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MONTE CARLO EFFICIENCY PREDICTIONS FOR A PORTABLE ^3H NEUTRON DETECTOR

Austin A. O'Dell

October 20, 1976

Prepared for U.S. Energy Research & Development
Administration under contract No. W-7405-Eng-48

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5255 Port Royal Road
Springfield, VA 22161
Price: Printed Copy \$: Microfilm \$3.00

Page Range	Domestic Price	Page Range	Domestic Price
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026-050	4.00	351-375	10.50
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Contents

Abstract	1
Introduction	1
Detector Description	2
Efficiency Measurements	4
Monte Carlo Simulations	8
Results and Discussion	10
Acknowledgments	15

MONTE CARLO EFFICIENCY PREDICTIONS FOR A PORTABLE ^3He NEUTRON DETECTOR

Abstract

We have built a small, man-portable neutron detector using 18 ^3He proportional counters arranged in 3 banks within a polyethylene moderator. Each counter is 25 mm in diameter and 340 mm long (sensitive length) and is filled with highly purified ^3He to a pressure of 400 kPa (4 atm). Measurements of the detector efficiency were made using a calibrated ^{252}Cf

neutron source. Then, independent calculations of the detector efficiency were performed with the TART Monte Carlo transport code. In this report, we compare calculations and measurements for several source/detector arrangements and moderator configurations to evaluate the accuracy of the TART code in predicting the efficiency of small ^3He neutron detectors.

Introduction

We have built an experimental neutron detector for locating small quantities of misplaced nuclear materials. The detector is roughly the size of a large attaché case and weighs about 13 kg (29 lb). It could be hand-carried and is thus well suited for searches in buildings or in other areas where access is limited. The detector consists of three identical banks, each with six cylindrical ^3He counters in a solid polyethylene moderator slab. Sheets of polyethylene moderator can be placed between the banks, in front, and in back to alter the overall moderator configuration.

The primary objective of this study was to determine how well the

TART Monte Carlo code can predict the efficiency of such a detector with various moderator configurations. Using a ^{252}Cf neutron source of known strength, we measured the efficiency of various detector designs. These experiments were then simulated using the TART code, and calculated efficiency values were obtained. Although the effects of thermal upscattering and molecular binding at low energies were not treated directly by TART, cross-section adjustments were used to provide first-order corrections. The measurements and calculations were then compared to assess the validity of TART simulation for other detectors with similar moderator/counter geometries.

Detector Description

As shown in Fig. 1, the detector was made up of three identical banks of ^3He counters, with added layers of polyethylene between and in back of the banks. This modular design permitted us to vary the moderator configuration easily and thus to evaluate the efficiency of a number of different arrangements.

As shown in Fig. 2, each detector bank was designed to have six cylindrical ^3He counters contained in a common moderator slab. To accommodate the ^3He counters, we machined six 26.4-mm-diameter cylinders in a polyethylene block 42 mm $\times$ 204 mm $\times$ 385 mm. A 9-mm-thick polyethylene

end plate secured one end of the bank, and a metal terminal box was attached to the anode-connector end of the bank. The anodes of all six counters were connected to a high-voltage coaxial feedthrough on one wall of the terminal box. The terminal box provided high-voltage protection and effective electrical shielding from external noise sources. The coaxial connector supplied high-voltage bias to the proportional counters and accessed the output signal for external monitoring.

As shown in Fig. 3, the proportional counters were 25.4 mm in diameter and 413 mm long, with a sensitive length of 343 mm. They were manufactured by Reuter-Stokes as Model RS-P4-0814-205. The counters were filled with ultra-high-purity ^3He ($<10^{-16}$ mole % tritium) to a nominal pressure of 400 kPa (4 atm). The actual fill pressure of each counter was adjusted by the manufacturer to balance the output of all 18 counters operated at a common high-voltage bias of 1100 V. The stainless steel anode wire was nominally 51 μm in diameter.

The moderator slabs were fabricated using high-density stress-relieved polyethylene.

