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ENERGY RESPONSE AND PHYSICAL PROPERTIES OF NTA* PERSONNEL NEUTRON DOSIMETER NUCLEAR TRACK FILM

Richard L. Lehman

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ABSTRACT

This paper reports the chemical and physical properties of the NTA film packet. It correlates with these properties the response of this packet to neutrons of various energies. In this correlation the concept of the track unit is introduced as a basic unit for reporting film-packet response.

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I. INTRODUCTION

Health physicists have used nuclear track emulsion to determine neutron exposure since 1944[1]. In 1947 Eastman Kodak produced a special fine-grained film, type NTA, in dental packet size for use as a personnel neutron monitor. Since this time, nuclear track film has proven a useful neutron dosimeter; today, thousands of persons who work near neutron sources such as nuclear reactors and particle accelerators normally carry these films. To master the use of nuclear track film as an instrument that detects neutrons, the health physicist must ask: "What kind of and how much neutron exposure information can be found in the developed film?" In this paper we examine this question. We describe the NTA film packet in some detail, discuss track formation, and finally predict the response of the film packet to neutrons of various energies.

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*Now called Eastman Type A. For convenience, it will be called "NTA" throughout this paper

II. COMPOSITION OF STANDARD NTA FILM PACKET

The NTA film packet consists of an outer paper wrapper, an inner black-paper wrapper, a plastic sheet serving as the film base, and a thin film of NTA nuclear emulsion arranged as shown in Fig. 1. Description of the layers is as follows:

(1) Front outer wrapper. The thickness of this layer is 16 mg cm^{-2}, density about 1.00. The inner surface is coated with a substance opaque to visible light. Assuming this paper is cellulose, the hydrogen density is 60 mg cm^{-3}.

(2) Inner wrappers. Each inner wrapper is of the same opaque black paper, thickness 7.7 mg cm^{-2} per layer, density 1.05. Again, assuming cellulose paper, the hydrogen density is 60 mg cm^{-3}.

(3) The nuclear emulsion film. This film is the portion of the packet that detects fast charged particles. It is 24 to 33 μ thick, depending on the batch, and consists of crystals and grains of silver bromide highly concentrated at random in a gel matrix. These crystals and grains occupy about half the emulsion volume. Nuclear emulsion gelatin is derived from clippings of animal skin and bones. Its major component is "collagen", one of the natural fibrous proteins. At room temperature, collagen is insoluble in water, but at about 40°C it melts and may be infinitely diluted with water; at room temperature, it hydrates to an extent determined by the relative humidity. Therefore, density and chemical composition of nuclear track emulsion varies with relative humidity. In addition to silver bromide and gelatin, nuclear track film contains some silver iodide and trace amounts of "sensitizers", whose nature and concentration in NTA emulsion are trade secrets. A very thin protective gelatin layer (approx 0.5 μ) covers the emulsion surface.

In order to make quantitative predictions about the response of NTA film to neutrons, one must know the density of each element present in the film. We present these densities in Table 1, determined as follows. We first measured the per cent by weight of silver and nitrogen in the emulsion, and then measured the total emulsion density: 3.60 ± 0.06 g cm^{-3} at 50% relative humidity (21°C). We calculated the density of the other elements from atomic ratios supplied by the manufacturer, and from the gel: silver halide ratio in an Ilford emulsion of similar sensitivity.

We infer from work by Oliver on Ilford emulsions[2] that the density of NTA increases 0.5% with each 10% decrease in relative humidity below 50%, and decreases 1.7% with each 10% increase in relative humidity above 50%.

(4) Plastic film base. The film base supports the nuclear emulsion film and serves as a proton radiator. It has the chemical properties of cellulose triacetate, $C_6H_7O_2(OOCCH_3)_3$. Its thickness in many batches has remained constant at 203 ± 2 microns. We have measured its density at 1.28, and its nitrogen content, <2 mg cm^{-3}. The hydrogen density is about 71 mg cm^{-3}. The area of the film base is 12.40 cm^2.

(5) Back outer wrapper. This wrapper is not lighttight. It is 13.4 mg cm^{-2} thick, density 1.0.

The NTA packet is not symmetrical front to back. There is about 23.5 mg cm^{-2} thickness of paper in front of the emulsion layer. Hydrogen contributes 1.5 mg cm^{-2} to this total. In back of the emulsion is the 26 mg cm^{-2} plastic base (1.5 mg cm^{-2} hydrogen) and 29 mg cm^{-2} in paper wrappers (1.8 mg cm^{-2} hydrogen).

III. TRACK FORMATION IN NUCLEAR EMULSION

Neutrons may be detected in the standard NTA packet by three mechanisms: (a) elastic collision with hydrogen nuclei, (b) the exoergic (n, p) reaction with nitrogen nuclei, and (c) inelastic interaction with any nucleus that results in a "star". In each case, high-energy charged particles are released. It is these charged particles that create a trail of developable grains of silver bromide in the emulsion.

Elastic collision with hydrogen is important only at neutron energies above about 0.4 MeV; at energies below this the proton recoil tracks are in practice too short to be observed. The nitrogen (n, p) reaction is important only at neutron energies below about 10 eV, since at greater energies the reaction probability (cross section) drops, so that the sensitivity of the emulsion as a personnel neutron monitor is impractically low. The (n, p) reactions with elements in the packet other than nitrogen are unimportant, as are all (n, α) reactions. Star formation is important only for neutrons of energy above about 20 MeV; we do not consider neutron detection by star density in nuclear emulsion in this paper.

High-energy recoil and (n, p) protons travelling through the emulsion release bound electrons in the silver bromide grains through which they pass. By imperfectly understood mechanisms, this electron released within a grain renders it developable. A developable grain, or latent image, consists of aggregates of metallic silver atoms within the grain. The photographic process depends upon the fact that the reduction of silver ions within a grain of silver halide by a developing solution proceeds more rapidly for an exposed grain than for an unexposed one.

In all sensitive radiation detectors there is a tremendous magnification of the energy lost by a charged particle. It is instructive to calculate the

extent of the magnification in the photographic process. Energy lost by a fast charged particle appears as electron-excitation energy in the silver halide crystal. The duration of this energy exchange is about 10^{-15} sec. There is a threshold excitation energy of about 2.5 eV before the lowest unoccupied electron energy levels are reached in silver bromide. In these conduction levels, electrons migrate freely through the crystal. The pulse of electromagnetic field produced by a fast charged particle is equivalent to many photons, some having energies much greater than the 2.5 eV threshold. NTA emulsion is sensitive to particles with a linear energy loss greater than about 60 MeV cm^{-1}. The mean grain diameter is about 0.2 μ; therefore, the minimum amount of energy required to create a latent image is roughly 1000 eV per grain of mean size. Six to ten eV is the average energy needed to produce one free electron in silver halides, so that about 100 "ionizations" are required within a grain of emulsion silver bromide to make it developable. These free electrons reduce about 100 silver ions within the grain. During processing, the chemical energy of the developer amplifies the effect of the 100 ionizations by facilitating reduction of more silver ions. These atoms condense on the free silver already created in the latent image, until the silver speck is about 0.6 μ, the diameter of fully developed NTA grains. Electron micrographs of latent images and developed grains reveal their structure as a spongy or filamentous network of crystalline silver rather than a solid mass. There are roughly 4×10^9 atoms of silver in a developed grain. Therefore each ionization taking part in the creation of a latent image is magnified in the latent image and development to form about 10^7 silver atoms.

IV. PREDICTION OF NTA RESPONSE TO NEUTRONS OF VARIOUS ENERGIES

A. Introduction and Proposal of a Fundamental Unit of NTA Response

Standard practice in nuclear track detection of neutrons is to report the response of the film packet in tracks (in depth) per field of view, as seen through a microscope. This is tantamount to tracks (in depth) per unit area scanned. If one knows the area of the microscopic field of view, and the total neutron exposure in neutrons per unit area, then one may express the response in the dimensionless unit tracks per incident neutron. These units are useful if emulsion thickness and wrapper thickness (proton-radiator thickness) are constant between calibrated and experimentally exposed films. In general, these units have not been useful for comparison of neutron exposure calibrations between one laboratory and another. Nor have they been useful for reporting in the literature the "absolute" response of NTA packets to neutrons.

The reason for this is not hard to find. We measured the thickness of the emulsion layer in many NTA packets. Although in any one emulsion number or manufacturing batch the thickness of this layer is remarkably constant, thickness between batches varies between 24 and 33 microns. This led us to examine the wrapper and plastic film base thickness. These layers remain constant to a few per cent within a batch and between batches.

For the purpose of establishing an "absolute" calibration response of NTA packets to neutrons, so that the response of this packet may be compared between manufacturing batches in a given laboratory, between laboratories, and finally in the literature, we are forced to seek a more fundamental unit than the track per field or the track per neutron.

