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CONF- 680302--5A SPECTROMETER FOR NEUTRONS FROM 10 TO 100 MEV

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MASTERAbstract

A new radiation detector instrument system has been designed to measure the spectra of neutrons in the energy region from about 10 to 100 MeV. The principle of the energetic-neutron spectrometer requires first that the incident neutron lose a small fraction of its energy in a collision with a proton in an hydrogenous scintillator and then that the scattered neutron interacts in another scintillator spaced a suitable distance from the first scintillator. The time interval between the two scintillation pulses provides a measure of the neutron energy. Means for discriminating against background events include an anti-coincidence arrangement for rejecting charged particles and a pulse-shape discrimination scheme for rejecting neutron interactions with carbon nuclei. Gamma rays are rejected by time-of-flight and also by pulse-shape discrimination circuitry.

The energetic-neutron spectrometer may be used to measure (1) the fluxes and spectra of the energetic-neutron component of stray radiation fields around high-energy particle accelerators, (2) the energy and angular distributions of energetic-neutrons produced in the bombardment of both thin and thick targets, and (3) the energy of energetic-neutrons in nuclear reactions. For the case of an isotropic radiation flux of the order of 30 neutrons/cm²-sec in the energy interval from 10 to 100 MeV, the expected counting rate at 10 MeV is about 16 per hour. This estimate is for a first scintillator with a volume of 785 cc spaced at a distance of 1.91 meters from a second cylindrical scintillator with a diameter of 20 cm and a height of 15 cm. For this case, the energy resolution for a system with a time dispersion (fwhm) of 3 nanoseconds varies from 16 percent at 10 MeV to 27 percent at 100 MeV. In experiments with higher fluxes, the energy resolution can be improved substantially by utilizing smaller detectors.

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A SPECTROMETER FOR NEUTRONS FROM 10 TO 100 MEV

Introduction

There is a need for a detector that can measure the spectra of neutrons in the energy region from about 10 to 100 MeV and higher. For brevity, we shall use the term "energetic neutrons" to refer to neutrons with kinetic energies above 10 MeV. An energetic-neutron spectrometer would be useful in dosimetry and in energetic particle experiments; for example, it would be useful to have a device that can measure (1) the fluxes and spectra of the energetic-neutron component of stray radiation fields around high-energy particle accelerators, (2) the energy and angular distributions of energetic-neutrons produced in the bombardment of both thin and thick targets, and (3) the energy of energetic-neutrons in nuclear reactions.

The purpose of this paper is to describe an energetic-neutron spectrometer and to illustrate its properties for use in radioprotection.

Principle

The principle of the energetic-neutron spectrometer requires first that the incident neutron lose a small fraction of its energy in a collision with a proton in an hydrogenous scintillator and then that the scattered neutron interacts in another scintillator spaced a suitable distance from the first scintillator. The time interval between the two scintillation pulses is the time-of-flight of the scattered neutron. The small energy-transfer condition on the scattering process is satisfied by requiring that the kinetic energy of the recoil proton be less than a predetermined value T_p^* . In addition to this upper energy limitation on the recoil proton energy, there is also a lower or threshold energy requirement T_p^{th} on the recoil proton energy which arises because of the desire to detect these protons with 100 percent efficiency. Thus, the kinetic energies of the recoil protons are restricted to the interval $T_p^{th} \leq T_p \leq T_p^*$. These limits on the recoil proton kinetic energy are established by setting upper and lower bias levels on the discriminator of the first detector so that the amplitudes of

the recoil proton pulses fall within the desired kinetic energy interval.

