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A MONTE CARLO PROGRAM FOR CALCULATING
NEUTRON DETECTION EFFICIENCIES IN
PLASTIC SCINTILLATOR*

MASTER

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129

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ABSTRACT

A FORTRAN IV Monte Carlo program to calculate the neutron detection efficiency of plastic scintillators of rectangular or cylindrical geometry as a function of neutron energy and light collection threshold has been written and tested. The existing cross-section data for neutron-carbon interactions have been adjusted to give a good fit to existing measurements of efficiency. This document contains a complete description of the physics input and method of approach, together with detailed instructions for use of the program. A listing of the source code, the data deck, and output of a sample calculation are appended.

CONTENTS

	Page
I. Introduction	1
II. Approach	1
III. Outline of the Calculation	4
A. Data Input and Initialization	
B. Neutron Tracing	
C. Resolution and Binning	
D. Output	
IV. Physics Input	8
A. Processes Contributing to Neutron Detection	
B. Light Output from Plastic Scintillator	
C. Simulation of Finite Resolution	
D. Kinematics	
V. How to Use the Program	15
A. Data Deck	
B. Time, Core and Library Requirements	
VI. Comparison with Experiment	19
References	22
Figures	24
Appendix I: Source Program Listing	28
Appendix II: Data Deck Listing	78
Appendix III: Sample Output	82
Appendix IV: Additional Features of the Program	88
Appendix V: Scintillator Geometry and Coordinate System	91
Appendix VI: Some Examples of the Monte Carlo Method	92

I. Introduction

The motivation for this program came from the author's involvement in a high-statistics experiment¹ to measure the differential cross-section for neutron-proton charge-exchange scattering. Since the yield in this two-arm experiment was proportional to the detection efficiency for the recoil neutrons, it was desirable to know this quantity to an accuracy substantially better than the statistical errors in the yield, or to about $\pm 5\%$. The recoil neutrons, which had kinetic energies between 1.0 and 400 MeV, were detected by plastic scintillation counters of three different sizes. The efficiency of one of these counters was calibrated experimentally² at 13 energies between 1.0 and 200 MeV. It was then necessary to use a computer program to interpolate the efficiency between measured values, and to extend the measurements to counters of different sizes and shapes; in this way also our efficiency measurements could be checked against those of other groups.³⁻¹¹

II. Approach

Since a neutron has no charge, its detection results from the ionization produced by the charged products from its nuclear interactions. In organic scintillators these interactions nearly always occur with hydrogen and carbon nuclei, producing protons, alpha particles, heavier ions, and possibly secondary neutrons which may interact again if the scintillator size is larger than or comparable to the nuclear mean free path. It is the intensity spectrum of light from the charged particles (pulse height spectrum) which the program must simulate. The light output of organic scintillators is not linear in the energy loss when the

ionization per unit path is large, i.e. for heavy particles moving slowly. This effect (called saturation) must also be simulated for each type of particle; it may depend also on the type of scintillator. The unit of light output used in this program is the MeV electron equivalent (MeVee), which is defined as the kinetic energy of a stopping electron which produces the same amount of light as the stopping heavy particle in question; for example, a stopping 4 MeV proton will produce about 1.4 MeVee of light in plastic scintillator.

In order to calculate the neutron detection efficiency of a counter, one must have the following information:

- 1) The size and shape of the counter.
- 2) Its density and composition (ratio of hydrogen to carbon atoms).
- 3) The total cross-sections for all interaction channels of neutrons with hydrogen and carbon in the energy range considered.
- 4) The distributions in energy of all charged particles produced in these interactions, and the distribution in energy and angle of secondary neutrons and γ -rays.
- 5) The saturation properties of the scintillator for each type of charged particle.
- 6) The resolution of the detector.

A Monte Carlo approach¹² to the calculation of neutron counter efficiency is not mandatory. In fact, the program of Kurz¹³ which uses analytical methods has enjoyed remarkable success in simulating the efficiency measurements of several groups;⁶⁻⁸ discrepancies are typically less than 10%. However, there are certain undesirable features of the Kurz program which a Monte Carlo approach can improve: 1) For thick scintillators and low neutron energies the Kurz program seriously underestimates

the efficiency by ignoring the contributions from third and higher order scatters. 2) It assumes cylindrical symmetry of the scintillator around the direction of the incoming neutron; for counters whose shape violates this assumption, it is uncertain how far one may trust the calculations. 3) It is often desirable to have a simulated pulse height spectrum to compare with a measured spectrum, instead of having only the efficiency, at some fixed value of bias. 4) It is often interesting to know how the detection efficiency depends on where the neutron enters a counter (i.e., edge effects). The aim of this calculation is to keep the many good features of the Kurz program while eliminating some of the defects: the Kurz program was reworked in Monte Carlo form, preserving its physical assumptions whenever possible and extending them only when necessary.

In addition, it appears likely that the present large body of existing neutron efficiency data contains more useful information about inelastic neutron-carbon cross sections than is available from the limited number of direct measurements; that is, one should be able to "tune" these cross sections to improve the overall fit to existing efficiency data. The available total cross-section data¹²⁻¹⁹ has been "tuned" within reasonable limits (typically ± 2 standard deviations) to reproduce the efficiency data of Ref. 2. The program and its adjusted cross-section data were then tested on the efficiency measurements of several groups; the results are presented in Section VI.

It should be noted that for neutron energies below about 25 MeV the major contribution to the efficiency comes from elastic scattering on hydrogen, $np \rightarrow np$, for which the total and differential cross-sections

are known much better than the intended accuracy of this program; they have not been adjusted. For these low energies only small changes to the calculated efficiency can be made, and these must come from large adjustments to cross-sections in other channels. Below the carbon inelastic threshold of 4.7 MeV there is no freedom to adjust any cross-sections. For neutrons more energetic than about 50 MeV, on the other hand, carbon inelastic channels dominate the efficiency and cross-section data is very limited, so that the measured efficiency data of Ref. 2 has been used to establish the cross-sections for this program; these "cross sections" are probably better described as efficiency parameters than as physically meaningful quantities.

III. Outline of the Calculation

A complete listing of the FORTRAN IV source program is given in Appendix I; the program is extensively documented and the details of the calculations are generally given by the comment cards. The following outline provides an overall view of what is being done. Some additional features of the program which are not discussed below are described in Appendix IV.

A. Data Input and Initialization (MAIN routine).

1) Read in the necessary data about the size, shape, density and composition of the scintillator, the experimental resolution and the tables of total cross-sections and angular distributions. The data deck is described in Section V-A.

2) Clear the arrays used as differential pulse-height analyzers. For each set of histories desired read the initial position vector and direction cosines, the initial energy, the number of histories to be run and the bin width for the pulse height analyzers. Provision is made to choose the initial position and/or energy of the neutron randomly from a uniform distribution between specified limits.

B. Neutron Tracing. Follow each incident neutron until it either escapes from the scintillator or its energy becomes negligible (subroutine FOLNUT).

1) Choose the kinetic energy E , direction cosines $C(I)$ and position coordinates $X(I)$ of the incident neutron.

2) Look up the total cross-sections for all interactions of a neutron of energy E with hydrogen and carbon by linear interpolation in the data table (subroutine SIGTOT); find the nuclear mean free path in scintillator.

3) Choose, by Monte Carlo (MC) the distance D the neutron travels before interacting.

4) Propagate the neutron a distance D along directions $C(I)$ to a new position $X(I)$.

5) Check whether $X(I)$ is still inside the scintillator (subroutine INBND). If not, go to step C.

6) Decide (by MC) whether the interaction occurred in hydrogen or carbon; and if in carbon, through which channel it proceeded.

7) Call the subroutine corresponding to the chosen interaction channel (NPNP, NCEL, NCNCGM, NALPHA, NN3AL, or NPB). Each such subroutine has access to information on angular distributions, so that the

energy and lab scattering angle of the outgoing neutron (if any) may be chosen by MC. The new direction cosines of the neutron (if any) are found by subroutine SCATTR. The lab energies of all charged secondaries are similarly found, and their light output is calculated by the appropriate saturation function (EEQUIV, EEQAL). The light output in each channel is added to the previous total for this history. Note: no charged prongs are followed; all are assumed to stop in the scintillator.

8) If the outgoing neutron has remaining energy E above some specified cutoff (e.g. 0.1 MeV) the program returns to step 2 and continues to follow the neutron.

C. Resolution and Binning. Nine separate "differential pulse height analyzer" arrays are maintained; one for the light from each reaction channel (6 analyzers), one for the total light output, and two more for the total light output subjected to two different amounts of resolution broadening. Increment the appropriate arrays according to the light output (if any) in each channel for this history, and also the analyzer for the total output from all channels. Simulate by MC the jitter in light output due to finite resolution, and increment the two analyzers containing smeared spectra. Return to step B if more histories are to be run.

D. Output. A sample output for the program is included in Appendix III. The following information is printed out:

- 1) The data on the size, shape, density and composition of the scintillator, the neutron energy interval, and the number of histories run.

2) The differential pulse height spectra, a) for each of the six reaction channels, and b) for the total light output with three values of the resolution (including perfect resolution).

3) Three integral pulse height spectra, corresponding to the three differential spectra in (2b) above. The contents of each bin has been divided by the total number of incident neutrons, so that (3) gives integral efficiencies.

4) Information about the frequency of first and second interactions in the various channels, and about the time and position jitters due to neutron "random walks" (Appendix IV).

III. Physics Input

A. Processes Contributing to Neutron Detection. The following interaction channels have been simulated in this program:

1) Elastic scattering from protons, $np \rightarrow np$. Below 5 MeV this is the only significant channel producing a detectable recoiling charged particle, and it is the dominant detection mechanism for neutrons less energetic than about 25 MeV. In this energy range the total cross-section for $np \rightarrow pn$ is known¹⁴ to an accuracy much better than that attempted by this program ($\pm 5\%$), and the differential cross-section in the center-of-mass (cm) system is very nearly isotropic.¹⁶ Above about 30 MeV the np angular distribution becomes nonisotropic, but the inelastic carbon channels (whose cross-sections are poorly known) begin to dominate the efficiency, so that the details of the np interaction become less important.

