

CARLO DTS: A MONTE CARLO CODE FOR THE DUAL THIN SCINTILLATOR NEUTRON DETECTOR

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A Monte Carlo code called CARLO DTS, developed for the efficiency and proton recoil spectra calculation of the Dual Thin Scintillator (DTS) neutron detector is described. The code CARLO DTS covers the neutron energy range between 1 and 20 MeV. The cross sections and angular distributions were taken from the ENDF/B-V data file for the nuclear reactions involved: H(n,n)H, C(n,n)C and inelastic scattering, (n, α), (n,n') β reactions on carbon-12. The theoretical calculations are compared to experimental results at two neutron energies, namely: 2.446 and 14.04 MeV, obtained by means of the Time Correlated Associated Particle Technique.

INTRODUCTION

The Monte Carlo code CARLO DTS, developed for the efficiency and proton recoil spectra calculation of the DUAL THIN SCINTILLATOR (DTS) neutron detector is described. Complete details about the DTS characteristics and performance have been published (Dias et al., 1984, Dias et al., 1985 and Dias, 1988). Basically, The DTS neutron detector consists of two thin cylindrical pieces of plastic scintillators, 0.254 cm thick, 4.70 and 4.90 cm in diameter, respectively, placed coaxial in front of each other (figure 1). Each scintillator was coupled to a pair of phototubes, by means of a perspex light guide, in a head-on geometry.

A detailed description of the code CARLO DTS will be published elsewhere (Dias and Johnson, 1990). In the present paper, only the main aspects are emphasized.

The code CARLO DTS covers the neutron energy range between 1 and 20 MeV. The detector parameters and the coordinate system orientation are shown in Figure 1. The detector is considered as a cylinder of height H_T and radius R , filled with scintillator containing hydrogen and carbon of concentrations N_H and N_C , respectively. The neutron beam, with a radius R_N , is assumed to be homogeneous and normally incident to the detector frontface. Nonhomogeneity or other incidence angles may be introduced by changing subroutine SOURCE

* Formerly National Bureau of Standards.

according to the case of interest.

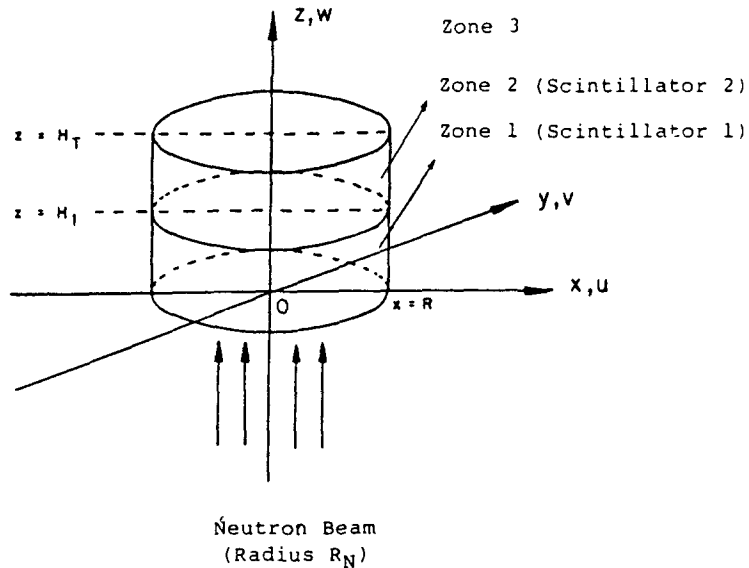


Fig. 1: Coordinate system. ZONE 3 is the region outside the scintillators.