Fig. 1. Detector assembly.

Fig. 2. Detector bank sketch
(dimensions are in mm).

Because of its superior mechanical properties, this material maintained good stability through machining operations and exhibited only minimal warpage. The measured average density of the stock used was 0.92 ± 0.01 Mg/m³.

The overall dimensions of the assembled detector depend on how much additional polyethylene is used. A typical detector assembly would measure approximately 180 mm × 205 mm × 435 mm and would weigh approximately 13 kg (29 lb).

Fig. 3. ^3He proportional counter.

Efficiency Measurements

The detector efficiency measurements were performed at the Z-Division low-mass tower. The experimental arrangement is shown in Fig. 4. The tower has an overall height of approximately 17 m, including a top-mounted handling crane. The two landings (decks) are located at 6.5 m and 13 m above the ground and are accessible by a stairway along one side of the tower structure. An instrumentation van, located approximately 10 m from the tower,

serves as a field laboratory for data acquisition and analysis. Cables to accommodate input test pulses, output signals, and regulated power are permanently installed between the van and a patch panel on the top deck of the tower. A security fence encloses the entire facility.

Each bank of the detector was monitored separately during the tower experiments. The instrumentation used is shown in Fig. 5. The six ^3He counter anodes for a given

Fig. 4. Tower experimental arrangement.

detector bank are electrically tied together and routed to a Tennelec 164 charge-sensitive preamplifier. The Canberra 814 main amplifier has two outputs: a linear output directed to a Northern-Scientific 910 multichannel pulse-height analyzer and a discriminator (logic) output routed to a Tennelec 555 scaler. The scaler data for all three banks is recorded by a Shephard 201 daisy-chain printer. Regulated high voltage (+1200 V dc) is provided by a Tennelec 941 power supply. An ORTEC 480 pulser is used for calibrating and checking the monitoring circuitry. Pulse-height spectra are recorded using a Hewlett-Packard 7004B x-y plotter attached directly to the multichannel analyzer.

The typical pulse-height spectrum shown in Fig. 6 was obtained using a ^{252}Cf source in a polyethylene/lead "WD-1" container. The prominent

Fig. 5. Monitor electronics block diagram.

Fig. 6. Typical pulse-height spectrum.

peak near channel 840 is the so-called thermal peak resulting from ${}^3\text{He}(n,p){}^3\text{H}$ reactions for thermalized neutrons. This peak corresponds to complete deposition of the 0.764 MeV of kinetic energy (reaction Q) shared between the proton and the triton. The spectrum tail extending down to lower pulse heights (channels) represents those events for which incomplete energy deposition occurs, primarily because of a collision of the proton or triton with the counter walls. The abrupt decrease in the spectrum observed near channel 200 occurs where the proton energy is absorbed at the walls and only the

triton energy is deposited in the counter gas. The kinematics of the reaction place this threshold at 0.191 MeV (channel 205), as observed. The low energy region of the spectrum (below channel 80) is produced by gamma radiation from the ${}^{252}\text{Cf}$ source, as can be easily verified with a pure gamma-ray source. In the region of the spectrum between channels 100 and 160, very few events are observed. By setting a pulse-height discriminator within this region, we effectively reject unwanted detector events produced by gamma ray interactions.

In our experiments, we used two different source positions and four

moderator configurations. The source positions are indicated in Fig. 4. In position 1, the source was almost midway between the detector and the ground, and the source-to-detector distance was 6.24 m. In position 2, the source was 1.0 m above the detector (14.1 m above the ground). In both series of tests, the detector was oriented with bank 1 closest to the source. Thus, incident source neutrons always entered the detector through bank 1. As shown in Fig. 1, the moderator configurations tested differed only in the thickness T of polyethylene inserted between bank 1 and bank 2. A series of preliminary experiments were performed to estimate the range of detector efficiency for various amounts of added moderator. As a result of these measurements, we selected four values for T (0, 12.7, 25.4, and 38.1 mm) that produced significant changes in the response of each detector bank.

