Radiation Physics Note #76
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MOBILE ENVIRONMENTAL RADIATION MONITORING

The intensity of both neutron and muon radiation fields on- and off-site are monitored by detectors mounted in a Mobile Environmental Radiation Laboratory (MERL).

I. Muons

A. Detector and Electronics

The detector consists of a pair of 0.64 cm thick plastic scintillator paddles with transverse dimensions of 20.32 cm by 20.32 cm. The paddles are separated by 15 cm with a 2.54 cm thick aluminum plate placed in the gap to remove knock-on electrons. These counters are mounted in the vehicle usually at a height of 1.2 meters above the ground and oriented so that the muons are approximately at normal incidence. Standard electronic modules are used to record on scalers both singles and coincident events.

Figure 1 shows a block diagram of the electronics. Pulses from events within the scintillators pass through the photo-multiplier tube bases into fast discriminators. Standard NIM logic pulses at the output of the discriminators for each paddle are sent into a coincidence unit and into scalers. Both singles and coincidence events are recorded. The scalers are gated on during both beam-on (usually a 23-sec beam spill time during fixed target running) and beam-off (for background determination) periods in synchronization with the TEVATRON accelerator cycle.

B. Setup and Calibration

Photo-multiplier tube gains and discriminator threshold levels are setup by measurements in a "known" muon radiation field. This is usually at a site location directly in back of one of the experimental halls. Pulses from each scintillator pass into a linear amplifier and then to a multichannel analyzer (MCA) gated by the output from the discriminators. Figure 2 displays typical gain-matched threshold-gated pulse height spectra for the two paddles S1 and S2, showing the peaks associated with high-energy minimum ionizing muons. In order to match the gain of the two detectors, the high voltage to the phototubes is varied separately for each scintillator paddle. The threshold discriminators are set to correspond to pulse heights in the "valley" below the muon peak and above electronics noise.

Two scintillator paddles operated in coincidence serve to distinguish muons from other radiation, and, where the fluence is small, provide a more sensitive measure of their presence than do the individual singles rates. However, under conditions in which there are no other components of the radiation field for which the plastic scintillator has a finite efficiency, the singles rate provides a better measure of muon flux. This is because the coincidence rate depends upon the direction and divergence of the incident beam. For a broad, parallel beam incident normal to the scintillators, the ratio of coincidence-to-singles-rates should be close to unity. For a non-parallel beam, or one that is not incident normally, the ratio will be less than one and can vary depending on the divergence in the muon trajectories. See Appendix B for a simplified explanation of the variation of coincidence efficiency with muon direction. Appendix A provides a semi-quantitative estimate of the efficiency of a plastic scintillation counter assembly to an incident muon.

C. Measurements

Measurements of muon fluence are performed by scanning across the muon radiation field with the MERL on a line approximately normal to an extension of the beam line associated with muon production. Detector counts are generally recorded for at least two beam spills at each position along a scan at each location. Primary proton beam intensity for each beam spill is obtained from secondary emission beam intensity monitors (SEM) upstream of the target stations in each beam line and relayed to the MERL through a telemetry system.

D. References

These references describe the experimental procedures used in muon radiation surveys in more detail.

1. A.J. Elwyn and W.S. Freeman, "Muon Fluence Measurements at 800 GeV," Fermilab Report TM-1288 (November 1984).

2. A.J. Elwyn, "Muon Fluence Measurements at the Site Boundary for 1985," Fermilab Report TM-1394 (March, 1986).

3. A.J. Elwyn and W.S. Freeman, "Muon Fluence Measurements During the 1987-1988 Fixed-Target Run," Fermilab Report TM-1518 (April 1, 1988).

4. A.J. Elwyn, J.D. Cossairt and W.S. Freeman, "The Monitoring of Accelerator-Produced Muons at Fermilab," Proc. of the 22nd Midyear Topical Meeting on Instrumentation of the Health Physics Society, page 152 (San Antonio, TX, December 1988).

5. J.D. Cossairt, A.J. Elwyn, and W.S. Freeman, "A Study of the Transport of High Energy Muons Through a Soil Shield at the TEVATRON," Fermilab Report Pub 88/147 (October 1988) and Nucl. Instr. Methods (to be published).

II. Neutron Intensity Measurements

A. Detector and Electronics

The DePangher Long Counter is the primary instrument used for environmental fast neutron detection. The neutron efficiency is approximately constant with energy up to about 10 MeV and then rapidly decreases, and the detector is relatively insensitive to gamma and muon radiation. In this device, a BF_3 tube with gas enriched to 96% in ^{10}B, operated as a proportional counter, is placed at the center of a specially designed cylindrical polyethylene moderator. Thermal neutrons interact with the ^{10}B through the ^{10}B (n, α) ^7Li reaction (Q = 2.9 MeV) to produce a large signal relative to competing photon and muon pulses. In operation the signal from the detector passes through a preamplifier into an amplifier, then an integral discriminator, and is recorded in a scaler.