The cylindrical regions where the scintillators 1 and 2 are located are called ZONES 1 and 2, respectively. ZONE 3 is located outside the scintillators. The contribution of the perspex light guide in the detector response is not considered. It has been estimated to be negligible for neutron beam diameters much smaller than the detector diameter (Dias, 1984). Easy modifications can be introduced in the code to calculate the response for neutron beams comparable or larger than the scintillators. Because the scintillators are thin, a neutron with energy in the range of 1 to 15 MeV will have, on the average, only one collision inside the detector. The maximum number of collisions is below nine and the majority of neutrons escape the detector before being absorbed.

To achieve a statistical uncertainty around 0.4% about 10^5 histories are necessary, applying the forced collision technique. Good pulse height distributions are obtained with about 4×10^5 histories.

NEUTRON KINEMATICS

Table 1 shows the reactions which contribute to the DTS detector response, including the Q value and the first and second reaction thresholds. The reaction cross sections were considered to be zero below the second reaction threshold. All cross section values were taken from the ENDF/B-V evaluation (ENDF/B-V, 1979). Intermediate values to those contained in the cross section tables are obtained by linear interpolation, for all reactions involved. The

tables contain mesh points appropriate to the cross section structure in order to minimize interpolation errors, mainly near the carbon resonances.

Table 1: Reactions which contribute to the Dual Thin Scintillator (DTS) detector response.

Reaction	Q (MeV)	1 st Threshold (MeV)	2 nd Threshold (MeV)
${}^1_0\text{H}(n,n){}^1_0\text{H}$	-	-	-
${}^{12}_6\text{C}(n,n){}^{12}_6\text{C}$	-	-	-
${}^{12}_6\text{C}(n,n'\gamma){}^{12}_6\text{C}$	-4.433	4.805	5.840
${}^{12}_6\text{C}(n,\alpha){}^9_4\text{Be}$	-5.704	6.183	6.428
${}^{12}_6\text{C}(n,n'){}^{12}_6\text{C}^*$	-7.656	8.299	8.359
+ ${}^8_4\text{Be} + \alpha$	+0.289	-	-
+ 3α	+0.102	-	-

The angular distribution for the elastic scattering on hydrogen, $\text{H}(n,n)\text{H}$, was obtained from Hopkins and Breit (1971). The angular distribution data for the elastic scattering on carbon, $\text{C}(n,n)\text{C}$, has been obtained from ENDF/B-V (1979). Since the coefficients for the expansion in Legendre polynomials are given for the center-of-mass system, it was necessary a transformation to the laboratory system in order to be compatible with the Monte Carlo code.

For the $\text{C}(n,n'\gamma)\text{C}$ reaction the anisotropy in the angular distribution of scattered neutrons has been considered. The Legendre coefficients were taken from Glasgow et al. (1976) for the energy range between 8970 and 14930 KeV. For the remaining energy range (between 4812 and 20000 keV) the coefficients were taken from the ENDF/B-V (1979).

The detection of gamma-rays from ${}^{12}_6\text{C}(n,n'\gamma){}^{12}_6\text{C}$ reaction has been calculated separately by means of a simplified Monte Carlo code as described by Dias (1988). The correction factor due to this effect is less than 0.4% for a neutron beam incident on the detector axis. For finite beam sizes the correction tends to be lower.

The angular distribution of alphas from the ${}^{12}_6\text{C}(n,\alpha){}^9_4\text{Be}$ reaction has been considered as isotropic in the laboratory system. This simplification has very little effect on the results since the discrimination level of the proton-recoil spectrum can always be chosen above the channel corresponding to the maximum energy of the alpha particles produced by this reaction.

The angular distribution of alphas from the ${}^{12}_6\text{C}(n,n')3\alpha$ reaction has been considered as isotropic in the laboratory system. The Q value for this reaction has been determined considering all the excitation energy levels, real or virtual, contained in the ENDF/B-V (1979). For each neutron energy a set of excitation probabilities values, P_i , has been generated for the compound nucleus states. This probability is the ratio between the partial cross section for a given excitation state and the total cross section for that neutron energy. These cross section values were also obtained from ENDF/B-V (1979).

