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MONTE CARLO MODEL FOR A THICK TARGET $T(D,n)^4$ He NEUTRON SOURCE

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CONTENTS

Abstract	1
Introduction	1
Anisotropy	2
Energy Dispersion	4
Time Dependence of Source	7
Monte Carlo Code	8
Application of the Monte Carlo Model	11
References	14
Appendix. FORTRAN Listing of a Monte Carlo Code to Generate a Neutron Source	15

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MONTE CARLO MODEL FOR A THICK TARGET $T(D,n)^4\text{He}$ NEUTRON SOURCE

ABSTRACT

This report briefly describes a calculational model developed to simulate a $T(D,n)^4\text{He}$ neutron source which is anisotropic in energy and intensity. The model also provides a means for including the time dependency of the neutron source. Although the model has been applied specifically to the Lawrence Livermore Laboratory ICT accelerator, the technique is general and can be applied to any similar neutron source.

INTRODUCTION

To fully exploit the Lawrence Livermore Laboratory (LLL) pulsed sphere measurements, we need a detailed description of the neutron source in the Monte Carlo simulation of these experiments. This need has become increasingly important as neutron cross section evaluations have become more detailed, largely because pulsed sphere data have been accepted as benchmarks for testing transport codes and cross section libraries. This report describes a calculational model successfully used in the MCNEUT (Monte Carlo NEUtron Transport) code developed by the author. It is generally applicable to any neutron source similar to the LLL ICT accelerator.

A comprehensive description of the ICT facility can be found in the program summary.¹ Briefly, neutrons are produced by a pulsed 400-keV beam of deuterons impinging upon a tritium-loaded titanium target through the $T(D,n)^4\text{He}$ reaction. The resulting neutron flux is anisotropic in energy and intensity in the laboratory coordinate system.² Because the deuterons slow down in the thick tritiated target, the neutrons emitted at any given angle* have a finite distribution (spread) in energy. In addition, the neutron pulse is time-dependent because the deuteron beam bunches asymmetrically.

* In this report the laboratory angle is always given with respect to the deuteron beam center line.

We deal with these problems of anisotropy, energy dispersion, and time dependence in subsequent sections of the report.

ANISOTROPY

Using an average reaction energy of 200 keV, we calculated the intensity and mean energy of the neutrons as a function of the emission angle. The mean energy was expressed as a polynomial:

$$\bar{E} = 14.120 + 0.955 \cos \theta + 0.035 \cos^2 \theta. \quad (1)$$

The differential emission probability which was normalized to $\bar{I}(\theta) = 1.0$ at $\theta = 0^\circ$ is shown in Fig. 1. It was also expressed as a polynomial:

$$I(\theta) = 0.93643 + 0.06505 \cos \theta - 0.00148 \cos^2 \theta. \quad (2)$$

If the integral of the emission probability is normalized to unity,

$$\int_{-1}^{+1} I(\cos \theta) d(\cos \theta) = 1.0,$$

there is a single-valued one-to-one correspondence between the cumulative emission probability over the interval $[0,1]$ and the emission cosine over the interval $[-1,+1]$; that is,

$$\varphi_a = \int_{-1}^a I(\cos \theta) d(\cos \theta)$$

where φ_a is the emission probability into the interval $[-1 \leq \cos \theta \leq a]$. The differential probability can be reconstituted by numerically differencing the integral function

$$\Delta \varphi = \int_{-1}^{a_2} I(\cos \theta) d(\cos \theta) - \int_{-1}^{a_1} I(\cos \theta) d(\cos \theta)$$

Fig. 1. Angular anisotropy of neutron source. $I(\theta) = 0.93643 + 0.06505 \cos \theta - 0.00148 \cos^2 \theta$.

where $\Delta\varphi$ is the emission probability into the interval $[a_1 \leq \cos \theta \leq a_2]$. If, for convenience, the integral is partitioned into N equiprobable intervals, and if we assume that the integral function is constant over each $\Delta\varphi$, then the emission cosine can be easily calculated by the algorithm

$$\cos \theta = \cos \theta_i + (\cos \theta_{i+1} - \cos \theta_i)r$$

where

i = truncated integer value of (NR + 1.0),

R = random number chosen from the open interval (0,1),

r = fractional remainder = (NR + 1.0) - i,

$\cos \theta_i$ = tabulated equiprobable boundary values.

