# SOME RECENT DEVELOPMENTS IN TECHNIQUE FOR MONITORING HIGH-ENERGY ACCELERATOR RADIATION*

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**Abstract**—In order to accurately evaluate the exposures received by individuals working near high-energy accelerators it is necessary to measure the separate components in the radiation field and to determine their energy spectrum. Since no single instrument or detector will do this, a variety of different detectors and instruments must be used. Three recent developments in technique for monitoring particulate radiation above 20 MeV use nuclear emulsion, elemental mercury, and $Be^7$ production in light elements; below 20 MeV, the use of moderated foils of In, Au, and Co has been extended to include Ta.

When emulsion is used, the number of stars formed by high-energy inelastic collisions is counted, together with the number of gray prongs. The ratio of gray prongs per star was previously found to be linearly related to the energy of the neutron which formed the star, over the energy range 20 to 300 MeV. This technique is used to measure average neutron energy and to estimate spectrum shape for neutron energies above 20 MeV. A second technique makes use of the spallation of Hg to $Tb^{149}$, an alpha-emitter of 4.12-hr half-life. The threshold for this reaction is near 500 MeV, and it therefore extends the use of threshold detectors for the estimation of spectrum shape to a higher energy domain and gives additional confidence in previous estimates of spectrum shape made with Bi fission, $C^{12}(n, 2n)C^{11}$, and $Al^{27}(n, a)Na^{24}$. Thirdly, production of $Be^7$ from $C^{12}$, $N^{14}$, and $O^{16}$ has been studied; it offers a method of high-energy neutron threshold detection with practical thresholds extending from 30 to 40 MeV for carbon to 45 to 55 MeV for oxygen. The practical sensitivity can be arbitrarily high without making the extraction process either too lengthy or unwieldy. Another recent development involves the inclusion of Ta in the class of detectors which use a thermal-neutron-sensitive activation element inclosed in a Cd-clad hydrogenous moderator to allow an integration period of a few months and a sensitivity considerably greater than with Co. Finally, recent improvements in the performance of our large parallel-plate Bi fission chamber are discussed.

## RADIATION MEASUREMENTS AT LRL

### *Application to Personnel Safety and Shielding Evaluation*

The instruments and methods described here should be viewed in the light of the type of problems we encounter and our approach to their solutions. In addition to evaluating extraneous radiation fields of high-energy accelerators so that adequate personnel protection is assured, we are also called upon to determine shielding requirements both for personnel safety and for experimental equipment. In the course of this work we develop instruments and techniques appropriate to the task.

Radiation fields are measured in physical terms, using the tools and techniques of the experimental physicist. We strive to identify the various components of the radiation field and to determine their energy distribution. Extensive use is made of threshold detectors to yield both flux density and spectral information. This information is directly applicable to shielding problems, and, in conjunction with National Bureau of Standards Handbook No. 63 and ICRP recommendations, the dose

* Work done under auspices of the U.S. Atomic Energy Commission.

delivered by the radiation field can be computed.[1] Direct measurements of accelerator radiation in rad or rem units are not generally made because of their limited usefulness in situations which require a quantitative evaluation of shielding.

## INSTRUMENTS AND TECHNIQUES

The threshold detector systems we use can be grouped into two categories.[2] The first category (activation elements) consists of those detectors which can be used with a $\gamma$-ray spectrometer system along with a digital computer program to provide great spectral detail over a limited energy range of about 2 to 30 MeV (Table 1). Data analysis with this system can be time-consuming. Gamma-ray spectra are often quite complex, and lack of neutron cross section data for energies greater than about 15 MeV, and production of activities of interest by reactions other than $(n, p)$, $(n, \alpha)$, and $(n, 2n)$, are problems that require careful consideration.

Detectors which fall in the second category (mixed activation elements and pulse counters) include pulse counters such as $BF_3$, polyethylene-lined gas proportional counters, and Bi fission counters. Other detectors in this category are moderated thermal-neutron-sensitive foils, aluminum disks, and plastic scintillators for carbon activation. These detectors can be used to determine the broad spectral features of a neutron field while embracing a wide range of neutron energies from about 0.02 MeV up to the highest energy of the primary particle. A digital computer program produces a neutron spectrum by comparison of the observed detector response to trial neutron spectra. We also determine neutron spectra by measurement of proton recoil track length in Ilford L.4 600-$\mu$ emulsions.

The use of $4\pi$ detectors is favored because quite often the radiation fields we encounter are nearly isotropic, and particle spectrometers that depend on knowing the direction of the incident particle can not be used.

## RECENT DEVELOPMENTS

In addition to the instruments and techniques just described, we have added the following items.