However, this takes us directly to an impasse resting on the basic mechanisms of track production in the NTA packet. In a developed film, that fraction of the visible tracks originating within the emulsion depends directly

on emulsion thickness. However, that portion of the tracks originating in a radiator adjacent to the emulsion is independent of emulsion thickness. The former fraction of the tracks should be measured as a track density or in units of tracks per unit of emulsion volume. The latter portion should be measured as a track exposure, or in units of tracks per unit emulsion area.

The impasse in establishing an "absolute" calibration response is then precisely this: a fraction of film response to neutrons depends directly on emulsion thickness, while the remainder is independent of emulsion thickness. Therefore, in general one cannot normalize film response to a given constant emulsion thickness. In doing this he would also "normalize" that portion of the response that is independent of thickness!

To achieve a fundamental unit we must normalize to constant thickness that portion of the response which depends on the emulsion thickness. To do this we must know the thickness of emulsion in the experimental film and the energy of incident neutrons. For any experimental dosimetry, the energy spectrum of the neutron source should be known. There are two satisfactory methods for determining emulsion thickness of the experimental film in any batch. The most direct is to measure the thickness of several sample films in the same batch with a micrometer, before and after washing the emulsion off with hot water (90 ^{o}C). The second method is to weigh several sample films in the same batch before and after washing the emulsion off. The weight of the emulsion, together with its density (see Sec. I-A) and the area of the film, will yield the thickness.

We have examined the need for a fundamental unit of NTA response. For a new unit to be useful, the response of NTA film must be predictable in these units, and must be experimentally measurable in the units without excessive bother. We have found that the following concept of a track unit meets these requirements.

One track unit is the number of tracks per cm^2 of emulsion (normalized to the most frequent emulsion thickness, 33 μ) resulting from 10,000 neutrons per cm^2 incident normally on the back of the film packet. Thus the track unit is a direct measure of the efficiency of the NTA film packet as a neutron detector. The track unit is a function of the energy of the incident neutrons.

B.(3) Use of the track unit. In order to demonstrate the usefulness of the track unit concept, we now show how the response of NTA film to neutrons of various energies may be predicted; and how we determine the experimental response of this film.

(1) Thermal and low-energy neutrons. Knowing the nitrogen density of the emulsion, we may readily compute the response of the film to both thermal and slow neutrons. We assume there is no track contribution from the plastic backing or the paper covering; and we ignore correction for those protons released near the edge of the emulsion and which leave the emulsion before creating a recognizable track. For a 33-μ emulsion this correction is about 5%. The following equation predicts the response in track units:

$$10^4 \rho_N \sigma_{n,p}(E)\, t.$$

For the nitrogen density we use 5.1×10^{21} atoms cm^{-3}; the thermal (n,p) cross section is 1.76×10^{-24} cm^2/atom; and for emulsion thickness t we use 0.0033 cm. The predicted response at this energy is 0.29 track unit. Assuming the nitrogen (n,p) cross section drops as $1/v$ from 1.76 at 0.025 eV, the predicted response to 1.0-eV neutrons is 0.047 track unit; and for neutrons of 100 eV the predicted response is one-tenth of this. Experimentally, we measure the track density of the film exposed to thermal neutrons (tracks per cm^3 of emulsion). To find this number, we must know the emulsion thickness of the undeveloped film[8] and the number of tracks (in depth) per

unit area.[3] We then normalize to 33-μ thickness and an exposure of 10^4 neutrons per cm^2. The response of NTA to thermal and slow neutrons is independent of the direction of incidence of the neutrons.

(2) Intermediate-energy neutrons. The NTA packet gives virtually no response to neutrons of energy between the eV range and 0.4 MeV.

(3) Fast neutrons. There are two sources of proton recoil tracks in NTA film packet emulsions: the hydrogen atoms in the emulsion and also the hydrogen atoms in the plastic backing and paper wrapping of the film. Let us consider the contribution of tracks from each source separately.

We predict the number of track units arising from the emulsion hydrogen with the help of the formula

$$10^4 \rho_{H^e} \sigma_H(E)\, t \left(1 - \frac{E_m}{E}\right). \quad \text{(See Appendix B)} \qquad (1)$$

Hydrogen density in the emulsion is 3.5×10^{22} atoms cm^{-3}; the elastic-scattering cross section for hydrogen for neutrons of energy E (the total cross section in this energy region) is 4.3×10^{-24} cm^2/atom at 1.0 MeV; emulsion thickness t is 0.0033 cm; and E_m is the energy of a recoil proton that leaves a barely detectable track. For the scanning technique at Lawrence Radiation Laboratory in Berkeley we use an E_m of 0.40 MeV. In this prediction we also ignore the edge correction, which amounts to about 5% for 33 μ emulsion thickness. At 1.0 MeV the predicted response from the emulsion hydrogen is 3.0 track units. This source of tracks is also independent of the direction of the incoming neutrons. Appendices A and B examine the importance of the direction of incident neutrons in the response of the NTA packet.

J. E. COOK derived an exact equation giving the response of an emulsion due to protons radiated from a hydrogenous film base[4]. The derivation is for neutrons incident normally on the radiator; it is exact only for neutron energies E such that the thickness of the radiator exceeds R(E), the range in the radiator of proton recoils of this energy. Cook's result for $T > R(E)$ is

$$10^4 \rho_{H^r} \sigma_H(E) \left[\frac{2}{2n+3} R(E) - \frac{2}{3} R(E_m) + \frac{4n}{6n+9} R(E_m) \left(\frac{E_m}{E} \right)^{3/2} \right]. \quad (2)$$

In this equation the hydrogen density is that of the film base for back normal exposures, or that of the front outer wrappers for front normal exposures. Following Cook, we set $R(E) = aE^n$. For neutrons of E= 1.0 MeV, R(E) is 0.00177 cm, and n is 1.63. $R(E_m)$ is 0.00040 cm. This equation gives the radiator response of NTA packets to 1.0-MeV neutrons as 0.64 track unit for back normal incidence, and 0.50 track unit for front normal incidence. The difference is due to the difference in hydrogen density of the radiators, not to their difference in thickness.

The Cook equation is no longer exact when R(E) exceeds the radiator thickness. For a front normal exposure, this thickness is 23.5 mg cm^{-2}, and for a back normal exposure (including wrappers and film base) 55 mg cm^{-2}. These are the ranges of a 4.0-MeV proton and a 6.5-MeV proton respectively. Therefore the radiated track response is the same for neutrons of energy less then 4 MeV, back-normal or front-normal incidence, except for the slight difference in hydrogen densities of the radiators. With neutrons of energy greater than 4 MeV, the direction of incidence is important. In this case, response to back normal incidence is greater because of greater radiator thickness.

In Appendix B, we extend Cook's analysis to cover the case where incident neutrons are of greater energy than that corresponding to the range

of recoil protons equal to the radiator thickness $\left[R(E) > T\right]$. The result is an approximation correct to within a few per cent for the NTA packet:

$$10^4 \rho_{H^r} \sigma_H(E)\, T \left[1 - 0.70\left(\frac{T}{R(E)}\right)^{0.45}\right], \text{ for } R(E) > T . \qquad (3)$$

Here T is the radiator thickness: 0.0185 cm front-normal, and 0.0440 cm back-normal. For 14-MeV neutrons with back normal incidence we calculate a response of 7.9 track units, using 3.8×10^{22} atoms cm^{-3} for ρ_{H^r} – a weighted combination of the hydrogen densities in the film base and in the paper wrapper, both of which serve as the proton radiator. For neutrons of this energy, incident normally on the front of the packet, this relationship gives 3.2 track units.

We predict the total proton-recoil track response of the NTA packet to neutrons of a given energy by adding the "radiator" response to the response from the hydrogen in the emulsion. For 1.0-MeV neutrons, this amounts to 3.6 track units.

To report the response in track units of NTA packets experimentally exposed (back normal) to fast neutrons, we first determine the number of tracks (in depth) per unit area scanned. We then refer to the predicted fraction (Table II) of the response which depends on emulsion thickness. This fraction of the response we adjust to 33-μ thickness. We add this result to the remaining fraction of the response and normalize to 10,000 neutrons cm^{-2} exposure.

In this section we have introduced the track unit of NTA packet response. We have shown how to predict this response and how to report the response of experimentally exposed packets in these units. We now present the results of experimental exposures of NTA packets to neutrons of known energies (Table III). We compare with this the predicted response of the NTA packet (Table I.I and Fig. 2)

V. DISCUSSION

BEISER reports a density of 3.64 g cm^{-3} for dry NTA emulsion[5]. This corresponds to about 3.3 g cm^{-3} at 50% relative humidity (21°C), and is 10% lower than our value of 3.60 g cm^{-3}. We use a stopping power of 2000 for NTA emulsion (with respect to air) rather than the 1750 given by Yagoda[6]. Table IV gives the computed sensitivity limits of NTA emulsion, based on a minimum rate of energy loss in air of 0.030 MeV cm^{-1} given in an Eastman Kodak Data Sheet dated "6-58".

