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A HIGHLY SENSITIVE SILVER-ACTIVATION DETECTOR FOR PULSED NEUTRON SOURCES*

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A silver-activation detector has been built and calibrated to measure the neutron yield produced by pulsed D(d, n) and T(d, n) sources. The detector has three principle virtues. Its high sensitivity (registering as little as 20 n/cm^2) results from 1.7 kg of silver incorporated into a plastic scintillator. Its modular design allows several efficiency vs energy responses to be obtained, including one configuration in which the efficiency is the same at 2.5 and 14 MeV. Also, the dynamic range spans five to seven decades of useful neutron intensity. Construction details and measured efficiencies are given.

1. Introduction

Detectors used to monitor short pulses from a neutron source generally must preserve the fluence information for analysis after the pulse. One neutron detector with such a capability is the activation detector, which captures neutrons to produce a radioactive species. The decay of this species must be distinct from the background and directly related to the incident neutron intensity. Activation detectors in which silver is the active element have been used for many years to measure neutron fluence from pulsed sources[1-4]. These instruments generally consist of a silver foil wrapped around a Geiger–Müller counter and enclosed within a hydrogenous moderator. Neutrons produced during the source pulse are slowed down to thermal energies in the hydrogenous moderator, then captured in the silver to produce ^{110}Ag(24.4 s half-life) and ^{108}Ag (2.43 min half-life). Subsequent beta decay of the activation products is counted with a beta-sensitive detector, and the neutron fluence is inferred from the beta activity.

The pulsed neutron detector developed at Los Alamos Scientific Laboratory[2]) (LASL) is in common use, and its response is well known. However, this instrument has insufficient sensitivity for some experiments where the neutron yield is low or where the neutron detector must be placed a considerable distance from the source. At the same time, high neutron fluences cannot be monitored with this detector because Geiger–Müller tubes saturate at relatively low count rates. In developing the detector described in this paper, our objectives were: to obtain a substantial increase in sensitivity over the LASL detector, to increase the useful range of neutron intensities by using a detector whose beta response is very fast, and to design a detector whose response is the same for 2.5 and 14 MeV neutrons. The last requirement was imposed on the design so that total yield measurements could be made in a simple way even for sources producing neutrons by both T(d, n) and D(d, n) reactions. When data are also available from a detector that is sensitive only to T(d, n) neutrons, such as that of ref. 5, then the relative contributions of T(d, n) and D(d, n) neutrons can be determined.

In the next section, we describe the design of the detector we have developed. Following that we discuss the calibration procedure and give the measured sensitivities for several moderator configurations.

2. Instrument construction

The detector described here resembles another highly sensitive detector designed by Severyn and Ellis[6]) but also meets the other two objectives listed above. It consists of 31 silver foils (101.6×203.2×0.245 mm) sandwiched between 32 plates of NE110* plastic scintillator, each 102.0×204.0×3.2 mm. The silver foils and plastic plates are assembled into a light-tight housing and optically coupled through a clear silicon rubber pad to a Lucite light pipe and an RCA 8575 photomultiplier tube, as shown in fig. 1. Beta de-

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* Reference to a company product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