B. Setup and Calibration

1. Threshold Determination

With both a ^{60}Co gamma ray source (1.17 and 1.33 MeV photons) and a PuBe or AmBe neutron source (average neutron energy ~4.1 MeV), and with the detector high-voltage set to about +1800 V, the lower level discriminator is varied until all gamma-ray pulses are effectively eliminated. Continuing to raise the discriminator level should verify that neutron count rate efficiency is independent of threshold up to fairly high values of the discriminator voltage.

2. Detector "Plateau"

At the threshold value set in 1.), the operating high-voltage must lie on a flat region or "plateau" on the counting curve. With the neutron source verify that the count rate is constant as a function of high-voltage for a number of values both above and below the initial setting (i.e., +1800 V) at which the threshold was set. It may be necessary to change the high-voltage so that the operating value lies near the center of the "plateau". If so, threshold determination as discussed in 1). must be redone.

3. Calibration

The count rate C_T in the Long Counter at a distance r from an isotropic point - like neutron source is given by $C_T = C_o (r+r_o)^{-2} + S$, where S is the scattered neutron contribution, assumed constant over distances r of interest, and r_o is the effective center of the instrument (about 12 cm). C_o is the product of the known neutron source strength (divided by 4π) and the Long Counter response in counts cm^2 per neutron. Measurements over a number of distances r allow the determination of C_o, r_o, and S, and thus the Long Counter response. A good estimate of this quantity can be determined at a single distance r by setting $r_o = 12$ cm and correcting approximately for scattered neutrons by use of the prescription of Jenkins (see Ref. 2 in C below). A value of about 4.4 counts cm^2 per neutron has been obtained; this number should be verified periodically during Long Counter use.

C. References

More complete discussion of the Long Counter and its uses for neutron intensity measurements can be found in the following references:

1. J. DePangher and L.L. Nichols, "A Precision Long Counter for Measuring Fast Neutron Flux Density," Pacific Northwest Laboratory Report #BNWL-260 (June, 1966).

2. T.M. Jenkins, "Simple Recipes for Ground Scattering in Neutron Detector Calibration," Health Physics 39, 41 (1980).

3. J.D. Cossairt, "Calibration of MERL Long Counter with a PuBe Source," Fermilab Radiation Physics Note #26 (June 1980).

4. J.D. Cossairt, "Neutron Measurements at the Neutrino Wonder Building with a Precision Long Counter," Fermilab Report TM-1053 (June 1981).

5. J.D. Cossairt and L.V. Coulson, "Neutron skyshine Measurements at Fermilab," Health Physics 48, 175 (1985).

6. A.J. Elwyn and J.D. Cossairt, "A Study of Neutron Leakage Through an Fe Shield at an Accelerator," Health Physics 51, 723 (1986).

III. Neutron Spectral Measurements

A. Detector and Electronics

The energy spectra of neutrons outside of shielding, within access penetrations, and in enclosures are determined by use of a Bonner multisphere spectrometer. This consists of seven polyethylene spheres with diameters of 5.08, 7.62, 12.7, 20.3, 25.4, 30.5 and 45.72 cm that serve as moderators for fast neutrons. ^{6}LiI(Eu) scintillators, sensitive to thermal neutrons through the ^{6}Li(n, α)^{3}H reaction (Q-value = 4.78 MeV), are placed at the center of the moderating spheres and inserted into the field of interest. A measurement is also made with a bare (unmoderated) scintillator.

Two scintillator configurations are available for use. In one, the ^{6}LiI(Eu) crystal (8 mm diameter by 8 mm long) is embedded in a small cylinder of plastic scintillator (outside dimensions 12.7 mm by 12.7 mm long), and the light output from both is viewed by a single photomultiplier tube. This is called a phoswich detector. Fast pulses (2-3 nsec) from the plastic scintillator are separated from the slow (1-2 μsec) pulses of the ^{6}LiI(Eu) by passive filtering at the phototube output. Standard pulse-processing electronics are used to accumulate a spectrum of all slow pulses in anti-coincidence with fast signals. This method rejects events due to the passage of charged particles (e.g., muons) through the ^{6}LiI(Eu), reducing the background. In a second configuration, recently acquired, the scintillators are small cylinders of ^{6}LiI(Eu) crystals 1.27 cm in diameter and 1.27 cm long. There are eight scintillator, light-pipe, phototube combination assemblies available for simultaneous use in those neutron fields for which the muon contribution is small. The output from all eight phototubes are passed directly to eight spectroscopy amplifiers, then into multiplexer/router modules, and finally to a fast ADC. By use of the Canberra Industries S100 personal computer based multichannel analyzer and a PS/2 Model 30 computer, pulse height spectra are accumulated simultaneously for all eight detectors.