A 10 KeV electron creates a two-to three-grain "track". When NTA packets receive an X-or gamma-ray exposure, the background or fog in the developed film consists of one to three grain tracks (see Fig. 3). The presence of three grain electron tracks sets a lower limit for unequivocal detection of proton tracks. This limit is a four-grain track which is the range of a 0.26-MeV proton. In practice, we find that a six- to seven-grain track (the range of a 0.4-MeV proton) is our limit of detection.

Working with "30-μ" NTA emulsion, CHEKA reports a thermal neutron response of 0.23×10^{-4} track per neutron[7]. Normalized to 33 μ this is 0.255 track units, or 13% less than our value of 0.29 track unit.

HANDLOSER examined the energy response of NTA packets[8]. He uses the response unit of tracks per 25 fields per exposure of 10^6 neutrons cm^{-2}. If we normalize* his result for PoBe neutrons to ours, we obtain a value for his "field": 1.69×10^{-4} cm^2. If we use this value, and assume that his emulsions were 33 μ thick, we may compare his results with ours in track units (t. u.) in Table V.

CHEKA found an NTA packet response of 4×10^{-4} track per neutron for fission neutrons of mean energy 1.5 MeV[9]. Normalized from 30 to 33 μ, this is 4.3 track units. We predict 4.2 track units for this energy.

At Hanford, WATSON found a response of 6.9×10^{-4} tracks per neutron (t/n) with the NTA packet for PuBe neutrons[10]; and at Canoga Park, HART and HALE found an identical response for PoBe neutrons[11]. We compare their values in t/n with ours in track units (t.u.) in Table VI.

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APPENDICES

A. Intensity, Energy, and Range of Proton Recoils vs Lab Angle

Figures 6 through 9 describe the intensity, energy, and range of proton recoils vs lab angle (the angle the recoils make with the incident neutron direction). The figures refer to S-wave scattering, which obtains, to good approximation, for neutrons below 20 MeV.

Intensity (or number of recoils) per unit solid angle $dn/d\Omega$ is proportional to the cosine of the lab angle. Figure 6 represents the actual intensity distribution of recoils in space. For a detector of given aperture at a constant distance from the origin, the maximum intensity occurs at 0 deg. or head-on.

The energy and range figures are not intensity distributions. One should consider them envelopes or surfaces which the end points of the E_p and R_p vectors generate. The range figure is correct for nuclear emulsion. For plastic radiators, the range follows the 1.7 power of the energy, not the 1.6 power. We obtain intensity per unit lab angle, $dn/d\theta$, by the product of the intensity per unit solid angle, $dn/d\Omega$, and the solid angle subtended, $\frac{d\Omega}{d\theta}$. The latter is proportional to sin θ, the former to cos θ. To recognize the meaning of this function see Figs. 9 and 10. At $\theta = 45$ deg, $dn/d\theta$ is maximum because when $d\theta$ revolves about the axis of the figure, it generates the conical shell which cuts the maximum area on the surface of the intensity sphere. At $\theta = 0$ deg, $dn/d\theta$ vanishes because when $d\theta$ revolves about the figure axis it cuts a vanishingly small surface on the intensity sphere. Figure 9 does not represent a space distribution of recoils; it is useful, however, in visualizing the fraction of the total recoils scattered forward into certain acceptance angles. For instance, 25% of the recoils enter a cone of half angle 30 deg., 50% a cone of half angle 45 deg., etc.

(cont.)

The intensity sphere surface concept is useful to achieve an isotropic exposure of film to a neutron source. To do this, place the film at the tip of a spinning rod and construct a hypothetical spherical surface about the film (see Fig. 11). Then arrange apparatus that allows the source to slide on the surface (along a 180-deg arc as shown) in such a way that the surface is "painted" or exposed evenly as the sphere spins with the film. To do this, the duration of the source at any angle θ must be proportional to sin θ. In practice it is difficult to devise a mechanical system which moves a source sinusoidally along an 180 deg arc. As an approximation to sinusoidal motion, we place the source at 6 to 8 angular positions on the arc and make the duration or each exposure proportional to the sine of its angular position.

B. Derivation of the Basic Equation for Radiator Proton-Recoil Film Response

The function (flux) $\rho_{H^r}\,\sigma(E)$ gives the number of recoils originating per unit volume of the radiator. This must be fortified by an effective radiator thickness x, and a fraction $(E-E_{min})/E$, to give that portion of the recoils entering unit area of the emulsion (see Figs. 12 and 13). For monoenergetic neutrons of incident energy E, E_{min} varies with x, and x varies from 0 to $R(E)-R_m$, for $T>R(E)$, or from 0 to $T-R_m$ for $R(E)>T$. If the neutrons are not incident normal to the radiator, new limits on E_p and on x must obtain.

Basic equation:

$$10^4\,\rho_{H^r}\,\sigma(E)\int_x\int_{(E_p)_{min}}^{E}\frac{dE_p}{E}\,dx \qquad \text{(Normal incidence)}, \qquad \text{(B-1)}$$

where

$10^4 = 10^4 n\ cm^{-2}$,

ρ_{H^r} = hydrogen density of radiator,

$\sigma(E)$ = hydrogen cross section at neutron energy E,

E_p = proton recoil energy. (See Fig. 14).

Limits on E_p for the first integration:

$(E_p)_{max} = E$, $(E_p)_{min} = E \cos^2 \theta_{max}$,

but $\cos \theta_{max} = \dfrac{x}{R(E \cos^2 \theta_{max}) - R_m} \doteq \dfrac{x + R_m}{R(E \cos^2 \theta_{max})}$.

Let $R(E)$ be of form aE^n,

then $\cos \theta_{max} \doteq \dfrac{x + R_m}{a(E\cos^2 \theta_{max})^n}$,

and $(E_p)_{min} = E \cos^2 \theta_{max} \doteq E \left[\dfrac{x + R_m}{R(E)}\right]^{\frac{2}{2n+1}}$.

Basic Equation after the first integration:

$$10^4 \rho_{H^r} \sigma(E) \int_x \left[1 - \left(\frac{x + R_m}{R(E)}\right)^{\frac{2}{2n+1}}\right] dx \ . \qquad \text{(B-2)}$$

Limits on x for the second integration:

$x_{min} = 0$, $x_{max} = R(E) - R_m$, or $T - R_m$, if $R(E) > T - R_m$.

COOK has solved this problem exactly for the case $x_{max} = R(E)$,[4] so we examine only $x_{max} = T - R_m$ here.

Basic Equation after the second Integration, with $R(E) > T$:

$$10^4 \rho_{H^r} \sigma(E) \left[T - R_m - \frac{2n+1}{2n+3} T \left(\frac{T}{R(E)}\right)^{\frac{2}{2n+1}} + \frac{2n+1}{2n+3} R_m \left(\frac{R_m}{R(E)}\right)^{\frac{2}{2n+1}}\right]. \qquad \text{(B-3)}$$

For R(E) >T; E >4.0 MeV for front-normal incidence and E>6.5 MeV for back-normal incidence. For E>4.0 MeV, n = 1.8. In this case, the second and fourth terms are very small and we obtain the final result, correct to within a few per cent with R(E) > T:

$$10^4 \rho_{H^r} \sigma(E) T \left[1 - 0.70 \left(\frac{T}{R(E)} \right)^{0.45} \right] . \qquad \text{(B-4)}$$

This relation gives the radiator response of the NTA packet to neutrons of energy E(4.0 - 20 MeV) incident normally. The front-normal or back-mormal response may be obtained if appropriate ρ_{H^r} and T values are used.

To find R(E), the range of a proton recoil of energy E in the radiator, we refer to RICH and MADEY, who tabulate the range of protons in plexiglas $(C_5H_8O_2)$[12] which very closely approximates cellulose triacetate $(C_6H_8O_4)$. From Rich and Madey we obtain:

$$R(E) = 0.00177E^{1.63} (0.4 < E < 2),$$

$$R(E) = 0.0016E^{1.77} (2 < E < 10),$$

$$R(E) = 0.00146E^{1.81} (10 < E < 50).$$

R(E) is in cm if E is in MeV. In this analysis one should note that E is the energy of the incident neutrons and R(E) is the maximum range of a recoil proton after colliding with a neutron of this energy.

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Table I.

Chemical composition of NTA emulsion at 50% relative humidity (21°C)

Element	Density (g/cm^3)	Atomic density ($atoms/cm^3$)
Ag	1.52±0.05	0.85×10^{22}
Br	1.09	0.83
I	0.050	0.024
C	0.33	1.65
N	0.119±0.004	0.51
O	0.44	1.65
H	0.058	3.5
S	trace	~0.01
Totals	3.60±0.06	9.00×10^{22}

Table II.

Comparison of Predicted and Experimental Response of NTA packet: f is the fraction of total back normal response originating in the emulsion.

