OPTIMIZATION OF A STATE-OF-THE-ART POSITRON LIFETIME MEASUREMENT APPARATUS

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INTRODUCTION

Positron lifetime analysis techniques provide an effective and sensitive tool for the non-distructive study of solids and surfaces. The distribution of positron lifetimes can be related to the distribution of voids within a solid, to the state of the surface of a sample, and to the surface area of a sample of very fine powder.

One limitation on a positron lifetime measurement apparatus is its ultimate time resolution. Lifetimes on a nanosecond time scale are of interest which requires a system resolution in the order of several hundred picoseconds. The coincident gamma-rays of ^{60}Co are often used to characterize the timing performance.

This paper describes the optimization of a positron lifetime measurement apparatus for the Shanghai Metallurgical Institute. Proper adjustment of the apparatus yielded timing resolution of less than 180 ps measured with ^{60}Co and narrow energy windows.

THE POSITRON LIFETIME ANALYSIS TECHNIQUE

The positron, first predicted by Dirac, was experimentally identified in the 1930's. Besides its interesting properties as anti-matter, the positron has proven to be very useful in studying various structures and processes. Positron lifetime techniques are one of the few methods sensitive to vacancies on the monoatomic scale.

Historically, defect studies in metals have been a major application area for positron livetime techniques. In more recent years, this work has extended to defect studies in alloys and non-metals. In addition, some biological systems can now be studied with the aid of positrons. Chemical properties, such as the extent of cross linking of certain polymers and the specific surface areas of finely divided powders, also are being determined by the variation and range of positron lifetimes. The usefullness of positron characteristics also extends to Astrophysics where the characteristic 511 keV radiation of positron-electron annihilation has been observed from certain solar flares and from a source near the center of the Galaxy. The Proceedings of the International Conferences on Positron Annihilation show the wide range of application of this unique analytical tool[1,2].

EXPERIMENTAL TECHNIQUES

Several techniques other than lifetime measurements are used to study the properties of positrons and gain insight into void structures. The center-of-mass motion of the positron-electron pair produce a broadening in the line-width of the 511 keV annihilation gamma rays. This same motion also produces a deviation from collinearity in the direction of the two annihilation gamma-rays. These conditions form the basis of the Doppler-broadening and angular correlation experiments.

A Doppler broadening spectrometer generally consists of a germanium detector and associated electronics to acquire the spectrum in the energy range around 511 keV. While the Doppler-broadening spectrometer is insufficient for many detailed studies, its high counting efficiency and simplicity make it promising for nondestructive testing especially when the underlying processes are known[3].

The angular correlation of the two annihilation gamma-rays also depends on the momentum distribution of the positron-electron pair. This technique has been used in surface studies. However, the angles involved are very small, only a few milliradians, which requires that the detectors be placed some distance from the sample. This relatively large distance, several meters, requires unusually strong radioative sources which limit its application[3].

Because of the limitations of the Doppler broading and angular correlation experiment, the positron lifetime measurement technique is generally the perferred method of studying positrons and their interaction with surrounding media. The remainder of this paper will discuss this measurement and the optimization of the measurement apparatus.

POSITRON LIFETIME MEASUREMENT APPARATUS

The history of positron lifetime measurement apparatus is found in nuclear timing spectroscopy. The original technique used a Fast/Slow Timing Coincidence System. A newer system, the Fast Timing Coincidence System, was specifically developed for use in positron lifetime studies[4]. Both techniques are described below.

A. FAST/SLOW TIMING COINCIDENCE SYSTEM

A typical fast/slow timing system is shown in Fig. 1. An integral mode constant fraction discriminator, CFD, is used as the time pickoff device in each channel leading to the Time to Amplitude Converter, TAC. An energy side channel is associated with each detector and is composed of a preamplifier, a shaping amplifier, and a timing single-channel analyzer, TSCA. The function of the TSCA is to select the energy range for which timing information is desired. If two detected events fall within the selected energy ranges, and if they are coincident within the preset resolving time of the fast coincidence unit, the precise timing information related to these events is strobed from the TAC. The timing information is accumulated in the Multi-Channel Buffer, MCB, and displayed on the PC-350 Professional Computer[4].

In the fast/slow timing system, the dead time of the TAC can impose a count rate limitation. The TAC in Fig. 1 must handle the count rate associated with the single events exceeding the thresholds of the timing discriminators. This count rate can be greater than an order of magnitude higher than the coincidence rate at which the TAC is strobed. The dead time of the TAC can range from approximately 5 us to approximately 125 us, even for an invalid TAC start conversion[4].

The count rate performace of the linear side channel in a fast/slow timing system can impose a severe count rate limitation. Input data rates exceding 100,000 counts per second in the linear side channels can cause saturation in some charge preamplifiers. Also, many shaping amplifiers begin to lose baseline control at such count rates. These effects can result in erratic timing information from the TSCA's and a consequent loss in coincidence efficiency to strobe the TAC[4].

B. FAST TIMING COINCIDENCE SYSTEM

A block diagram of a fast timing coincidence system in shown in Fig. 2. The fast timing system performs the same function as the fast/slow system described above. In the fast timing system, each time pick-off unit is a constant fraction differential discriminator, CFDD, which generates the timing information and determines the energy range of interest simultaneously. If two detected events fall within the selected energy ranges, and if they are coincident within the preset resolving time of the fast coincident unit, the TAC is gated to accept only the delayed, precise timing pulses. Thus the TAC must handle start-stop signals only for events that are of the correct energy and are coincident[4].

C. PERFORMACE CHARACTERISTICS

Several important performace differences exist between the fast/slow and the fast timing systems. Because of the excellent performace of the modern preamplifier, amplifier and TSCA's, the fast/slow system is capable of excellent energy selection and resolution. However, the fast/slow system has much poorer high rate performace since the TAC must handle all start signals regardless of whether they represent valid events[4].

In contrast, the fast timing system has excellent high rate performace because only valid start-stop pulse pairs are processed by the TAC. The disadvantage of the fast timing system is its poorer energy selection and resolution since the PMT pulses are not processed to enhance their energy signal-to-noise ratio. At low count rates, both the fast/slow and the fast timing system have similar timing performace.[4]

Most positron lifetime measurement apparatus use small plastic scintillators and photomultiplier tubes as the detector element. This type of detector has poor energy reolution compared to large NaI(Tl) or HPGe detectors. Consequently, the relatively higher energy resolution of the fast/slow timing system offers little advantage. The fast timing system is the system of choice for most positron lifetime measurements.

OPTIMIZATION PROCEDURES

Optimization of a positron lifetime measurement apparatus involves both timing and energy performance. The detector element, consisting of the scintillator, PMT, PMT base and high voltage power supply, are of critical importance. Proper optimization of the constant fraction discriminator and energy calibration are also important. An optimization procedure is described below.

A. Optimization of the Detector Element.

The detector element consists of the scintillator, the photomultiplier tube , PMT, the PMT base, and high voltage supply. The optimal use of each component is important in achieving the best overall timing performace of the positron lifetime measurement apparatus.