Simulation of this channel is handled by subroutine NPNP (see comments in listing). The angular distribution is assumed to be isotropic below 30 MeV, while above 30 MeV the shape becomes increasingly parabolic, with $d\sigma/d\Omega^* = A + B \cos^2\theta^*$, where $B/A = E_n/30$ MeV (here θ^* is the CM angle, and E_n the neutron kinetic energy in the lab.). The light output from the proton is found by the function EEQUIV.

2) Elastic scattering of neutrons from carbon, $n + C \rightarrow n + C$. Because of the large saturation effect for heavy ions in plastic scintillator, the carbon recoil will not be detected with typical bias settings. This channel thus makes a second-order contribution to the efficiency which may, however, be significant since the cross-section is large. The effects depend on the shape of the counter as follows:

a) For a counter which has transverse dimensions small compared to its depth, elastic scattering from carbon can reduce the efficiency by scattering neutrons out of the counter before they can interact with the hydrogen. b) For a counter which has transverse dimensions large compared to its depth, the efficiency can be increased by the scattering back into the counter of neutrons which would otherwise escape. c) For neutron energies below 4.5 MeV the cross-section for a near-backward elastic scattering from carbon is comparable to that for near-forward scattering. These back-scattered neutrons have significantly lower energy (e.g. 4 MeV $\rightarrow$ 2.9 MeV) and hence can contribute less light output when they interact with hydrogen. With marginal bias settings this channel thus "destroys" some neutrons which would otherwise be seen.

The angular distribution for nC elastic scattering has a complicated energy dependence. Above about 10 MeV the forward diffraction peak is the dominant feature; at lower energies the shape undergoes rapid qualitative and quantitative changes with energy. The knowledge of the magnitude and shape of the cross-section is sufficiently good that it makes negligible contribution to the uncertainty in the efficiency.

Simulation of this channel is performed by subroutine NCEL, which reproduces the general features of the angular distributions. Separate total cross-sections for diffractive and non-diffractive elastic scattering are available, and the two processes are treated differently. a) Diffractive scattering (above 7.5 MeV) is assumed to follow an exponential distribution whose width is inversely proportional to the laboratory neutron energy E_n and to the nC total nonelastic cross-section: $d\sigma/d\Omega^* \propto \exp[-\lambda E_n (1 - \cos\theta^*)]$, with $\lambda = (1.17 \text{ MeV}^{-1} \text{ barn}^{-1}) \sigma_{inelastic}$

b) Nondiffractive elastic scattering is treated by the model shown in Fig. 1; the shape is a rectangle upon which sit a forward and a backward triangle. A choice is first made between diffractive or non-diffractive scattering; if nondiffractive scattering is chosen, a choice is made among the rectangle and the forward and backward triangles, based on the area under each.

Subroutine KINNR calculates the laboratory energy and angle of the emitted neutron. The light output (MeV electron equivalent) of the carbon recoil of lab energy E_c is taken to be $0.017 E_c$; it is rarely significant.

3) Inelastic scattering from carbon, $n + C \rightarrow n + C + \gamma$ (threshold, 4.7 MeV). This process contributes to the efficiency in two ways:

a) As a source of neutrons of different direction and lower energy.

The remarks in (2) about the qualitative effects of nC elastic scattering are also true here. In addition, because of the inelastic nature of this channel, the outgoing neutrons have significantly reduced energy near threshold. Because of the rapid monotonic decrease of the np elastic scattering cross-section (which dominates the efficiency), the lower energy secondary neutrons have a larger probability of detection. b) The emitted 4.4 MeV γ -ray may be detected by Compton scattering in the scintillator. The contribution to the efficiency of the channel $n + C \rightarrow n + C + \gamma$ is typically small ($< 10\%$) compared to the dominant np contribution in the range 6 - 16 MeV, and is negligible above about 25 MeV. The cross-sections from Ref. 17 were used as a starting point for tuning.

Simulation of $n + C \rightarrow n + C + \gamma$ is handled by subroutine NCNCGM and the subsidiary routines FOLGAM and CMPSCT. The treatment is

probably unnecessarily elaborate but was included because many of the subroutine modules already existed. The CM angular distribution of the neutron is estimated from proton-carbon¹⁸ data at 10 MeV to be $d\sigma/d\Omega^* \propto 1 + 5 \cos^2\theta^* - 4 \cos^4\theta^*$; the CM angular distribution of the photon is assumed to be¹⁰ $1 + 1.75 \cos^2\theta^*$. The photon is followed through successive Compton collisions by FOLGAM (similar in structure to FOLNUT) until it escapes from the scintillator; the total light output from the Compton electrons is returned. The total Compton cross-section per electron is found by CMPSCT from

$$\sigma = 2\pi r_0^2 \{ b[2(1 + \gamma)/a - (\ln a)/\gamma] + (\ln a)/2\gamma - (1 + 3\gamma)/a^2 \}$$

where

$$\gamma = E_\gamma / M_e c^2$$

$$a = 1 + 2\gamma$$

$$b = (1 + \gamma)/\gamma^2$$

$$r_0 = e^2 / M_e c^2$$

Subroutine CMPSCT also simulates the electron energy distribution from individual Compton scatters, using the integral kinetic energy distribution

$$P(E) = 2\pi r_0^2 \{ b[bE/2 - \ell] + \ell/2 + E(f - \gamma E/2)/2\gamma^4 \}$$

where

$$E = (\text{electron lab KE}) / M_e c^2$$

$$f = \gamma / (\gamma - E)$$

$$\ell = (\ln f) / \gamma$$

and $P(E)$ is the probability that the electron energy is between 0 and E .

4) The inelastic reaction $n + C \rightarrow \alpha + {}^9\text{Be}$ (threshold 6.2 MeV). This channel makes a small contribution to the efficiency between 6 and 20 MeV through detection of the recoil alphas. The cross-section is subject to some tuning. Simulation is performed by subroutine NALPHA, which assumes a two-body reaction isotropic in the CM. The laboratory energy of the alpha is found by KINNR and its light output by EEQAL.

5) The inelastic reaction $n + C \rightarrow n + 3\alpha$ (threshold 7.9 MeV) is simulated by subroutine NN3AL. This channel and channel 6 below dominate the detection efficiency above about 40 MeV. It is assumed that the outgoing neutron obeys a four-body phase-space distribution^{13,19} $N(\delta)d\delta = C\delta^{\frac{1}{2}}(1-\delta)^2d\delta$, where $\delta = (\text{neutron CM energy})/(\text{maximum neutron CM energy})$. The CM energies of the alphas are found from the simpler assumption that the energy of alpha #1 is uniformly distributed between zero and the left-over energy from the neutron, while that of alpha #2 is uniformly distributed in the remaining energy, etc. The light output from each alpha is found by EEQAL.

6) The inelastic reaction $n + C \rightarrow p + {}^{12}\text{B}$ (threshold 13.6 MeV) is simulated by subroutine NPB, which assumes a CM distribution for the proton which is identical to that for the neutron in channel 5.¹³ The light output from the proton is found by EEQUIV.

7) Omissions. Not included in this program are the channels $n + C \rightarrow n + p + {}^{11}\text{B}$, $n + C \rightarrow 3n + {}^{11}\text{C}$, and the meson-production channels at high energy. It is felt that the effects of the former can be adequately described by channels 5 and 6.

B. Light Output from Plastic Scintillator. It is necessary to take account of saturation effects in the light output of massive charged particles moving slowly. Light outputs in this program are expressed in MeV electron equivalent, which is the energy L of a stopping electron yielding the same amount of light as a heavy particle of energy E . For protons (function EEQUIV) the conversion used is²⁰

$$L_p = -10.68 [1.0 - \exp(-.07 E_p^{0.89})] + 0.929 E_p,$$

while for alphas (function EEQAL)

$$L_\alpha = 0.046 E_\alpha + 0.007 E_\alpha^2.$$

These are the same functions used by Kurz.¹³ It is likely that other organic scintillators (e.g. liquid scintillators) may have different saturation properties; there is also some evidence that the above descriptions of saturation need improvement (see Section VI).

C. Simulation of Finite Resolution. Because of the finite pulse height resolution of a real counter the measured pulse height spectrum is not identical to the intensity spectrum of light output from the scintillator, but has a resolution function folded in. The resolution is parameterized in this program by the one-photoelectron level L_0 , defined as that light output (in MeVee) which is needed (on the average) to create one photoelectron in the photomultiplier(s) looking at the scintillator. Differential and integral pulse height distributions are found for three values of L_0 : zero (perfect resolution) and two other values read in from the data deck.

Simulation proceeds as follows (the coding is in the MAIN routine): To the light output L for each history is added a "jitter" ΔL , chosen randomly from a Gaussian distribution (subroutine GAUSS). The standard deviation of the distribution is $\sigma_L = L_0 (L/L_0 + .5)^{\frac{1}{2}}$. Two values of ΔL are found, one for each non zero value of L_0 . The smeared light output is then $L' = L + \Delta L$, except L' is set to zero if it is found negative.

D. Kinematics. All kinematics except that of the Compton scatters is treated nonrelativistically. Although the classical approximation is rather poor near the high-energy limit (~ 400 MeV) of the program, it is equally true that all interactions except nC elastic scattering release such a large amount of light at these energies that they will be detected with any reasonable bias setting, so that no significant error in the efficiency is made. Since KINNRR is fully documented no formulae will be given here.