Neutron energy	"Radiator" response (track units)		Emulsion response (track units)		f	Total response (track units)		Expt. Response (track units)		
	FN	BN				FN	BN	FN	BN	
thermal		0	(n, p)	0.295	1.0		0.295		0.29± .01	
1.0 eV		0	(n, p)	0.047	1.0		0.047		---	
10 eV		0	(n, p)	0.015	1.0		0.015		---	
0.40 MeV		0		0	---		0		0	
0.50 MeV		0.04		1.4	0.97		1.4		---	
0.60 MeV		0.13		2.15	0.94		2.3		1.9± .2	
0.80 MeV		0.355		2.75	0.89		3.1		3.4± .25	
1.0 MeV	(0.50)	0.64		3.0	0.82	(3.5)	3.6		3.7± .2	Mock fiss.
2.0 MeV	(1.50)	1.87		2.7	0.59	(4.2)	4.55		---	
4.0 MeV	(3.4)	4.26		1.9	0.31	(5.3)	6.2	(5.0± .2)	6.4± .1	PuBe
6.0 MeV	(4.5)	6.3		1.55	0.20	(6.0)	7.8		---	
8.0 MeV	(4.2)	7.5		1.25	0.14	(5.4)	8.75		---	
10. MeV	(3.9)	8.0		1.1	0.12	(5.0)	9.1		---	
14. MeV	(3.2)	7.2		0.78	0.10	(4.0)	8.0	(4.7± .4)	8.3± .8	
20. MeV	(2.5)	6.0		0.56	0.085	(3.1)	6.6		---	

Table III.

Experimental response of NTA packets to neutrons of various energies. Exposures were determined by long counters. Our microscopic "field" is 0.00060 cm^2. FN is front-normal; BM is back-normal. The mean energy of mock fission neutrons is near 1.0 MeV; that of PuBe neutrons is near 4.0 MeV.

Film No.	Neutron energy (MeV)	Exposure ($n\ cm^{-2}$)	Tracks (Fields)	Background (t/f)	net response (t/f)	Thickness (μ)	Track units	Incidence	Time	Distance (cm)
13-4,13-5	thermal	4.5×10^8	1234/200	0.14	6.0	25	0.29 ± 0.01			
14-10	0.40	1.0×10^8	119/100	0.17	1.0	33	0.17 ± 0.02	FN	2 hr	10
14-11	0.60	1.0×10^8	112/10	0.17	11.0	33	1.85 ± 0.20	FN	2 hr	10
14-12	0.80	1.0×10^8	205/10	0.17	20.33	33	3.4 ± .25	FN	2 hr	10
13-1	mock fiss.	5.0×10^6	102/80	0.15	1.133	33	3.8 ± 0.4	FN	70 hr	145
13-2	mock fiss.	1.0×10^7	103/45	0.15	2.12	33	3,5 ± 0.4	FN	70 hr	103
13-4	mock fiss.	5.0×10^7	92/8	0.15	11,4	33	3.8 ± 0.4	FN	70 hr	46
2-1,2-2	PuBe	2.3×10^7	1107/154	0.18	7.0	33	5.0 ± 0.2	FN	25 hr	22
152	PuBe	8.0×10^7	3096/100	0.10	30.8	33	6.4 ± 0.1	BN	72 hr	20
172	14.5	6.5×10^6	103/31	0.08	3.24	30	8.3 ± 0.8	BN	25 min	37
171	14.5	3.6×10^6	112/100	0.10	1.02	30	4.7 ± 0.5	FN	2-1/2 hr	20

Table IV.

Sensitivity limits of NTA emulsion.

Particle	Maximum kinetic energy detected (MeV)	Minimum rate of energy loss (MeV cm^{-1})	Maximum detectable velocity (c)	Range (μ)	Maximum δ-ray[a] energy (keV)	Maximum δ-ray[a] frequency (cm^{-1})
Electron	0.010	60	0.20	1.5	---	----
Mu mesons	3	60	0.20	300	---	----
Protons	20	60	0.20	1800	44	96
Deuterons	40	60	0.20	3700	---	----
Alpha	200	60	0.40	9000	---	----

[a] Walter H. Barkas, in High-Energy Particle Physics, University of California Radiation Laboratory Report UCRL-2426 (rev.), ----Dec. 1959 (unpublished), p. 80.

Table V.

Comparison of NTA packet response in the region 0.4 to 2.0 MeV.

Neutron energy (MeV)	HANDLOSER[8] (t.u.)	This paper predicted (t.u.)	This paper Found (t.u.)
0.40	0	0	0
0.50	0.50	1.4	---
0.60	1.7	2.3	1.9±.2
0.80	3.8	3.1	3.4±.25
1.0	4.8	3.6	3.7±.2 (mock fission)
2.0	5.9	4.5	---
4.0	6.4 (PoBe)*	6.2	6.4±.1 (PuBe)*

Table VI.

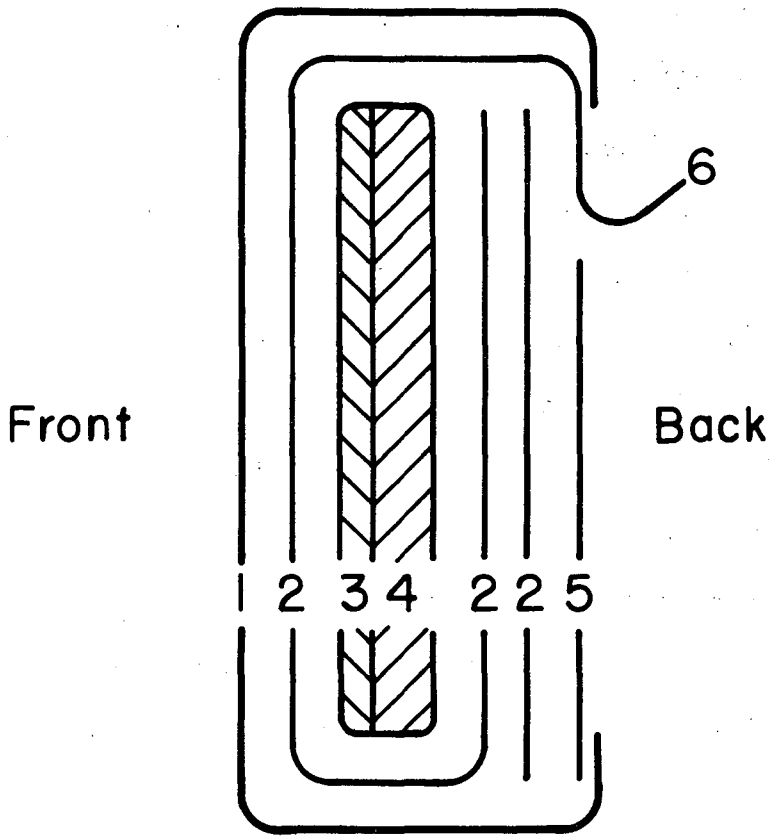
Comparison of NTA packet response in the 1- to 4-MeV region. FN is front-normal incidence, BN is back-normal incidence. (See Fig. 1.)

Neutron energy (MeV)	Orientation	WATSON[11] t/n	HART and HALE[12] t/n	This paper Predicted t.u.	This paper Found t.u.
1.0 (mock fiss)	FN	---	---	3.5	3.4 ± .25
1.0 "	End-on	---	---	---	3.3 ± .3
4.0 (PuBe, PoBe)	FN	6.9	6.9	5.3	5.0 ± .2
4.0 "	BN	---	6.9	6.2	6.4 ± .1
4.0 "	End-on	---	3.3	---	4.3 ± .2
4.0 "	Isotropic[a]	---	---	---	4.0 ± .3

[a] See Appendix A for a discussion of isotropic exposure.

FIGURE LEGENDS

1. Cross-section view of NTA film packet: (1) front outer wrapper, (2) inner wrapper, (3) NTA emulsion film, (4) plastic film base, (5) back outer wrapper, and (6) opening-tab.
2. Response of NTA packets to neutrons of various energies.
3. NTA Response to thermal neutrons at WBNS, Lawrence Radiation laboratory, Livermore. Note many 1-3 grain electron tracks. Upper right photo shows a typical $N^{14}(n,p)C^{14}$ 11-12-grain proton track.
4. Response of NTA Films Exposed at U.S. Naval Radiological Defense Laboratory, van de Graaff.
5. Response of NTA Film Exposed to PuBe Source, and to stray neutrons at the Bevatron. Mean energy of the stray neutrons was 0.4 MeV at the location where film 62 was exposed, but some neutrons of considerably greater energy were present.
6. Envelope of scattered proton-recoil intensity per unit solid angle vs lab angle θ; $d\sigma/d\Omega$ or $dn/d\Omega$.
7. Envelope of scattered proton-recoil energy vs lab angle θ.
8. Envelope of scattered proton-recoil range vs lab angle θ: $R_p \propto E_p^{1.6}$ for nuclear emulsion.
9. Envelope of scattered proton-recoil intensity per unit lab angle vs lab angle θ; $dn/d\theta$ or $d\sigma/d\theta$.
10. A sketch that helps to interpret $dn/d\theta$.
11. Use of intensity surface concept to obtain isotropic exposure of film.
12. Energy distribution of proton recoils from monoenergetic neutrons of energy E.
13. Normal and non-normal incidence and the limits of E_p and x. Dotted lines outline range envelopes.
14. The basic equation applied in a diagram.



