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THE ENHANCEMENT OF THE 14-MEV NEUTRON SENSITIVITY OF
SOLID STATE DETECTORS

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THE ENHANCEMENT OF THE 14 MEV NEUTRON SENSITIVITY OF
SOLID STATE DETECTORS

Abstract:

The enhancement of the 14 MeV neutron sensitivity of solid state detectors was experimentally measured and calculated when both hydrogenous and fission foils were placed in front of the detectors. Both the foils and detectors were designed in conjunction with diagnostic requirements at NTS to give the best possible sensitivity enhancement. Experimental results showed that the neutron sensitivity is not appreciably enhanced by the addition of either hydrogenous or fission foils. The hydrogenous foil enhanced the sensitivity by a factor of 1.6 while the fission foil produced no noticeable enhancement within the experimental error. Calculations agreed with experimental results within 30%.

Introduction:

Radiation fluxes of the type encountered at NTS are usually made up of both neutrons and gammas. It would be desirable if a detector could be designed with an enhanced sensitivity to one of these fluxes

over the other. This report is concerned with the design of a solid state detector to enhance the 14 MeV neutron sensitivity. Both a U-238, fission foil and a polyethylene (CH_2), hydrogenous foil are considered.

Previous Experimental Work:

Previous work in this area has been done by Solid State Radiations (SSR) in Los Angeles.¹ They observed a broad distribution of pulses from a series of pulse height spectra and found that this occurred whenever the detector was exposed directly to the neutron flux no matter whether the detector was bare or coated. The broad distribution was the result of the (n,p) threshold of 4.5 MeV in silicon. SSR concluded in general a detector coated with a hydrogenous foil can determine with better sensitivity the maximum energy neutrons in a certain high energy neutron flux than a detector coated with fissionable material can. Detectors coated with fission foils were found to have relatively poor sensitivity due to the small finite energy ranges of the coatings. This is in spite of the fact that fission fragment pulses can be distinguished from lower energy events. Detectors with hydrogenous foils have good sensitivities for observing high energy neutrons because of the relatively high (n,p) scattering cross section and the large number of hydrogen atoms present in many organic coating materials.

SSR designed a detector with hydrogenous material on either side of the silicon to increase the ratio of neutron to gamma sensitivity.² See Fig. 1. The best design obtained was a detector with a 25mm^2 area and a 100μ depletion depth. Entrance and exit windows were $1-2\mu$ and $<10\mu$ respectively. Reverse biases of up to 250 volts could be applied

with full depletion occurring at 60 volts. Sensitivities obtained were:³

Linac bremsstrahlung sensitivity -- 0.7×10^{-17} amps/ γ MeV/cm² sec.

14 MeV neutron sensitivity -- 2×10^{-16} amps/neut/cm² sec.

Calculations made by SSR show that a detector and hydrogenous foil are equivalent to the same detector with no foil and a depletion depth ten times as thick.

Theory:

Two types of detectors were used. The first, an LiD, had a 1350 μ depletion depth that was thick enough to stop a 14 MeV proton scattered out of a CH₂ foil. The thickness of the foil was 88 mils, the range of a 14 MeV proton in CH₂. The energy at which a proton is scattered out of a hydrogenous foil is obtained from the formula, $E_p = E_n \cos^2 \theta$, where E_n is the incident neutron energy and θ is the scattering angle of the recoil proton. The differential (n,p) scattering cross section for 14 MeV neutrons is:⁴

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_T \cos \theta}{\pi}$$

where σ_T is the total (n,p) scattering cross section for 14 MeV neutrons and equals 0.688 barns.

The second detector, a PIN, had a depletion depth of 125 μ . This is more than thick enough to stop 90 MeV fission fragments made in a U-238 foil since the range of a 90 MeV fragment in silicon is about 17 μ . Although a thicker depletion depth increases the gamma sensitivity, a compromise had to be reached between applied bias on the depletion layer

and dead layer thickness. Field use requires a large bias; fission fragments can penetrate only thin dead layers; SSR could guarantee only 1-3 volts of bias per micron of depletion depth for a 1μ dead layer. Thus, a detector with a 125μ depletion depth could be biased at only 200 volts. Although a higher bias was desired, the above detector together with a 20 mil, U-238 foil was used. The foil was also thicker than range-energy considerations required, but it was readily available, and it could be cooled to low temperatures without becoming extremely brittle. More will be said on the cooling shortly.