### 1. *Neutron Spectroscopy Using Stars in Emulsions*

The average number of gray prongs per star in nuclear emulsion is found to be proportional to the average incident neutron energy.[3] This

*Table 1. Threshold Detectors**

| Reaction | Theoretical threshold† (MeV) | Effective threshold† (MeV) | Half-life of residual nucleus | Form of detector |
|---|---|---|---|---|
| $Ni^{58}$ $(n, p)$ $Co^{58}$ | −0.4 | 1.2 | 71 days | 4-in. metal disk |
| $Al^{27}$ $(n, p)$ $Mg^{27}$ | 1.8 | 2.7 | 9.5 min | 4-in. metal disk |
| $Co^{59}$ $(n, \alpha)$ $Mn^{56}$ | −0.3 | 5.3 | 2.58 hr | 4-in. metal disk |
| $Fe^{56}$ $(n, p)$ $Mn^{56}$ | 2.9 | 5.0 | 2.58 hr | 4-in. metal disk |
| $Ti^{48}$ $(n, p)$ $Sc^{48}$ | 3.2 | 5.2 | 44.0 hr | 4-in. metal disk |
| $Mg^{24}$ $(n, p)$ $Na^{24}$ | 4.7 | 6.1 | 15.0 hr | 4-in. metal disk |
| $Al^{27}$ $(n, \alpha)$ $Na^{24}$ | 3.1 | 5.9 | 15.0 hr | 4-in. metal disk |
| $I^{127}$ $(n, 2n)$ $I^{126}$ | 9.3 | 9.4 | 13.2 days | Boxed crystals |
| $Co^{59}$ $(n, 2n)$ $Co^{58}$ | 10.2 | 10.8 | 71 days | 4-in. metal disk |
| $Ni^{58}$ $(n, 2n)$ $Ni^{57}$ | 11.8 | 12.5 | 36 hr | 4-in. metal disk |

* From Alan R. Smith, Threshold detector applications to neutron spectroscopy at the Berkeley accelerators, Lawrence Radiation Laboratory Report UCRL-16312, Nov. 19, 1965.

† The theoretical threshold is calculated as $-Q \times (1 + M)/M$, where $Q$ is the $Q$ value for the reaction and $M$ is the mass number of the target nucleus. The effective threshold is the energy at which the cross section is 1/100 of its peak value.

has been investigated for neutron energies from 20 to 300 MeV. Two advantages to this system over measurement of proton recoil track length are clearly seen. Because the kinetic energy of a proton from a nuclear star is less than that of a recoil proton, the range in the emulsion is considerably less. Recoil proton tracks, on the other hand, seldom have both beginning and end in the same emulsion. Also, the direction of the incident neutron need not be known for counting prongs from nuclear stars.

Neutrons of 20 to 260 MeV from stripped deuterons were used to irradiate six Ilford K.5 emulsions (3 × 1 in., 600 $\mu$). The neutrons were considered to be monoenergetic, with a peak energy of one-half the deuteron energy. There is, of course, a symmetrical spectrum of energies about the peak with a full width at half-maximum energy given by

$$E_{1/2} = 4.18\, E_D.$$

Neutrons of 300 $\text{MeV}_{peak}$ were obtained by bombarding Be with 360-MeV protons.

Over the energy region from 20 to 300 MeV the ratio gray prongs/star increased by a factor of 50 from $\approx 0.01$ at 20 MeV to $\approx 0.5$ at 300 MeV (Fig. 1). Between 500 and 1400 stars were scanned for each energy region. Figure 2 defines the classes of prongs.

The rigor involved in track selection and identification is recognized as being an important aspect of work of this nature, and a certain amount of subjectivity could influence the results. A comparison, between the gray-prong method and an independent determination using threshold detector methods was made by Patterson and Omberg.[4] They found substantial agreement between these two methods for flux shapes derived from cosmic rays and for radiation fields at the Bevatron.