Note:

Horizontal scale greatly enlarged.

MU-22608

Fig. 1.

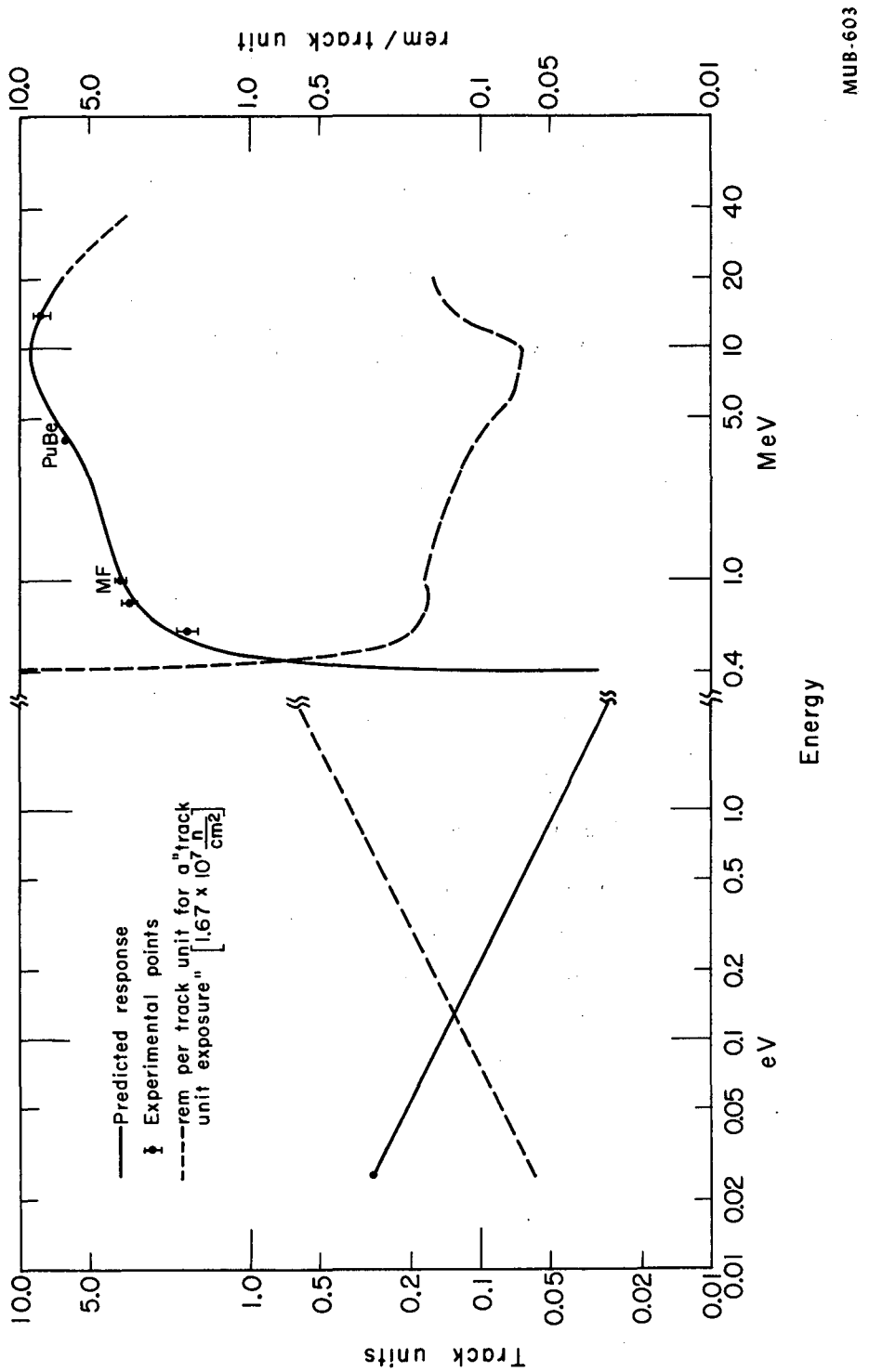
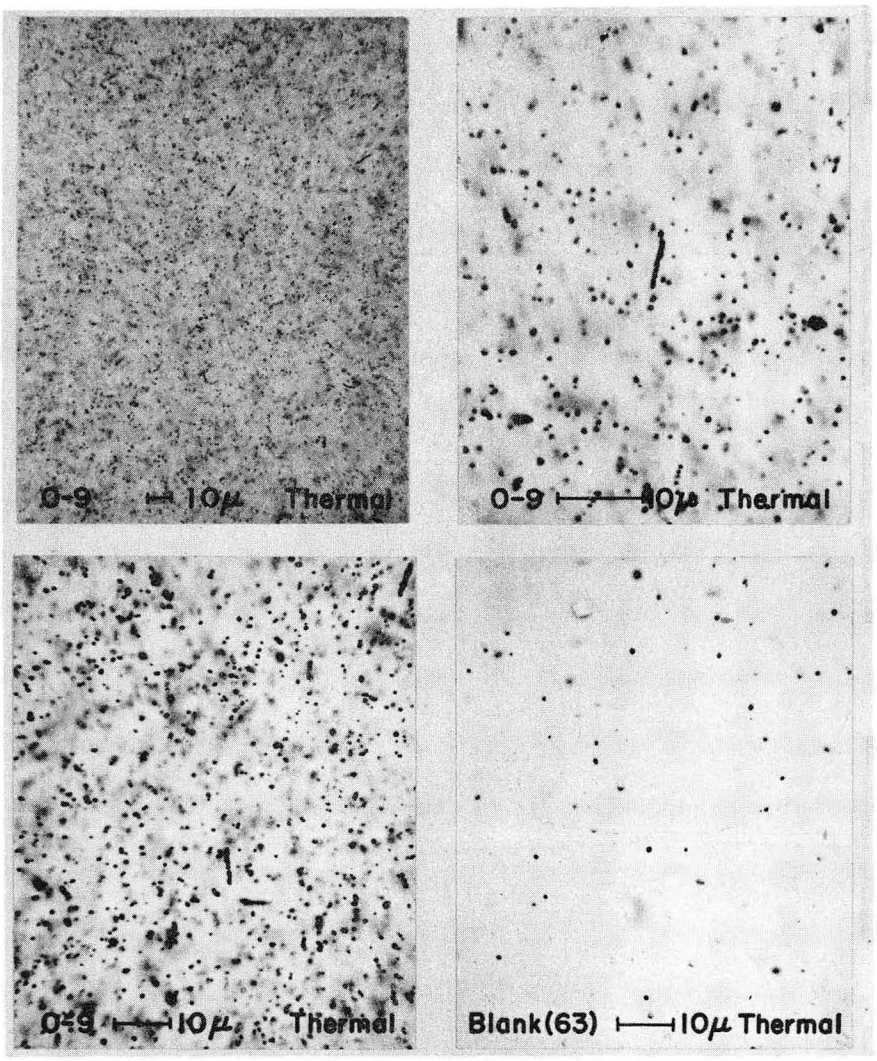

Track units
10.0
5.0
1.0
0.5
0.2
0.1
0.05
0.02
0.01
eV
0.01
0.02
0.05
0.1
0.2
0.5
1.0
MeV
0.4
1.0
5.0
10
20
40
rem / track unit
10.0
5.0
1.0
0.5
0.1
0.05
0.01
PuBe
MF
Predicted response
Experimental points
rem per track unit for a "track unit exposure" [1.67 x 10^7 n/cm^2]
Energy
MUB-603

Fig. 2.



NTA film 0-9
Exposure: $2.5 \times 10^9 \frac{\text{neutrons}}{\text{cm}^2}$
Dose:~2.6 rem

ZN-2681

Fig. 3.