Background and source data were accumulated for the four moderator configurations with the source placed at both positions. These measurements were taken and repeated over a

period of approximately 4 months. The observed background count rate was roughly the same for each moderator configuration and was remarkably constant during this period. The average background was approximately 0.55 counts per second per bank. For the source-in measurements described in this report, background contributed approximately 1% and 20% to the 1.0-m and 6.24-m results, respectively.

The ^{252}Cf source was calibrated by the Lawrence Livermore Laboratory (LLL) Hazard Control Calibration and Standards group on 27 March 1973. A precision long counter was used to compare this source with a $^{238}\text{Pu-Be}$ source calibrated previously at and by the National Bureau of Standards. Correcting for the 2.65-year half-life of ^{252}Cf , we calculated the source strength at the time of our measurements to be $(1.3 \pm 0.1) \times 10^5$ neutrons per second.

The detection efficiency was determined for each bank by computing the ratio of the net count rate to the number of primary neutrons per unit time incident on the front surface of bank 1.

Monte Carlo Simulations

The LLL TART Monte Carlo transport code was used to simulate the experiments described above. The TART collision routine tracks source and secondary neutrons in three-dimensional configurations through 175 energy groups from 15 to 1.31×10^{-9} MeV. Thermal upscattering and molecular binding effects are not explicitly treated. Free-atom cross sections can be combined for any homogeneous isotopic mixture within a given spatial region (zone). The TART code uses a built-in, evaluated, cross-section library developed and maintained by LLL. Any part of this library can be readily modified or replaced by user input.

Hydrogen atoms in polyethylene are not free atoms but are bound within long chains of CH_2 molecules. At neutron energies below ~ 1 eV, molecular effects on neutron moderation become important in polyethylene and other common moderator materials. As demonstrated in Fig. 7, thermal motion of hydrogen atoms produces an effective $\frac{1}{v}$ dependence for the elastic cross section at low neutron energies. A thermalized neutron spectrum is produced both by "downscatter" collisions, where incident neutrons slow down, and by "upscatter"

collisions, where incident neutrons gain kinetic energy. In addition, the excitation by the neutrons of vibrational or rotational molecular states can result in nonelastic or hyperelastic (energy gain) interactions in CH_2 . Such nonelastic collisions can produce significant cross-section and collision-spectrum changes. Finally, interference effects, produced by neutron scattering from spatially correlated targets, can increase or decrease the effective bound-hydrogen cross section, depending on the phase (sign) and amplitudes of the scattering.

Fig. 7. Hydrogen elastic cross section. See E. Melkonian, Phys. Rev. 76, 1750 (1949).

As stated previously, the primary objective of this study was to evaluate the use of TART, a fast-neutron Monte Carlo code, to simulate slow-neutron phenomena. We clearly had reason to question whether the TART free-atom collision model is sufficiently detailed to describe low-energy interactions with molecule-bound hydrogen. We attempted to correct the model partially by adjusting the carbon and hydrogen elastic cross sections for the polyethylene moderator. Five cross-section sets were constructed based

on modifications of the 13 TART energy groups below ~1 eV. These sets are defined in Table 1. The first set, labeled UTL (unmodified TART library), is that normally used in TART. Cross-section sets A, B, C, and D have each been adjusted to provide the correct elastic cross section for the ethylene group (CH_2) based on the bound-hydrogen data shown in Fig. 7. In set A, we have smoothly reduced the H cross section to zero below ~0.1 eV and have increased the C cross section appropriately. This was done in an effort

Table 1. Cross-section sets.