The bias restrictions on the recoil proton kinetic energy require that a neutron of kinetic energy T be scattered (with azimuthal symmetry about the incident neutron direction) into the solid angle Ω_B :

$$\Omega_B = 2\pi \int_{\Theta_{th}}^{\Theta^*} \sin \Theta d\Theta = 2\pi(\cos \Theta_{th} - \cos \Theta^*) \quad (1)$$

The subscript B denotes that this solid-angle is defined by the bias settings of the recoil proton kinetic energies. The limits Θ_{th} and Θ^* on the neutron scattering angle Θ are determined through the kinematic relationship for the neutron-proton scattering process for the corresponding recoil proton kinetic energy limits T_p^{th} and T_p^* . The relativistic kinematic relation is

$$\cos^2 \Theta = \frac{(T - T_p)(T + 2M)}{T(T - T_p + 2M)} \quad (2)$$

where M is the nucleon mass.

The solid angle subtended at the scattering center by detector D2 is

$$\Omega_G = 2\pi \int_0^{\Theta_G} \sin \Theta d\Theta = 2\pi(1 - \cos \Theta_G) \quad (3)$$

The geometric angle Θ_G is defined by the geometry as follows:

$$\Theta_G \equiv \tan^{-1}(r_2/x) \quad (4)$$

where r_2 is the radius of the second detector, and x is the mean separation between the two detectors.

Scattered neutrons can be detected only when there is some overlapping between Ω_G , the solid angle defined by the geometry, and Ω_B , the solid angle defined by the bias settings. Since Ω_B is a function of the kinetic energy of the incident neutron, the overlap is energy-dependent.

For an omnidirectional neutron flux incident on the spectrometer, the requirement for overlap between Ω_B and Ω_G means that no scattered neutrons are detected when the incident neutron angle Θ_1 , measured with respect to the spectrometer axis, lies outside of the following limits:

$$\Theta^* + \Theta_G \equiv \Theta_1^{\max} \geq \Theta_1 \geq \Theta_1^{\min} \equiv \Theta_{th} - \Theta_G \quad (5)$$

Note that axially incident neutrons can be detected only if $\Theta_1^{\min}$ is zero, which is the case if $\Theta_G \geq \Theta_{th}$.

Figure 1 shows the various angles of interest in the spectrometer. The incident neutron angle Θ_1 and the geometric angle Θ_G are measured with respect to the axis of the spectrometer, whereas the neutron scattering angles (Θ_{th} , Θ , and Θ^*) are measured with respect to the direction of the incident neutron. Figure 2 illustrates the dependence on the neutron energy of the scattering angles allowable for a spectrometer with recoil proton kinetic energies restricted to an interval from 1.0 to 2.0 MeV.

Experimental Arrangement

The experimental arrangement consists of the detector configuration shown in Figure 3 in combination with the electronic system shown schematically in Figure 4. Detectors D1 and D2 are connected in coincidence and respond to the desired neutron interactions discussed previously. Detector D3, which surrounds detector D1 on all but the photomultiplier viewing surface, is connected in anticoincidence in order to discriminate against charged particles. The flight time between detectors D1 and D2 is converted to a pulse amplitude in the time-to-amplitude converter unit. The timing discriminator, preamplifier, and time pickoff control units at the output of each photomultiplier provide start and stop signals for the time-to-amplitude converter unit. Another time-to-amplitude converter unit measures the time difference between the leading edge of a bipolar pulse and its zero crossover point. The zero crossover point of a

bipolar pulse that is generated from a scintillation counter depends on the shape of the scintillation light pulse, which varies with the nature of the ionizing particle. The scintillation pulse contains a fast initial decay and a component with a long decay time. The decay time of the slow component for a particle with a high specific ionization is greater than that for a particle with a low specific ionization; thus, the time difference between the leading edge and the zero crossover point of a bipolar pulse increases for gamma rays, protons, alpha particles, and carbon nuclei, respectively. The second time-to-amplitude converter unit converts these measurable time differences to pulse amplitudes. The timing signal channel analyzer at the output of the second time-to-amplitude converter unit selects those amplitudes corresponding to protons. Descriptions of electronic schemes capable of measuring this zero crossover point and discriminating on this basis have been reported by Forte (1962), Peele and Love (1964), Love, et al (1966), and Verbinsky et al (1966). The timing signal channel analyzer at the input to the second time-to-amplitude converter unit provides energy selection of the pulse from detector D1 by requiring that the pulses from detector D1 be between the limits set for the recoil proton in detector D1. If the energy selection and the pulse shape discrimination measurements both correspond to protons, and if at the same time there is no signal from the anticoincidence detector D3, then the multi-channel pulse-height analyzer is gated on to accept the pulse amplitude from the first time-to-amplitude converter unit. The output of the multichannel analyzer gives the number of pulses per channel versus the channel number. After calibrating the channel numbers in terms of known time delays, the output of the multichannel analyzer gives a flight-time distribution which is easily translated into a neutron energy distribution.