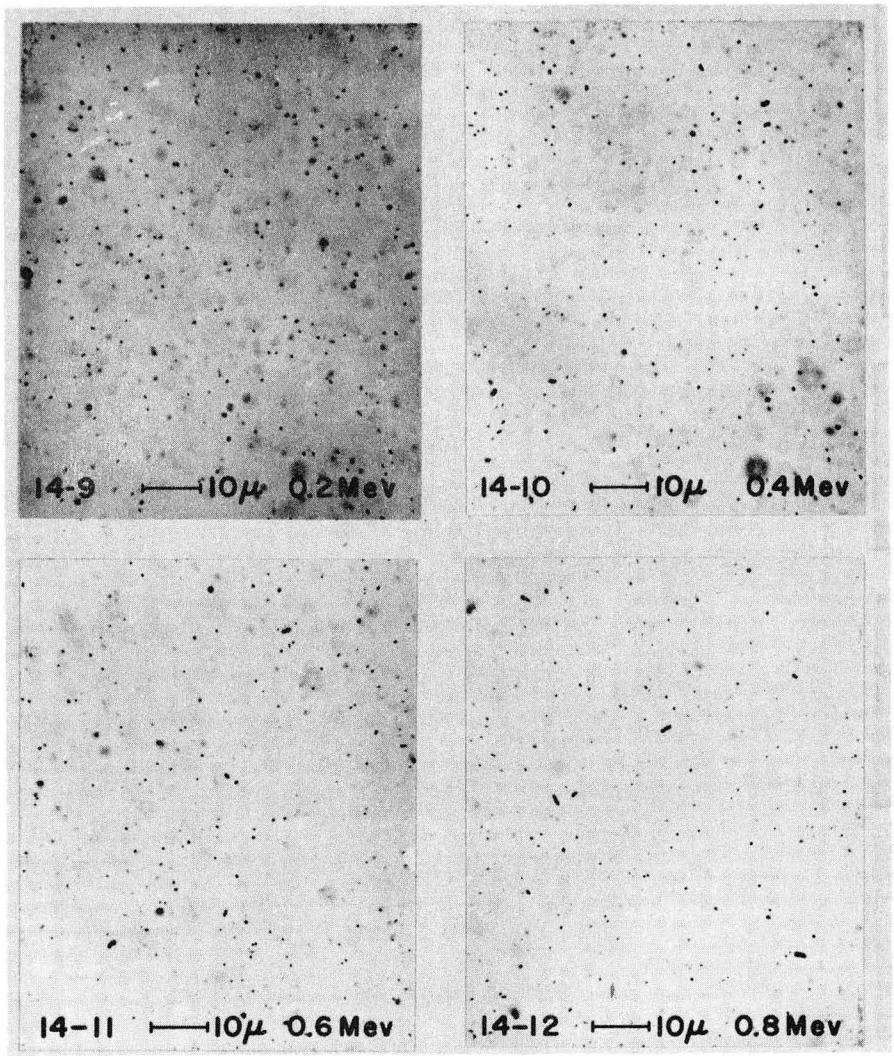
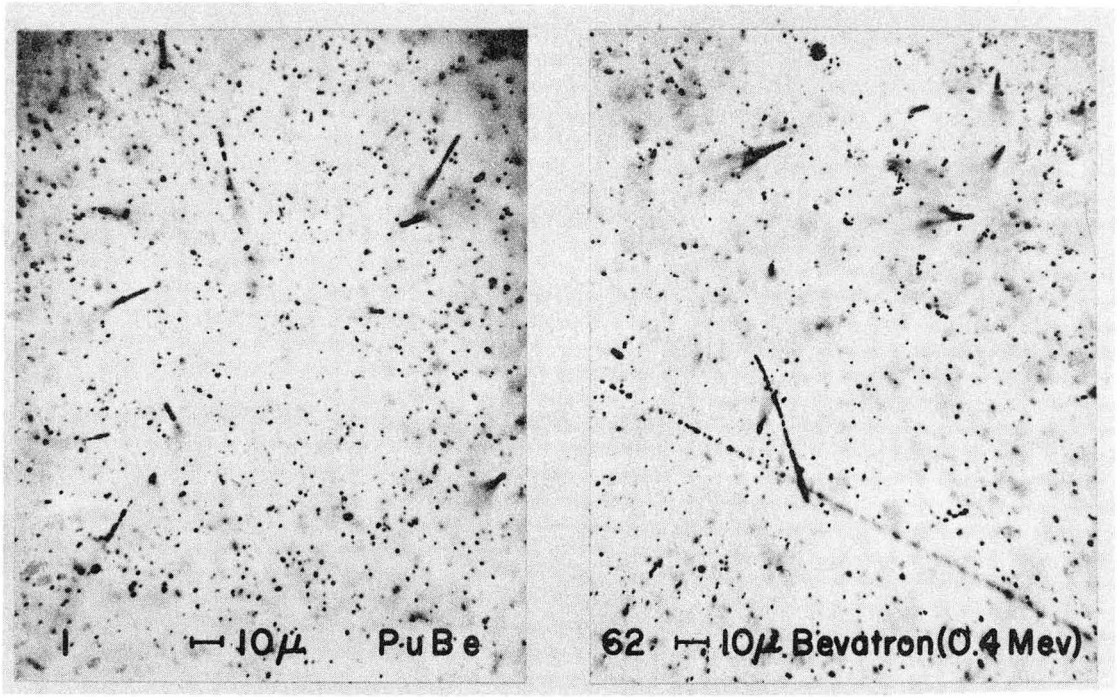

14-9 ⟵10μ 0.2 Mev
14-10 ⟵10μ 0.4 Mev
14-11 ⟵10μ 0.6 Mev
14-12 ⟵10μ 0.8 Mev
NTA films 14.9 to 14.12
Exposure: 1.0 x 10^8 neutrons/cm^2
Dose: 1-3 rem
ZN-2682

Fig. 4.



NTA films 1 and 62

Exposure 1: $1.4 \times 10^8 \frac{\text{neutrons}}{\text{cm}^2}$

62: $3.2 \times 10^8 \frac{\text{neutrons}}{\text{cm}^2}$

Dose~6 rem in each case

ZN-2683

Fig. 5.

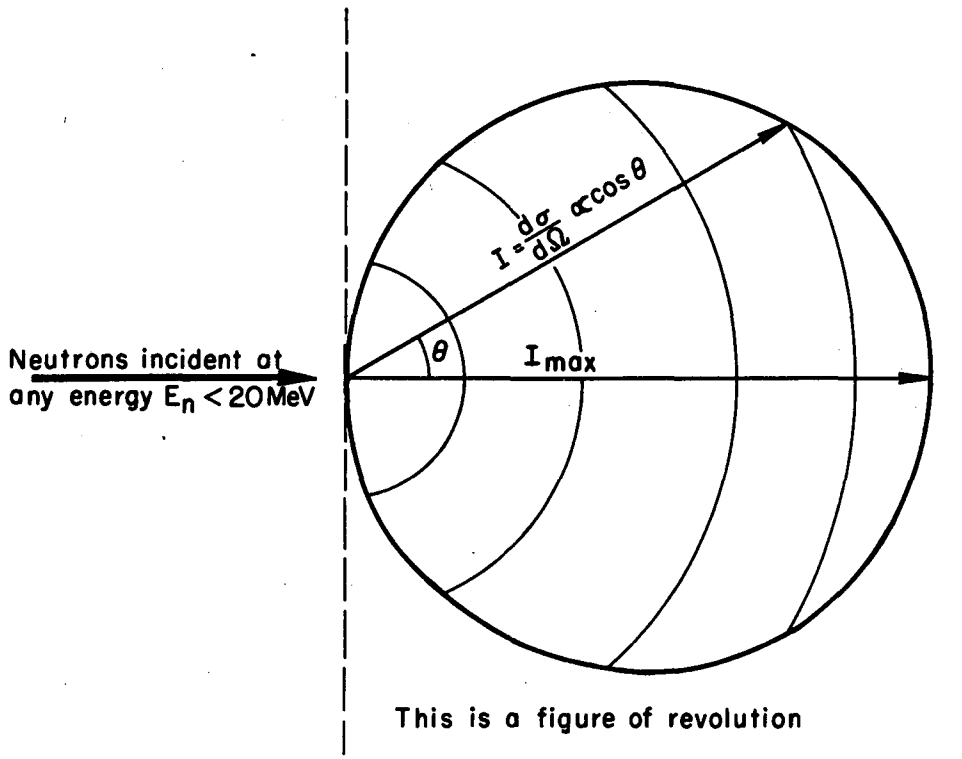

Neutrons incident at
any energy $E_n < 20$ MeV
$I = \frac{d\sigma}{d\Omega} \propto \cos\theta$
θ
I_{max}
This is a figure of revolution
MU-22609

Fig. 6.