B. Setup

A neutron source is used and the signal from the phototube output is traced through each element in the signal processing modules. When the phoswich detector is used, it is necessary to ensure that the timing of the signals at various points in the chain is correct. When all eight scintillators are to be used simultaneously, it is necessary to set the threshold levels on the multiplexer/router (M/R) units in accord with the instructions from the manufacturer of the M/R modules (Canberra Industries), and to match (at least approximately) the gains for all assemblies by varying the high-voltage and/or the amplifier coarse and fine controls. In this mode of operation, the relative response of the eight detectors must be determined; this can be accomplished by measuring count rates for each assembly in the same spherical moderator when placed at the same point in the neutron field due to an AmBe or PuBe source.

C. Measurement

When sphere responses are obtained one at a time at the measurement location, relative normalization can be provided by the use of either tissue-equivalent ion chambers or relevant beam line instrumentation (ion chambers or secondary emission intensity monitors). For data taken simultaneously with the array of eight ^{6}LiI(Eu) scintillation assemblies it is necessary to correct measured rates for any nonuniformity in the neutron flux over the length of the detector array. Flux measurements can be obtained by the judicious placement of ion chambers at various locations within the array.

Measured detector response to the neutrons that comprise the radiation field can be obtained from the pulse height spectrum for each detector. The (n, α) peak due to thermal capture events is usually very clearly resolved from background events. A typical pulse height spectrum is shown in Fig. 3.

D. Analysis

Conversion of the raw response data into a neutron spectrum involves the multisphere unfolding problem, which requires the specification of a set of energy dependent response functions for each sphere. We generally use those calculated by Sanna (see Ref. 1 below).

The spectrum unfolding problem has inherent difficulties, due to its under determined and sometimes ill-conditioned nature. The former manifests itself as more than one solution spectrum that describe the data equally well, while the latter implies that small uncertainties in the data or response functions may translate into large uncertainties in the unfolded spectrum. Three different computer programs are usually used to gain some confidence in the reasonableness of the unfolded spectrum. These are BUNKI, LOUHI, and SWIFT. The latter is based upon Monte-Carlo techniques without *a priori* assumptions as to the character of the spectrum. The other two are based, respectively, on an iterative recursion method (BUNKI) and a least-squares method (LOUHI), both with user-controlled constraints.

As a check on the measurement and analysis procedures, the techniques discussed were applied to a ^{238}PuBe neutron source, whose properties are reasonably well-known. This is described in Ref. 5 below. Various properties of the unfolded spectrum are found to be in good agreement with values given previously in the literature.

E. References

1. R.S. Sanna, "Thirty One Group Response Matrices for the Multisphere Neutron Spectrometer Over the Energy Range Thermal to 400 MeV," USAEC Report HASL-267 (1973).

2. M. Awschalom and L. Coulson, "A New Technique in Environmental Neutron Spectroscopy," Proc. 3rd Int. Cong. of IRPA, USAEC Report CONF-730907-P2, page 1464 (1973).

3. J.D. Cossairt, J.G. Couch, A.J. Elwyn, and W.S. Freeman, "Radiation Measurements in a Labyrinth Penetration at a High-Energy Proton Accelerator," Health Physics 49, 907 (1985).

4. A.J. Elwyn and J.D. Cossairt, "A Study of Neutron Leakage Through an Fe Shield at an Accelerator," Health Physics 51, 723 (1986).

5. A.J. Elwyn, "The Neutron Spectrum from a PuBe Source," Fermilab Radiation Physics Note 59 (June, 1986).

6. J.D. Cossairt and A.J. Elwyn, "Personal Dosimetry in a Mixed Field of High-Energy Muons and Neutrons," Health Physics 52, 813 (1987).

7. J.D. Cossairt, A.J. Elwyn, W.S. Freeman, W.C. Salsbury, and P.M. Yurista, "Measurement of Neutrons in Enclosures and Outside of Shielding at the TEVATRON," Fermilab Report Conf-88/106, and Proc. of the 22nd Midyear Topical Meeting on Instrumentation of the Health Physics Society, page 190 (San Antonio, TX, December 1988).

IV. Quality Factor Measurements

A. Detector

The Model REM-2 Recombination Chamber, which consists of two separate tissue-equivalent high-pressure ion chambers placed in a single cylindrically-shaped container, is used to determine the quality factor (QF) of an unknown radiation field. This chamber is used in conjunction with a sensitive electrometer such as a Keithley Model 617, or the older, less versatile, Keithley Model 610C, and a well regulated high-voltage supply (such as Bertan Model 313A).