For measurements of stray radiation fluxes and spectra in the vicinity of particle accelerators, typical values for the detector dimensions are as follows:

Diameter of cylindrical scintillator D1	$d_1 = 10 \text{ cm}$
Height of scintillator D1	$h_1 = 10 \text{ cm}$
Volume of scintillator D1	$V_1 = 785 \text{ cc}$
Diameter of cylindrical scintillator D2	$d_2 = 20 \text{ cm}$
Height of scintillator D2	$h_2 = 15 \text{ cm}$
Volume of scintillator D2	$V_2 = 4710 \text{ cc}$
Outside diameter of cup scintillator D3	$d_3 = 12.7 \text{ cm}$
Height of cup scintillator D3	$h_3 = 15 \text{ cm}$

For a detector D2 radius of 10 cm, and for a geometric angle Θ_G of 3 degrees, the mean spacing x between detectors D1 and D2 is 191 cm. For these detector dimensions, the path length uncertainty $\Delta x = 0.5 (d_1 + h_2) = 12.5 \text{ cm}$; accordingly the relative error in the flight path is 6.5 percent.

Energy Resolution

The velocity resolution of the time-of-flight spectrometer depends on the geometry and the time dispersion of the system. The time dispersion is a function of the light output produced in the first scintillator by the recoil protons. The time dispersion (fwhm) of a commercially available timing system with small plastic scintillators (1 inch diameter by 1 inch high) mounted on Amperex type 58 AVP photomultiplier tubes is less than 1 nanosecond for a dynamic range of pulse heights of 20 to 1 from a cobalt-60 source. The pulse-height distribution from a cobalt-60 source serves as a standard of reference for the scintillator light scale. One "cobalt" is defined as the light output from the extrapolated end point of the Compton edge from the 1.17 MeV and the 1.33 MeV gamma rays from cobalt-60. Verbinsky et al (1964) determined experimentally for an NE-213 liquid scintillator that one "cobalt" equalled the light output produced by a $1.27 \pm 0.2 \text{ MeV}$ electron. Verbinsky et al (1964) also calculated the light response of an NE-213 liquid scintillator to protons, alpha particles and carbon nuclei in units of "cobalts" versus the kinetic energy of the particle. Based on these data, the time dispersion in small scintillators from proton pulses in the

energy interval from 1 to 2 MeV varies from 1.25 down to 0.72 nanoseconds. The time dispersion increases for large scintillators because of the greater dispersion in the time to collect the light as it travels over longer optical paths.

The relative error in the determination of the incident neutron energy may be found from the following quadrature relations:

$$\left(\frac{\Delta T}{T}\right)^2 = \left(\frac{T'}{T}\right)^2 \left(\frac{\Delta T'}{T'}\right)^2 + \left(\frac{\Delta T_p}{T}\right)^2 \quad (6)$$

$$\frac{\Delta T'}{T'} = \frac{(T' + M)(T' + 2M)}{M^2} \left[\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta t}{t}\right)^2 \right]^{\frac{1}{2}} \quad (7)$$

The values of the energy resolution listed in Table I are for a spectrometer with a flight time uncertainty $\Delta t = \pm 1.5$ nanoseconds, a flight path uncertainty $\Delta x = \pm 12.5$ cm, a mean flight path $x = 191$ cm, and an uncertainty $\Delta T_p = 1.0$ MeV in the energy of the recoil proton. The energy resolution can be improved at the expense of counting rate by reducing the size of the detectors. Smaller detectors decrease the flight path uncertainty and the time dispersion.