The differential emission probability can be represented as closely as desired by a suitable choice of the number of equiprobable intervals, N. For this application, N = 10 is more than adequate. The calculated values are given in Table 1. Note that this is an idealized distribution. It does not include the attenuation due to neutron scattering in the tritium target which must be included in the Monte Carlo transport calculation.

Table 1. Neutron emission probability. $I(\theta) = 0.93643 + 0.06505 \cos \theta - 0.00147 \cos^2 \theta$.

Cumulative probability	Cos θ
0.0	-1.000
0.1	-0.785
0.2	-0.575
0.3	-0.370
0.4	-0.165
0.5	+0.035
0.6	+0.235
0.7	+0.430
0.8	+0.625
0.9	+0.810
1.0	+1.000

ENERGY DISPERSION

The tritium target is "infinitely" thick to the deuterons. Therefore, the $T(D,n)^4\text{He}$ reactions are produced by deuterons having energies from 400 keV down to zero. The spread in deuteron energy introduces a spread in the emitted neutron energy at any given angle. (See Table 5 in Ref. 1).

The neutron energy distribution from a thick target has been calculated as a function of the laboratory angle.^{3,4} The resulting idealized shapes can be represented by the following empirical relation:

$$P(E') = E_{\max}(\theta) - k[1 - p(E_0)]$$

where

$$k = 2[E_{\max}(\theta) - \bar{E}(\theta)].$$

The maximum allowed emission energy, $E_{\max}(\theta)$, was calculated from the formulas in Ref. 2 and expressed as a polynomial

$$E_{\max}(\theta) = 14.1849 + 1.3563 \cos \theta + 0.0652 \cos^2 \theta.$$

The mean energy, $\bar{E}$, is given by Eq. 1 above; $p(E_0)$ is the normalized energy distribution at $\theta = 0^\circ$. The coefficients in the polynomial expressions for $E_{\max}$ and $\bar{E}$ are valid only for a 400-keV deuteron beam.

We used the same Monte Carlo sampling technique as is described above. We found that 20 equal intervals in $\cos \theta$ were adequate to represent the energy distribution provided that quadratic interpolation was used for the "tail" of the probability function. The normalized distribution, $p(E_0)$, and the cumulative probability as a function of the dimensionless variable X are shown in Fig. 2. Tabulated values are given in Table 2.

The energy spread from deuteron downscatter in the target becomes very small at $\theta \approx 90^\circ$; in fact,

Table 2. Energy dispersion probability function at $\theta = 0^\circ$.

Cumulative probability	X
0.0	0.0
0.05	0.1627
0.10	0.2144
0.15	0.2477
0.20	0.2780
0.25	0.3035
0.30	0.3291
0.35	0.3527
0.40	0.3760
0.45	0.4003
0.50	0.4259
0.55	0.4528
0.60	0.4834
0.65	0.5167
0.70	0.5533
0.75	0.5966
0.80	0.6470
0.85	0.7074
0.90	0.7807
0.95	0.8754
1.00	1.00

Fig. 2. Normalized energy distribution at $\theta = 0$.

the calculational model predicts zero dispersion when $E_{\max} = \bar{E}$. Therefore, we needed to include in our calculation an effect which leads to a relatively small energy spread at other angles: successive small angle scatters will not significantly degrade the deuteron energy but will deflect the deuteron away from the beam line. If the trajectory ends by producing a neutron, this neutron can be emitted into the detector view angle with an energy distribution of $E(\theta + \delta\theta)$. For a given view angle, θ , the neutron can have an energy greater or less than the nominal energy, depending upon the sign and magnitude of the total deflection angle, $\delta\theta$. This effect was included in the calculational model by adding a truncated Gaussian distribution term to the mean energy with a full width at half area equal to 43 keV, the average value calculated by M. Gardner³ who refers to this phenomenon as "straggle."

TIME DEPENDENCE OF SOURCE

The deuteron beam on the tritium target of the ICT accelerator has a nominal FWHM of about 2 ns and is approximately Gaussian in shape. This shape is similar to the time response shape of the neutron detectors. Thus it is usually sufficient to consider the neutron source to be instantaneous and to fold a Gaussian time response function into the calculated time-of-flight spectrum. However, for the thin spheres (1 mfp), we must consider the shape of the deuteron pulse if we want to test differential elastic and direct inelastic scattering cross sections against the pulsed sphere measurements.