1. Scintillator Selection.

In addition to the basic scintillator material, the size, shape and coating are of importance. Many fast plastic materials have been used in positron lifetime experiments. One popular type was origionally marketed as Pilot U. The same formulation is available today as BC 418. NE 111 and BC 422 are also popular material. KL 236 has also found application in many positron lifetime systems. The principle characteristic of all these materials is their very fast rise and fast decay times. In a good timing system, the rise time of the signal is of extreme importance.

Traditionally, the shape of the scintillator was a right circular cylinder of various dimensions with 2.5 x 2.5 cm a popular size. NE 111 and BC 422 often have a 2.5 cm diameter but a smaller height, about 2 cm. Several years ago, John McGervy reported on the improved timing performace of a truncated cone geometry[5]. Several versions of the picosecond timing spectrometer described in the paper verify this result. Improvements in timing resolution FWHM exceeding 10% were achieved using truncated cones instead of right circular cylinders of the same volume.

Plastic scintillators are generally clear in color and are usually coated with a white reflector paint to improve efficiency. Typical coating material includes NE 560 and BC 620 white reflector paint.

2. PMT Selection.

Many PMT's have been used in positron lifetime measurements. Principle suppliers include RCA, Phillips, Hamamatsu, and EMI. Our experience at EG&G ORTEC is primarily with the RCA 8575 and 8850 PMT's. New PMTs with microchannel plates and special cross field arrangements also find application.

3. Scintillator Mounting.

Special care must be taken in mounting the scintillator to the face of the PMT. Both the surface of the PMT and the base of the scintillator should be very clean and free of dust and lint. A thin layer of optical coupling compond, such as Dow Corning Q2-3067, is applied to the scintillator base. The scintillator is pressed firmly onto the PMT face and rotated back and forth to remove any air bubbles.

4. PMT Base.

PMT base is an important part of the detector assembly as it distributes the high voltage to the various dynodes and couples the anode signal from the PMT to the timing electroncis. In general, each PMT has a different divider string for optimal timing performance. The EG&G ORTEC 265 is optimized for the RCA 8575 and the EG&G ORTEC 265S is optimized for the RCA 8850. Both PMT bases are designed to faithfully preserve the anode signal waveform for optimal timing performance.

The EG&G ORTEC PMT bases are equiped with both a GAIN and a FOCUS adjustment. For optimal operation, both are adjusted to maximize the anode output signal.

5. High Voltage.

The first rule in high voltage adjustment is to not saturate the PMT. The high voltage setting is an effective way to control the gain of the PMT and in turn the signal-to-noise ratio. Typical settings for the RCA 8575 and 8850 PMTs is -2000 V. Generally, the high voltage in a positron lifetime spectrometer is adjusted such that the maximum anode signal into a 50 ohm load is about -1.5 V for ^{22}Na or ^{60}Co.

B. Optimization of the CFDD,

The principle adjustments in a CFDD are the WALK, the CF DELAY, the BLOCKING WIDTH, and the UPPER and LOWER LEVEL thresholds. The initial settings for the EG&G ORTEC 583 CFDD are easily made. Final optimization requires experimental adjustment using the complete timing spectrometer. Threshold adjustments are described in a later section.

The initial walk adjustment is to set the potentiometer such that the WALK test point reads about -0.5 mV. After final experimental adjustment, the walk setting should not exceed the range +/- 5 mV.

One very useful method of checking the WALK adjustment is to view the MONITOR signal on a fast oscilloscope which is triggered by the 583 CFDD timing output signal. The MONITOR signal should be delayed slightly with a length of coaxial cable to compensate for the propagation delay of the unit. The resulting signals are shown in Fig. 3. Note the precise cross-over signal definition of the MONITOR output which indicates excellent timing and good WALK adjustment.

The initial CF DELAY setting depends on the rise time of the input signal and is calculated as

$$\text{CF DELAY} = (1.1)(\text{Rise Time}) - 0.7 \text{ ns} \qquad (1)$$

For example, a PMT with a rise time of 2.2 ns requires a delay of about 1.72 ns. Using 50 ohm coaxial cable with a propogation delay of 50 ps/cm corresponds to a cable length of approximately 35 cm. This is the typical length required for an RCA 8850. However, the CF DELAY is a critical adjustment for the timing spectrometer and extensive experimental adjustment is suggested to achieve optimal timing results. Cable length adjustments in 2 cm steps are recommended when seeking the minimum timing resolution of the system.

The BLOCKING WIDTH is another front panel adjustment of the 583 CFDD. This width, read with an oscilloscope connected to the front panel BNC connector, indicates the deadtime of the unit. No additional outputs can be generated by the 583 CFDD during this period. Initial setting of the BLOCKING WIDTH is about 500 ns or a time equal to the maximum conversion time of the TAC.

C. INITIAL SYSTEM SETTINGS

Several other initial settings are required prior to operation of the Fast Timing System. The Fast Coincidence unit can be set from 10 to 110 ns with 20 ns a good initial value.

The TAC range must be set consistent with the expected range of positron livetimes to be measured. For initial system resolution measurement, the 100 ns range is acceptable. This setting corresponds to approximately 12.5 ps/ch using the 8000 channel 918 Multichannel Buffer.

The passive delay unit DB463 is set to compensate for the propagation delay of the Fast Coincidence unit and to insure that the TAC operates in a very linear range. Two of the four sections are used in the Start channel and two of the four sections are used in the Stop channel. Initial setting of the total Start delay is approximately 64 ns and initial setting of the total Stop delay is approximately 96 ns.

Initial settings of the ADCAM system are minimal. Generally, the 918 MCB is operated with all 8000 channels. The link between the 918 MCB and the PC-350 Professional Computer can be with RS-232 or IEEE-488.

CALIBRATION PROCEDURES

The Positron Lifetime Measurement Apparatus must be calibrated in both energy and time for proper operation. Both procedures are described below.

A. ENERGY CALIBRATION

The principle difficulty with energy calibration is the rather poor energy resolution of the scintillator/PMT detector. A block diagram of the system connected for energy calibration is shown in Fig. 4. Note the addition of a preamplifier and amplifier connected to the dynode output of the PMT base. The energy spectrum collected in the 918 MCB is gated by the timing channel, either the Start channel or the Stop channel, which ever is being calibrated. The gating signal is taken from the VALID START output of the TAC, a signal that begins with the START input and remains true through the entire conversion time of the TAC. In this test, the conversion time is increased from 100 ns to about 10 us to insure a gating signal of adequate length. The 918 MCB must be set in the Coincidence Mode which requires removing the right side panel of the unit and moving the MODE jumper.

An energy spectrum for ^{22}Na is shown in Fig. 5. This spectrum is collected with the Start 583 CFDD Lower Level set at minimum value and the Upper Level set at maximum value. ^{22}Na has characteristic lines at 1.28 MeV and 511 keV. However, the small plastic scintillator does not respond to the photo peaks and the Comption edge values must be used. Table 1 lists the photo peak and Compton edge values for ^{22}Na and ^{60}Co.