Counting Rate

Energetic-neutron fluxes in stray radiation fields are generally omnidirectional. For the case neutrons incident isotropically on the spectrometer, the expression for the counting rate per neutron kinetic energy interval is

$$\frac{dR}{dT} = \rho_{H1} V_1 \frac{\Omega_1}{4\pi} \epsilon_2 (T) \bar{\sigma} (T) \bar{\Omega} (T) j (T) \quad (8)$$

where $j(T)$ is the incident isotropic differential flux spectrum, ρ_{H1} is the numerical density of hydrogen nuclei in scintillator D1, V_1 is the volume of scintillator D1, ϵ_2 is the efficiency or probability for detecting neutrons in scintillator D2, Ω_1 denotes the acceptance solid-angle of the spectrometer, $\bar{\sigma}$ is the elastic neutron-proton differential scattering cross-section averaged

over the solid-angle Ω , and $\bar{\Omega}$ is the mean value of the solid-angle Ω . The defining equation for the mean solid angle $\bar{\Omega}$ is

$$\bar{\Omega} \int_{\Theta_1^{\min}}^{\Theta_1^{\max}} \sin \Theta_1 d\Theta \equiv \int_{\Theta_1^{\min}}^{\Theta_1^{\max}} \Omega(T, \Omega_1) \sin \Theta_1 d\Theta_1 \quad (9)$$

The integral on the left-hand side occurs in the defining equation for the acceptance solid angle of the spectrometer for an isotropic flux:

$$\Omega_1 \equiv 2\pi \int_{\Theta_1^{\min}}^{\Theta_1^{\max}} \sin \Theta_1 d\Theta_1 = 2\pi (\cos \Theta_1^{\min} - \cos \Theta_1^{\max}) \quad (10)$$

As shown in the Appendix, the integral on the right-hand side of Eq. (9) is just twice the expression given as the right-hand member of Eq. (11); hence, Eq. (9) may be rewritten:

$$\frac{\Omega_1}{4\pi} \bar{\Omega} = \int_{\Theta_{th}}^{\Theta^*} \sin \Theta d\Theta \int_{\Theta - \Theta_G}^{\Theta + \Theta_G} \arccos \left(\frac{\cos \Theta_G - \cos \Theta_1 \cos \Theta}{\sin \Theta_1 \sin \Theta} \right) \sin \Theta_1 d\Theta_1 \quad (11)$$

This double integral has been evaluated numerically with the aid of a digital computing machine.

The neutron energy dependence of the counts per target proton per unit time-integrated flux is given by

$$C_n^I (\text{counts/proton-neutron-cm}^{-2}) = \frac{\Omega_1}{4\pi} \bar{\Omega} \epsilon_2 \quad (12)$$

Each of the factors in this equation is tabulated in Table II as a function of the kinetic energy of neutrons incident isotropically on a spectrometer with a

geometric angle of 3 degrees and with recoil proton kinetic energies restricted to an interval from 1.0 to 2.0 MeV. Since the differential scattering cross section varies slowly over the interval of allowable scattering angles, the mean cross section has been approximated by the value of the cross section at the mean laboratory scattering angle corresponding to a recoil proton kinetic energy interval from 1.0 to 2.0 MeV. Values for the neutron detection efficiency ϵ_2 of scintillator D2 are from the curve calculated by Kurz (1964) for a cylindrical plastic scintillation counter 20 cm in diameter and 15 cm high with a threshold bias corresponding to 1.1 ± 0.5 MeV equivalent electron energy. The results of the calculation agree with the measurements of Wiegand et al (1961) in the neutron energy interval from 4 to 76 MeV for a similar type neutron counter. Kurz states that the uncertainty in the calculated efficiency is about $\pm 10\%$ arising from an uncertainty of this magnitude in the total non-elastic neutron-carbon cross section.