B. Operation

The usual procedure for measurement of the QF is to measure the chamber response by collecting the liberated charge at the anode with the electrometer over a range of operating potentials from -20V up to -1200V in steps of 10 or 15V below 100V, and in 100V steps above. (The Keithley Model 617 and the chamber with voltage applied should be allowed to warm-up for about 1 hour before use.) For measurements made with a source, charge should be integrated for a certain time at each operating voltage. For measurements in accelerator produced radiation fields, the chamber responses should be normalized to another detector (such as an independent tissue-equivalent ion chamber) placed in the same radiation field, or to a proton beam monitoring SEM.

C. Analysis

Over a considerable range of voltages the chamber response is given by $I=kV^N$ (see Ref. 1 below), where V is the applied voltage, k is a function of dose rate and radiation type, and N is an index which is a function of QF. By fitting the chamber response to this expression by use of a least-squares procedure, the index N can be obtained. Note that N is the slope of the straight line that results when the logarithm of the chamber response is plotted as a function of the logarithm of the operating potential. The relationship between N and QF can be determined by calibration (see D. below).

The REM-2 instruction manual suggests that the QF can be estimated from

$$QF = \left(1 - \frac{I_{recom}}{I_{satur}}\right) \times 25$$

I_{recom} is the chamber response at a voltage that allows appreciable columnar recombination, and is taken at -65V. This is the voltage at which the chamber response drops to a value 96% of the response at saturation voltage for a ^{60}Co source (QF=1). The response well into the saturation region I_{satur} is the response at -1200V.

D. Calibration

The chamber response has been measured as suggested above in radiation fields of known QF. (See Ref. 3.) Fig. 4 shows the relationship between the index N and QF. This measurement should be rechecked at periodic intervals during use of the chamber.

The sensitivity of the device should be tested periodically as a check on the chamber tightness. With the chamber connected in the parallel mode (as above) with -1200V applied, place in a field produced by a ^{60}Co source. Determine the dose rate (not lower than 100 mRad/hr) as accurately as possible. The sensitivity is then the chamber response divided by the dose rate. A value of 1.2 pA per mrad hr^{-1} was the sensitivity at the time the device was obtained.

E. References

1. A.H. Sullivan and J. Baarli, "An Ionization Chamber for the Estimation of the Biological Effectiveness of Radiation," CERN Report 63-17 (May 1, 1963).

2. C. Moore, "Quality Factor Measurements at Fermilab Using a Recombination Chamber," Fermilab Radiation Physics Note 19 (June, 1977).

3. J.D. Cossairt, D.W. Grobe, and M.A. Gerardi, "Measurements of Radiation Quality Factors Using a Recombination Chamber," Fermilab Report TM-1248 (March, 1984).

4. J.D. Cossairt, J.G. Couch, A.J. Elwyn, and W.S. Freeman, "Radiation Measurements in a Labyrinth Penetration at a High-Energy Proton Accelerator," Health Physics 49 907 (1985).

5. A.J. Elwyn and J.D. Cossairt, "A Study of Neutron Leakage Through an Fe Shield at an Accelerator," Health Physics 51, 723 (1986).

Appendix A

Scintillation Counter Efficiency

The efficiency of a scintillation counter consisting of scintillator, light pipe, and photomultiplier tube is determined by the number of photoelectrons emitted from the photocathode of the tube. It can be written as $1-e^{-\bar{n}}$, where $\bar{n}$ is the mean number of photoelectrons emitted from the photocathode. This average number of photoelectrons per incident charged particle (say, a minimum-ionizing muon) can be estimated as the product of the following factors.

1. The energy deposited per incident muon, which in the absence of quenching is essentially the energy loss in the medium. For minimum-ionizing muons in a 0.64 cm thick plastic scintillator (density=1 g cm^{-3}) the value is 1.7 x 0.64 = 1.1 MeV per muon.

2. The intrinsic efficiency of the scintillator. For plastic this is typically about 0.5-0.6 times that of anthracene, or 1 photon per 100 eV deposited (10^4 photons per MeV).

3. The overall efficiency of light collection (since some of the light is attenuated in scintillator and light guide). Collection efficiency is estimated at about 10%.

4. The quantum efficiency of the phototube. This is typically 0.2-0.25 photoelectrons per photon.

With the values suggested in 1. through 4., the mean number of photoelectrons is:

$$\bar{n} = 1.1 \times 10^4 \times 0.1 \times 0.25 = 275$$

The efficiency as defined above is therefore equal to 100% for reasonable and typical values of plastic scintillator, light guide, and phototube properties.