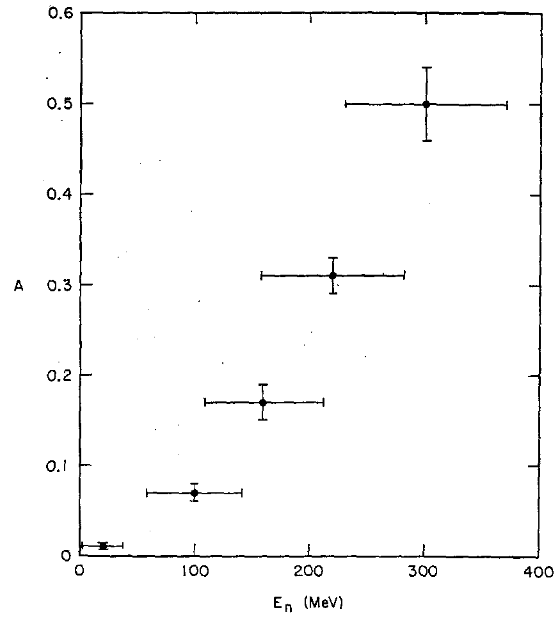


FIG. 1. Average number of gray prongs per star $A$ versus incident neutron average energy $E_n$. Errors shown in $A$ are statistical errors due to counting. Errors shown in $E_n$ are values of $\triangle E_{1/2}$. (From René Remy, Neutron spectroscopy by the use of nuclear stars from 20 to 300 MeV. Lawrence Radiation Laboratory Report UCRL-16325, Aug. 1965.)

### 2. *Hg Spallation at* 500 *MeV as a Sensitive Flux Detector*

The high-energy spallation reaction in Au has been previously reported along with cross-sections for the $\alpha$-emitting branch ($\approx 10^{-27}$ $\text{cm}^2$), $\alpha$ energy (3.95 MeV), and half life (4.12 hr) of the reaction product, $\text{Tb}^{149}$.[5] Use of Hg instead of Au for this reaction allows us to effectively and easily concentrate the Tb in a form suitable for counting.[6] The task of removing Tb from $\frac{1}{2}$ kg quantities of Hg proved less formidable a problem than might be expected because Tb slowly rises toward the top of the irradiated Hg pool. We simply accelerate this process by centrifuging the Hg, and remove a large portion of the Tb from the top of the Hg pool with a cellulose acetate pressure-sensitive adhesive tape. The ultimate sensitivity of this system for measuring $\text{Tb}^{149}$ relative to a thin gold foil depends on the amount of Hg used and the ability of the centrifuge to process it. However, a modest centrifuge which can accommodate 500-g samples will allow one to achieve an $\alpha$-counting rate $> 10^4$ times as high as with a 10-mg gold foil. It then becomes possible to measure flux densities of about 10 n/$\text{cm}^2$-sec. And with larger volumes of Hg the sensitivity improves proportionally.

The threshold for this reaction in Hg was

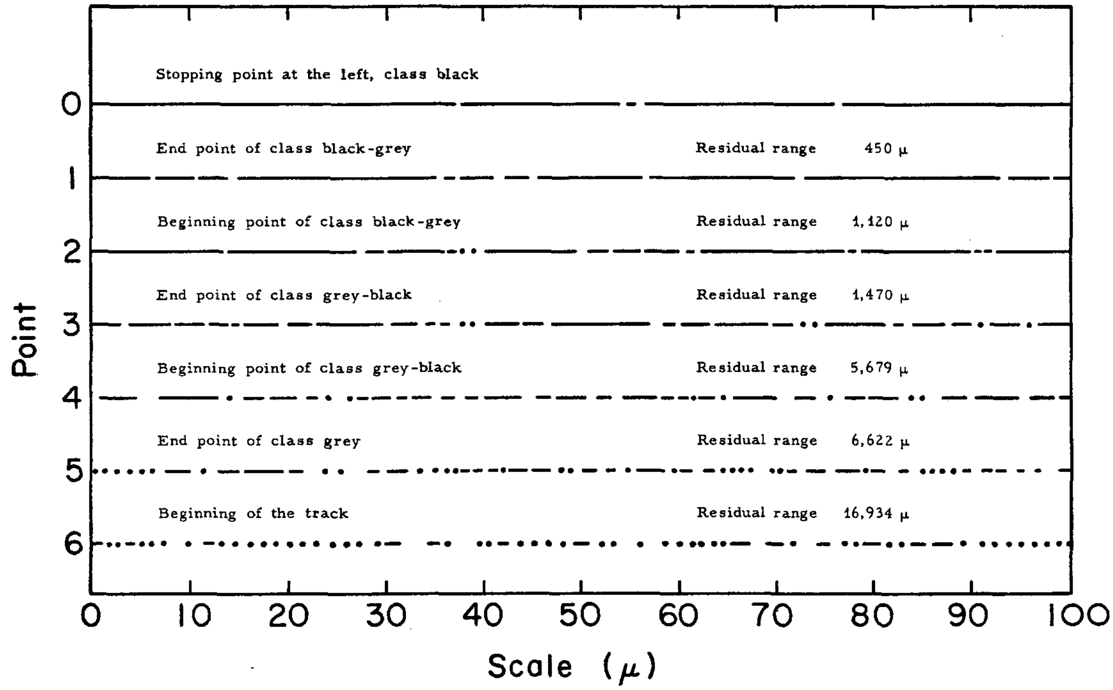


FIG. 2. Calibration track (recoil proton with 70-MeV kinetic energy).