An obvious solution would be to use the measured, time-resolved beam current on the tritium target as the source function and to fold the time response of the detector and associated electronics into the calculated time-of-flight spectra. But in practice this approach is not feasible because we lack accurate beam diagnostics on the ICT accelerator.

An alternative method is to use the measured gamma pulse in the neutron detector as the time-dependent source function in the Monte Carlo calculations. The gamma rays, which are produced by inelastic collisions in the target assembly, are insensitive to the energy and angular dispersion of the source neutrons and are not subject to time-of-flight spread in arrival time at the detector. Since the arrival time of the gammas at the detector is synchronous with their production rate, any broadening of the gamma pulse in

the detector is due solely to the time response of the detector electronics. Thus, if we use the measured gamma pulse as the time dependency of the neutron source, the deuteron pulse shape and the detector time response are both simultaneously included in the calculated time-of-flight spectrum.

The calculational model to describe the time dependency of the neutron source is similar to that described above for the differential emission probability. However, we have dropped the restriction of equal, constant intervals in the probability distribution function. Instead, the cumulative integral is represented by piecewise continuous line segments connecting arbitrary cuts in the independent variable space.

The computational algorithm is slightly more complicated since it involves searching a probability table and then making a linear interpolation between the end points of the line segment. The order-of-magnitude increase in the reproduction accuracy of the differential probability function more than offsets the small increase in computation time. (See the FORTRAN listing in the Appendix for details.)

To illustrate this technique, we converted the gamma signal from a typical ICT neutron source calibration to a normalized cumulative time distribution function, represented by 16 line segments. The Monte Carlo code was exercised to generate a neutron sample size of 50,000 particles. The neutrons were tallied in 0.5 ns time bins, and the distribution was plotted as a histogram in Fig. 3. The calculated distribution accurately reproduces the measured gamma signal which was plotted as a smooth curve in Fig. 3.

MONTE CARLO CODE

All of the above calculational techniques were incorporated into a code to generate source neutrons for Monte Carlo calculations of the pulsed sphere experiments. Except for the LLL library routine RNFL which generated random numbers,⁵ the code is in basic FORTRAN.

The code was tested, and the output was tallied in a two-dimensional array, $I(E, \theta)$. The calculated distribution was plotted with a computer code PLOT3D furnished by Don Burton of LLL,⁶ which produces isometric or "3D" CRT plots. Figures 4a-4d show the neutron source distribution from four

Fig. 3. Gamma ray pulse in neutron detector.

Fig. 4. Energy and intensity of the neutron source as a function of angle.

perspectives. Energy and intensity are shown as a function of the emission angle. The integral over energy at any specific emission angle is given by Eq.(2).

The Appendix gives a FORTRAN listing of the computer source code. Comment cards were included to make the coding easier to follow. With a time-dependent source probability distribution of 21 pairs of input data, the routine, as compiled by the LLL ORDERLIB system, will generate a 100,000-neutron sample in 178 ms on a CDC 7600 machine.

APPLICATION OF THE MONTE CARLO MODEL

During a recent measurement of the time-of-flight spectra from the ICT neutron source, NE213 neutron detectors were placed in tightly collimated ports at 30 and 120° from the deuteron beam line. A Monte Carlo calculation of the experiment included:

- the tritium target assembly (Fig. 6 in Ref. 1)
- target room air
- detector geometry and view angle
- detector efficiency vs energy (Fig. 13 in Ref. 1).

A time-dependent source distribution was derived from the measured gamma signal as described previously. Neutron transit time through the 5-cm long NE213 scintillator was included by assuming a constant detection efficiency along the detector axis.

The calculated neutron time-of-flight spectra are shown in Figs. 5 and 6 together with the measured spectra. The calculated line shapes agree very well with the measurements. The structure in the late-time tail results partly because of statistics and partly because we have represented the continuum inelastic scattering in the tungsten backing of the tritium target and the nitrogen in the target room air by pseudonuclear levels in the MCNEUT neutron transport collision routine.

Fig. 5. Neutron source at 30° . ICT Run No. 060402.

Fig. 6. Neutron source at 120° . ICT Run No. 060402.