V. How to Use the Program

A. Data Deck. A listing of the data deck is given in Appendix II; the comment cards included in the data deck make this discussion somewhat redundant. The data deck consists of the following:

- 1) A comment card.
- 2) A card (FORMAT (6I1,14)) containing the array NSW and the variable NDUMP. The 6 elements of NSW give the initial settings of the simulated sense switches (Appendix IV); these are ordinarily set to 2. NDUMP is the number of individual histories to print out in detail (Appendix IV).
- 3) A comment card.
- 4) A card (FORMAT (10F8.3)) containing the density RHO (gm/cm^3) and the H/C ratio COMP of the scintillator.
- 5) A comment card.
- 6) A card (FORMAT (10F8.3)) containing the variables TBIAS, DTIM, and DPOS for the timing and position study (Appendix IV). TBIAS is the threshold (in MeVee) at which the "measurements" of time and position are taken; DTIM and DPOS are the bin widths (in nsec and in inches, respectively) for the accumulated histograms.
- 7) A comment card.
- 8) A card (FORMAT (13)) containing the number N of cross-section cards to follow.
- 9) A comment card.
- 10) N cards (FORMAT (8F5.3)) each containing an energy EDAT(I) (MeV) and seven total cross-sections SDAT(I,J) (barns) for each of the

seven channels listed below:

J = 1	NP elastic scattering
J = 2	NC nondiffractive elastic scattering
J = 3	$N + C \rightarrow N + C + \gamma$
J = 4	$N + C \rightarrow \alpha + {}^9\text{Be}$
J = 5	$N + C \rightarrow N + 3\alpha$
J = 6	$N + C \rightarrow P + {}^{12}\text{B}$
J = 7	NC diffractive elastic scattering.

(Note: The labeling of reaction channels J returned by subroutine SIGTOT is slightly different. See SIGTOT listing for details.)

11) A comment card.

12) A card (FORMAT (13)) containing the number M of angular distribution coefficient cards to follow.

13) A comment card.

14) M cards, (FORMAT(10F8.3)) each containing an energy ED(1) (MeV) and five coefficients AD(I,J) for describing NC nondiffractive elastic scattering. These coefficients are defined in Fig. 1.

15) A comment card.

16) A card (FORMAT (3F6.2,2I2)) containing the variables XB, YB, ZB, IGE0, and IRANP giving the dimensions and geometry of the scintillator, and whether the neutron illumination is point or uniform. If IGE0 = 1, the scintillator is taken to be a rectangular prism $\pm$ XB inches wide, $\pm$ YB inches high, and ZB inches deep; IRANP = 0 will send in all neutrons at the point specified in (20) below, while IRANP = 1 will distribute the neutrons uniformly in the vertical direction. If IGE0 = 2,

the scintillator is taken to be a cylinder of radius $X_B = Y_B$ inches and depth Z_B inches. If $IRANP = 0$, all neutrons will enter at the point specified in (20); if $IRANP = 1$, the flat face will be uniformly illuminated.

17) A comment card.

18) A card (FORMAT (3F6.2)) giving $ELOPE(2)$ and $ELOPE(3)$, the light levels (in MeVee) corresponding to one photoelectron for the two values of resolution smearing desired (Section IV C).

19) Four comment cards. The contents of the fourth card will be reproduced on the output as a heading.

20) Any number of cards, one for each group of histories desired. Each card contains (FORMAT 3F5.2, 3F7.4, 2F8.3, I8, F8.3)):

a) The initial position vector $XI(1)$ in inches, if $IRANP = 0$ (see 16 above). The center of the coordinate system is at the center of the front face of the counter. If $IRANP = 1$ and $IGEO = 1$, $X(2)$ will be randomly chosen; if $IRANP = 1$ and $IGEO = 2$, $X(1)$ and $X(2)$ will be chosen randomly so as to illuminate uniformly the front face.

b) The initial direction cosines $CI(1)$. For normal incidence these are 0.0, 0.0, 1.0.

c) The limits of the neutron energy $E1$ and $E2$ (MeV). If $E2$ is less than or equal to $E1$ all neutrons will be assigned initial energy $E1$; otherwise the initial energy will be randomly chosen from a uniform distribution between $E1$ and $E2$.

d) The number of histories to be run, NEV .

e) The bin width (in MeV) for the output differential and integral (efficiency) pulse height spectra.

B. Time, Core and Library Requirements. The execution time for a fixed number of histories depends on the thickness of the counter and on the neutron energy; simulating interactions take time. In particular, low energy neutrons often interact several times in scintillators, of typical size. As a guide, the run which produced the output in Appendix III (10,000 neutrons of energy 20 - 25 MeV impinging on a scintillator 11.26 inches deep) took 1 min 46 sec on an IBM 360-75. The program occupies about 85K (decimal) bytes of core (1 byte = 8 bits). In addition to the usual library routines for trig functions, square root, exponential, etc., a random number generator is needed; subroutine UNIRND calls RANDU, which is available from the IBM scientific subroutine package. Two other routines from this package, RTNI and GAUSS, have been included with the source program.

VI. Comparison with Experiment

The existing total cross-section data for neutron-carbon inelastic interactions have been adjusted within reasonable limits (two standard deviations) to fit the efficiency data of Ref. 2 for a plastic scintillator 6 x 6 x 20 inches; the resulting agreement between calculation and data is shown in Fig. 2a for neutron energies between 1.5 and 200 MeV and biases between 0.2 and 4.0 MeVee. Except at the highest bias the agreement is better than 5%. The excellent fit above 50 MeV is the result of our freedom to adjust the carbon cross-sections; it is the good agreement below 10 MeV which is especially gratifying because of the lack of adjustable parameters. Figure 2e shows the total cross-sections used by the program as a function of neutron kinetic energy for five of the six reaction channels simulated by the program; the cross-section for the carbon elastic channel is given in Ref. 15.

The efficiencies for neutron counters used in three other recent calibration experiments have been calculated using the same cross sections. Comparisons with the data^{6,7,8,11} are shown in Figs. 2b-2d. The smallest counter was 2 inches thick, while the largest was 12 inches thick. Biases ranged from 0.80 to 16 MeV. Once again the agreement is typically better than 5% except for the high-energy end of Fig. 2d, where the data of Ref. 8 show a rise in efficiency at low bias which is not predicted by the Monte Carlo program.

High-statistics data on the dependence of efficiency on threshold²¹ are available from the tapes of the n-p charge-exchange experiment of Ref. 1, which contain the neutron kinetic energy and scintillator pulse height for

each of 180,000 events satisfying the kinematic constraints for this reaction. We can thus select neutrons in any narrow interval of kinetic energy between 1 and 450 MeV and plot yield against threshold; if the measured distribution is normalized to the Monte Carlo efficiency at one value of the threshold for each distribution, the threshold dependence of the Monte Carlo efficiency may be compared with experiment. The absolute calibration of pulse height against light output (in McVee) using a Co^{60} source, described in Ref. 2, is believed accurate to $\pm 5\%$.

Comparisons of measured and predicted threshold dependence are presented in Fig. 3, for selected neutron energies between 1.25 and 313 MeV and for rectangular scintillators of three different sizes: the "Long" counters are 10 x 10 x 40 inches, the "Short" counters 6 x 6 x 20 inches, the "Wee" counters 3 x 3 x 10 inches (thickness in the incident neutron direction is underlined). It was found that the Long counter threshold dependence agreed very well with the Monte Carlo predictions, but that for the Short and Wee counters the agreement was significantly improved by multiplying the measured pulse heights by 1.15. This has been done for the data in Fig. 3, which implies that the pulse height calibration is in error. However, since the threshold dependence is most sensitive for low light levels where the saturation effect is largest, it is also plausible to interpret the discrepancy as arising from an overestimate by the program of the light output from low-energy proton recoils. This interpretation is supported by more recent measurements of the response of plastic scintillator to low-energy protons,²² which show a larger saturation effect than was used for our calculation, with light output up to 40% less for 1 MeV

protons. It is likely that a more accurate simulation of the saturation properties of plastic scintillator in the Monte Carlo program will remove most of the remaining small disagreement with measured efficiencies.

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FIGURE CAPTIONS

- Figure 1. Shape parameters for angular distribution of neutron-carbon nondiffractive elastic scattering.
- Figure 2. (a) - (d) Comparison of the predictions of the Monte Carlo program with the efficiency measurements from References 2, 11, 6, 8, and 9. (e) Total cross-sections used by the Monte Carlo program. The neutron-carbon elastic channel is not shown.
- Figure 3. Dependence of neutron counter efficiency on threshold (bias) for several intervals of neutron energy. The curves are predictions of the Monte Carlo program; the measured integral pulse height distributions are from Reference 21. Each measured distribution has been normalized to the calculation at the shaded point.

SHAPE PARAMETERS FOR ANGULAR DISTRIBUTION OF N-C NONDIFFRACTIVE ELASTIC SCATTERING

THE ARRAY AD (I,J) AT ENERGY ED (I)

$$AD(I,1) = a \quad (\text{mb/sr})$$

$$AD(I,2) = b \quad (\text{mb/sr})$$

$$AD(I,3) = c$$

$$AD(I,4) = d \quad (\text{mb/sr})$$

$$AD(I,5) = e$$

Appendix I: Source Program Listing

This Appendix contains a complete listing of the FORTRAN IV source program for the Monte Carlo neutron counter efficiency calculation described in Sections I - VI. A Table of Contents for the subroutines is provided below.