| Class | Criteria |
|---|---|
| Black | < 10 gaps in the field of view (100 microns)* |
| Black-gray | 10 to 20 gaps in the field of view |
| Gray-black | 21 to 50 gaps in the field of view |
| Gray | > 50 gaps in the field of view |

* The number of gaps were counted in the field of view (100 microns of projected length) so that the error made in counting gaps in tracks having a great dip angle is more or less compensated for.

bracketed between 300 and 700 MeV (values in between will be determined at a later date) by irradiating samples of HgF and Au in the internal proton beam at the 184-in. cyclotron. Pending completion of the threshold studies, it is reasonable to assign the same activation threshold value to Hg as is used for Au.

Although it is easy to count α particles directly from the surface of the centrifuged Hg, the vagaries involved in unavoidable mechanical and convective mixing, relaxation of the Tb concentration gradient at the surface, etc., were considered to be too difficult a problem for our initial studies. Instead, we have found a practical and effective method of Tb concentration and extraction. We centrifuge the Hg at about 1700 g for the somewhat arbitrarily determined time of 1 hr, with the tape on top of the Hg and a 2.5-g Al disk on top of the tape. The tape is then removed for counting which is started between 100 and about 1500 min after the end of the irradiation so as to avoid $\alpha$ particles with shorter or longer half-lives. This process, when repeated several times on the same Hg sample, shows that the activity on the first tape is about 58% of the total activity in the Hg. Each successive tape sample removes about half of the remaining Tb. Four tapes remove about 91%, appropriate corrections being made for decay during the 5-hr extraction time. Comparison of $Tb^{149}$ $\alpha$ activity in a 400-g Hg sample with $Tb^{149}$ $\alpha$ activity in a thin (1.6 mg/cm$^2$) Au foil irradiated simultaneously in the external 6.2-GeV proton beam at the Bevatron showed that the Hg-Tb activity was greater than the Au-Tb activity by the ratio of their respective numbers of target atoms. And the activity in the Hg was exactly what would be expected by calculation that uses a 1-mb cross section and the proton flux density indicated by the thin Au foil activity. Activity in the 400-g Hg sample is $1.1 \times 10^{-3}$ disintegrations/min/g at zero time when irradiated to saturation in a field of 1 $p^+$/cm$^2$-sec above the threshold.

A windowless $\alpha$ counter of 50% of $4\pi$ geometry, and a 90-min processing time following irradiation to saturation at 12 $p^+$/cm$^2$-sec and a 50% extraction, would yield an initial counting rate of 0.2 count/min. This can be compared to an easily attainable counter background of 0.2 count/min.

It is assumed that the reaction cross section for $Tb^{149}$ production for neutrons bears a close resemblance to that for protons.

### 3. *$Be^7$ Production from $C^{12}$, $N^{14}$, and $O^{16}$ with Near 100% Extraction Efficiency*

It would be advantageous for some purposes to have a high-sensitivity reaction which has an energy threshold as high as $C^{11}$ or Bi fission without either the short half-life of $C^{11}$ (20.4 min), which limits both integration time and the number of simultaneous measurements, or the low sensitivity and unwieldiness of the large Bi-fission counter.

Production of 53-day $Be^7$ from light nuclei would seem to be a useful reaction, but the difficulty in detecting the 0.478-MeV $\gamma$-ray (12% of all disintegrations) from large volumes of target material has until now been a sizeable obstacle. However, a simple, reproducible, and rapid separation process for extracting $Be^7$ from large volumes of liquid target material has been found.[7] $Be^7$ from irradiated water (O), benzene (C), or liquid nitrogen is deposited on filter paper when the liquid flows through the filter. Reproducible and nearly complete separation is achieved from an arbitrarily large volume of liquid with a series of four or five separate filters. Each filter (Whatman No. 541) extracts about 50% of the $Be^7$ in the carrier.

$Be^7$ does not adhere to the walls of polyethylene containers as it does to glass.

The reaction threshold for $Be^7$ production should increase from carbon to nitrogen to oxygen with $C^{12} \rightarrow Be^7$ at 30 to 40 MeV and $O^{16} \rightarrow Be^7$ at about 45 to 55 MeV, depending somewhat on the reaction paths. Good cross-section information exists only for the proton-induced reaction in C. Neutron cross-sections are not known for any of these reactions. Calculation of sensitivities, assuming a cross-section of 10 mb in all cases, is as follows.