APPLICATION OF THE FORCED FIRST COLLISION TECHNIQUE

This technique allows a reduction in the number of histories followed by the Monte Carlo code, without significant loss in the statistical accuracy achieved. It was used to define the point where the first neutron collision will occur or

to make the neutron collide preferentially with the hydrogen atoms in the scintillator.

Forced first collision inside the detector

The DTS detector has high transmission for MeV neutrons, and consequently a low detection efficiency. Therefore a great number of incident neutrons should be necessary to get a low statistical uncertainty, demanding a long processing time. This problem has been solved by confining the neutron first collision inside the detector (Cashwell and Everett, 1959). This procedure results in a 100% detection efficiency. The reduction in the processing time reaches a factor around 20 at 15 MeV. To the calculated efficiency an appropriate factor is applied. The distance to subsequent collisions are calculated in the usual way.

Forced first collision on hydrogen and ZONE 1

Table 2 shows the percentage contribution in the DTS detector efficiency from events originates by neutron first collision on hydrogen and carbon for different neutron energies. Between 89-96% contribution comes from events where the first neutron collision was on hydrogen.

Table 2: Contribution to the DTS detection efficiency of events originated by neutron first collision on hydrogen, carbon and ZONES 1 and 2 (in percent).

Neutron Energy (MeV)	Contribution to the Efficiency (%)			
	Hydrogen	Carbon	ZONE 1	ZONE 2
1.0	89.0	11.0	95.6	4.4
2.4	93.8	6.2	96.7	3.3
14.0	96.4	3.6	98.6	1.4

Since the ratio between the total cross sections of hydrogen and carbon are in the range of 0.5 to 3, for 1 to 15 MeV neutrons, the fraction of neutrons which have first collision on hydrogen is between 30 and 77%. Therefore it becomes convenient to force the first collision on hydrogen in order to reduce the processing time by a factor up to about 3.

A fraction f_H of the incident neutrons is forced to collide against hydrogen and $(1 - f_H)$ collide against carbon atoms. The number of counts in the proton-recoil spectrum becomes real numbers. The number of processed neutrons, N_S , gives rise to a larger number of counts in the proton-recoil spectrum, N'_S . The processing time is reduced by the factor N'_S/N_S . At 14 MeV and using $f_H = 0.9$, this factor is equal to 2.4.

As shown in table 2, between 95 to 99% of the counts which contribute to the efficiency are originated by a neutron first collision in the first scintillator (ZONE 1). Because of the high transmission through the detector for 1 to 15 MeV neutrons, about half of the neutrons are incident in ZONE 1 and half are incident in ZONE 2. Therefore applying the forced first collision in the first scintillator (ZONE 1) it is possible to reduce the processing time by a factor of 2.

A fraction f_S of the incident neutrons is forced to collide in ZONE 1 and $(1 - f_S)$ collide in ZONE 2. The number of processed neutrons N'_S gives rise to a larger number of counts, N''_S . The processing time is reduced by the factor N''_S/N'_S . The total reduction, including the forced collision on hydrogen becomes N''_S/N_S . At 14 MeV and using $f_S = f_H = 0.9$, the total reduction is 4.3.

LOST COINCIDENCES EFFECT

For MeV neutrons, there is a large effect due to the escape of protons from the forwardface of the first scintillator in the DTS detector. However, the corresponding distortion in the proton recoil spectrum is eliminated experimentally by detecting these escaped protons at the second scintillator, placed behind the first one. Since this procedure requires a coincidence signal, there is a lower limit for the first scintillator pulse amplitude to be detectable. The sum-coincidence pulses originated from pulses in the first scintillator below this limit will be lost. Some of these lost sum-coincidence pulses can have an amplitude above the discrimination level adopted for the detection efficiency calculation (usually 30% of the maximum proton energy). Therefore, a correction for these lost coincidences is required. At low neutron energies there are sum-coincidence pulses also due to neutron multiple scattering inside the scintillators. The loss of such events must be taken into account.