Energy group	Lower bound, eV	Elastic cross section, b/atom									
		UTL set		Set A		Set B		Set C		Set D	
		H	C	H	C	H	C	H	C	H	C
1	1.31×10^{-3}	20.5	5.1	0	201.1	20.5	160.1	67.0	67.0	98.0	5.1
2	5.23×10^{-3}	20.5	5.0	0	135.0	20.5	94.0	45.0	45.0	65.0	5.0
3	2.09×10^{-2}	20.5	5.0	0	104.6	20.5	63.6	35.0	34.5	49.8	5.0
4	3.27×10^{-2}	20.5	5.0	0	94.6	20.5	53.6	32.2	30.3	44.8	5.0
5	4.70×10^{-2}	20.5	5.0	0	83.0	20.5	42.0	28.6	25.7	39.0	5.0
6	8.32×10^{-2}	20.5	4.9	1.0	68.9	20.5	29.9	24.8	21.3	33.0	4.9
7	1.31×10^{-1}	20.5	4.9	6.0	51.3	20.5	22.3	22.5	18.4	29.2	4.9
8	1.88×10^{-1}	20.5	4.9	10.0	37.3	20.5	16.3	20.9	15.5	26.2	4.9
9	2.56×10^{-1}	20.5	4.9	12.5	28.5	20.5	12.5	20.1	13.4	24.3	4.9
10	3.34×10^{-1}	20.5	4.9	15.0	21.7	20.5	10.7	20.2	11.4	23.4	4.9
11	4.23×10^{-1}	20.5	4.8	16.5	16.8	20.5	8.8	19.9	10.0	22.5	4.8
12	5.12×10^{-1}	20.5	4.8	18.3	11.2	20.5	6.8	19.8	8.1	21.5	4.8
13	7.53×10^{-1}	20.5	4.8	20.0	6.4	20.5	5.4	20.0	6.5	20.8	4.8
	1.18										

to simulate scattering on bound hydrogen by increasing the effective target mass. In set B, the free-atom values have been retained for H, and in set C, the cross sections have been adjusted to obtain equal collision probabilities for C and H. Finally, set D was constructed using free-atom values for C and CH_2 -bound values for H. These five cross-section sets do not, of course, correct for thermal upscattering.

The detector was modeled directly by use of quadratic/plane zone boundaries allowed in TART. The ^3He counters were simulated by ^3He -filled cylinders in the polyethylene moderator block. The measured density of polyethylene (0.92 Mg/m^3) was used in the calculations. The ^3He density was computed assuming ideal-gas conditions at a fill pressure of 400 kPa. To reduce the number of Monte

Carlo runs required, we elected not to include the air or the ground in this model. As it was, detection efficiencies were determined to within 10% using between 4 and 12 min of CDC 7600 computer time per run. We estimated that including the air and the ground would have increased the computation time by at least a factor of 10. (Measurements were made at two source heights, permitting us to estimate the magnitude of ground scattering.) The spontaneous-fission spectrum of the ^{252}Cf source was represented by a Maxwellian distribution with an effective (nuclear) temperature of 1.43 MeV.

Calculations were performed for all five cross-section sets, assuming inserted polyethylene thicknesses of 0, 12.7, 25.4, and 38.1 mm between banks 1 and 2 and source-to-detector distances of 1.0 m and 6.24 m.

Results and Discussion

The measured efficiency of each bank for the two source-to-detector distances and four values of polyethylene thickness is shown in Table 2. The efficiencies represent the percentage of direct (uncollided) neutrons incident on the front surface that were actually detected by the bank in question. The average background rate at the tower facility

was approximately 0.55 counts/s for each bank; it was remarkably independent of bank position, moderator configuration, and time. The direct neutron incidence was computed based on the solid angle subtended by the front surface of the detector and on an average neutron mean free path in air of 80 m. Air-buildup and ground-scattering

Table 2. Measured detection efficiency.^a

Source-to-detector distance, m	Detector bank	Incident neutrons detected, %			
		Added polyethylene thickness, mm			
		0	12.7	25.4	38.1
6.24	1	7.2	8.8	9.6	10.9
	2	12.2	13.2	12.9	12.6
	3	9.9	8.3	7.0	6.2
1.0	1	4.4	5.6	6.5	6.9
	2	8.5	9.4	9.4	8.5
	3	6.9	5.7	4.7	3.7

^a Average background = 0.55 ± 0.05 counts per second per detector bank. Counting statistics error < 1%; overall estimated error $\leq 3\%$. Air attenuation correction for the 6.24-m measurements was based on an average neutron mean free path of 80 m.

effects were not considered. Counting-time intervals were chosen to keep statistical errors below 1% after background correction. The overall error in the measured efficiency values (Table 2) was estimated to be less than 3%.