<u>Subroutine</u>	<u>Page</u>
MAIN	29
FOLNUT	40
SIGTOT	46
INBND5	48
NPNP	49
NCEL	50
NCNCGM	52
FOLGAM	54
CMPSCT	56
NALPHA	58
NN3AL	59
NPB	61
KINNR	63
ANGDIS	65
ENGDIS	66
SCATTR	67
EEQUIV	69
EEQAL	70
IBNSH	71
RTNI	72
GAUSS	75
SSWTCH	76
UNIRND	77

C MONTE CARLO NEUTRON COUNTER EFFICIENCY PROGRAM. JANUARY 1971

C MAIN ROUTINE

C

```

DIMENSION X(3),C(3),EL(9),S(8),XI(3),CI(3)
DIMENSION LT(200,9),LTOT(200),LCON(9),LHI(9),ELOPE(3),EFF(200)
COMMON /CRBANG/ED(32),AD(32,8)
COMMON /SIGDAT/ EDAT(128),SDAT(128,7)
EQUIVALENCE (LTOT(1),LT(1,7))
COMMON /BNDS/XB,YB,ZB
COMMON/SWBLK/NSW(6)
COMMON /FIRSC/ NFS(6,5,2)
COMMON /SCIN/ DHYD,DCARB
COMMON /GEOM/ IGEO
COMMON /DUMP/NDUMP,MDUMP
COMMON /TIMING/ TBIAS,DTIM,DPOS,NTIM(100),NPOS(100)
DIMENSION COMMNT(20)
    
```

C

C

C

```

***** SECTION A *** DATA INPUT *****
(FOR MORE DETAILS SEE DESCRIPTION OF DATA DECK)
    
```

C

C

C

INPUT SENSE SWITCH SETTINGS, AND MAXIMUM NUMBER OF EVENTS TO DUMP

```

READ (3,55) COMMNT
WRITE (1,54)
WRITE (1,56) COMMNT
READ(3,9001)NSW,MDUMP
WRITE (1,9002) NSW,MDUMP
    
```

54 FORMAT(10H1DATA DECK)

55 FORMAT (20A4)

56 FORMAT (1H0/1X,20A4)

9001 FORMAT (6I1,14)

9002 FORMAT (1X,6I1,14)

C

READ IN DENSITY (GM/CM3) AND COMPOSITION (H/C RATIO) OF SCINTILLATOR.

C

CALCULATE DHYD AND DCARB, THE NUMBER OF H AND C ATOMS PER BARN-INCH.

C

READ (3,55) COMMNT

```
WRITE (1,56) COMMNT
READ (3,4) RHO,COMP
WRITE (1,7) RHO,COMP
4 FORMAT (10F8.3)
7 FORMAT (1X,10F8.3)
DCARB=.6025*2.54*RHO/(12.*COMP)
DHYD=DCARB*COMP
```

```
C
C READ IN BIAS AND BIN WIDTH INFORMATION FOR TIMING AND POSITION STUDY
READ (3,55) COMMNT
WRITE (1,56) COMMNT
READ (3,4) TBIAS,DTIM,DPOS
WRITE(1,7) TBIAS,DTIM,DPOS
```

```
C
C READ IN CROSS SECTION DATA
C
C EDAT(I) CONTAINS THE ENERGY (IN MEV) FOR THE ITH DATA POINT
C (UNUSED ELEMENTS OF EDAT ARE INITIALIZED TO 1.0E7 FOR BINARY SEARCH)
C SDAT(I,J) CONTAINS TOTAL CROSS-SECTION (IN BARNS) FOR REACTION
C CHANNEL J FOR ITH DATA POINT
C REACTION CHANNELS ARE AS FOLLOWS
C J=1 NP ELASTIC SCATTERING
C J=2 NC NONDIFFRACTIVE ELASTIC SCATTERING
C J=3 N&C--N&C&GAMMA
C J=4 N&C--ALPHA&9BE
C J=5 N&C--N&3 ALPHAS
C J=6 N&C--P&12B
C J=7 NC DIFFRACTIVE ELASTIC SCATTERING
C NOTE--THE LABELING OF REACTION CHANNELS J IN THE ARRAY S(J) RETURNED
C BY SUBROUTINE SIGTOT IS SOMEWHAT DIFFERENT.SEE LISTING OF SIGTOT.
```

```
C
DO 2 I=1,128
2 EDAT(I)=1.0E7
READ (3,55) COMMNT
WRITE (1,56) COMMNT
READ (3,1) N
1 FORMAT (I3)
READ (3,55) COMMNT
```

C
M
MONTE CARLO NEUTRON COUNTER EFFICIENCY PROGRAM, JANUARY 1971

PAGE 3

```
      WRITE (1,1) N
      WRITE (1,56) COMMNT
C (N CROSS-SECTION CARDS FOLLOW)
C
      DO 1331 I=1,N
1331  READ (3,3) EDAT(I), (SDAT(I,J),J=1,7)
      3 FORMAT (8F5.3)
      WRITE(1,1334) (EDAT(I),(SDAT(I,J),J=1,7),I=1,N)
1334  FORMAT (F8.2,5X,7F7.3)
C
C  READ IN COEFFICIENT ARRAY FOR NC NONDIFFRACTIVE ELASTIC SCATTERING
C  ED(I) CONTAINS ENERGY FOR ITH DATA POINT
C  AD(I,J),J=1 TO 5, CONTAINS JTH SHAPE PARAMETER FOR ITH DATA POINT
C  (SEE WRITEUP OF SUBROUTINE NCEL FOR DEFINITION OF PARAMETERS)
C
      READ (3,55) COMMNT
      WRITE (1,56) COMMNT
      READ (3,1) M
      READ (3,55) COMMNT
      WRITE (1,1) M
      WRITE (1,56) COMMNT
C (M DATA CARDS FOLLOW)
      DO 1349 J=1,32
1349  ED(J)=1.0E7
      DO 1350 I=1,M
      READ (3,4) ED(I),(AD(I,J),J=1,5)
C
C  AD(I,J),J=6 TO 8, CONTAINS JTH AREA PARAMETER FOR ITH DATA POINT
C
      AD(I,6)=2.*AD(I,1)
      AD(I,7)=(1.-AD(I,3))*(AD(I,2)-AD(I,1))*0.5
      IF (AD(I,7) .LT. 0.) AD(I,7)=0.
      AD(I,8)=(1.6AD(I,5))*(AD(I,4)-AD(I,1))*0.5
      IF (AD(I,8) .LT. 0.) AD(I,8)=0.
1350  WRITE (1,4) ED(I), (AD(I,J),J=1,8)
C
C  READ SCINTILLATOR BOUNDARIES AND 1 PHOTOELECTRON LEVELS
C
```

C SCINTILLATOR IS ZB INCHES DEEP AND HAS TRANSVERSE DIMENSIONS
 C OF 2.*XB AND 2.*YB
 C IF SCINTILLATOR IS A CYLINDER, ITS RADIUS IS XB (=YB)
 C THE PARAMETER IGEO IDENTIFIES THE SCINTILLATOR GEOMETRY
 C IGEO=1 FOR BOX, IGEO=2 FOR CYLINDER (NEUTRONS ENTER FLAT FACE)
 C IF IRAND =1, INITIAL POSITION WILL BE CHOSEN RANDOMLY (SEE BELOW)
 C OTHERWISE SET IRAND=0

C
 READ (3,55) COMMNT
 WRITE (1,56) COMMNT
 READ (3,5) XB,YB,ZB,IGEO,IRANP
 WRITE(1,5) XB,YB,ZB,IGEO,IRANP
 5 FORMAT (3F6.2,2I2)

C
 C READ THE TWO DESIRED (NONZERO) VALUES OF THE LIGHT OUTPUT (IN MEV
 C ELECTRON EQUIVALENT) CORRESPONDING TO ONE PHOTOELECTRON. THESE WILL
 C BE USED IN SIMULATING EXPERIMENTAL RESOLUTION.

READ (3,55) COMMNT
 WRITE (1,56) COMMNT
 READ (3,5) (ELOPE(1),I=2,3)
 WRITE(1,5) (ELOPE(I),I=2,3)

C
 C
 C ***** SECTION B ** SET UP FOR EACH GROUP OF HISTORIES *****
 C

C INITIALIZE HISTOGRAM ARRAYS AND COUNTERS

C
 READ (3,55) COMMNT
 WRITE (1,56) COMMNT
 READ (3,55) COMMNT
 WRITE (1,56) COMMNT
 READ (3,55) COMMNT
 WRITE (1,56) COMMNT
 READ (3,55) COMMNT
 WRITE (1,56) COMMNT

1000 DO 10 I=1,9
 DO 9 J=1,200
 9 LTC(J,I)=0

```

LCON(I)=0
10 LHI(I)=0
NDET=0
NDUMP=0
IN=0
ELOPE(1)=0.

```

C ZERO TIMING AND POSITION ARRAYS

```

DO 11 I=1,100
NTIM(I)=0
11 NPOS(I)=0
DO 12 I=1,5
DO 12 J=1,6
NFS(J,I,1)=0
12 NFS(J,I,2)=0

```

C
C
C
C
C
C
C
C
C
C
C
C
C
C
C

FOR EACH SET OF HISTORIES DESIRED, READ ONE CARD CONTAINING
 THE INITIAL NEUTRON POSITION COORDINATES XI(I), I=1 TO 3
 THE INITIAL NEUTRON DIRECTION COSINES CI(I), I=1 TO 3
 THE INITIAL NEUTRON ENERGY RANGE E1 TO E2
 (IF E2=0. EVERY NEUTRON WILL BE ASSIGNED ENERGY E1. OTHERWISE THE
 NEUTRON ENERGIES ARE DISTRIBUTED UNIFORMLY BETWEEN E1 AND E2)
 THE NUMBER OF HISTORIES TO BE RUN, NEV
 THE DESIRED BIN WIDTH (MEV ELECTRON EQUIVALENT) FOR THE OUTPUT
 PULSE HEIGHT HISTOGRAMS, BINW

```

READ (3,15) (XI(I),I=1,3),(CI(I),I=1,3),E1,E2,NEV,BINW
15 FORMAT (3F5.2,3F7.4,2F8.3,I8,F8.3)
DE=E2-E1
IF (DE .LE. 0.) DE=0.