The lost coincidences effect caused by the escape of protons has been incorporated in the CARLO DTS code, by calculating the proton energy fraction deposited inside each scintillator. The total light produced by a given neutron in the Monte Carlo code has been divided into two parts: the first one corresponds to the total light produced in the first scintillator (ZONE 1) and the second one corresponds to the total light produced in the second scintillator (ZONE 2). The events which produce a light yield below a given threshold are rejected. In this way, the loss of coincidences caused by multiple scattering are also included.

The correction for lost coincidences are shown in fig. 2 as a function of the fractional discriminator lower level (ratio between the channel at the discriminator lower level and the channel at the end of the spectrum), for several energies of the incident neutron. In this figure, the discrimination level adopted for the calculated efficiency corresponds to 30% of the maximum proton energy.

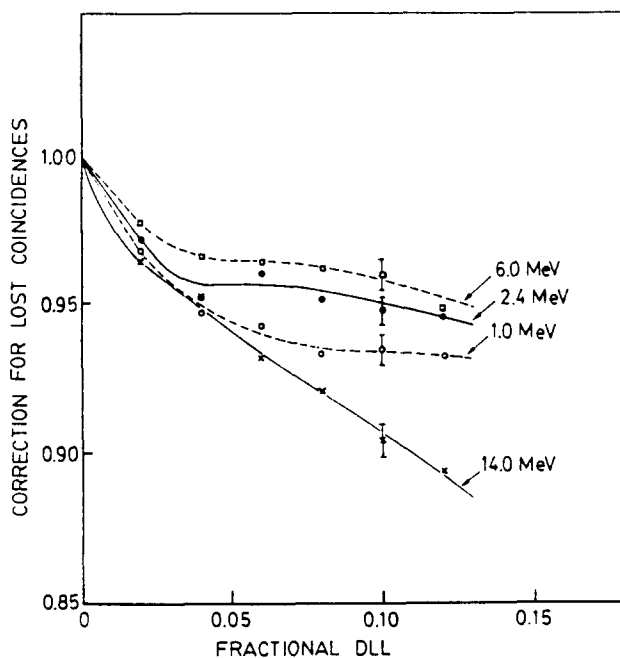


Fig. 2: Lost coincidences correction as a function of the fractional lower discrimination level.

VARIATION IN LIGHT COLLECTION

The variation in the light collection efficiency at different points in the scintillator has been taken into account by assuming a quadratic dependence of the average light response as a function of the distance from the center of the scintillator. The coefficients were obtained by a least square fit to experimental light response values (Dias et al., 1984).

RESULTS OF THE CALCULATIONS

The behavior of the calculated biased (the word biased meaning above a given discriminator level) efficiency with neutron energy is shown in fig. 3 together with two experimental points obtained at 2.446 and 14.04 MeV (Dias et al., 1984). The curve follows essentially the $H(n,n)H$ cross section. Contributions from $C(n,n)C$ and $^{12}C(n,n'\gamma)^{12}C$ cross section cause some small irregularities in the efficiency curve, mainly in the regions of carbon resonances. For this curve, the bias energy was located at 30% of the maximum energy.

