent of the input pulse shapes or overlap times. The updating feature ensures deadtimeless operation, while the double-pulse resolution is 7.5 nSEC for fast counting applications.

The outputs are the current source type with two pairs of negative bridged outputs and one complement for each channel. When only one output of a bridged pair is used, a double-amplitude NIM pulse (-32 mA) is generated for driving long cables with narrow pulse widths. The outputs have transition times of typically 1.0 nSEC, and their shapes are virtually unaffected by the loading conditions of the other outputs.

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# INPUT CHARACTERISTICS

**A, B, C, D:**

Four inputs per section, LEMO connectors; accepts NIM level logic signals (-500 mV); 50 ohm input impedance direct coupled; input reflections are less than ±5% for a 1 nSEC rise-time. Inputs are protected against damage from ±50 volt input transients. Inputs respond to a 1 nSEC or greater input width.

**Fast Veto:**

One input per section, LEMO connector; accepts NIM level logic signal (-500 mV); 50 ohm input impedance, direct coupled; less than ±5% input reflection for a 1 nSEC risetime, protected against damage ±50 volt input transients. Requires a 3.5 nSEC minimum input width in time with the input pulse leading edge to inhibit.

**Bin Gate:**

Rear-panel slide switch enables or disables the slow bin gate via the rear connector. Signal levels are in accordance with the TID-20893 standard.

# OUTPUT CHARACTERISTICS

**General:**

Five outputs per section, two pairs of negative bridged and one complemented NIM. The two pairs of bridged outputs are quiescently 0 mA and -32 mA during output. (-1.6 V into 50 ohms or -.8 V into 25 ohms). The complemented output is quiescently -16 mA and 0 mA during output. Risetimes and falltimes are less than 1.5 nSEC, and the output pulse shapes are optimized when the bridged outputs are 50 ohm terminated.

**Width Control:**

One control per section; 15-turn screwdriver adjustment. Outputs are continuously variable from 4 nSEC to 1 uSEC; better than 0.15%/°C.

**Updating Operation:**

The output pulse will be extended if a new input pulse occurs while the output is active. This provides deadtimeless operation and 100% duty cycle can be achieved.

# GENERAL PERFORMANCE

**Functions:**

Logic AND, OR, majority logic, and logic fan-in/fan-out. All functions have leading edge inhibit with standardized outputs.

**Rate:**

150 MHz minimum, input to output. Typically 160 MHz.

**Double-Pulse Resolution:**

Less than 6.5 nSEC; Typically 6 nSEC with output width set at minimum.

**Input to Output Delay:**

Less than 8 nSEC.

**Multiple Pulsing:**

One and only one output pulse regardless of input pulse amplitude or duration.

**Power Supply Requirements:**

| | |
|---|---|
| -6 V @ 400 mA | +6 V @ 250 mA |
| -12 V @ 165 mA | +12 V @ 0 mA |
| -24 V @ 60 mA | +24 V @ 35 mA |
| 115 VAC @ 60 mA | |

**Note: All currents within NIM specifications limits allowing a full-powered bin to be operated without overloading.**

**Operating Temperature:**

0°C to 70°C ambient.

**Packaging:**

Standard single width NIM module in accordance with TID-20893 and Section 524.

**Options:**

Call Phillips Scientific to find out about available options.

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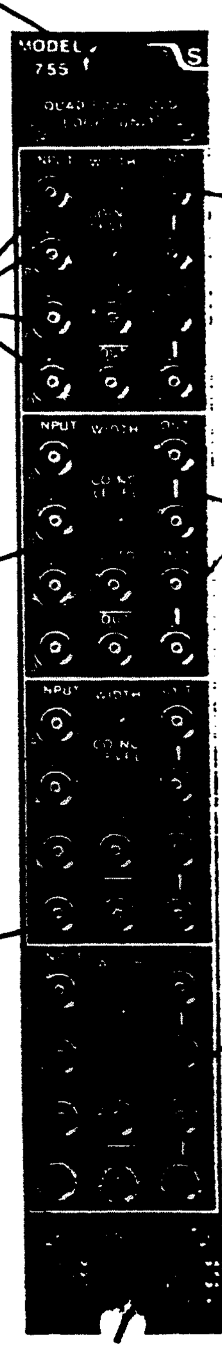
# MODEL 755 QUAD FOUR-FOLD MAJORITY LOGIC UNIT

(FRONT PANEL DESCRIPTION)

Standard #1 NIM Packaging in accordance with TID-20893




Output Width Control; 15-turn Screwdriver Adjustment, Variable from 4 nSec to 1 μSec.

Four Logic Inputs; Accepts Normal NIM Logic (-500 mV) 50 ohm Impedance

Two pairs of bridged outputs; each pair delivers -32 mA (-1.6 Volts across 50 ohms, -.8 Volt with both outputs 50 ohm terminated).

Four Position Coincidence Level Switch; Selects Logical "OR", "AND", or Majority Logic Functions.

One Complemented NIM Output. Quiescently -16 mA (-800 mV). Goes to 0 mA (0 Volts) during output.

Fast Inhibit Input accepts normal NIM Logic (-500 mV) 50 ohm Impedance

Voltage and Current Requirements

NOTE: Bin Gate Enable/Disable Switch on Rear Panel permits Inhibiting via Bin Connector.

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