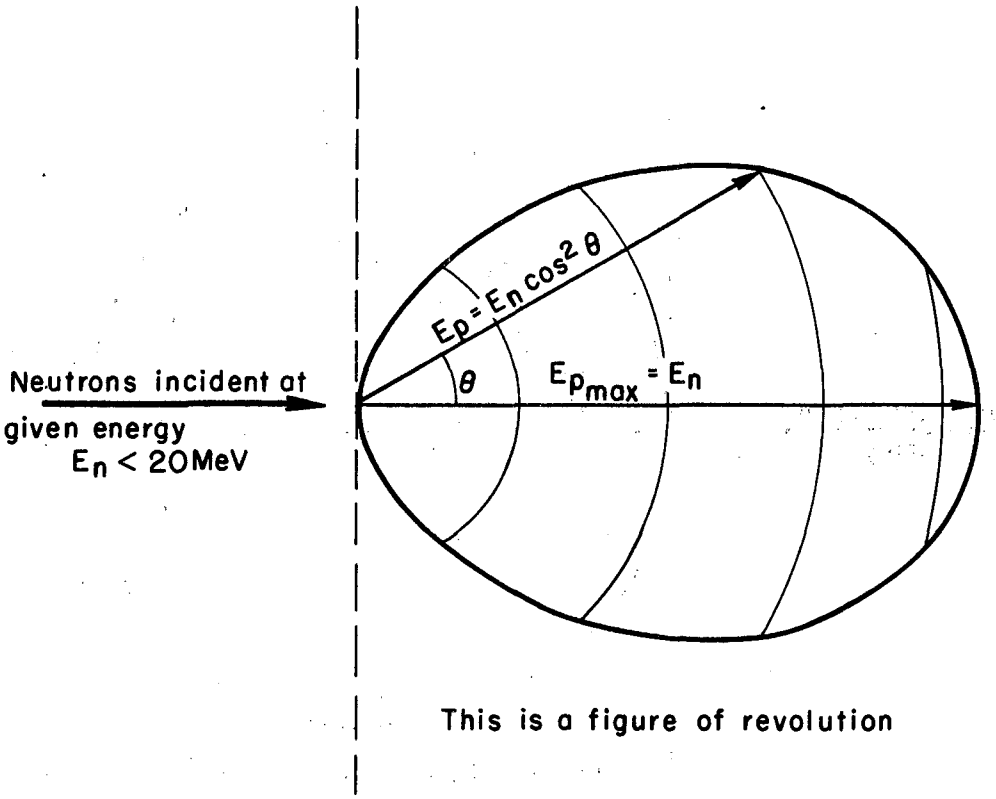

Neutrons incident at
given energy
$E_n < 20$MeV
$E_p = E_n \cos^2\theta$
θ
$E_{p_{max}} = E_n$
This is a figure of revolution
MU-22610

Fig. 7.

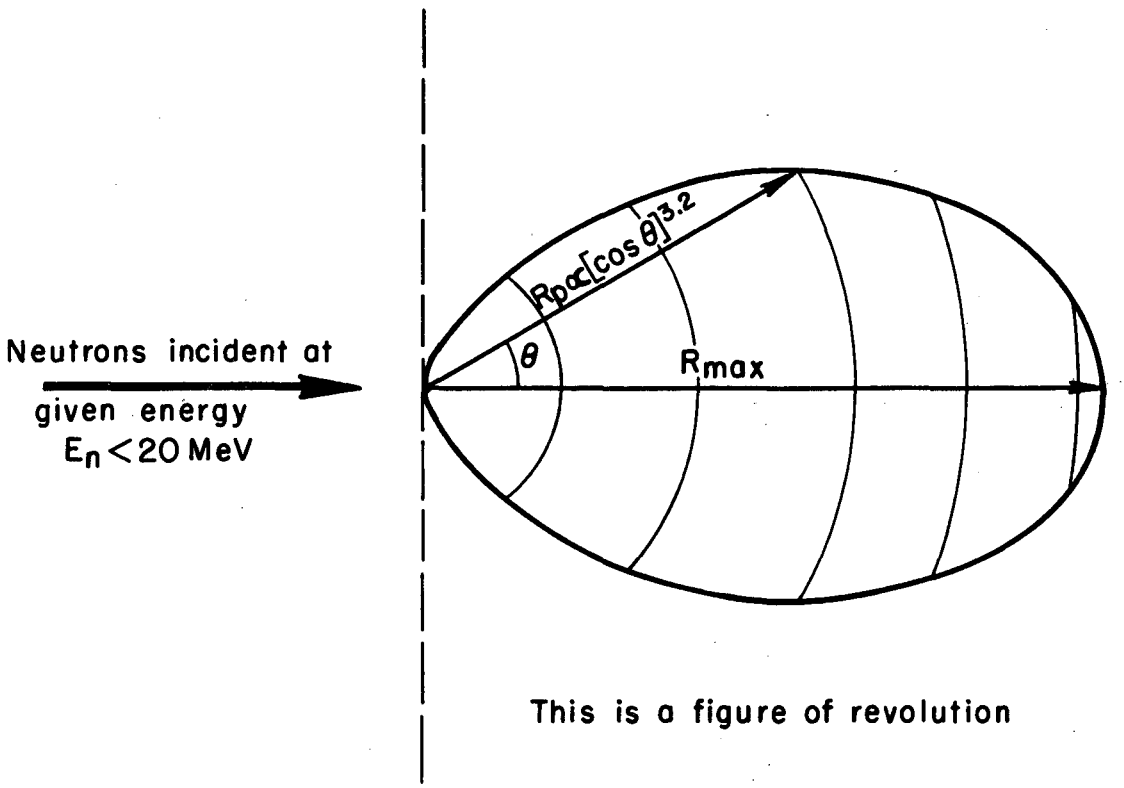
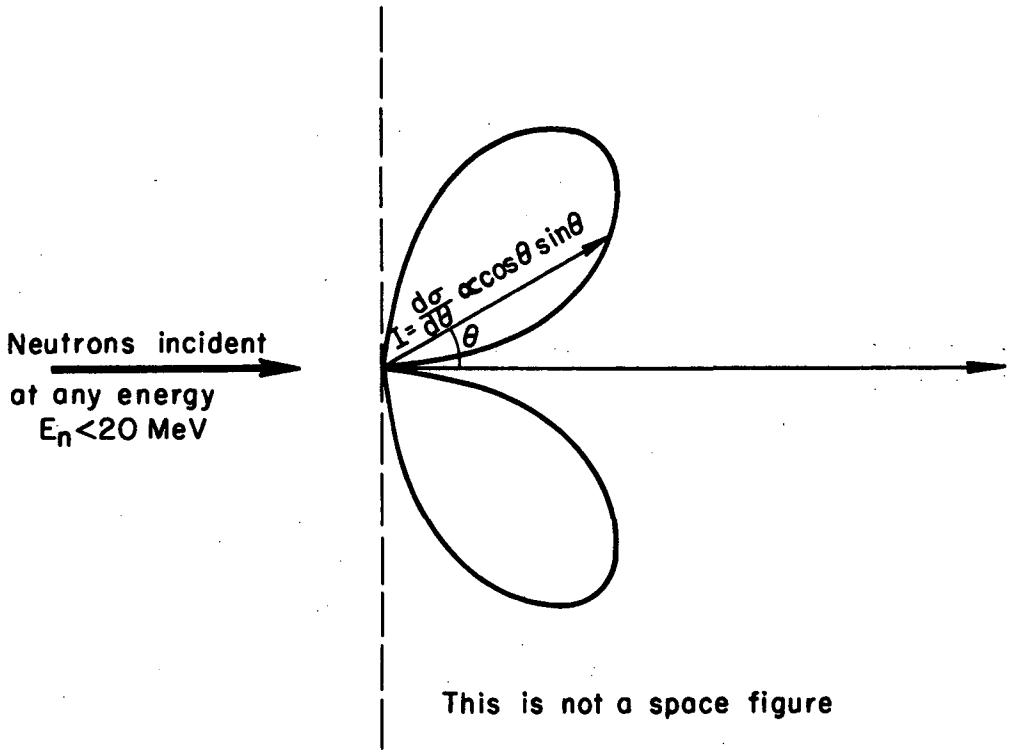

Neutrons incident at
given energy
$E_n < 20$ MeV
$R_\theta \propto [\cos\theta]^{3.2}$
θ
R_{max}
This is a figure of revolution
MU-22611

Fig. 8.



MU-22612

Fig. 9.

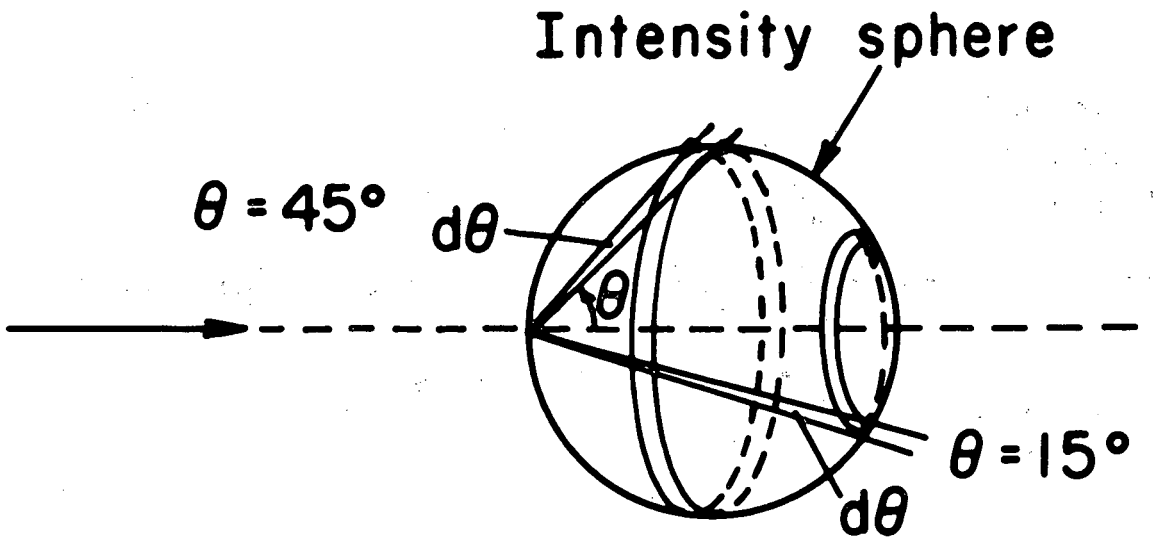


Fig. 10.