In Fig. 5, the Compton edge of the 511 keV line can be found by taking the mean count value between A and B. The corresponding channel is labeled E_1 and corresponds to 340 keV. Dividing 340 keV by E_1 gives the calibration in keV/channel. This value can be verified using the second ^{22}Na line at 1.28 MeV. The channel corresponding to the Compton edge is labeled E_2 in Fig. 5, and the corresponding energy is 1062 keV. The calibration value $1062/E_2$ keV/channel should equal $340/E_1$.

Next the Lower Level of the CFDD is raised to nominally -800 mV. The resulting energy spectrum is shown in Fig. 6. The Lower Level should be set so that the lower edge of the spectrum falls midway between the two Compton edges. The mean count value in the Compton region is indicated by C in Fig. 6, and the Lower Level value is equal to channel E_3 corresponding to a count value of C/2. Multiply channel E_3 by the keV/channel calibration obtained above for the energy equivalent of the CFDD Lower Level setting. This energy divided by the threshold setting gives the Lower Level calibration in keV/mV.

Calibration of the Upper Level of the Start CFDD follows the same procedure. First the Lower Level is reduced to a minimum value. Then the Upper Level is adjusted to nominally -800 mV and the calibration in keV/mV is found. However, due to the similarity of the two circuits, the calibration value of the Lower Level is usually identical to the calibration value of the Upper Level.

The procedure outlined above is also used to calibrate the Stop channel CFDD. First, the Start CFDD Timing output is disconnected from the START input on the TAC and replaced by the Stop CFDD Timing output. Thus the TAC VALID START output, which is used to gate the 918 MCB, will be derived from the Stop CFDD. A ^{22}Na spectrum is collected with the Stop CFDD Lower Level set at minimum value and the Upper Level set at maximum value. Using the procedure outlined above and indicated in Fig. 5, a calibration in keV/channel is obtained. Raise the Lower Level of the Stop CFDD and obtain a spectrum similar to that shown in Fig. 6. Convert channel E_3 into keV and divide by the Lower Level setting to obtain the required keV/mV calibration. This calibration value can be used for both the Lower Level and the Upper Level controls of the Stop CFDD.

B. TIME CALIBRATION

A block diagram of the system setup for time calibration is shown in Fig. 7. The preamplifier and amplifier used in energy calibration are removed. The TAC is reset to a 100 ns range and the 918 MCB is set in the anti-coincidence mode. During time calibration, only the Start CFDD will be used. Both TIMING outputs of the Start CFDD are connected through the DB463 to the TAC. A very narrow timing peak should occur at the time corresponding to the difference between the Start channel DB463 setting and the Stop channel DB463 setting. Based on the initial settings of 64 and 96 ns, the timing peak should occur near the channel associated with 32 ns. With the TAC set at 100 ns full scale, the timing peak should occur at approximately 1/3 full scale.

Next, a precise value of delay is introduced into either the Start channel or the Stop channel. This is easily done by changing the DB463 setting. For best results, change the 1 ns, 2 ns, and 4 ns settings of each of the four sections of the DB463 to obtain a good average value of time calibration in ps/ch. A very good approximation of the time calibration is simply the maximum time range divided by the number of channels or

$$(100\ \text{ns})/(8000\ \text{channels}) = 12.5\ \text{ps/ch} \qquad (2)$$

FAST TIMING SYSTEM PERFORMANCE

Once the Fast Timing System is calibrated, the experiment of interest can be performed. This section describes the system performance using the coincident gamma-rays of ^{60}Co to test the timing system resolution. Note that this is not a positron lifetime measurement but rather a system calibration experiment.

A. ENERGY CALIBRATION

First step in the timing experiment is to set the Lower Level and Upper Level of both the Start and Stop CFDD. The Start CFDD is set to bracket the Compton edge of the 1.33 Mev line and the Stop CFDD is set to bracket the Compton edge of the 1.17 MeV line. The corresponding Compton edges are given in Table 1 as 1.12 and 0.96 MeV. The Start Lower Level is set at 1.05 MeV and the Upper Level is set at 1.15 MeV. The Stop Lower Level is set at 0.90 MeV and the Upper Level is set at 1.00 MeV.

To insure proper settings, the system was reconfigured as shown in Fig. 4 and the energy spectrum, both gated and ungated, was recorded. The ^{60}Co spectrum for the Start channel with the Lower Level set at minimum and the Upper Level set at maximum is shown in Fig. 8. The ^{60}Co spectrum gated by the Start CFDD set for the energy range 1.05 to 1.15 MeV is shown in Fig. 9. The ^{60}Co spectrum gated by the Stop CFDD set for the energy range 0.90 to 1.00 MeV is shown in Fig. 10. Note that a separate ungated spectrum must be taken for both the Start channel and the Stop channel if the gain of the two channels are not identical.

B. TIMING PERFORMANCE

A typical timing spectrum obtained with the Shanghai Metallurgical Institute Positron Lifetime Measurement Apparatus is shown in Fig. 11. The Start energy range was 1050-1150 keV and the Stop energy range was 900-1000 keV. The FWHM value of 155.60 ps and FWTM value of 339.30 ps represent nearly the best values obtained at the EG&G ORTEC timing laboratory. Numerous other experiments indicated that 180 ps FWHM represents a typical value for this system measured in the EG&G ORTEC laboratory environment. Specific values and setting for this experiment are given in Table 2.

Additional tests were conducted on site at the Shanghai Metallurgical Institute. The spectra is shown in Figs. 12 and 13. In Fig. 12, the Start energy range is 800-1150 keV and the

Stop energy range is 700-1000 keV. The resulting timing resolution was 164.60 ps FWHM and 307.47 ps FWTM. In Fig. 13, the Start energy range is 700-1000 keV and the Stop energy range is 240-340 keV. The resulting timing resolution was 221.60 ps FWHM and 424.65 ps FWTM. ^{60}Co was the excitation source for both tests. All other setting are the same as listed in Table 2.

CONCLUSIONS

Optimization of a Positron Lifetime Measurement Apparatus requires care and proper selection of all major components. Scintillator size and shape, type of PMT and PMT base, and high voltage settings are all important. A major adjustment is the CF DELAY for the 583 Constant Fraction Differential Discriminator. Special care must be taken with all cables to reduce ground loop and stray coupling effects. Sources of high electromagnetic radiation must be avoided or shielded against. A stable Time-to-Amplitude Converter and ADC are needed. The ADCAM approach, which incorporates the power of the Personal Computer into the system, is ideal for both data acquisition and later manipulation.