In Table III, we show a sample calculation of the counting rate in the energetic neutron spectrometer for an isotropic inverse first-power spectrum normalized to an integral flux of $30 \text{ neutrons/cm}^2\text{-sec}$ in the interval from 10 to 100 MeV. With this flux normalization, the differential flux spectrum is

$$j(T) = 13/T(\text{MeV}) \text{ (n/cm}^2\text{-sec-MeV)} \quad (13)$$

The number of counts and the relative error in the number of counts expected after 24 hours are also shown in Table III. The incident spectrum is determined from the number of counts ΔC obtained in a time interval Δt :

$$j(T) = \frac{\Delta C}{\rho_{H1} V_1 C_p^I \Delta T \Delta t} \quad (14)$$

Figure 5 illustrates the precision in the determination of the assumed incident isotropic flux spectrum from the number of counts after 24 hours for a spectrometer with a time dispersion (fwhm) of 3 nanoseconds, a first scintillator volume of 785 cc, a geometric angle of 3 degrees, and with recoil proton

kinetic energies restricted to an interval from 1 to 2 MeV. The relative error in the incident flux is a quadrature combination of the relative error in the number of counts and a relative error of 10 percent in the determination of the efficiency ϵ_2 of the second detector. This calculation is illustrative of the potential of the spectrometer for measuring the fluxes and spectra of the energetic-neutron component of stray radiation fields around high-energy particle accelerators.

Discrimination against Background

Background events in the energetic-neutron spectrometer arise from processes of the following types:

- a. A gamma-ray Compton scattering process in the first scintillator followed by an interaction of the scattered gamma-ray in the second scintillator.
- b. Neutron interactions with carbon nuclei in the first scintillator.
- c. Chance coincidences between uncorrelated events in the first and second detectors.

Discrimination against these background processes occurs in the following ways:

- a. The gamma-ray interactions are discriminated from neutrons by means of the difference in their times of flight between scintillators D1 and D2. The pulse-shape discrimination requirement also discriminates against gamma-ray interactions in the first scintillator.
- b. The dual requirements of pulse-shape discrimination and recoil proton energy selection discriminate against neutron-carbon interactions in the first scintillator.

As noted by Kurz (1964), almost no data other than the total cross section and the elastic cross section are available for neutron-carbon interactions. In order to detect a neutron that is elastically scattered from a carbon nucleus, the incident neutron must transfer sufficient energy to the carbon nucleus to produce a detectable pulse in the scintillator D1 and the scattered neutron must interact in scintillator D2. The pulse-shape discrimination requirement rejects

carbon recoil pulses that would be accepted in the pulse-height window for proton recoils.

In order to detect neutron-carbon inelastic scattering processes, there must be a pulse (in the pulse-height window for proton recoils) in scintillator D1 followed by the interaction of the degraded neutron in scintillator D2. In the case of the $C^{12}(n, n'\gamma)C^{12}$ reaction, the pulse in scintillator D1 can arise either from the recoiling nucleus or from a gamma interaction. In the case of the $C^{12}(n, n' 3\alpha)$ reaction, the pulse in scintillator D1 must be produced by one or more alpha particles. In the case of the $C^{12}(n, n' p)B^{11}$ reaction, the required pulse in scintillator D1 may be produced either by the recoiling boron-11 nucleus or by the outgoing proton. The pulse-shape discrimination requirement rejects all such pulses except those from protons in the reaction $C^{12}(n, n' p)B^{11}$; however, the limited information available on the cross section for the $C^{12}(n, n' p)B^{11}$ reaction indicates that the $C^{12}(n, p)B^{12}$ is much more likely at least up to 17.5 MeV. Kreger and Kern (1959) measured the $C^{12}(n, p)B^{12}$ cross section for neutrons from 14.9 to 17.5 MeV. By comparing the measurements of the Kreger and Kern cross section for the $C^{12}(n, p)B^{12}$ reaction with the cross-section curve presented by Schuttler (1966) for the sum of the $C^{12}(n, p)B^{12}$ and the $C^{12}(n, n' p)B^{11}$ reactions in the energy region from about 16 to 30 MeV, $C^{12}(n, p)B^{12}$ is the dominant reaction,

- c. The dual requirements of recoil proton energy selection and pulse-shape discrimination reduce the counting rate in the first scintillator that can contribute to the chance coincidence rate.