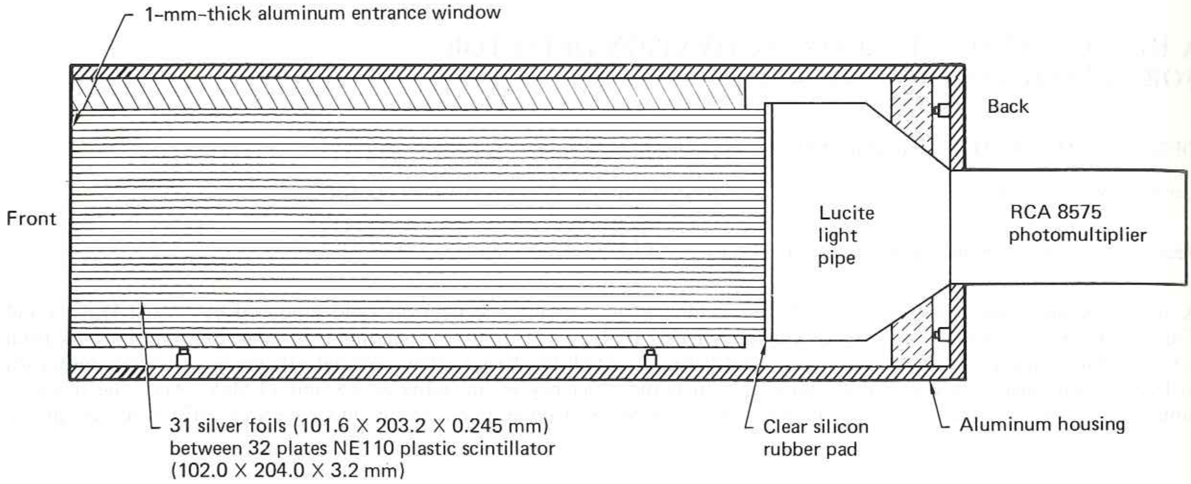

Fig. 1. Schematic of scintillator module.

cay of the silver causes scintillation in the plastic so that the pulse rate at the photomultiplier tube is proportional to neutron fluence. This scintillator module has been manufactured commercially* and

* Nuclear Enterprises, Inc., San Carlos, California.

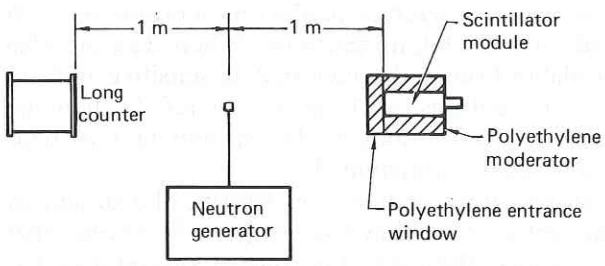

Fig. 2. Configuration used for testing efficiencies of silver-activation detector (moderated scintillator module). The entrance window is a solid sheet of polyethylene whose thickness is changed to get different energy responses. The long counter gives the actual neutron flux used to determine the efficiency.

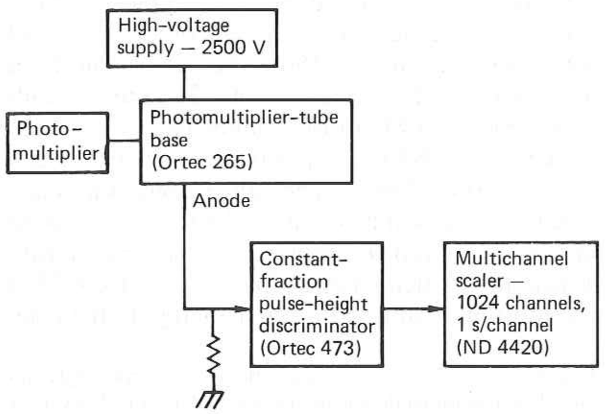

Fig. 3. Configuration of electronics for counting pulses from the photomultiplier tube.

can be modified to suit a variety of applications. Because the silver foil is thin compared to the range of β-particles in the silver, the sensitivity can be reduced, without changing the energy response, by a homogeneous reduction of the silver mass. This mass reduction can be accomplished by using thinner foils, foil strips, or foils with evenly spaced punched holes.

The scintillator module can be surrounded on the sides by up to 11.4 cm of polyethylene to increase its response to neutrons entering from the front and to suppress its response to thermal and epithermal neutrons entering from the sides. Configuration of the polyethylene blanket is shown in fig. 2. After a source pulse, beta decay of the silver is observed by counting the pulses at the anode of the photomultiplier tube using the counting system shown schematically in fig. 3.

3. Detector-efficiency measurements

We made efficiency measurements for this detector in a low-scattering cell at the Lawrence Livermore Laboratory calibration facility. Neutrons were produced by T(d, n) or D(d, n) reactions on a neutron generator whose output was measured using a long counter. Fig. 2 shows the arrangement of the source, long counter, and scintillation module. Adjustment of the pulse-height discriminator is critical. A ^{137}Cs source is used to produce Compton electrons up to 0.478 MeV in the plastic. The discriminator is set just high enough to eliminate any response to these when the ^{137}Cs source is placed on the side of the detector and within 30 mm of the front. This discriminator setting is reproducible within a few percent, and the resulting measured efficiency, within about 2%.