(a) *Benzene* (*C*). One liter irradiated to saturation in a field of 1 neutron/cm$^2$-sec would yield a count rate of 0.88 count/min in the $Be^7$ peak. NaI(Tl) background in this spectral interval is 12 counts/min.

(b) *Water* (*O*) would yield 0.72 count/min under the above conditions. Background is 12 counts/min. It has been found that the distilled water should have a pH of 4.5 to 6.5 for proper extraction.

(c) *Liquid nitrogen* (*N*). Comparable to benzene and water.

### 4. *Moderated Ta as a Fast-neutron Flux Integrator*

This detector is an extension of our use of thermal neutron-activated elements encased in Cd-clad hydrogenous moderators.[8] Six-in.-diameter moderators have been shown to exhibit a response characteristic nearly independent of incident neutron energy in the range 0.2 to 20 MeV. In, Au, and Co have been extensively used in this manner[9, 10] in a number of laboratories.

Integration time for Ta, with a 115-day half-life for $Ta^{182}$, extends to several months. In and Au integrate over periods of minutes or hours, respectively, and Co is used for integration periods of at least 1 year.

By using a 4-in. diam by 2-in. NaI(Tl)

crystal, a flux integral of $10^7$ n/cm$^2$ produces 1.8 counts/min in the selected energy band for a Co disk 2 in. in diam by 1/8 in., while the background is 10.1 counts/min. A Ta integrator of the same size produces 9.46 counts/min with a background of 8.01 counts/min.

In foils (1 in. diam by 0.005 in.) and Au foils (1 in. diam by 0.002 in.) are counted in a methane gas-flow proportional counter. Nominal initial count rates at saturation in a field of 1 neutron/cm$^2$-sec and zero time is 10 counts/min-gram and 3 counts/min-gram respectively.

### 5. *Bi-Fission Counter Improvements*

Advantage has been taken of recent improvements in the noise characteristics and transconductance of *p-n* junction field-effect transistors to upgrade the performance of our large parallel-plate Bi-fission counter. This has resulted in a simplification of the arrangement of the parallel plates and a substantial improvement in the signal-to-noise ratio.

Previously, delay line coupling of the plates was essential to proper performance in order that an event on one set of plates not be adversely affected by the full capacitance of all of the plates ($\approx$ 8000 pF).[11] By using a recently available high-trans-conductance *p-n* junction FET as the preamplifier input stage, we are able to remove the delay line from the chamber and, with all plates in parallel, achieve an overall increase in performance as shown in Figs. 3 and 4. Figure 5 shows the simplicity of the FET input stage.

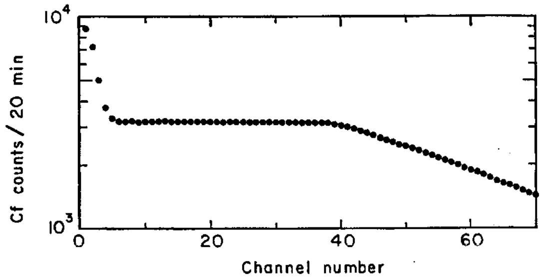


FIG. 4. Discriminator curve for Cf$^{252}$ source with plates stacked in parallel and with FET preamplifier.

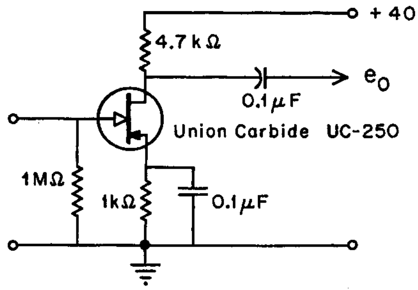


FIG. 5. FET preamplifier stage.

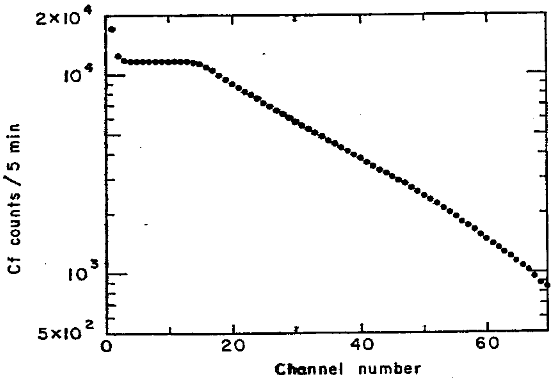


FIG. 3. Discriminator curve for Bi fission counter with delay line and Cf$^{252}$ spontaneous fission source.

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