In the first scintillator, the counting rate from an isotropic neutron flux per unit neutron energy interval is

$$\frac{dN_1}{dT} = \rho_{H1} V_1 \bar{\sigma} \Omega_B j \quad (15)$$

The restriction to 2.0 MeV on the maximum allowable recoil proton energy

reduces the relevant counting rate in the first scintillator by a factor of over 200 in the energy interval centered at 100 MeV; the reduction factor, $2\pi/\Omega_B$, is nearly 20 in the energy interval centered at 10 MeV.

The accidental coincidence counting rate in a given energy interval is

$$\Delta A = 2 \Delta t N_1 N_2 \quad (16)$$

where N_1 and N_2 are the energy interval counting rates in the first and second detectors, and Δt is the overlap time in the given energy interval for the uncorrelated counting rates in the two detectors. As the neutron energy increases, the fact that the resolvable energy interval increases means that the associated time interval available for a chance coincidence also increases. In our example, this time interval varies from about 11 nanoseconds at 10 MeV to about 4 nanoseconds at 100 MeV.

The ratio of the real-to-accidental counting rates in a given energy interval is

$$\frac{\Delta R}{\Delta A} \equiv \frac{\Delta R}{2 \Delta t N_1 N_2} = \frac{C_p^{I/\sigma} \Omega_B}{2 \Delta t N_2} \quad (17)$$

In the second scintillator, the counting rate from an isotropic neutron flux in an energy interval δT of width $2\Delta t$ may be obtained from

$$N_2 = j \delta T \epsilon_2 A_2 = j \delta T \frac{\epsilon_2^{(T)}}{\epsilon_2^{(10)}} \sigma_H^{(10)} \rho_{H2} V_2 \quad (18)$$

where A_2 is the effective cross-sectional area of the scintillator, ρ_{H2} is the numerical density of hydrogen nuclei in scintillator D2, V_2 is the volume of scintillator D2, $\sigma_H^{(10)}$ is the total neutron-proton scattering cross-section at 10 MeV, and $\epsilon_2^{(10)}$ is the efficiency of scintillator D2 for 10 MeV neutrons. The right-hand member of Eq. (18) is based on a result of Kurz (1964) which shows that the contribution to ϵ_2 at 10 MeV is principally from neutron-proton scattering. At neutron energies above 10 MeV, the calculation by Kurz shows that the reactions $C(n,p)B$ and $C(n,n'\alpha)$ make significant contributions to ϵ_2 .

A pulse-shape discrimination requirement may be used to reduce the gamma-ray contribution to the event rate in the second scintillator.

If a spectrometer with the energy resolution given in Table I is exposed to the normalized isotropic spectrum given in Table III, the accidental coincidence counting rate in each energy interval from 10 to 100 MeV is expected to be a small fraction of the real coincidence counting rate.

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Figure 1. Geometric Relations in the Energetic-Neutron Spectrometer

Figure 2. The Range of Scattering Angles Allowable for a Spectrometer with Recoil Proton Kinetic Energies Restricted to an Interval from 1.0 to 2.0 MeV versus the Kinetic Energy of the Incident Neutrons

Figure 3. Detector Arrangement in the Energetic-Neutron Spectrometer

Figure 4. Electronic System in the Energetic-Neutron Spectrometer

Figure 5. An Illustration of the Precision in the Determination of an Assumed Isotropic Inverse First-Power Spectrum.