```

C
C
C

***** SECTION C ** CHOOSE INITIAL POSITION X(I) , DIRECTION
 COSINES C(I) , AND ENERGY E OF EACH NEUTRON *****
 NOTE THAT COORDINATE ORIGIN IS AT CENTER OF FRONT FACE OF COUNTER.

```

C
2000 IN=IN&1
      DO 30 I=1,3
      X(I)=XI(I)
      30 C(I)=CI(I)
C IF IRANP=1, USE RANDOMLY CHOSEN INITIAL COORDINATES
      IF (IRANP .NE. 1) GO TO 2006
      IF (IGEO=1) 2002,2002,2004
C IF RECTANGULAR GEOMETRY, CHOOSE RANDOM X(2)
2002 X(2)=YB *(1.-2.*UNIRND(Y))
      GO TO 2006
C IF CYLINDRICAL GEOMETRY, CHOOSE RANDOM RADIUS FROM LINEAR DISTRIBUTION
2004 R=XB *SQRT(UNIRND(Y))
      PHI=6.2832*UNIRND(Y)
C (UNIFORM DISTRIBUTION IN AZIMUTH)
      X(1)=R*COS(PHI)
      X(2)=R*SIN(PHI)
2006 CONTINUE
      E=E1&DE*UNIRND(Y)
C (ENERGY UNIFORMLY DISTRIBUTED BETWEEN E1 AND E2)
      DO 40 I=1,9
      40 EL(I)=0.
      CALL SSWTCH (1,N1)
C (SENSE SWITCH OPTIONS ARE DESCRIBED IN SUBROUTINE SSWTCH)
      CALL SSWTCH (5,N5)
C
C CALL SUBROUTINE FOLNUT, WHICH FOLLOWS THE NEUTRON UNTIL IT EITHER
C ESCAPES FROM THE SCINTILLATOR OR DROPS BELOW 0.1 MEV IN ENERGY
C
C FOLNUT RETURNS THE ARRAY EL(I), WITH ELEMENTS I=1 TO 6 CONTAINING THE
C LIGHT OUTPUT (IN MEV ELECTRON EQUIVALENT) IN EACH OF THE REACTION
C CHANNELS 1 TO 6 LISTED ABOVE, AND THE TOTAL LIGHT OUTPUT EL(7).
C IT ALSO RETURNS THE NUMBER OF INTERACTIONS MS DURING THE HISTORY.
C
      CALL FOLNUT (X,C,E,.1,EL,MS)
      IF (EL(7) .LE. 0.) GO TO 46
C
C

```

```

C ***** SECTION D *** SIMULATE FINITE PULSE HEIGHT RESOLUTION AND
C UPDATE PULSE HEIGHT HISTOGRAMS *****
C
C THE ARRAY ELEMENTS EL(8) AND EL(9) CONTAIN THE TOTAL LIGHT OUTPUT
C EL(7) FOR THIS EVENT, SHIFTED RESPECTIVELY BY TWO GAUSSIAN-DISTRIBUTED
C RANDOM NUMBERS WITH STANDARD ERRORS SIG WHICH DEPEND ON THE (INPUT
C DATA) ONE-PHOTOELECTRON LEVELS ELOPE(2) AND ELOPE(3). NOTE THAT SIG
C IS (NEARLY) PROPORTIONAL TO THE SQUARE ROOT OF THE NUMBER OF
C PHOTOELECTRONS RELEASED.
C
      DO 44 J=2,3
      K=J&6
      SIG=SQRT(EL(7)/ELOPE(J) &.5)*ELOPE(J)
44 EL(K)=EL(7)&SIG*GAUSS(Y)
C
C THE ARRAY LT(I,J), I=1 TO 200, J=1 TO 9, CONTAINS 9 200-BIN HISTO-
C GRAMS, EACH HAVING BIN WIDTH BINW (INPUT DATA), ACCUMULATED FROM THE 9
C ELEMENTS OF EL(J) RETURNED FOR EACH DETECTED NEUTRON. THUS LT(I,J),
C J=1 TO 6, CONTAINS A DIFFERENTIAL PULSE HEIGHT SPECTRUM (DPHS) FOR
C REACTION CHANNEL J, ASSUMING PERFECT RESOLUTION. LT(I,J), J=7 TO 9,
C CONTAINS A DPHS FOR THE TOTAL LIGHT OUTPUT, ASSUMING 1 PE LEVELS OF
C ZERO, ELOPE(1), AND ELOPE(3) RESPECTIVELY.
C
C THE ARRAY LCON(J), J=1 TO 9, IS INCREMENTED EACH TIME ANY ELEMENT I
C OF LT(I,J) IS INCREMENTED. IT THUS CONTAINS THE TOTAL IN EACH HISTOGRAM
C
C THE ARRAY LHI(J), J=1 TO 9, CONTAINS THE BIN NUMBER I OF THE HIGHEST
C NONZERO BIN OF LT(I,J)
C
46 DO 50 I=1,9
      IF (EL(I) .LE. 0.) GO TO 50
      L=IFIX(EL(I)/BINW) &1
      IF (L .GE. 200) L=200
      LT(L,I)=LT(L,I) &1
      LCON(I)=LCON(I) &1

```



```

      LHI(I)=MAX0(LHI(I),L)
50  CONTINUE
      IF (EL(7).GT. 0.) NDET=NDET&1
      IF (N5 .EQ.1) WRITE(1,51) IN,NDET
51  FORMAT (2I8)
      IF (IN .GE. NEV) GO TO 3000
      IF (N1 .EQ.1) GO TO 3000
      GO TO 2000

C
C
C ***** SECTION E ** OUTPUT *****
C
3000 CONTINUE
      XBB=2.*XB
      YBB=2.*YB
      GO TO (3002,3004),IGEO
3002 WRITE (1,3003) ZB,XBB,YBB
      GO TO 3006
3004 WRITE (1,3005) ZB,XB
3003 FORMAT(52H1RECTANGULAR SCINTILLATOR WITH DIMENSIONS (INCHES)
1  F8.3,8H DEEP BY ,F8.3,4H BY ,F8.3 )
3005 FORMAT(52H1CYLINDRICAL SCINTILLATOR WITH DIMENSIONS (INCHES)
1  F8.3,8H DEEP BY ,F8.3,10H IN RADIUS )
3006 CONTINUE
      WRITE (1,56) COMMNT
      WRITE (1,57) RHO,COMP
57  FORMAT (9H0DENSITY= ,F7.3,9H GM/CM**3 ,5X,10HH/C RATIO= ,F7.3)
      WRITE (1,3000) IN,E1,E2,(XI(I),I=1,3),(CI(I),I=1,3)
3000 FORMAT (1H0/17,20H NEUTRONS OF ENERGY ,F6.2,4H TO ,F6.2, 5H MEV /
1 20H INCIDENT AT X,Y,Z= ,3F7.2, 7H INCHES,3X,
2 20H DIRECTION COSINES= ,3F7.4 /)
      IF (IRANP .EQ. 1) WRITE (1,3001)
3001 FORMAT (30H ** RANDOM INITIAL POSITION ** )
      WRITE (1,3007)
      WRITE (1,3008)
3007 FORMAT (36H DIFFERENTIAL PULSE HEIGHT SPECTRA /)
3008 FORMAT (40H LIGHT OUTPUT IN MEV ELECTRON EQUIVALENT )
      DO 350 I=1,6

```

```
NC=LHI(I)
WRITE (1,302) I,BINW,LCON(I)
IF (LCON(I) .EQ. 0) GO TO 350
302 FORMAT( 9H0CHANNEL ,I3,5H ONLY ,5X,11H BIN WIDTH ,F5.3,6X,18,
1 8H EVENTS )
350 WRITE (1,304) (LT(L,I),L=1,NC)
304 FORMAT (10I5,5X,10I5)
DO 360 I=1,3
K=I&6
WRITE (1,306) ELOPE(I),BINW,LCON(K)
NC=LHI(K)
306 FORMAT (33H0LIGHT OUTPUT FROM ALL CHANNELS ,5X,
1 28H ONE PHOTOELECTRON LEVEL AT , F7.3,5H MEV /
2 11H BIN WIDTH ,F5.3,5H MEV ,6X,17, 8H EVENTS )
360 WRITE (1,304) (LT(L,K),L=1,NC)
C
C FIND AND PRINT OUT THE INTEGRAL EFFICIENCY HISTOGRAMS CORRESPONDING
C TO THE DIFFERENTIAL PULSE HEIGHT SPECTRA LT(I,J), J=7 TO 9 (SEE
C ABOVE)
C
WRITE (1,3009)
3009 FORMAT (1H0//,30H INTEGRAL PULSE HEIGHT SPECTRA /)
WRITE (1,3008)
DO 380 I=1,3
K=I&6
NC=LHI(K)
WRITE (1,308) ELOPE(I),BINW
308 FORMAT (1H0/30H INTEGRAL EFFICIENCY,ONE P.E.= ,F7.3,5H MEV ,3X,
1 12H BIN WIDTH ,F5.3,5H MEV )
WRITE (1,309)
309 FORMAT (43 H NOTE FIRST BIN CORRESPONDS TO ZERO BIAS. )
EN=LCON(K)
DO 370 J=1,NC
EFF(J)=EN/FLOAT(IN)
370 EN=EN-FLOAT(LT(J,K))
380 WRITE(1,310) (EFF(J),J=1,NC )
310 FORMAT (20F6.3)
```

C OUTPUT FIRST SCATTER INFORMATION
C (SEE SUBROUTINE FOLNUT FOR A DESCRIPTION OF THE FIRST- AND SECOND-
C SCATTER BOOKKEEPING FEATURE. ARRAYS ARE PASSED THROUGH THE
C LABELED COMMON BLOCK /FIRSC/)
C

```
      WRITE (1,400)
400  FORMAT (20H0FIRST SCATTER DATA      )
      WRITE (1,3010)
3010  FORMAT(7H0 BIAS ,6X,35HCH.1  CH.2  CH.3  CH.4  CH.5  CH.6  )
420  FORMAT (1H0,F6.2,6X,6I6)
      BIAS=.125
      DO 410 I=1,5
      BIAS=BIAS*2.
410  WRITE (1,420) BIAS,(NFS(J,I,1),J=1,6)
```