Appendix B

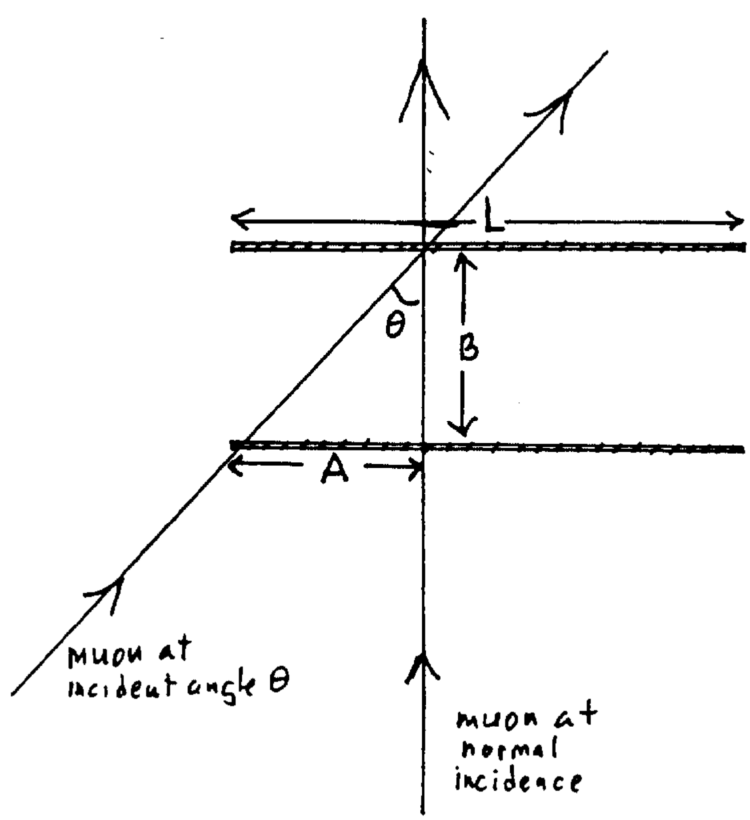
Coincidence Efficiency (Simplified)

As shown in Appendix A, a muon that impinges on a plastic scintillation counter will be detected with ~100% efficiency. Thus, the number of muons detected in a "beam" with dimensions larger than the size of the scintillator is proportional to the area of the scintillator paddle, or for a square paddle, proportional to the length of a side L. This number will be the same for the coincident detection in two paddles S1 and S2 separated by a distance B for muons incident along the normal to both paddle surfaces.

On the other hand, for muons incident on S1 at an angle θ with the normal, the efficiency for coincident detection in S2 relative to that at normal incidence, is, in reference to the drawing below,

$$\epsilon = \frac{\epsilon_\theta}{\epsilon_\perp} = \frac{L-A}{L} = 1 - \frac{B}{L}\tan\theta$$

This is less than 1 at angles θ different from 0°. The ratio of the measured coincident counting rate to the singles counting rate in a pair of scintillator paddles is an estimate of this efficiency.