The measured efficiencies at 6.24 m are 40 to 60% larger than the corresponding 1.0-m values. The difference can be attributed mainly to ground scattering. At 6.24 m, the source is effectively midway between the detector and the ground. Table 2 also shows that the effect of added polyethylene thickness T is different for each bank. Initial observations of these differences

led to selection of the particular moderator thicknesses used in the experiments. The sensitivity of bank 1 increases with increasing T , as expected. The greater polyethylene thickness behind this bank scatters more slow neutrons back into the bank. The mean free path of neutrons in polyethylene varies from ~ 2 cm at 2 MeV to ~ 5 mm at 10 keV to ~ 2 mm at thermal energies. In moderated thermal detector such as ours, incident fast neutrons must first be thermalized in the moderator by multiple scattering. The resulting thermal neutrons must then escape from the moderator and be absorbed in the thermal-counter element. Because,

on the average, fast neutrons from a ^{252}Cf source will not penetrate more than ~60 mm in polyethylene, we expect that the bank 1 efficiency will not increase indefinitely. It should level out for values of T greater than ~50 mm. Such a trend is apparent in Table 2 even for $T \approx 30$ to 40 mm. For incident, slow (near thermal) neutrons, this saturation effect would occur at $T \approx 10$ mm.

It follows from this argument that the only neutrons actually detected by a moderated-thermal detector are thermal neutrons which are generated in and/or which diffuse into a region ~10 mm thick surrounding the thermal-counter element. Unfortunately, a fraction of these thermal neutrons will be absorbed by the moderator rather than the thermal counter. Thus, to detect fast neutrons, we need considerably more than 10 mm of polyethylene moderator because the fast neutrons must be thermalized. On the other hand, if the incident neutrons are effectively thermal, then little or no moderator is needed or desirable. To detect incident neutrons with an unknown energy spectrum (from thermal to a few MeV), some trade-off between fast and thermal detection efficiencies must be tolerated. The detector design must then be based on an

a priori evaluation of the expected neutron spectrum.

The sensitivity of bank 2 exhibits a maximum near $T \approx 20$ mm. That is, as T increases, the efficiency first increases, then levels off, and finally decreases. In this case, polyethylene is being added in front of the bank, and thus, an initial increase in thickness produces additional thermalization and greater efficiency. Beyond a certain point, however, added polyethylene only attenuates the slow flux in bank 2 by scattering and absorbing the neutrons.

For all measurements, a 12.7-mm-thick slab of polyethylene was inserted between bank 2 and bank 3, and a 25.4-mm slab was placed behind bank 3. This amount of moderator, together with that already included in bank 3, is sufficient to complete thermalization of the softened neutron spectrum that reaches the backmost position in the detector. Thus, increasing T can only reduce the neutron flux at bank 3.

The TART calculation results are summarized in Table 3. To avoid undue confusion, we present only those results necessary to illustrate the principal features of the calculations and to provide practical comparisons with the measurements. The calculated detection efficiencies

Table 3. Calculated detection efficiency (statistical uncertainty $\approx$ 5-10%).