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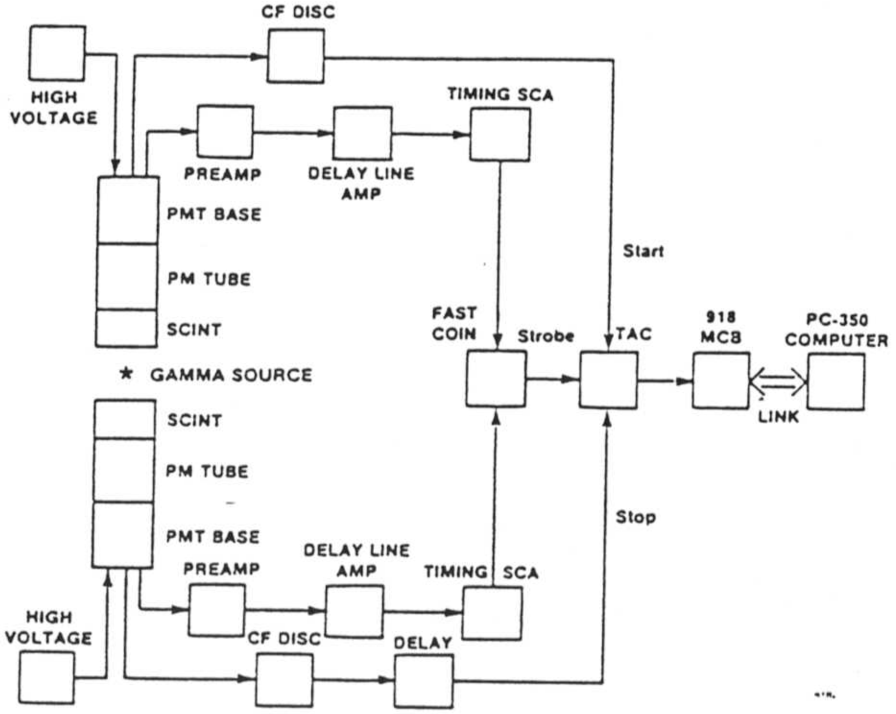


Fig. 1. Typical Fast/Slow System for Gamma-Gamma Coincidence Measurements with Scintillators and Photomultiplier Tubes.

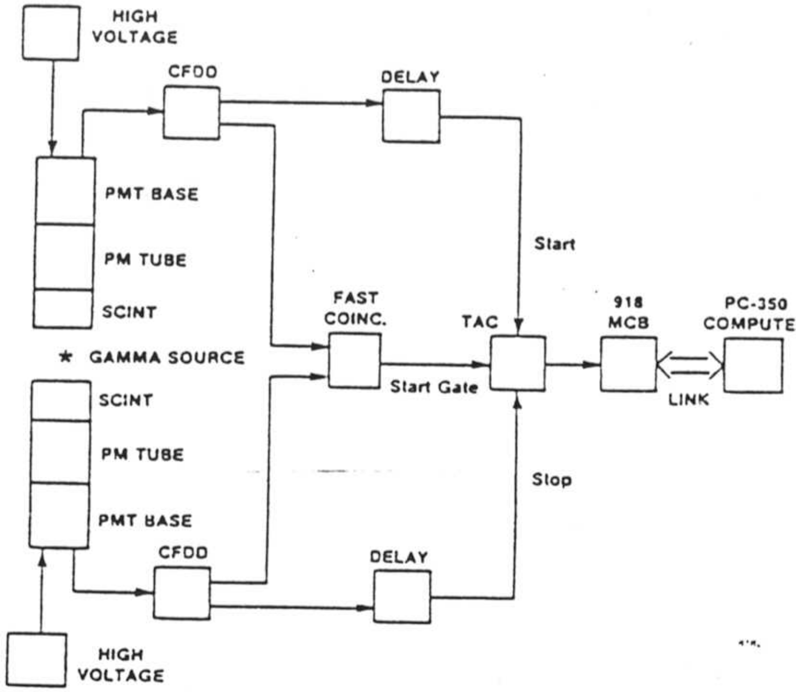


Fig. 2. A Fast Coincidence System for Gamma-Gamma Coincidence Measurements with Scintillators and Photomultiplier Tubes.

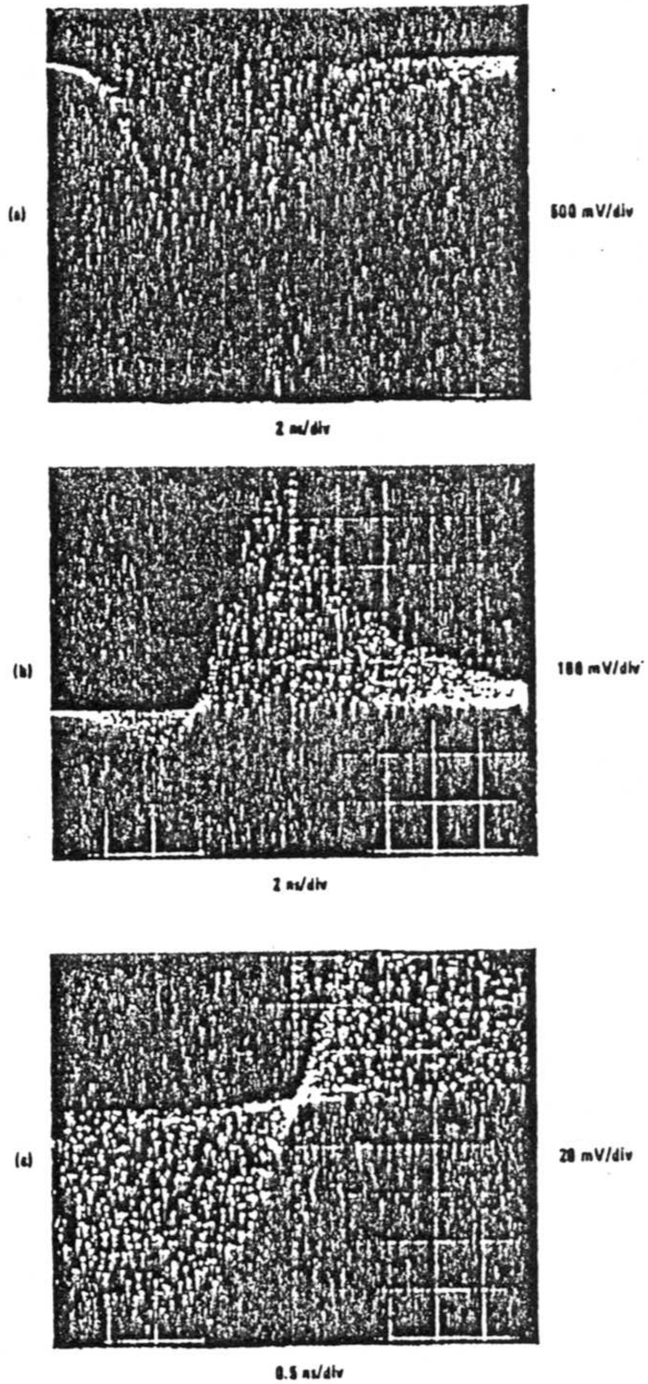


Fig. 3. RCA 8850 PMT Anode Signal, 583 CFDD Monitor Signal, and Expanded View of Monitor Signal.