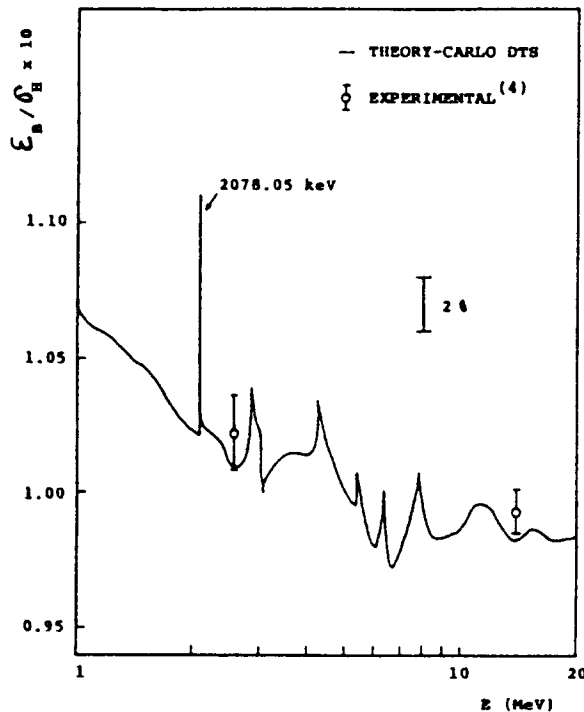


Fig. 3: DTS efficiency curve for 1 to 20 MeV neutrons. Spectrum discriminator at 30% of the maximum energy. The points at 2.446 and 14.04 MeV were obtained experimentally. The solid line is the Monte Carlo calculation.

A clear correlation between the biased efficiency and the carbon and hydrogen cross section has been observed. Particularly, good accuracy in the interpolation of the efficiency for various neutron energies was achieved by following formula:

$$\epsilon_B/\sigma_H = a_1 + a_2\sigma_C + a_3\sigma_H$$

where

- ϵ_B is the biased efficiency,
- σ_C is the carbon elastic plus inelastic scattering cross sections,
- σ_H is the H(n,n)H cross sections,
- a_1, a_2, a_3 are constants.

The values of a_1 , a_2 and a_3 were obtained by least squares fit between the biased efficiency and the cross sections. The efficiency has been calculated at several selected neutron energies, at points where the carbon cross section shows the largest variations. Updated results of the fits are presented in table 3 for three fractional bias energies, namely: 0.30, 0.35 and 0.40 of the maximum energy. These efficiencies were calculated at zero discrimination lower level. The average accuracy obtained in the interpolation goes from 0.8 to 1.8% at the fractional biases of 0.30 and 0.40, respectively.

Table 3: Coefficients of the interpolation formula applicable to the DTS biased efficiency.

Fractional Bias Energy	a_1 ($\times 10^{-3} b^{-1}$)	a_2 ($\times 10^{-4} b^{-2}$)	a_3 ($\times 10^{-4} b^{-2}$)	Reduced Chi Square
0.30	9.474	1.901	1.576	1.04
0.35	8.798	1.664	1.710	1.19
0.40	8.134	1.522	1.719	1.10

Figure 4 shows the uncertainties involved in the calculated efficiency. The uncertainty indicated for the H(n,n)H cross section has been taken from ENDF/B-VI (0.3%). The predominant contributions to the total uncertainty are from the hydrogen areal density and statistics in the calculation, except near the carbon resonance at 2078 keV where the multiple scattering uncertainty is predominant. The uncertainty in the correction for lost coincidences has not been included in fig. 4 since it depends on the discrimination level used. This uncertainty is estimated to be around 10% of the correction (i.e. 0.4%) and has little contribution in the total uncertainty. The total uncertainty is between 0.8 to 1.0% except near the carbon resonance at 2078 keV, where it reaches the maximum value of 1.2%.

The comparison between the results of proton recoil spectra calculated by the code CARLO DTS, in comparison to experimental spectra obtained at 2.446 and 14.04 MeV, is shown in figures 5 and 6. The fitting between the calculated and the experimental spectra was performed using a revised version of a code written by Meier (1984), which takes into account the Poisson statistics in the number of photoelectrons detected. The agreement between the calculated and the experimental spectrum shapes is excellent, indicating little sensitivity with respect to the selected bias energy.