To determine the detector efficiency, the neutron beam was turned on and held at constant intensity (±5%) for at least 125 s so that the 24 s silver activity would reach approximate equilibrium. Then the neutron source was abruptly turned off and the beta decay of the silver was multiscaled for about 400–600 s. Fig. 4 shows a typical recording of this sequence, where the abscissa scale is 1 s/channel. At first, only the background is observed. Then the count rate increases to a plateau, which is due to recoil protons and beta decay causing scintillation during the irradiation. Finally, the source is turned off and the beta decay is observed alone. Examination of fig. 4 shows that the count rate after t_0 (the instant the neutron beam is turned off) varies with time t according to:

$$C(t) = C_1 \exp[-\lambda_1(t-t_0)] + C_2 \exp[-\lambda_2(t-t_0)] + B, \qquad (1)$$

where

λ_1 and λ_2 are the decay constants for ^{110}Ag and ^{108}Ag, respectively,

t_0 is the time at which the beam is turned off,

B is the constant background count rate,

C_1 and C_2 are constants to be determined.

Counting data obtained after t_0 are fitted with the function given by eq. (1), and values of C_1, C_2, and B are determined to give the minimum

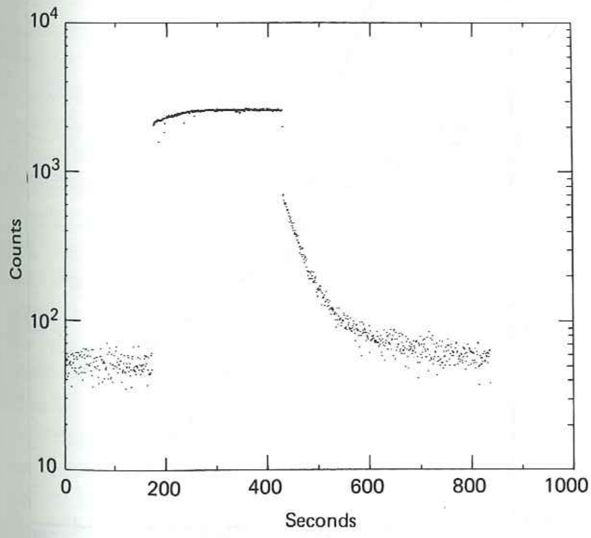

Fig. 4. Multichannel scaler data obtained during calibration of silver-activation detector. Data begins approximately 180 s before neutron beam is turned on and ends approximately 400 s after beam is turned off. The abscissa scale is 1 s/channel.

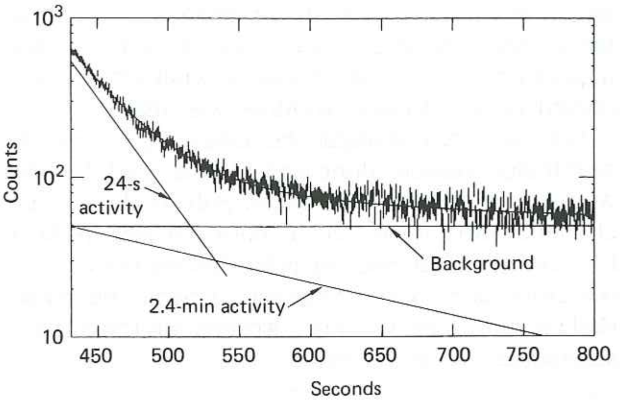

Fig. 5. A minimum chi-squared fit to the decay data in fig. 4 is used to determine the constant background count rate and the initial activities of 24.6 s ^{110}Ag and 2.4 min ^{108}Ag.

chi-squared. Fig. 5 shows results of applying this fitting procedure to the data of fig. 4. In this case chi-squared per degree of freedom is 0.3.

Detector efficiency ε is defined in terms of the ^{110}Ag decay rate after a short neutron pulse by:

$$\varepsilon \equiv C_1/\phi, \qquad (2)$$

where ϕ is the neutron fluence (n/cm^2) inferred at the front face of the scintillator module from the long-counter measurement.

For the purpose of this definition, the pulse duration is assumed to be much less than the detector decay time $1/\lambda_1$. In practice this detector is useful for pulses shorter than a few seconds. However, we were unable to produce short neutron pulses of known fluence for calibration. Instead, the efficiency was inferred from the decay rate following a long pulse as follows. A neutron source turned on at $t=0$ and held at constant intensity ψ for duration t_0 will produce the same 24 s beta activity at $t=t_0$ as will a short pulse of fluence ϕ so long as ψ and ϕ are related by:

$$\psi = \frac{\lambda_1 \phi}{1-\exp(-\lambda_1 t_0)}. \qquad (3)$$

Combining eqs. (2) and (3), we can infer the efficiency ε from the decay rate after a long exposure at constant intensity:

$$\varepsilon = \frac{\lambda_1 C_1}{\psi[1-\exp(-\lambda_1 t_0)]}. \qquad (4)$$

The count rate in the long counter was used to determine the intensity ψ at 1 m with an accuracy of about 5%. The long-counter sensitivity was assumed to be 3.10 counts per n/cm^2 at 2.5 MeV and 2.48 counts per n/cm^2 at 14 MeV [7]). The distance between the source and scintillator was maintained at 1 m regardless of whether or not a polyethylene entrance window was used.