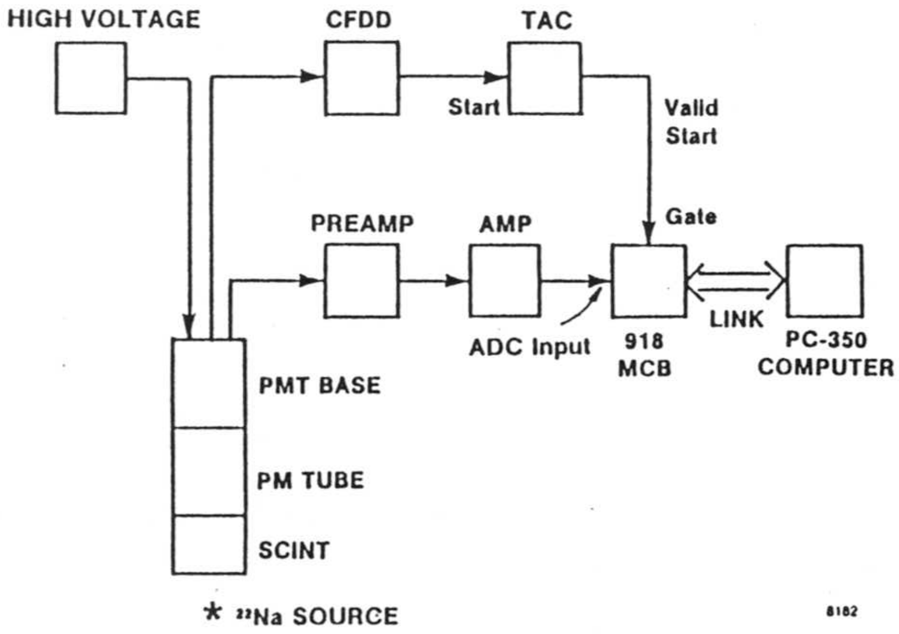


Fig. 4. A Block Diagram for Energy Calibration.

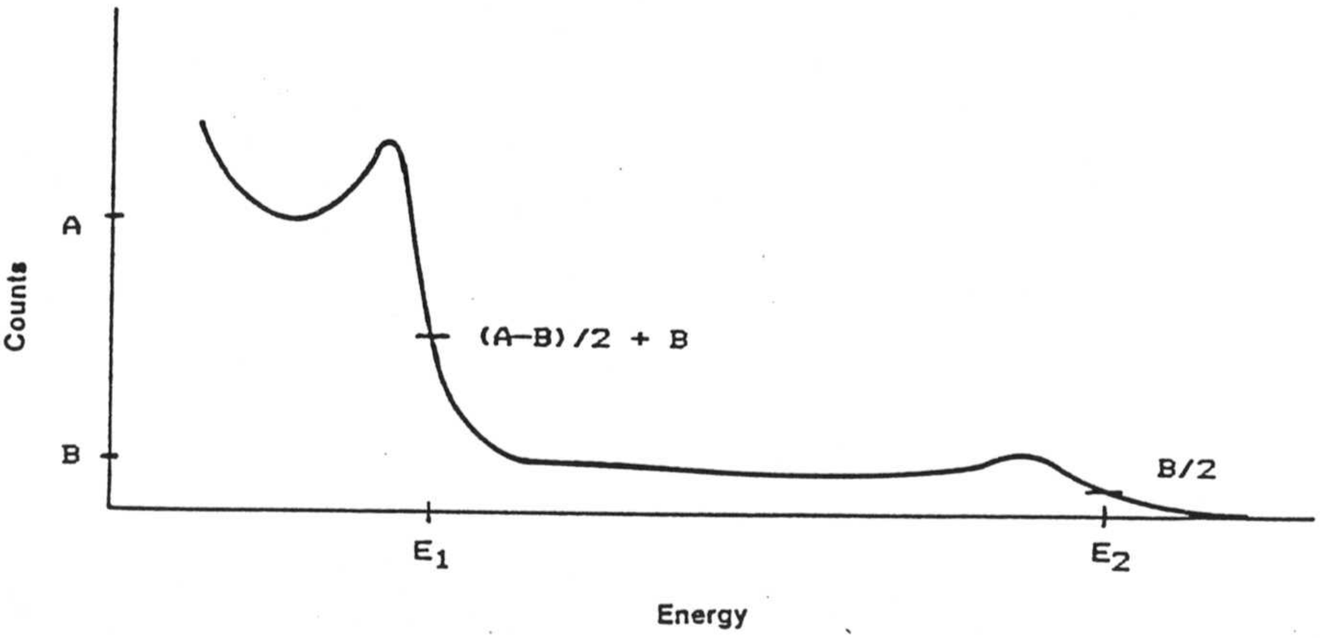


Fig. 5. Linear Energy Spectum for ^{22}Na with Low Threshold Setting.

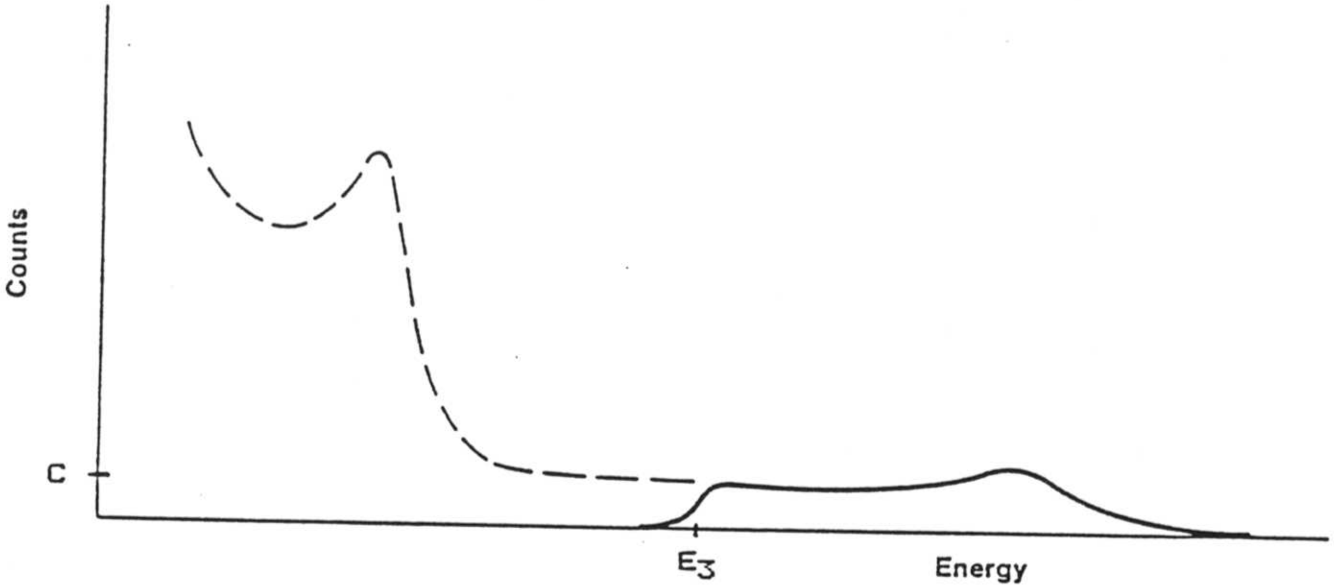


Fig. 6. Linear Energy Spectrum for ^{22}Na with Elevated Threshold Setting.