Fission fragments are made at many different energies, the spectrum peaking at two different energies for the average light and heavy fragments. 14 MeV neutrons incident on U-238 result in peak energies of 60.4 MeV and 89.7 MeV.⁵ The differential cross section for the production of fission fragments in U-238 from 14 MeV neutrons is:⁶

$$\frac{d\sigma}{d\Omega} = 0.305 \frac{(1 + .40 \cos^2 \theta)}{2\pi \sin \theta}$$

The integral of this quantity from 0 to π yields the total fission cross section of 1.15 barns.

Experiment:

The 14 MeV neutrons were obtained from an ICT, or isolated core transformer, machine. They are produced when an accelerated 0.5 MeV deuteron beam strikes a rotating tritium target cooled with water. Maximum fluxes varied between 7 and 8×10^{11} neut/sec over 4π . When the detector was positioned as close to the target as conditions would allow, the flux incident on the detector was about 5×10^8 neut/cm²sec.

A thin Pb foil was placed in front of the foil-detector system to stop protons, scattered off the CH₂ water jacket around the target, from reaching the detector.

Since the signals obtained were lower than the detector dark currents, the detectors had to be cooled. The effect of cooling the detectors with a mixture of dry ice and alcohol is seen in Fig. 2. The cooling chamber designed for this purpose is seen in Fig. 3. Care was taken in the design of the chamber to keep neutron scattering down.

All the detectors made by SSR can not be cooled. However, recently they designed for LASL an open-face detector, 2cm² in area with a 125μ depletion depth, which could be cooled to dry ice temperatures. See Fig. 4. Detectors with thicker depletion depths can be supplied with the same type of external housing. This was done for the LiD detector used in this experiment. The two connectors permit either positive or negative bias to be applied.

The 14 MeV neutron flux was monitored by activating thin Al foils. A record was kept of the time of day and total time the foils were exposed, and the betas emitted by the resulting Na²⁴ were then counted by chemistry. Usually 5 minute runs were made.

Gamma Calibration:

Calibration of the detectors to Co⁶⁰ gammas was done on the 3000 curie source. The detectors were cooled to keep expected signal levels above the dark current. The measured sensitivity of the bare PIN detector was 5.50×10^{-17} amps/γMeV/cm²sec while the calculated sensitivity was 7.41×10^{-17} amps/γMeV/cm²sec. The calculation, however, assumes electron equilibrium i.e., that those electrons emerging from the detector without being collected in the depletion depth are compensated for by electrons

made in a material placed in front of the detector.⁷ The sensitivity of the PIN detector was also measured with a 20 mil U foil in front; this value agreed with the calculated value within 3%. A 20 mil U foil is approximately the correct thickness to satisfy the condition of electron equilibrium.

Similar measurements were made with the LiD detector and the 88 mil CH₂ foil. The measured sensitivity of detector plus foil was 4.34×10^{-16} amps/ γ MeV/cm²sec. 88 mils was less than 0.1 of the amount required for electron equilibrium.

Codes:

Two separate codes were written by Robert Herrick to calculate the increased sensitivities of the solid state detectors when used with either U or CH₂ foils. These are now part of W. Mc Master's Semaphore Codes.⁸ Both codes carry out essentially the same manipulations; they differ only in particle ranges, energies, cross sections, and angular distributions. The codes divide the foil and the detector into a number of small segments and integrate over the particle path length using the range-energy curves. Particular results from the proton code are seen in Fig. 5.

The codes have the following restrictions:

1. The incoming neutrons must strike the foil at 90° and be mono-energetic.
2. All fission fragments are considered made with the same energy at all angles. The code is run twice, once for the light fragment and once for the heavy. The peak energies are used in each case, and the final results averaged.