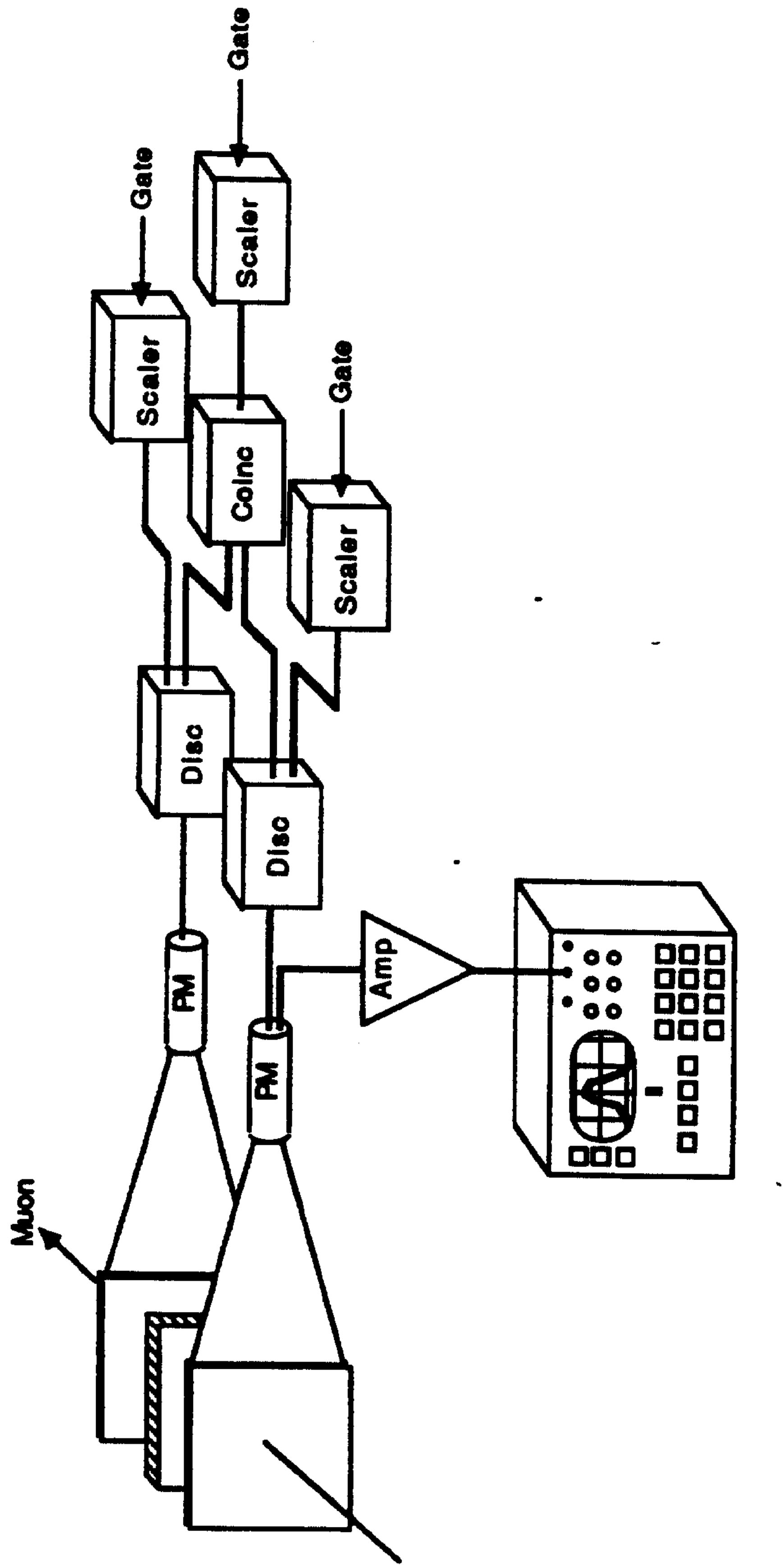
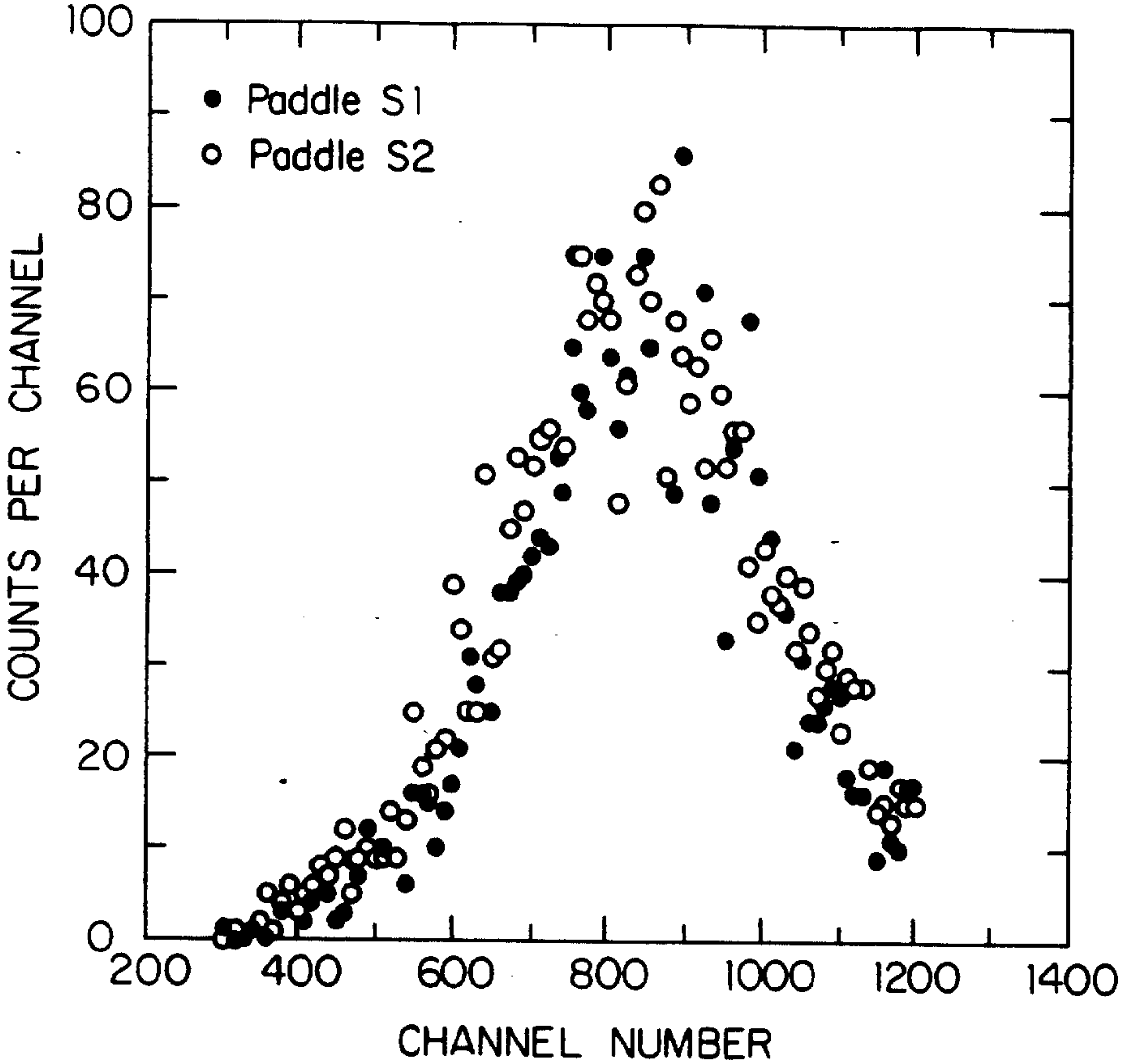