Source-to-detector distance, m	Cross-section set	Detector bank	Incident neutrons detected, %			
			Added polyethylene thickness, mm			
			0	12.7	25.4	38.1
6.24	UTL	1	4.7	6.3	7.0	7.9
		2	8.7	9.5	9.6	8.5
		3	6.8	5.6	4.4	3.2
6.24	A	1	4.3	5.0	5.3	5.3
		2	7.4	7.7	7.0	5.8
		3	5.1	4.4	3.5	2.8
6.24	D	1	4.6	5.4	6.0	6.2
		2	8.0	8.4	7.9	6.9
		3	6.1	4.8	3.8	3.0
1.0	UTL	1	4.4	6.0	6.7	6.9
		2	7.8	8.9	9.0	8.0
		3	6.3	5.1	4.2	3.4
1.0	A	1	4.3	4.9	5.2	5.1
		2	7.3	7.2	6.5	5.5
		3	5.0	3.9	3.1	2.5

of each bank for each moderator configuration with source-to-detector distances of 6.24 m and 1.0 m are shown. For the 6.24-m distance, results based on three cross-section sets (UTL, A, and D) are presented; for the 1.0-m distance, results based on two sets only (UTL and A) are presented. Because air and ground scattering were not taken into account, the calculated effi-

ciencies for the two distances should be identical except for path-divergence effects. With the source at 1.0 m, more neutrons will ultimately escape from the edges of the moderator because of more divergent arrival paths.

The T-dependence of the calculated efficiency of each bank is very similar to that observed in the experiments. Figures 8a, 8b, and 8c compare the

Fig. 8. Comparison of measured and calculated efficiencies. The curve represents the measured efficiency with a source-to-detector distance of 1.0 m.

measured and calculated efficiency of banks 1, 2, and 3, respectively, for various values of T . The curves represent the 1.0-m measurements, and the vertical error bars indicate the estimated uncertainty. The 6.24-m measurements were strongly perturbed

by ground scattering effects, and we have therefore deleted them from the comparisons. Calculated efficiency values at each T value considered are denoted by points on the figures. The open points denote 6.24-m results, and the darkened points denote 1.0-m results. Triangles indicate UTL-cross-section-set results, circles indicate A-set results, and squares indicate D-set results.

The general shape of the measured curve is well reproduced by the TART calculations. The absolute magnitude of the calculated results varies between 10 and 50% roughly, depending on the cross-section set used. Generally, this variation is larger with larger values of T , as would be expected.

The consistent effect of path divergence is revealed by the relative positions of the open and closed triangles or circles. This effect is small, as anticipated, averaging only 5%.

The adjustment of the polyethylene elastic cross sections below 1 eV clearly has a significant effect on the TART calculations. However, it appears that the unmodified TART library (UTL) set provides the best agreement with measurements. Although in the modified cross-section sets (A and D) we have corrected the elastic cross section for CH_2 groups

and have tried to compensate for molecular binding effects, the TART results produced by these sets tend to underestimate the measured efficiency in most cases. This observation was unexpected and has not yet been fully explained. It is possible that thermal-upscattering and molecular-binding effects may influence the efficiency calculations in effectively equal but opposite manners. It is also possible that neither effect is very important, at least for the amount and configuration of polyethylene considered here. In any case, further study is required to determine whether the effects of molecular structure and "target" motion are significant in efficiency calculations involving larger ^3He /polyethylene detector systems.

When the unmodified TART cross section library was used, the calculations performed in this study agreed with measurements to within approximately 5 to 10%. Attempts to modify the cross sections below

1 eV to compensate for thermal-upscattering and molecular-binding effects did not improve the absolute comparison with the measurements. We estimate that TART should be able to predict the efficiencies of other polyethylene-moderated ^3He detectors of similar dimensions to within 10 to 20%. It is likely that comparable accuracies can be obtained in efficiency calculations for larger systems. In these cases, however, it would be prudent to make selected measurements to verify key results at various intermediate stage in the calculations.

It appears that some treatment for molecular binding and/or thermal "target" motion will be needed in the TART collision routine to achieve any further improvement in the absolute agreement between calculation and experiment at neutron energies less than about 1 eV. Studies to explore such collision model revisions are planned and, when completed, will be the subject of a future report.

Acknowledgments

I am indebted to Randall B. Kennedy for his extensive assistance in the measurement phase of this study, to John R. Kimlinger for his competent help

in adapting and applying the TART code to our problem, and to Ernest F. Plechaty for his valuable suggestions in interpreting the calculated results.