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APPENDIX. FORTRAN LISTING OF A MONTE CARLO CODE TO GENERATE A NEUTRON SOURCE.

```

SUBROUTINE MCICT(TP,NP,G,E,T)
C
CC  MONTE CARLO CODE TO GENERATE THE ENERGY, ANGLE AND TIME
C    DEPENDENT NEUTRON EMISSION SPECTRA FROM A THICK TRITIUM
C    TARGET PULSED BY A 400 KEV DEUTERON BEAM
C
C
C*****
C*
C*                                GLOSSARY
C*
C*  TP   = TIME DISTRIBUTION TABLE: P(1),T(1), . . . ,P(NP),T(NP)
C*        ORDERED IN INCREASING VALUES OF TIME
C*  NP   = NUMBER OF PAIRS OF PROBABILITY VS. TIME IN ARRAY TP
C*  G     = COSINE OF LAB. EMISSION ANGLE W.R.T. DEUTERON BEAM LINE
C*  E     = EMISSION ENERGY (MEV)
C*  T     = ORIGIN TIME OF NEUTRON (UNITS CONSISTENT WITH TRANSPORT
C*          CODE AND TIME DISTRIBUTION TABLE
C*  EMIS  = PRECALCULATED EQUAL PROBABLE INTERVALS FOR EMISSION
C*          COSINE
C*  TABC  = PRECALCULATED TABLE OF EQUAL PROBABLE INTERVALS FOR
C*          ENERGY DISTRIBUTION(SPREAD) AT EACH ANGLE
C*  RNFL  = LLL. LIBRARY FUNCTION WHICH GENERATES A RANDOM NUMBER
C*          OVER THE OPEN INTERVAL (0,1)
C*  EAVE  = AVERAGE EMISSION ENERGY VS. ANGLE
C*  EMAX  = MAXIMUM ALLOWED ENERGY AT A SPECIFIC EMISSION ANGLE
C*  STRAG = ENERGY SPREAD DUE TO DEUTERON STRAGGLE:
C*          ( HALF AREA WIDTH = .0436 MEV )
C*
C*          NOTE: ALL ENERGIES AND ANGLES ARE IN THE LABORATORY SYSTEM*
C*
C*****
C
C
C    DIMENSION TP(1), EMIS(11), TABC(21)
C
C
CC  PRECALCULATED PROBABILITY DISTRIBUTION TABLES
C
C    DATA( EMIS = -1.0, -.785, -.575, -.370, -.165, +.035,
A     .235, .430, .625, .810, 1.00 )
C    DATA( TABC = 0., .1627, .2144, .2477, .2780, .3035, .3291,
A     .3527, .3760, .4003, .4259, .4528, .4834, .5167, .5533,
B     .5966, .6470, .7074, .7807, .8754, 1.00 )
C
CC  DETERMINE EMISSION TIME
C
C    IF( NP.GT.2 ) .102
C    INDEX = 3
C    R1 = RNFL(0)
C    DO 100 II = 1,NP-1
C    IF(R1-TP(INDEX))101,101,
C    INDEX = INDEX + 2
100 CONTINUE
101 CONTINUE
C    P1 = TP(INDEX-2)
C    T1 = TP(INDEX-1)

```

Appendix (continued)

```

P2 = TP(INDEX)
T2 = TP(INDEX+1)
SLOPE = (T2-T1)/(P2-P1)
T = T1 + SLOPE*(R1-P1)
GO TO 103
102 T = 0.0          $$C MONOTIME
103 CONTINUE

C
C
CC          SELECT EMISSION COSINE
C
XINDEX = 10.0*RNFL(0) + 1.0
INDEX = XINDEX
G = EMIS(INDEX) + (XINDEX-INDEX)*(EMIS(INDEX+1)-EMIS(INDEX))

C
C
CC          SELECT EMISSION ENERGY
C
EMAX = 14.1849 + 1.3563*G + .0652*G**2
EAVE = 14.120 + 0.955*G + .0350*G**2
R1 = RNFL(0)
R2 = RNFL(0)
R3 = RNFL(0)
SIGN = +1.0
IF( 1.0 - 2.0*R1 ) , , .201
SIGN = -1.0
201 CONTINUE
STRAG = 0.1744*SIGN*R2*R3
EAVE = EAVE + STRAG
SCALE = 2.0*(EMAX - EAVE)
XINDEX = 20.0*RNFL(0) + 1.0
INDEX = XINDEX
IF( INDEX - 1 ) , , .202
ES = TABC(1) + SQRTF(XINDEX-INDEX)*(TABC(2)-TABC(1))
GO TO 203
202 ES = TABC(INDEX) + (XINDEX-INDEX)*(TABC(INDEX+1) - TABC(INDEX) )
203 CONTINUE
E = EMAX - SCALE*(1.0 - ES)

C
C
RETURN
END

```

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