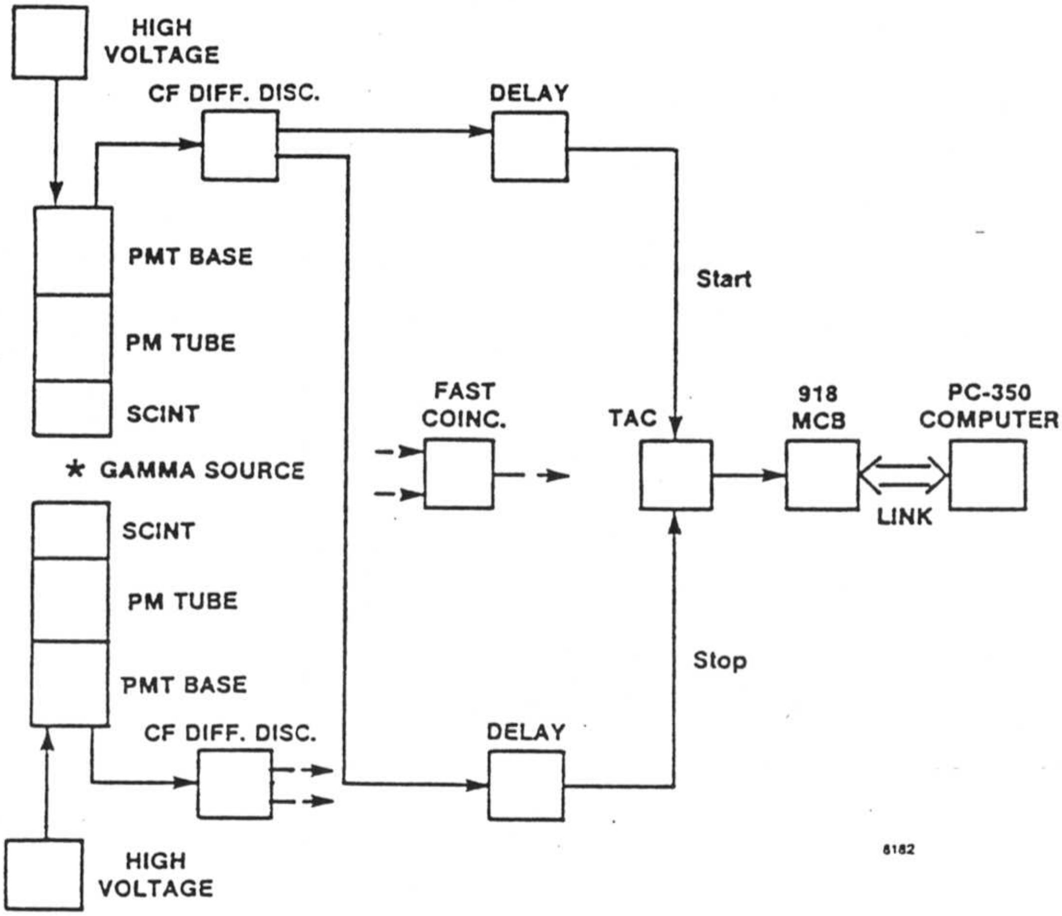


Fig. 7. A Block Diagram for Time Calibration.

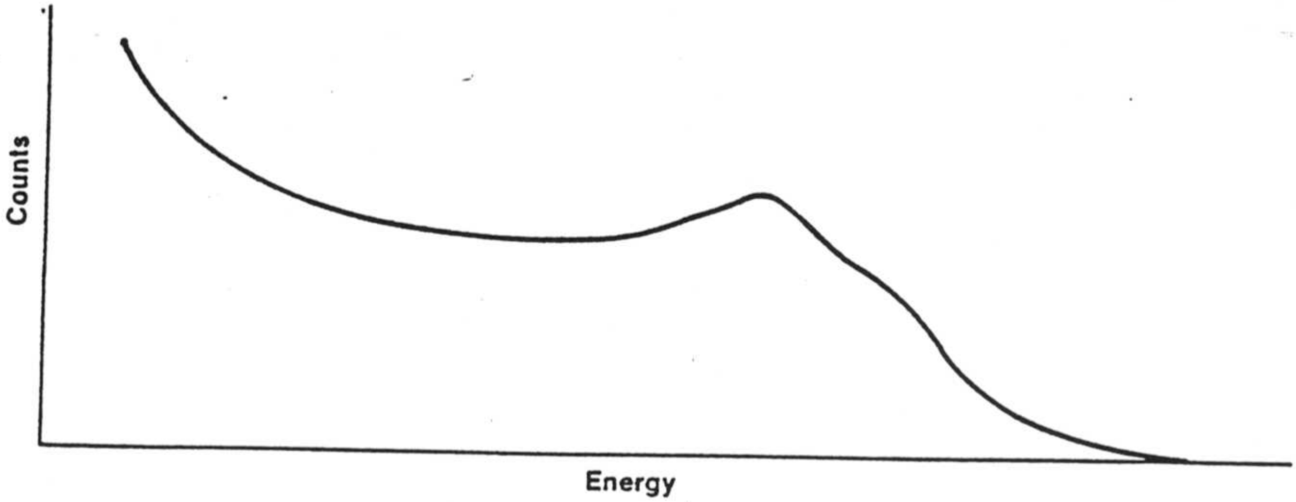


Fig. 8. Linear Energy Spectrum for ^{60}Co With Low Threshold Setting

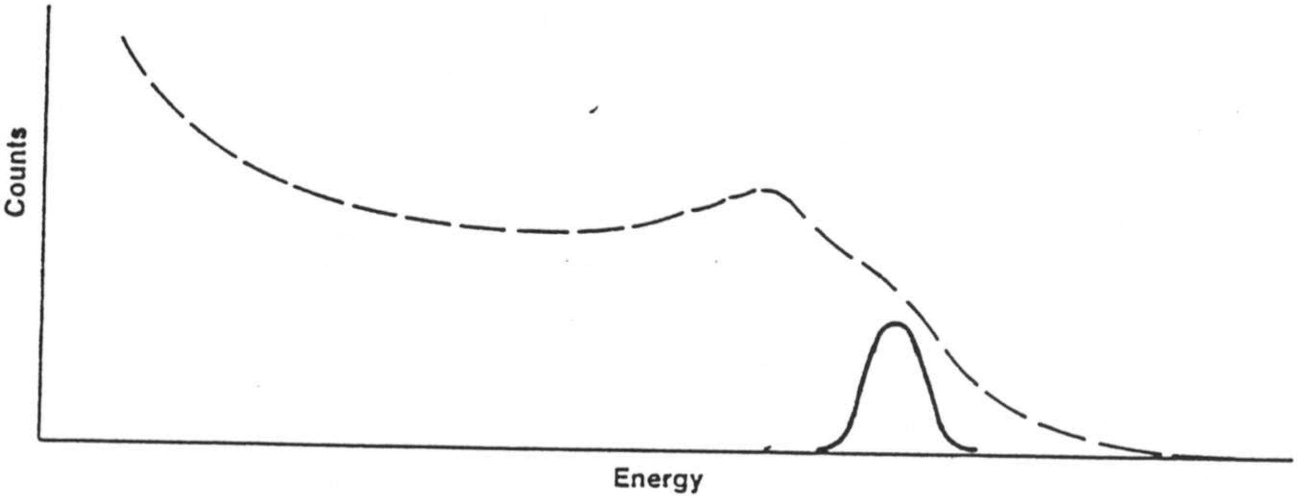


Fig. 9. Linear Energy Spectrum for ^{60}Co Gated by the Start CFDD. Energy Range of 1050 – 1150 keV.