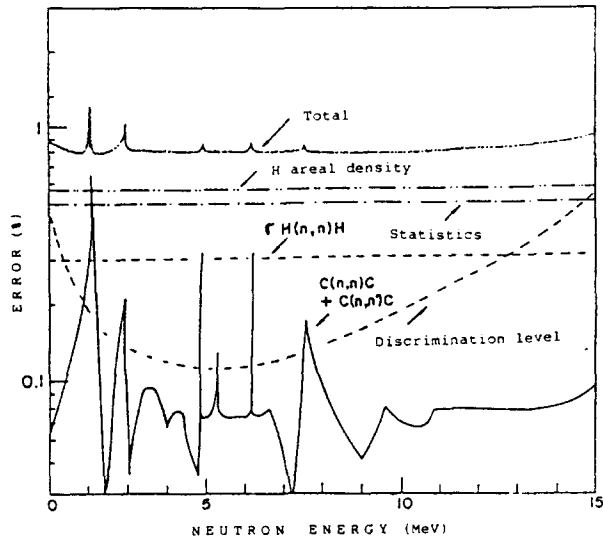


Fig. 4: Uncertainties in the CARLO DTS efficiency calculation. The indicated error corresponds to the relative standard deviation.

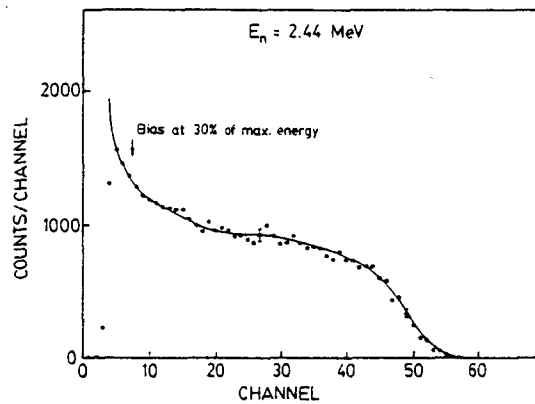


Fig. 5: Comparison between experimental (dots) and calculated proton-recoil spectra (solid line) at 2.446 MeV neutron energy.

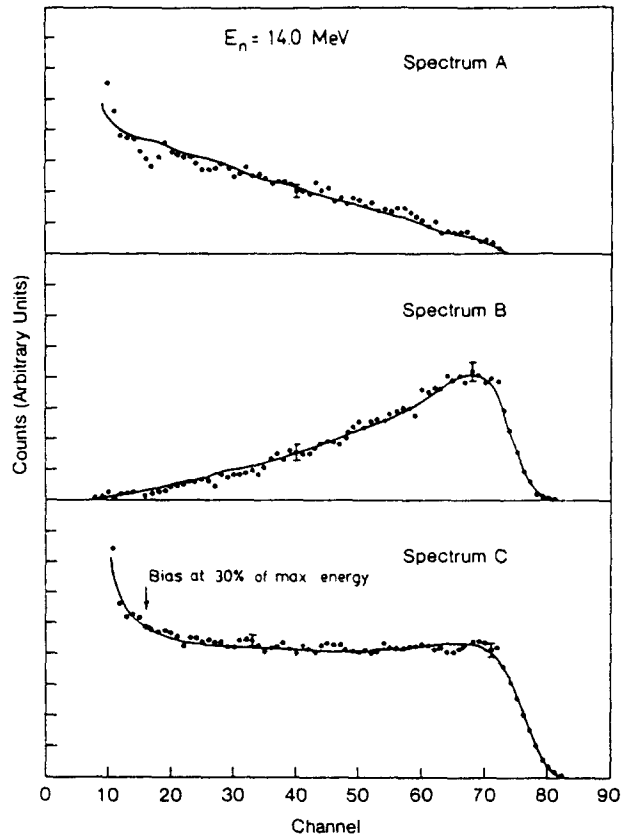


Fig. 6: Comparison between experimental (dots) and calculated proton-recoil spectra (solid line) at 14.04 MeV neutron energy. In this figure spectrum A corresponds to singles from the first scintillator; spectrum B are coincidences between the two scintillators and spectrum C is the sum spectrum which approximates the ideal thin scintillator response.

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