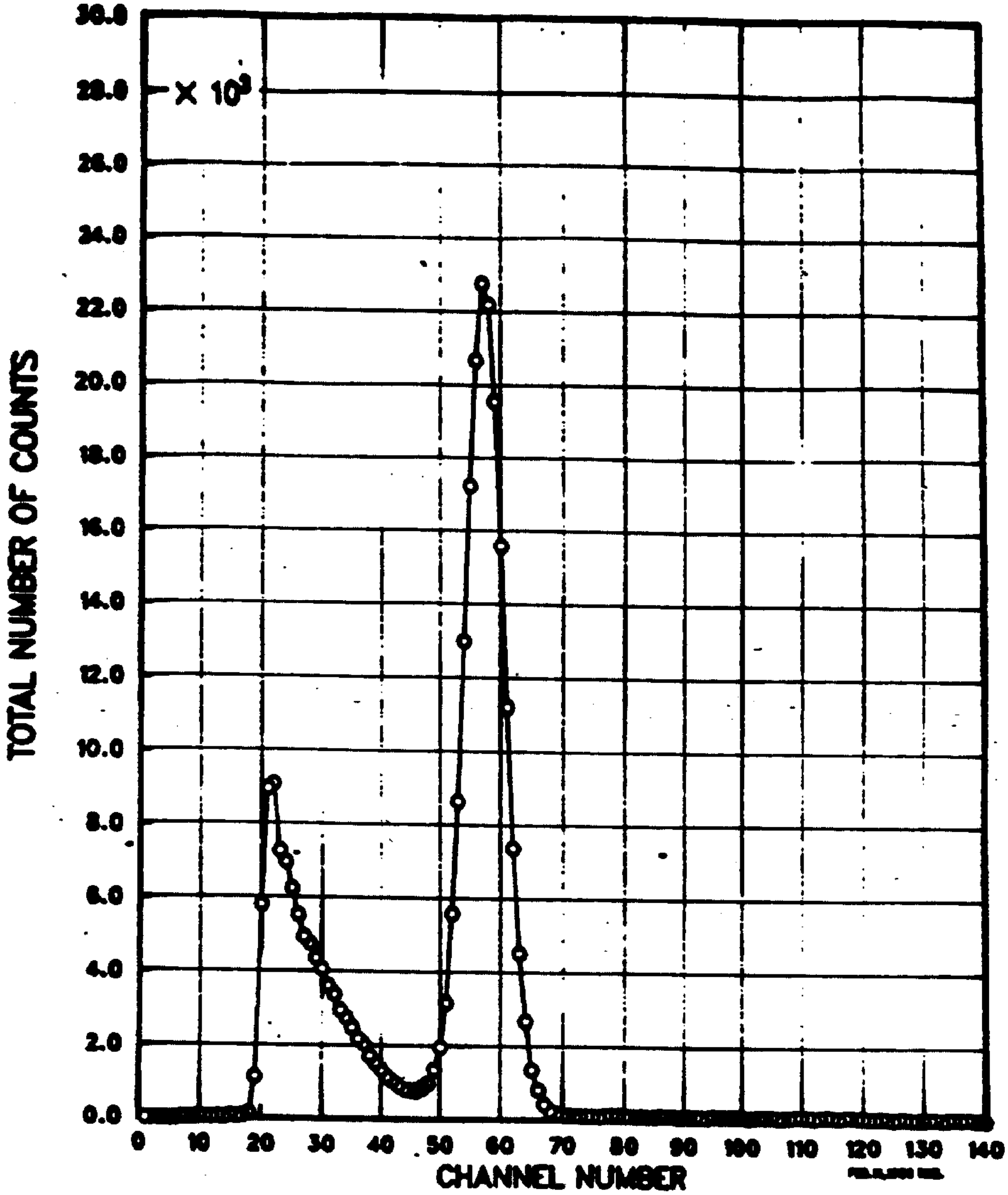