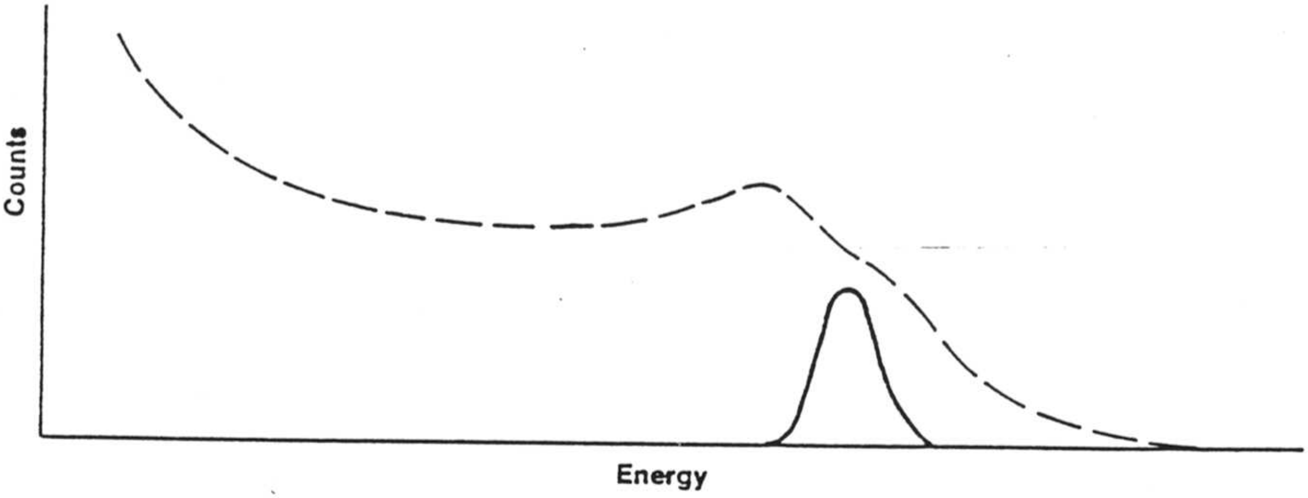
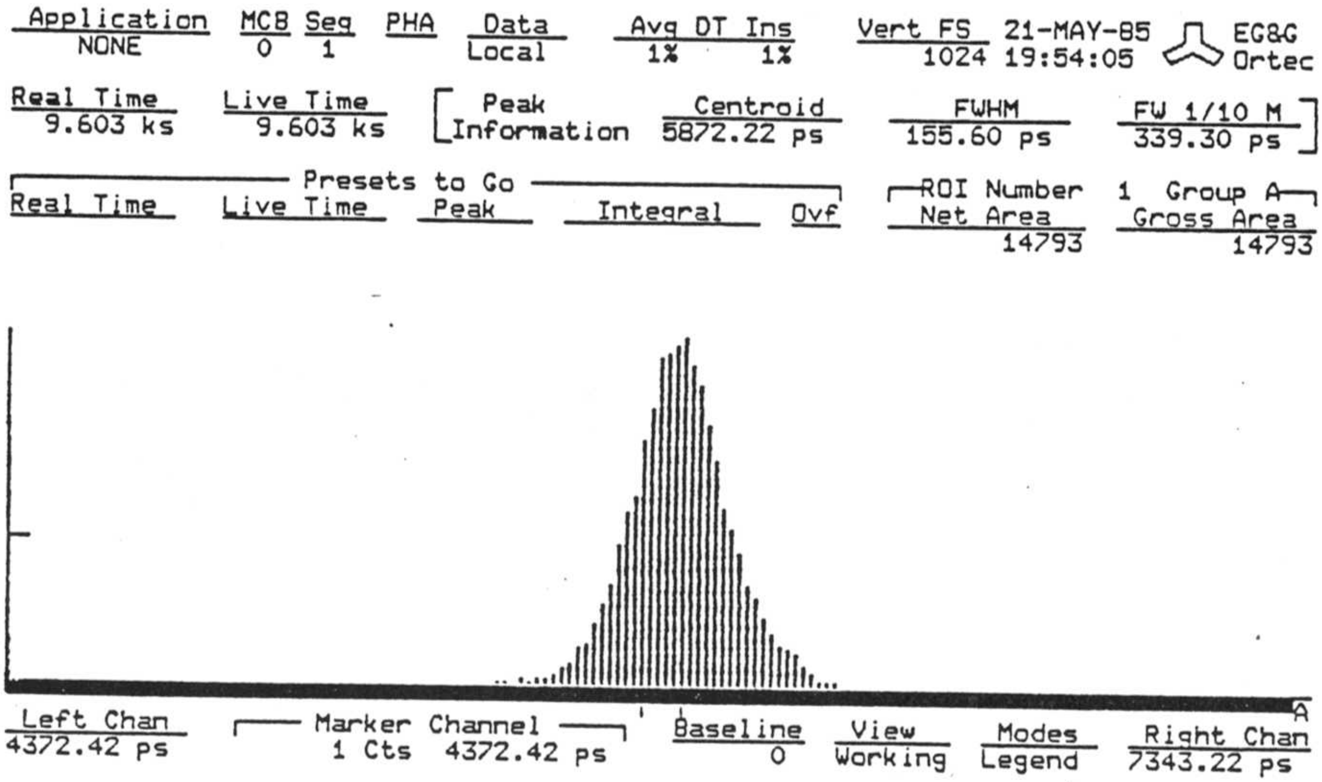


Fig. 10. Linear Energy Spectrum for ^{60}Co Gated by the Stop CFDD. Energy Range of 900 – 1000 keV.



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FW 1/10 M 339.30 ps

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Fig. 11. Timing Spectrum for ^{60}Co with Narrow Energy Windows.