3. Transmissions of the fission fragments and protons are not considered. This accounts for an error of about 3% in the proton code and about 6% in the fragment code.

4. No multiple scattering is considered. Integrations are over pathlength instead of energy.

Experimental Results:

Experimental results are listed in Table 1. Primary error in the measurements resulted from the unsteadiness at times displayed by the ICT beam. This resulted from a slight modification of the machine for a previous experiment. Unsteadiness in the beam during the length of time the machine was running caused error in the flux value determined by counting the betas from the activated Al foils. Beam unsteadiness was visible on the electrometer which read the D.C. signal current from the detector, and where this unsteadiness was significant, the run was repeated.

The only other error in the experiment came from the flux measurements. Chemistry quotes an absolute error of no more than $\pm 4\%$. Relative error is on the order of 1%. The efficiency of their counting equipment was re-determined by two separate methods shortly after this experiment was performed, and the new efficiency numbers agreed within 2% of the previous ones.

Discussion:

The above results indicate that the neutron sensitivity of a solid state detector can not be enhanced with a uranium foil. A detector used in conjunction with a hydrogenous foil can be designed to give a good ratio of neutron to gamma sensitivity as evidenced by the work of SSR. However, their detector is not practical for field use where high

bias and high current are important. The LiD detector and CH₂ foil used in this experiment are practical for field use, but the ratio of neutron to gamma sensitivity is reduced by a factor of 3.5 from SSR's ratio seen in Table 1.

JKB:gmo

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8. "Solid State Detector Signal per Incident Neutron from (n,p) Scattering in a Uniformly Irradiated Foil" (March, 1967) and "Solid State Detector Signal per Incident Neutron from Fission in a Uniformly Irradiated Foil" (July, 1967).

025-PIN-100

Fig. 1

Dark Current (amperes)

Fig. 2

COOLING SYSTEM

monocellular isofoam

Heavy lines are brass tubing (30-50 mils thick) except where indicated.

sides of lucite

back

drawn to scale

front

bottom

Fig. 3

Effective Area of Detector- 200mm^2

Fig. 4

Scale: 4x

Proton Code Results

Sensitivity $\times 10^{-15}$ $\frac{\text{amps}}{\text{neut./cm}^2 \text{ sec.}}$

K-E 10 X 10 TO THE CENTIMETER 46 1513
MADE IN U.S.A.
KEUFFEL & ESSER CO.

	(a)				(c)	(d)	(e)	
	Measured sens. (bare detector)	Measured sens. NTS (bare detector)	Measured sens. of detector and foil	Sens. due to foil only	Sens. due to foil from code	Sens. enhancement	Measured neutron to gamma ratio	SSR neutron to gamma ratio
PIN	2.40×10^{-16}	4.13×10^{-16}	2.40×10^{-16}	negligible	(b) 0.11×10^{-16}	1.0	3.13	29
LiD	2.22×10^{-15}	4.46×10^{-15}	3.63×10^{-15}	1.41×10^{-15}	1.98×10^{-15}	1.6	8.36	

In Table 1, the sensitivities in columns 1 through 6 refer to the neutron sensitivity in amps/neut/cm²sec. The ratios refer to the ratio of the neutron to gamma sensitivity. Gamma sensitivities are in amps/γMeV/cm²sec. The foil in front of the PIN detector was 20 mils of U; the foil in front of the LiD detector was 88 mils of CH₂.

- This detector was not an open-face type; it had brass housing around the front and sides of it.
- This is an average of code runs for both the light and heavy fission fragments. This value is within the experimental error so there is essentially no increased sensitivity due to the foil.
- The sensitivity enhancement is the ratio of the measured sensitivity of the detector and foil to the measured sensitivity of the bare detector.
- These ratios are for the detector plus foil.
- This ratio is for the special SSR design mentioned earlier in this report. The gamma sensitivity was measured with respect to a bremsstrahlung spectrum from a Linac instead of to Co⁶⁰ gammas.

TABLE 1

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