Table I

Energy Resolution and Mean Flight Time versus the Kinetic Energy of Neutrons Incident on an Energetic-Neutron Spectrometer with a Geometric Angle of 3.0 Degrees, a Mean Flight Path of 1.91 Meters, a Time Dispersion of 3.0 Nanoseconds (fwhm), and with Recoil Proton Kinetic Energies Restricted to an Interval from 1.0 to 2.0 Me V

Neutron Kinetic Energy T (MeV)	Energy Resolution ($\Delta T/T$)	Energy Uncertainty ΔT (MeV)	Mean Flight Time t (ns)
5	.22	1.1	74.0
10	.16	1.6	47.7
20	.16	3.2	32.6
50	.21	10.3	20.6
100	.27	27.4	15.0

Table II

The Expected Number of Neutron Counts per Target Proton per Unit Time-Integrated Neutron Flux versus the Kinetic Energy of Neutrons Incident Isotropically on a Spectrometer with a Geometric Angle of 3 Degrees and with Recoil Proton Kinetic Energies Restricted to an Interval from 1.0 to 2.0 MeV

Neutron Kinetic Energy	Mean Differential Scattering Cross Section	Efficiency of Second Detector	Acceptance Solid Angle Fraction	Mean Solid Angle	Counts per Proton per Time-Integrated Neutron Flux
T (MeV)	$\bar{\sigma}$ (mb/sr)	ϵ_2	$\Omega_1/4\pi$ (10^{-2} sr)	$\bar{\Omega}$ (10^{-3} sr)	C_P^I (C/ 10^{30} p-n-cm $^{-2}$)
5	432	.18	8.80	7.76	53.0
10	276	.30	4.69	7.46	29.0
20	154	.29	2.69	7.19	8.64
50	72.5	.24	1.38	6.86	1.65
100	35.7	.18	.855	6.66	.366

Table III

The Counting Rate and the Relative Error in the Determination of the Incident Flux Spectrum from the Number of Counts Expected after 24 Hours in an Energetic-Neutron Spectrometer with a Time Dispersion (fwhm) of 3.0 Nanoseconds, a Scintillator D1 Volume of 785 CC, a Geometric Angle of 3 Degrees, and with Recoil Proton Kinetic Energies Restricted to an Interval from 1.0 to 2.0 MeV versus the Kinetic Energy of Neutrons in an Isotropic Inverse First-Power Spectrum Normalized to an Integral Flux of 30 N/Cm²-Sec in the Interval 10 to 100 MeV

Neutron Kinetic Energy T (MeV)	Isotropic Flux Spectrum $j(T) = 13/T$ (n/cm ² -sec-MeV)	Counting Rate ΔR (counts/hr)	After 24 Hours		
			Counts C	Relative Error in Counts ($\Delta C/C$)	Relative Error in Incident Flux ($\Delta j/j$)
5	2.6	42.0	1008	.031	.10
10	1.3	16.5	397	.050	.11
20	.65	4.94	119	.092	.14
50	.26	1.21	29	.19	.21
100	.13	.357	8.6	.34	.36

Represented in Figure 1 are the areas intercepted on a unit sphere by the total scattering solid angle Ω_B and by the solid angle Ω_G that the detector D2 subtends at the scattering center. The solid angles Ω_B and Ω_G are defined by Eqs. (1) and (3), respectively. For the particular situation represented in Figure 1, the shaded area is the solid angle Ω , which is that solid angle subtended by the portion of detector D2 that encounters neutrons incident with kinetic energy T at an angle Θ_1 . The area subtended on the unit sphere by the solid angle Ω_G is a spherical cap. Let C refer to the center of this cap with polar coordinates C ($\Theta_1, 0$). The area intercepted on the unit sphere by the solid angle Ω_B is a frustrated cap. Let P refer to any point that is common to the frustrated cap for Ω_B and the cap for Ω_G ; that is, we consider a neutron that is scattered through point P with polar coordinates P(Θ, ϕ). Let A denote the apex of the frustrated cap. From the law of cosines for the sides of the spherical triangle A P C on the unit sphere, we may write

$$\cos \Theta_1 \cos \Theta + \sin \Theta_1 \sin \Theta \cos \phi = \cos \Theta_2 \quad (\text{A-1})$$

where Θ_2 denotes the angle between the scattered neutron and the axis of the spectrometer. In order that the scattered neutron strike the detector D2, the angle Θ_2 must not exceed geometric angle Θ_G , or $\cos \Theta_2 \geq \cos \Theta_G$. Hence, the condition that a neutron incident at an angle Θ would be scattered within the solid angle Ω_G is as follows:

$$\cos \Theta_1 \cos \Theta + \sin \Theta_1 \sin \Theta \cos \phi \geq \cos \Theta_G \quad (\text{A-2})$$