C
C
C OUTPUT SECOND SCATTER INFORMATION
C

```
      WRITE (1,500)
500  FORMAT (21H0SECOND SCATTER DATA      )
      WRITE (1,3010)
      BIAS=.125
      DO 510 I=1,5
      BIAS=BIAS*2.
510  WRITE (1,420) BIAS,(NFS(J,I,2),J=1,6)
```

C
C OUTPUT TIMING AND POSITION INFORMATION
C (SEE SUBROUTINE FOLNUT FOR A DESCRIPTION OF THE TIMING AND POSITION
C STUDY. ARRAYS ARE PASSED THROUGH LABELED COMMON BLOCK /TIMING/)
C

```
      WRITE (1,520) TBIAS
520  FORMAT ( 60H0HISTOGRAMS OF TIME DELAY AND X-COORD. DRIFT BEFORE BI
      IAS OF      ,F5.3, 17H MEV IS ATTAINED      )
      WRITE (1,521) DTIM
521  FORMAT (8H0TIMING ,F5.3,10H NSEC/BIN      )
      WRITE (1,522) NTIM
522  FORMAT (1X,2(10I5,5X))
      WRITE (1,523) DPOS
523  FORMAT (10H0POSITION ,F5.3,10H INCH/BIN      )
```

C MONTE CARLO NEUTRON COUNTER EFFICIENCY PROGRAM. JANUARY 1971

PAGE 11

WRITE (1,522) NPOS
GO TO 1000
END

SUBROUTINE FOLNUT (X,C,EO,EMIN,EL,NS)

```
C
C MONTE CARLO NEUTRON TRACER
C
C GIVEN A NEUTRON OF ENERGY E0 AT POSITION X(I), I=1 TO 3 ,
C AND MOVING ALONG DIRECTION COSINES C(I), I=1 TO 3 ,
C FOLNUT FOLLOWS THE NEUTRON THROUGH SUCCESSIVE INTERACTIONS
C UNTIL IT EITHER ESCAPES THE INTERACTION VOLUME, OR IS ABSORBED,
C OR UNTIL ITS ENERGY DROPS BELOW EMIN, OR MORE THAN 10 SCATTERS OCCUR.
C
C FOLNUT RETURNS EL(L), L=1 TO 7, AN ARRAY CONTAINING THE LIGHT OUTPUT
C IN EACH OF THE SIX REACTION CHANNELS (SEE BELOW) , AND THE TOTAL
C LIGHT OUTPUT (L=7). LIGHT OUTPUT IS EXPRESSED IN MEV ELECTRON EQUIVAL.
C FOLNUT ALSO RETURNS NS, THE NUMBER OF INTERACTIONS DURING THE HISTORY.
C FOLNUT ALSO PERFORMS THE BOOKKEEPING FOR THE STUDY OF CHANNEL
C DISTRIBUTIONS OF FIRST AND SECOND INTERACTIONS, AND THE STUDIES
C OF TIME DELAY AND POSITION DRIFT (SEE BELOW).
C
C
C   DIMENSION X(3),C(3),EL(7),S(8)
C   COMMON /FIRSC/ NFS(6,5,2)
C   COMMON /SCIN/ DHYD,DCARB
C   DIMENSION NF(5)
C   COMMON /DUMP/NDUMP,MDUMP
C   COMMON /TIMING/ TBIAS,DTIM,DPOS,NTIM(100),NPOS(100)
C
C INITIALIZE
C   L=7
C   NSMAX=10
C   NS=0
C   E=EO
C   TIME=0.
C   ICOUNT=0
C   X0=X(1)
C   DO 4 I=1,L
C     4 EL(I)=0.
```

```

C  PREPARE TO PRINT INDIVIDUAL HISTORIES, IF DESIRED.
      CALL SSWTCH(2,N2)
      IF(N2 .EQ. 1 ) MDUMP=MDUMP&1
      NDUMP=NDUMP&1
      IF (NDUMP .GT. MDUMP) GO TO 2000
      IF (NDUMP .EQ. 1) WRITE (1,9)
      9  FORMAT ( 31H1 DUMP OF INDIVIDUAL HISTORIES ,/,
      1  56H THE FOLLOWING VARIABLES ARE DUMPED AT EACH INTERACTION ,/,
      2  37H (SEE FOLNUT LISTING FOR DEFINITION) ,/,
      356H E,EL(7),MS,ELT,(X(I),I=1,3),(C(I),I=1,3),COSL,PHI,TIME )
      WRITE (1,11) NDUMP,E
      11 FORMAT (7H0EVENT ,15,5X,14HINITIAL ENERGY ,F8.3,4H MEV )

C
C  FIND TOTAL CROSS SECTIONS.
C
      2000 CONTINUE
      IF (E .LT. EMIN ) RETURN
      CALL SIGTOT (E,S)

C
C  THE ARRAY S(I) RETURNED BY SIGTOT CONTAINS THE TOTAL CROSS-SECTIONS
C  AT ENERGY E FOR EACH REACTION CHANNEL.
C
      ELT=0.

C
C  FIND DISTANCE TO NEXT SCATTER.
C  SHH AND SCC ARE THE TOTAL CROSS-SECTIONS IN HYDROGEN AND CARBON.
C  DHYD AND DCARB ARE THE NUMBER OF H AND C NUCLEI PER BARN-INCH
C  PASSED THROUGH COMMON BLOCK /SCIN/
C
      SHH=S(1)
      SCC=S(2)&S(7)&S(8)
      PATH=1./(DHYD*SHH&DCARB*SCC)
      D=-PATH*ALOG(UNIRND(Y))

C
C  PROPAGATE NEUTRON A DISTANCE D.
C
      DO 20 I=1,3
      20 X(I)=X(I)&C(I)*D

```

```
C
C  IS NEUTRON STILL IN BOUNDS.
C
C      IF(INBNDS(X) .LE. 0) RETURN
C  THE FUNCTION INBNDS(X)=1 IF VECTOR X IS INSIDE THE SCINTILLATOR,
C      =0 IF X IS OUTSIDE.
C
C      NS=NS&1
C  METER THE ELAPSED TIME (NANOSECONDS) SINCE NEUTRON ENTERED SCINT.
C      TIME =TIME &D*1.84/SQRT(E)
C      IF (NS .GT. NSMAX) RETURN
C
C  DECIDE WHETHER CARBON INTERACTION OCCURRED.
C      IF (DCARB*SCC *PATH .GT. UNIRND(Y) ) GO TO 200
C
C  ELASTIC SCATTER FROM HYDROGEN OCCURRED (REACTION CHANNEL 1)
C
C  100 MS=1
C      CALL NPNP (E,W,COSL,ELT)
C  NPNP RETURNS THE NEW NEUTRON ENERGY W, THE COSINE OF THE LAB
C  SCATTERING ANGLE COSL, AND THE LIGHT OUTPUT ELT.
C
C      GO TO 1000
C
C  CARBON INTERACTION OCCURED.DECIDE WHETHER ELASTIC OR INELASTIC.
C
C  200 IF (S(7)/SCC .GT. UNIRND(Y)) GO TO 300
C  (S(7) IS THE NONELASTIC CARBON CROSS-SECTION)
C
C  ELASTIC SCATTER FROM CARBON OCCURRED (REACTION CHANNEL 2)
C
C      MS=2
C      CALL NCEL(S,E,W,COSL,ELT)
C  W,COSL,ELT ARE DEFINED UNDER NPNP ABOVE
C
C      ELT=.017*(E-W)
C      GO TO 1000
C
```

SUBROUTINE FOLNUT (X,C,EO,EMIN,EL,NS)