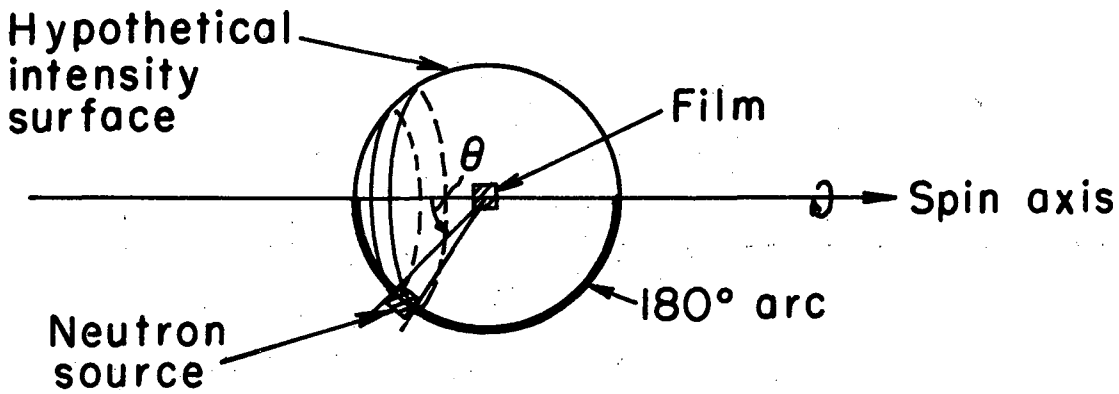
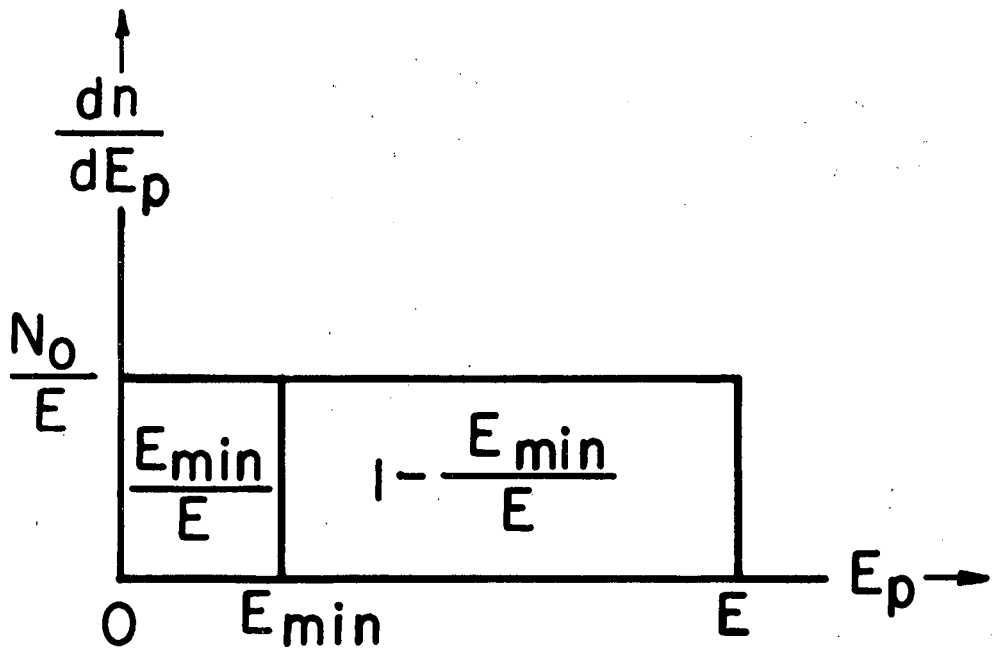
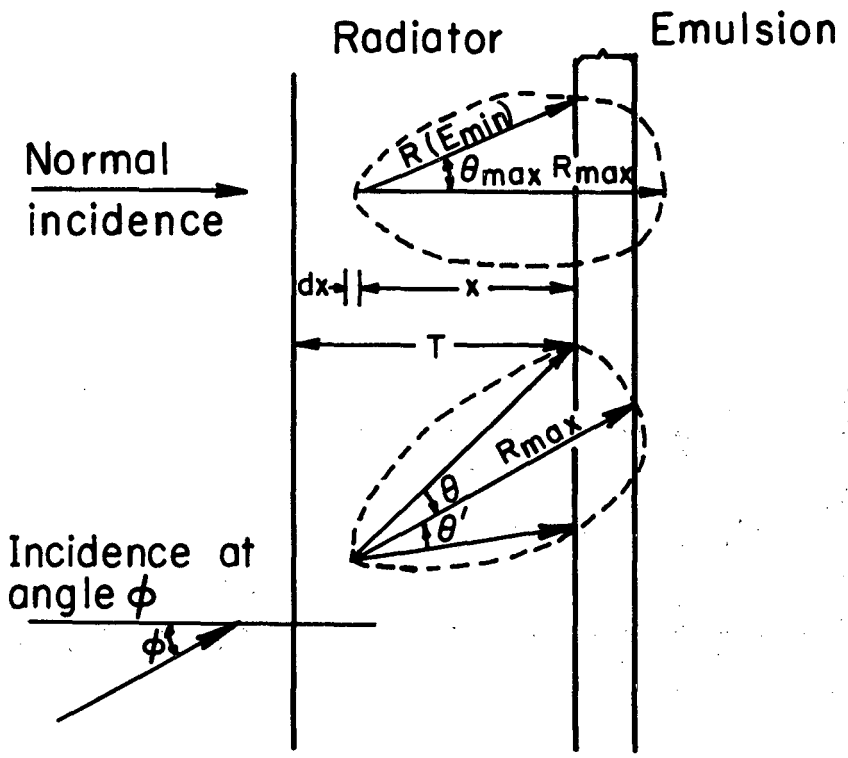

Hypothetical
intensity
surface
Film
θ
Spin axis
180° arc
Neutron
source
MU-22614

Fig. 11.



MU-22615

Fig. 12.



MU-22616

Fig. 13.

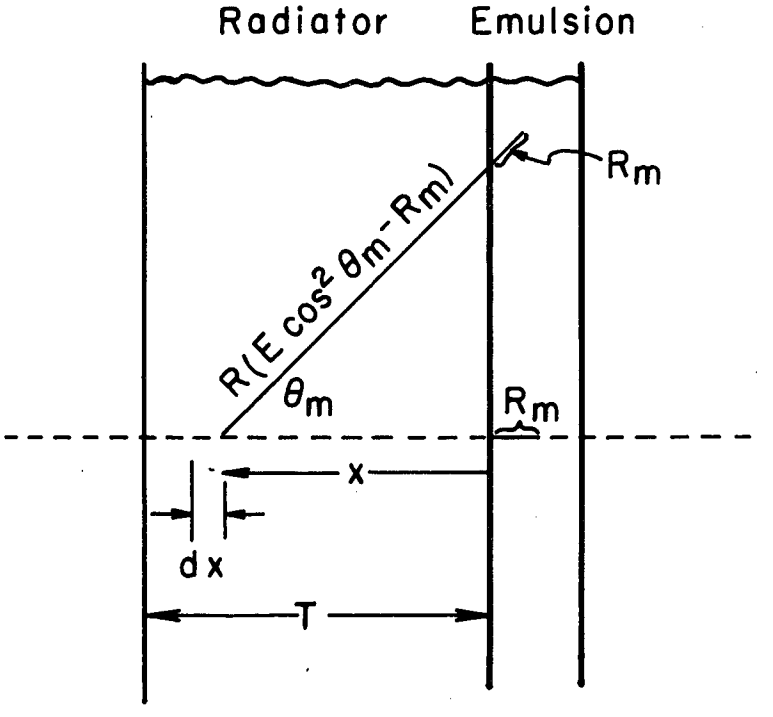


Fig. 14.