We have determined the efficiency ε for the scintillator module alone and for the module sides wrapped in 5.8 and 11.4 cm of polyethylene. Each efficiency was measured at both 2.5 and 14 MeV for several thicknesses of polyethylene placed over the front face of the detector to form the polyethylene entrance window. Results of these measurements are given below.

4. Results

Detector efficiency ε, as it is defined here, is the count rate (in counts per second) at t_0 that results from the 24 s ^{110}Ag decay when the neutron fluence through the front face of the scintillator module is 1 n/cm^2. Fig. 6 shows ε measured for the detector module with various thicknesses of polyethylene entrance window. There was no polyethylene on the sides for these measurements, but a sheath of 1.5 mm cadmium was used to suppress thermal neutrons entering the sides. Note that the detector response to 2.5 and 14 MeV neutrons is the same when the entrance window is about 75 mm thick; the efficiency with this configuration is given in table 1. In these measurements, the scintillator module was held in a fixed position as layers of polyethylene were added to form an attenuating entrance window. Thus neutron fluxes ψ (determined by the long counter) were always inferred at 1 m from the source.

Fig. 7 displays the efficiency obtained when the sides of the detector module are covered with 58 mm of polyethylene instead of 1.5 mm of cadmium. Note that a 110 mm polyethylene entrance window leads to equal responses at 2.5 and 14 MeV and that this response (see table 1) is higher than was obtained when the detector had no polyethylene on the sides. Fig. 8 shows the results obtained when the detector sides are wrapped in 114 mm of polyethylene. The 2.5 and

TABLE 1

Detector configurations that give the same efficiency for 2.5 and 14 MeV neutrons.

Polyethylene window thickness (mm)	Polyethylene sidewall thickness (mm)	Efficiency ε $\left(\frac{\text{count/s}}{\text{neutrons/cm}^2}\right)$
75	0	0.180±0.015
110	58	0.252±0.015
90	114	0.325±0.015

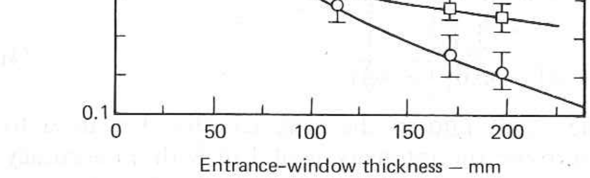

Fig. 6. Efficiencies of the detector without polyethylene on its sides.

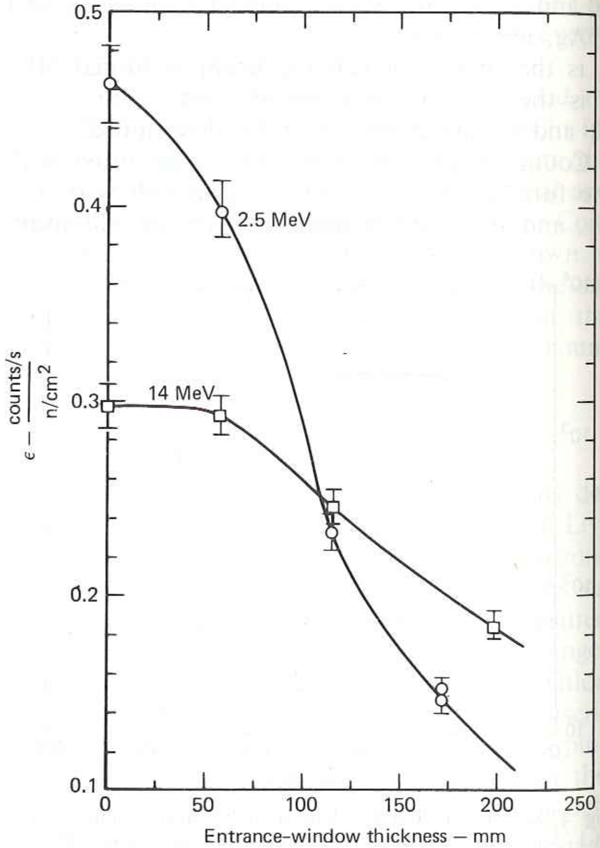

Fig. 7. Efficiencies of the detector with 58 mm thick polyethylene on its sides.