PAGE 4

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C   INELASTIC CARBON INTERACTION OCCURRED.CHOOSE WHICH.
C
300 IF (S(3)/S(7) .LE. UNIRND(Y)) GO TO 400
C
C   N&C--N&C&GAMMA   OCCURRED (REACTION CHANNEL 3)
C
      MS=3
      CALL NCNCGM (E,X,C,W,COSL,ELT)
      GO TO 1000
400 SR=S(4)&S(5)&S(6)
      U=UNIRND(Y)
      IF (S(4)/SR .LE. U) GO TO 500
C
C   N&C--ALPHA&9BE   OCCURRED (REACTION CHANNEL 4)
C
      MS=4
      CALL NALPHA(E,ELT)
      GO TO 950
C
500 IF ( (S(4)&S(5))/SR .LE.U) GO TO 600
C
C   N&C--N&THREE ALPHAS   OCCURRED (REACTION CHANNEL 5)
C
      MS=5
      CALL NN3AL(E,W,COSL,ELT)
      GO TO 1000
C
C   N&C--P&12B   OCCURRED (REACTION CHANNEL 6)
C
600 MS=6
      CALL NPB(E,ELT)
C
C   (NO NEUTRON RELEASED)
950 W=0.
      COSL=1.
C
C   INCREMENT THE ELEMENT MS=1 TO 6 OF THE LIGHT OUTPUT ARRAY ELT
C   CORRESPONDING TO THE CHANNEL OF INTERACTION,AND ELT(7),THE TOTAL

```


C LIGHT OUTPUT.

C
1000 EL(MS)=EL(MS)&ELT
EL(7)= EL(7) &ELT
E=W

C
C UPDATE DIRECTION COSINES
C CALL SUBROUTINE SCATTR, WHICH RETURNS THE NEW DIRECTION COSINES C
C FOUND FROM THE COSINE OF THE LAB SCATTERING ANGLE COSL OF THE
C NEUTRON AND A RANDOMLY CHOSEN AZIMUTH PHI.

C
PHI=6.2832*UNIRND(Y)
CALL SCATTR(C,COSL,PHI,C)
IF (NS-2) 800,900,1100

C
C PERFORM BOOKKEEPING FOR FIRST- AND SECOND-SCATTER STUDY
C THE ARRAY NFS(MC,I,NS) FOR NS=1 (FIRST SCATTER) CONTAINS THE NUMBER
C OF HISTORIES IN WHICH A FIRST INTERACTION OCCURRED IN CHANNEL MC
C GIVING A LIGHT OUTPUT GREATER THAN BIAS LEVEL I, WHERE I=1 TO 5
C CORRESPONDS TO BIASES OF 0.25, 0.5, 1.0, 2.0, AND 4.0 MEV ELECTRON EQUIV.
C FOR NS=2, NFS(MC,I,2) CONTAINS THE NUMBER OF HISTORIES IN WHICH A
C SECONDARY NEUTRON FROM A FIRST INTERACTION IN CHANNEL MC PRODUCES
C A TOTAL LIGHT OUTPUT GREATER THAN BIAS I. NOTE THAT THE CHANNEL
C INCREMENTED IS THAT OF THE FIRST, NOT THE SECOND, INTERACTION.

C
800 MC=MS
DO 802 I=1,5
802 NF(I)=1
900 BIAS=.125
DO 910 I=1,5
BIAS=BIAS*2.
IF (NF(I)) 910,910,902
902 IF (ELT-BIAS) 910,905,905
905 NFS(MC,I,NS)=NFS(MC,I,NS)&1
NF(I)=0
910 CONTINUE

C
1100 IF (ICOUNT .EQ. 1) GO TO 1110

SUBROUTINE FOLNUT (X,C,EO,EMIN,EL,NS)

PAGE 6

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C
C BOOKKEEPING FOR TIME AND POSITION STUDIES
C
C THE VARIABLE TIME CONTAINS THE TOTAL ELAPSED TIME (NSEC) SINCE THE
C NEUTRON ENTERED THE SCINTILLATOR. WHEN THE LIGHT OUTPUT EXCEEDS TBIAS
C (READ IN FROM DATA DECK) THE TIME IS BINNED IN THE HISTOGRAM ARRAY
C NTIM, WITH BIN WIDTH DTIM (FROM DATA DECK).
C WHEN THE LIGHT OUTPUT EXCEEDS TBIAS, THE POSITION HISTOGRAM ARRAY NPOS
C IS ALSO INCREMENTED. IT CONTAINS THE BINNED CHANGE OF X-COORDINATE
C SINCE THE NEUTRON ENTERED THE SCINTILLATOR. THE BIN WIDTH IS DPOS
C (FROM THE DATA DECK).
C
C CHECK WHETHER TIMING BIAS IS EXCEEDED. IF SO, SET FLAG AND INCREMENT
C ARRAYS.
      IF (ELT-TBIAS) 1110,1105,1105
1105 ICOUNT=1
      JT=TIME/DTIM &1.
      IF (JT .GT. 100) JT=100
      IF (JT .LT. 1) JT=1
      JP= (X(1) -X0)/DPOS &50.
      IF (JP .GT. 100) JP=100
      IF (JP .LT. 1) JP=1
      NTIM(JT)=NTIM(JT)&1
      NPOS(JP)=NPOS(JP)&1
C
C PRINT DETAILED INFORMATION FOR THIS EVENT
1110 IF (NDUMP .GE. MDUMP) GO TO 2000
      WRITE (1,1) E,EL(L),MS,ELT,(X(I),I=1,3), (C(I),I=1,3),COSL,PHI
1      ,TIME
      IF ORMAT (F6.1,3X,F6.2,13,F6.2,3X,3F6.2,3X, 3F6.2,3X,3F7.4)
      GO TO 2000
      END

```

SUBROUTINE SIGTOT (E,S)

```
C
C PURPOSE--TO RETURN THE ARRAY S(J) CONTAINING THE TOTAL CROSS-SECTION
C (IN BARNS) AT ENERGY E IN REACTION CHANNEL J. THE REACTION CHANNELS
C FOR S(J) ARE AS FOLLOWS--
C   J=1  NP ELASTIC SCATTERING
C   J=2  NC NONDIFFRACTIVE ELASTIC SCATTERING
C   J=3  N&C--N&C&GAMMA
C   J=4  N&C--ALPHA&9BE
C   J=5  N&C--N&3 ALPHAS
C   J=6  N&C--P&12B
C   J=7  TOTAL N-C NONELASTIC,SUM OF CHANNELS 3 THROUGH 6
C   J=8  NC DIFFRACTIVE ELASTIC SCATTERING
C
C THE ELEMENTS OF S(J) ARE FOUND BY LINEAR INTERPOLATION IN THE ARRAY
C SDAT(I,J),WHICH CONTAINS THE TOTAL CROSS-SECTION AT ENERGY EDAT(I)
C IN CHANNEL J.THE ARRAYS EDAT AND SDAT ARE READ IN FROM THE DATA DECK
C BY MAIN . (NOTE--THE LABELING OF CHANNELS IN S(J) AND SDAT(I,J) ARE
C SLIGHTLY DIFFERENT. CHANNELS J=1 THROUGH 6 ARE THE SAME,BUT FOR SDAT
C THE ELEMENTS FOR J=7 CONTAIN N-C DIFFRACTION ELASTIC CROSS-SECTIONS.)
C
C THE BINARY SEARCH FUNCTION IBNSH(E,EDAT,N) RETURNS THE INDEX OF THE
C LARGEST ELEMENT OF EDAT LESS THAN E. SINCE THE ELEMENTS OF
C EDAT CONTAIN MONOTONICALLY INCREASING NUMBERS,THIS TELLS WHICH
C ELEMENTS OF SDAT TO USE IN THE INTERPOLATION.
C NOTE--THE ARGUMENT N OF IBNSH SHOULD BE THE SMALLEST POWER OF TWO
C WHICH IS LESS THAN THE DIMENSION OF EDAT.
C
C   DIMENSION S(8)
C   COMMON /SIGDAT/ EDAT(128),SDAT(128,7)
C
C   L=IBNSH(E,EDAT,128)
C   DEL=(E-EDAT(L))/(EDAT(L&1)-EDAT(L))
C   DO 10 I=1,7
C10 S(I)= SDAT(L,I)&(SDAT(L&1,I)-SDAT(L,I))*DEL
C   S(8)=S(7)
C   S(7)=S(3)&S(4)&S(5)&S(6)
C   RETURN
```

SUBROUTINE SIGTOT (E,S)

PAGE 2

END

FUNCTION INBND(X)

PAGE 1

FUNCTION INBND(X)

```

C RETURNS 1 OR 0 ACCORDING TO WHETHER POSITION VECTOR X IS
C INSIDE OR OUTSIDE COUNTER BOUNDARIES
C NOTE THAT COORDINATE ORIGIN IS AT CENTER OF FRONT FACE OF COUNTER.
C THIS VERSION FOR EITHER RECTANGULAR OR CYLINDRICAL GEOMETRY
C IF IGEO=1, SCINTILLATOR IS A BOX Z0 THICK BY 2.*X0 BY 2.*Y0.
C IF IGEO=2, SCINTILLATOR IS A CYLINDER Z0 THICK BY X0 IN RADIUS.
C
  DIMENSION X(3)
  COMMON/BNDS/X0,Y0,Z0
  COMMON /GEOM/ IGEO
  INBND=1
  IF(X(3))9,2,2
  2 IF(X(3)-Z0) 3,3,9
  3 IF (IGEO-1) 32,32,34
C BOX
  32 IF (ABS(X(1))-X0) 33,33,9
  33 IF (ABS(X(2))-Y0) 10,10,9
C CYLINDER
  34 R=SQRT(X(1)**2+X(2)**2)
  IF(R-X0) 10,10,9
  9 INBND=0
  10 RETURN
  END

```

SUBROUTINE NPNP(E, EN,COSL,ELIGHT)

PAGE 1

SUBROUTINE NPNP(E, EN,COSL,ELIGHT)

C
C SIMULATES AN ELASTIC SCATTERING FROM HYDROGEN OF A NEUTRON OF
C ENERGY E . NPNP RETURNS THE NEW NEUTRON ENERGY EN , THE COSINE COSL
C OF THE LAB SCATTERING ANGLE OF THE NEUTRON, AND THE LIGHT OUTPUT
C ELIGHT FROM THE RECOIL PROTON. NONRELATIVISTIC KINEMATICS ARE USED.

C
C THE SCATTERING IS ASSUMED ISOTROPIC IN THE CM BELOW 30 MEV. ABOVE
C 30 MEV THE ANGULAR DISTRIBUTION BECOMES INCREASINGLY PARABOLIC.

C
C COMMON /COEF/ C,D,F,U
C EXTERNAL ANGDIS

C
C IF (E .GT. 30.) GO TO 10

C
C ISOTROPY BELOW 30 MEV.

C
C COSCM=-1.02.*UNIRND(X)
C 5 COSL=SQRT(.5*(1.0+COSCM))
C EN=E*COSL*COSL
C ELIGHT=EEQUIV(E-EN)
C RETURN

C
C ABOVE 30 MEV THE ANGULAR DISTRIBUTION IS GIVEN BY ANGDIS ,WITH
C THE COEFFICIENTS C,D,F AND U (COMMON /COEF/). RTNI INVERTS ANGDIS.

C
C 10 R=E/30.
C C=3./(3.0+R)
C D=R*C/3.
C F=0.
C U=UNIRND(X)
C CALL RTNI(COSCM,FN,DV,ANGDIS,.5,.001,20,IER)
C IF (UNIRND(X) .GT. .5) COSCM=-COSCM
C GO TO 5
C END

SUBROUTINE NCEL(S,E,EN,COSL,ELT)

SUBROUTINE NCEL(S,E,EN,COSL,ELT)

C
C SIMULATES THE ELASTIC SCATTERING FROM CARBON OF A NEUTRON OF ENERGY E
C NCEL RETURNS THE NEW NEUTRON ENERGY EN, THE COSINE COSL OF THE LAB
C SCATTERING ANGLE OF THE NEUTRON, AND ELT, THE LIGHT OUTPUT FROM THE
C RECOIL CARBON. (ELT IS ALMOST ALWAYS NEGLIGIBLE).