Gate
Gate
Gate
Scaler
Scaler
Scaler
Coinc
Disc
Disc
PM
PM
Amp
Muon

Figure 1



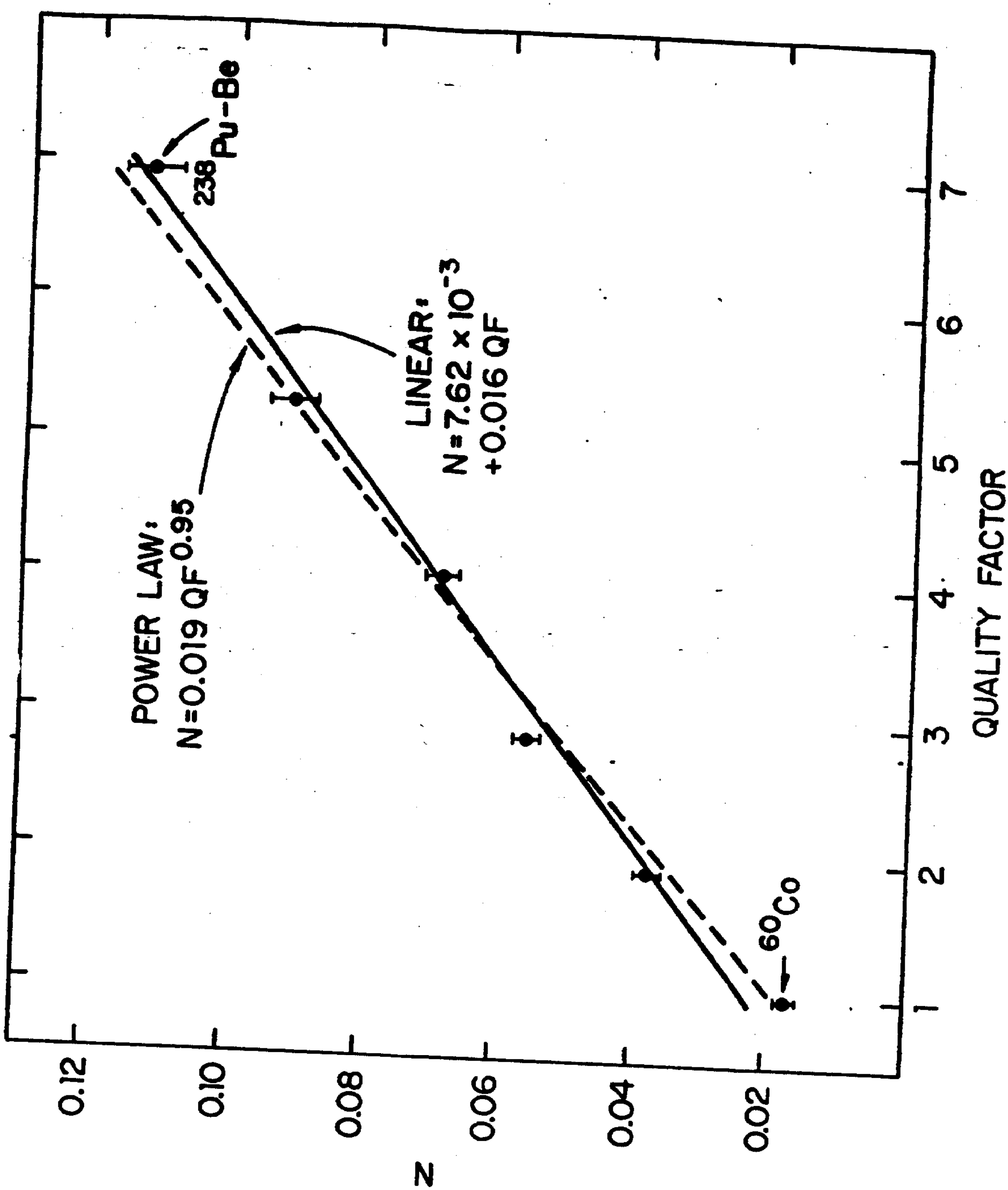
Paddle S1
Paddle S2
100
80
60
40
20
0
200
400
600
800
1000
1200
1400
COUNTS PER CHANNEL
CHANNEL NUMBER

Figure 2



× 10³
TOTAL NUMBER OF COUNTS
30.0
28.0
26.0
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140
CHANNEL NUMBER

Figure 3



POWER LAW:
N=0.019 QF^0.95
LINEAR:
N=7.62 x 10^-3
+0.016 QF
238Pu-Be
60Co
0.12
0.10
0.08
0.06
0.04
0.02
N
1
2
3
4
5
6
7
QUALITY FACTOR

Figure 4