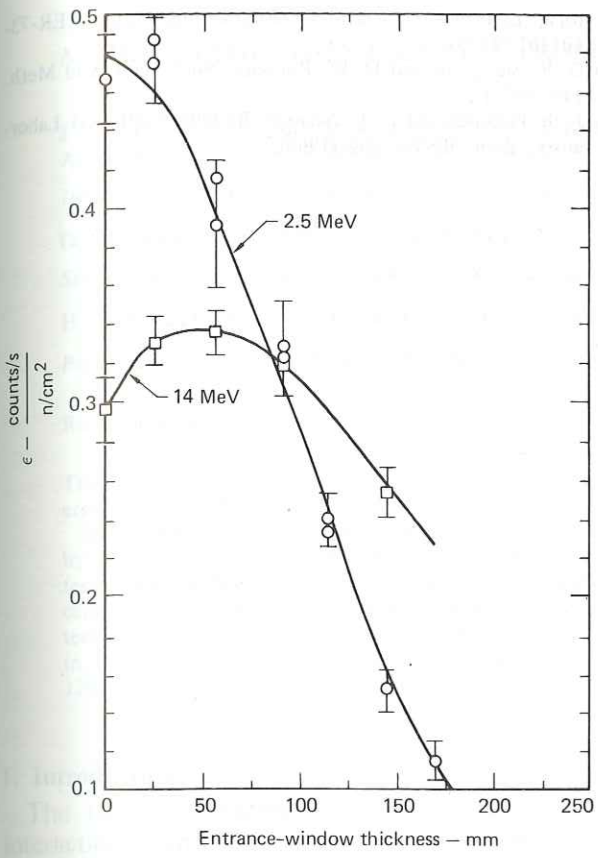

Fig. 8. Efficiencies of the detector with 114 mm thick polyethylene on its sides.

14 MeV responses are equal when the polyethylene entrance window is about 90 mm thick, and this response is still higher than those of the previous examples (see table 1).

The efficiency of this detector varies slowly with energy because the moderator and active element are long in the direction of the neutron flux. One weakness of this design is that low-energy neutrons produced by scattering in the environment of the detector can enter the sides and contribute to the activation. Exposures to a 14 MeV source and a ^{238}PuBe source from the front and the side of the detector show the response to be comparable for either front or side irradiation even at MeV energies. Consequently, the detector described here should either be calibrated in place and used in a constant scattering environment, or used in an environment in which neutron scattering is insignificant. We found that collimation from a 57 mm thick blanket of polyethylene lined with 1.5 mm of cadmium reduced the side response to MeV neutrons by about 40%, and, presumably, the response to low-energy neutrons by more than this. However, the front response was also reduced by a similar amount. A more complex collimator, resembling that used in the De Pangher[8]) long counter, might be more effective in increasing the ratio of front to side response.

5. Conclusion

The objectives given in the introduction have been attained in a relatively simple design, and the detector has been manufactured commercially. Various efficiency and energy characteristics can be obtained by varying the polyethylene-blanket and entrance-window thicknesses. For the most sensitive configuration giving equal efficiencies at 2.5 and 14 MeV, the efficiency of this detector is approximately 20 times that of commonly used silver-activation detectors. A user of this detector would most likely not use multiscaling and curve fitting to determine the neutron fluence but would instead count the beta activity for a fixed period of time and subtract the previously measured constant background. One can use the efficiency data reported here to infer the efficiency for a given counting period by integrating eq. (1). Sensitivity of the system then depends on background rate, length of count, and the signal level taken as indicating the presence of neutrons. For a background level of 50 counts/s, and a counting interval of 60 s, the detector will register a signal that is 3σ above background for a fluence of about 20 n/cm^2 at the front face of the scintillator module. The scintillator module can be used at count rates as high as about 10^7 counts/s, so fluences of about 5×10^6 n/cm^2 can be monitored without removing any silver plates. Of course, any homogeneous reduction of the silver mass would allow monitoring of larger neutron intensities without changing the energy-response characteristics. In this design, the efficiency is proportional to the silver mass for foils up to about 0.25 mm thick. Thus, for sources up to a few seconds long, two or more slightly different detectors could be used to monitor neutron fluxes across five to eight decades of intensity.

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