We shall refer to this condition as the geometry condition.

Now, the solid angle Ω is

$$\Omega = \int_{\Theta'}^{\Theta''} \sin \Theta \, d\Theta \int_{\phi'}^{\phi''} d\phi = \int_{\Theta'}^{\Theta''} (\phi'' - \phi') \sin \Theta \, d\Theta = 2 \int_{\Theta'}^{\Theta''} \phi'' \sin \Theta \, d\Theta \quad (\text{A-3})$$

In terms of the geometry condition given by Eq. (A-2) this integral becomes

$$\Omega = 2 \int_{\Theta'}^{\Theta''} \cos^{-1} \left(\frac{\cos \Theta_G - \cos \Theta_1 \cos \Theta}{\sin \Theta_1 \sin \Theta} \right) \sin \Theta d\Theta \quad (\text{A-4})$$

This integral may be rewritten

$$\Omega = 2 \int_{\Theta'}^{\Theta''} \cos^{-1} \left(1 - \frac{\cos (\Theta_1 - \Theta) - \cos \Theta_G}{\sin \Theta_1 \sin \Theta} \right) \sin \Theta d\Theta \quad (\text{A-5})$$

Note that the integrand remains real as long as

$$\cos (\Theta_1 - \Theta) > \cos \Theta_G \quad (\text{A-6})$$

This relationship is always true whenever the geometry condition is satisfied.

The lower and upper limits Θ' and Θ'' on the Θ -integration for the evaluation of the solid angle Ω in Eq. (A-5) take on the following values:

$$\Theta' = \max (\Theta_{th}, \Theta_1 - \Theta_G) \quad (\text{A-7})$$

$$\Theta'' = \min (\Theta^*, \Theta_1 + \Theta_G) \quad (\text{A-8})$$

These integration limits on the neutron scattering angle are diagrammed in Figure A-1 as a function of the neutron angle of incidence. Figure A-1 is for the case $\Theta^* - \Theta_{th} < 2\Theta_G$; however, the integration limits are the same for the case $\Theta^* - \Theta_{th} > 2\Theta_G$.

Upon substituting Eq. (A-4) for Ω into the defining Eq. (9) for $\bar{\Omega}$, we find that the product of the mean solid angle $\bar{\Omega}$ and the acceptance solid-angle fraction is

$$\bar{\Omega} \frac{\Omega_1}{4\pi} = \int_{\Theta_1}^{\Theta_1^{\max}} \sin \Theta_1 d\Theta_1 \int_{\Theta'}^{\Theta''} \arccos \left(\frac{\cos \Theta_G - \cos \Theta_1 \cos \Theta}{\sin \Theta_1 \sin \Theta} \right) \sin \Theta d\Theta \quad (\text{A-9})$$

By changing the order of integration, we see from Figure A-1 that the double integral in Eq. (A-9) becomes

$$\frac{\Omega_1}{4\pi} = \int_{\theta_{th}}^{\theta^*} \sin \theta \, d\theta \int_{\theta - \theta_G}^{\theta + \theta_G} \arccos \left(\frac{\cos \theta_G - \cos \theta_1 \cos \theta}{\sin \theta_1 \sin \theta} \right) \sin \theta_1 \, d\theta_1 \quad (A-11)$$

Figure A-1. Integration Limits on the Neutron Scattering Angle for Evaluation of the Solid Angle Ω versus the Neutron Angle of Incidence