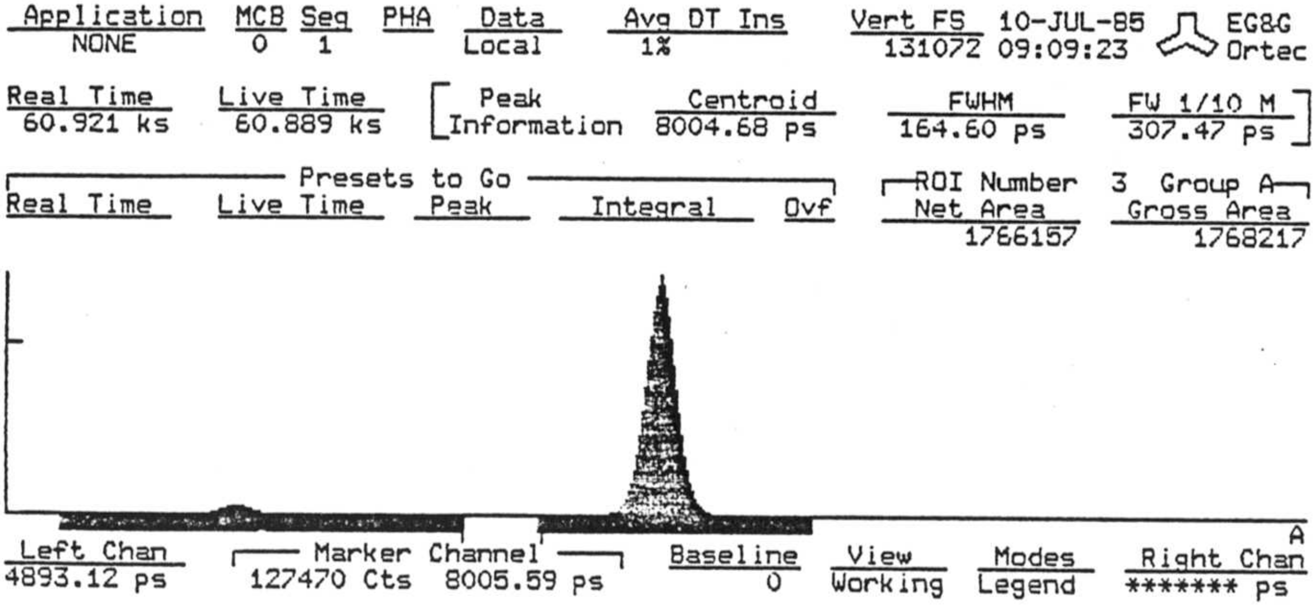

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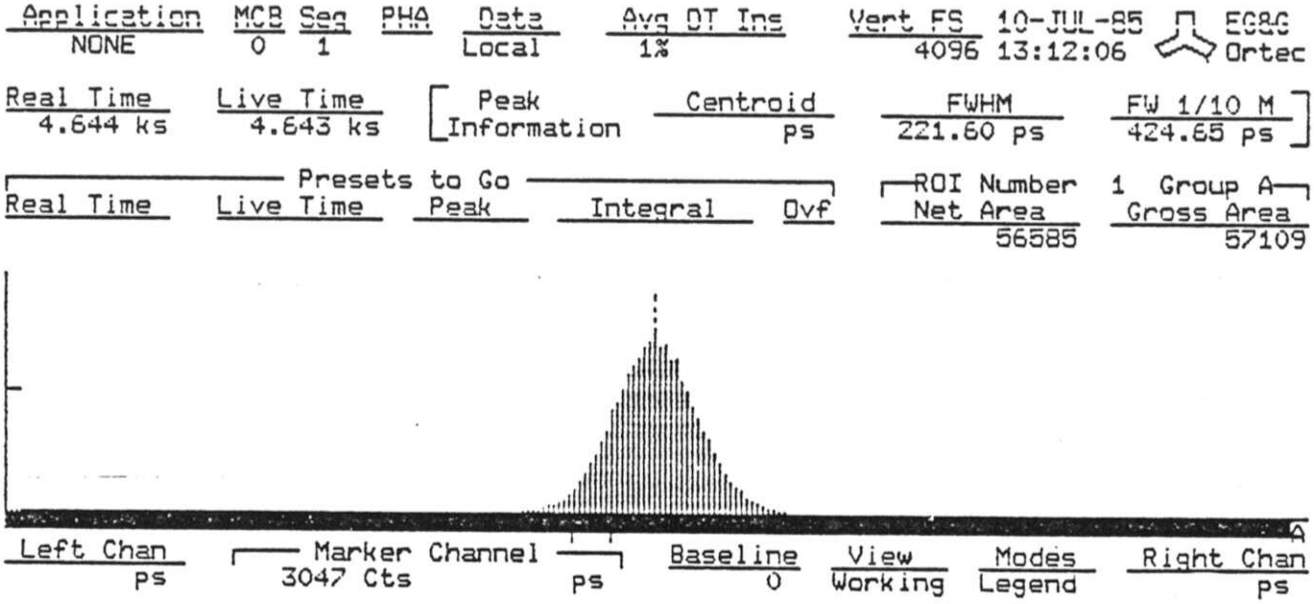
Fig. 12. Timing Spectrum for ^{60}Co with a Start Energy Range of 800-1150 keV and a Stop Energy Range of 700-1000 keV.



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                                                            56585         57109

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Left Chan     [-- Marker Channel --]           Baseline   View     Modes   Right Chan
       ps      3047 Cts          ps                  0    Working  Legend          ps
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Fig. 13. Timing Spectrum for ^{60}Co with a Start Energy Range of 700-1000 keV and a Stop Energy Range of 240-340 keV.

TABLE 1. PHOTO PEAK AND COMPTON EDGE CORRESPONDANCE

SOURCE	PHOTO PEAK	COMPTON EDGE
^{22}Na	1.28 MeV	1062 keV
	511 keV	340 keV
^{60}Co	1.33 MeV	1.12 MeV
	1.17 MeV	0.96 MeV

Table 2. Timing System Configuration for Timing Spectra Shown in Fig. 11.

Source: ^{60}Co, Approx. 50 uC
Start Channel:
Scintillator: BC418 (Pilot U), 12.9 cc truncated cone
PMT: RCA 8850
BASE: EG&G ORTEC 265-S with 218 Shield
High Voltage: EG&G ORTEC 556, -2100 V
EG&G ORTEC 583 CFDD
Lower Level: 1050 keV
Upper Level: 1150 keV
CF DELAY: 35.5 cm
EG&G ORTEC DB463 Delay Box(1/2): 64 ns
Stop Channel:
Scintillator: BC418 (Pilot U), 12.9 cc truncated cone
PMT: RCA 8850
BASE: EG&G ORTEC 265-S with 218 Shield
High Voltage: EG&G ORTEC 556, -2080 V
EG&G ORTEC 583 CFDD
Lower Level: 900 keV
Upper Level: 1000 keV
CF DELAY: 35.5 cm
EG&G ORTEC DB463 Delay Box(1/2): 96 ns
Coincidence Unit:
EG&G ORTEC 414A, 20 ns
Time-to-Amplitude Converter
EG&G ORTEC 566, 100 ns range, 12.5 ps/ch
Data Acquisition System
ADCAM consisting of EG&G ORTEC 918 MCB and DEC PC-350 with 512 kbytes RAM, dual floppy disks, 1 M byte hard disk, color monitor, LA-50 printer.