C
C DIFFRACTIVE AND NONDIFFRACTIVE SCATTERING RECEIVE DIFFERENT TREATMENT
C THUS THE TOTAL CROSS-SECTION ARRAY S FROM SIGTOT IS NEEDED.
C A DESCRIPTION OF THE ENERGY-DEPENDENT ANGULAR DISTRIBUTIONS USED
C APPEARS IN THE PROGRAM WRITEUP, AND BELOW.

C
COMMON /CRBANG/ED(32),AD(32,8)
DIMENSION A(3),S(8)

C
C DECIDE WHETHER DIFFRACTION SCATTER OCCURRED
C IF (S(8)/(S(2)&S(8))).GE. UNIRND(X)) GO TO 500

C
C NONDIFFRACTIVE ELASTIC SCATTERING. THE MODEL OF THE DISTRIBUTION
C IS A RECTANGLE (ISOTROPIC DISTRIBUTION) PLUS TWO TRIANGLES, FORWARD
C AND BACKWARD.

C
C INTERPOLATE IN TABLE
L=IBNSH(E,ED,32)
DEL=(E-ED(L))/(ED(L&1)-ED(L))
DO 2 I=1,3
A(I)=AD(L,I&5)&(AD(L&1,I&5)-AD(L,I&5))*DEL
2 IF (A(I) .LT. 0.) A(I)=0.
AT=A(1)&A(2)&A(3)

C
C CHOOSE PORTION OF ANGULAR DISTRIBUTION
C IF (A(1)/AT .GE. UNIRND(X)) GO TO 100
C IF (A(2)/(A(2)&A(3)) .GE. UNIRND(X)) GO TO 200
C GO TO 300

C
C RECTANGLE (ISOTROPIC)
100 COSCM=-1.&2.*UNIRND(X)
GO TO 1000

SUBROUTINE NCEL(S,E,EN,COSL,ELT)

PAGE 2

```
C
C FORWARD TRIANGLE
200 X1=AD(L,3)&(AD(L&1,3)-AD(L,3))*DEL
    COSCM=X1&(1.-X1)*SQRT(UNIRND(X))
    GO TO 1000
C
C BACKWARD TRIANGLE
300 X1=AD(L,5)&(AD(L&1,5)-AD(L,5))*DEL
    COSCM=X1-(X1&1.)*SQRT(UNIRND(X))
C
C CALL THE KINEMATICS SUBROUTINE KINN.
C
1000 IF(COSCM .GT. 1.) COSCM=1.
    IF(COSCM .LT. -1.) COSCM=-1.
    CALLKINN(940.,11280.,940.,11280.,E,COSCM,VB,WCM,PCM,COSL,EN)
C
C LIGHT OUTPUT FROM CARBON.
    ELT=.017*(E-EN)
    RETURN
C
C DIFFRACTION ELASTIC SCATTERING. EXPONENTIAL FORWARD PEAK, WITH WIDTH
C INVERSELY PROPORTIONAL TO THE TOTAL INELASTIC CROSS-SECTION, AND
C TO THE NEUTRON ENERGY E.
C
500 COSCM=1.&ALOG(1.-UNIRND(X))/1.17/S(7)/E
    GO TO 1000
    END
```


SUBROUTINE NCNCGM (E,X,C,EN,COSL,ELT)

PAGE 1

SUBROUTINE NCNCGM (E,X,C,EN,COSL,ELT)

C
C SIMULATE THE REACTION N&C--N&C&GAMMA.
C
C GIVEN A NEUTRON OF ENERGY E AT POSITION X(I),MOVING ALONG DIRECTION
C COSINES C(I),NCNCGM RETURNS THE ENERGY EN OF THE SCATTERED NEUTRON
C AND THE COSINE COSL OF THE LAB SCATTERING ANGLE. THE EMITTED GAMMA IS
C FOLLOWED THROUGH SUCCESSIVE COMPTON COLLISIONS BY FOLGAM,WHICH
C RETURNS THE TOTAL LIGHT OUTPUT ELT FROM THE COMPTON ELECTRONS.
C

DIMENSION X(3),XG(3),C(3),CG(3)

COMMON /COEF/C1,C2,C3,V

EXTERNAL ANGDIS

DATA EM1,EM2,EM3,EM4 /940.,11280.,940.,11284.3/

C
C FIND THE GAMMA ANGLE. THE ANGULAR DISTRIBUTION(TAKEN FROM 14 MEV
C DATA) IS GIVEN BY ANGDIS,WHICH IS INVERTED BY RTNI.
C C1,C2,C3,AND V ARE COEFFICIENTS FOR ANGDIS.
C

V=UNIRND(Y)

C1=.7444

C2=.4342

C3=-.1786

CALL RTNI (CSG,F,D,ANGDIS,.5,.001,10,IER)

IF (IER.NE.0) WRITE(1,1) IER,CSG,F,D

1 FORMAT (4H :*,I3,3E12.4)

IF(UNIRND(Y) .GT. .5) CSG=-CSG

C
C FOLLOW THE GAMMA
C SCATTR FINDS THE DIRECTION COSINES CG(I) OF THE GAMMA FROM THE
C INITIAL NEUTRON DIRECTION COSINES C(I) AND THE LAB COSINE CSG OF THE
C GAMMA EMISSION ANGLE AND A UNIFORMLY-DISTRIBUTED AZIMUTH ANGLE PHI.
C

DO 150 I=1,3

150 XG(I)=X(I)

EM=0.1

PHI=6.2832*UNIRND(Y)

EG=4.43

SUBROUTINE NCNCGM (E,X,C,EN,COSL,ELT)

PAGE 2

CALL SCATTR(C,CSG,PHI,CG)

CALL FOLGAM (XG,CG,EG,EM,ELT)

DETERMINE THE NEUTRON ANGLE. THE ANGULAR DISTRIBUTION IS TAKEN FROM
10 MEV PP DATA.

C1,C2,C3,AND V ARE COEFFICIENTS FOR ANGDIS.

C1=.5357

C2=.8929

C3=-.4826

V=UNIRND(Y)

CALL RTNI (CSN,F,D,ANGDIS,.5,.001,10,IERR)

IF (IERR.NE.0) WRITE (1,1) IERR,CSN,F,D

IF (UNIRND(Y).GT. .5) CSN=-CSN

TRANSFORM NEUTRON TO LAB COORDINATES.

KINNR IS THE KINEMATICS SUBROUTINE.

CALL KINNR(EM1,EM2,EM3,EM4,E,CSN,VB,WCM,PCM,COSL,EN)

RETURN

END

SUBROUTINE FOLGAM (X,C,E,EMIN,ELIGHT)

SUBROUTINE FOLGAM (X,C,E,EMIN,ELIGHT)

```

C
C MONTE CARLO GAMMA RAY TRACER
C
C GIVEN A GAMMA-RAY OF ENERGY E AT POSITION X(I),MOVING ALONG DIRECTION
C COSINES C(I),
C FOLGAM FOLLOWS THE GAMMA THRU SUCCESSIVE COMPTON COLLISIONS UNTIL
C IT ESCAPES FROM THE SCINTILLATOR OR ITS ENERGY FALLS BELOW EMIN.
C FOLGAM RETURNS ELIGHT,SUM OF ELECTRON RECOIL ENERGIES.
C
    DIMENSION X(3),C(3)
    COMMON /SCIN/ DHYD,DCARB
    ELIGHT=0.
    NSMAX=10
    NS=0
C
C CMPSCT(0,E,SIGT,Y,Y,Y) RETURNS THE TOTAL COMPTON SCATTERING CROSS
C SECTION SIGT (BARNS) PER ELECTRON FOR A GAMMA OF ENERGY E.Y IS A DUMMY
C DHYD AND 6.*DCARB ARE THE NUMBER OF HYDROGEN AND CARBON ELECTRONS PER
C BARN-INCH.
C
1000 CALL CMPSCT(0,E,SIGT,Y,Y,Y)
    PATH=1./(SIGT*(DHYD&6.*DCARB))
C
C PROPAGATE GAMMA A DISTANCE D TO NEXT SCATTER
C D=-PATH*ALOG(UNIRND(Y))
    DO 20 I=1,3
20 X(I)=X(I)+C(I)*D
C
C IS GAMMA STILL IN SCINTILLATOR
C IF (INBND(X) .LE. 0) RETURN
C
    NS=NS+1
    IF (NS .GT. NSMAX) RETURN
C
C SIMULATE A COMPTON COLLISION.
C SUBROUTINE CMPSCT(1,E,SIGT,EEL,E,COSGAM) RETURNS THE LIGHT OUTPUT EEL
C AND THE NEW GAMMA ENERGY E,AND THE COSINE COSGAM OF THE LAB

```

SUBROUTINE FOLGAM (X,C,E,EMIN,ELIGHT)

PAGE 2

C SCATTERING ANGLE OF THE GAMMA.
C SCATTR(C,COSGAM,PHI,C) CHANGES THE DIRECTION COSINES C(I) OF THE
C GAMMA, USING THE ANGLES ARCCOS(COSGAM) AND THE UNIFORMLY-DISTRIBUTED
C AZIMUTH ANGLE PHI.
C

CALL CMPSCT(1,E,SIGT,EEL,E,COSGAM)

ELIGHT=ELIGHT&EEL

IF (E .LE. EMIN) RETURN

PHI=6.2832*UNIRND(Y)

C FIND NEW DIRECTION COSINES

CALL SCATTR(C,COSGAM,PHI,C)

GO TO 1000

END

SUBROUTINE CMPSCT (NTRY,EGAM,SIGT,EEL,EGAMP,COSGAM)

C
C SIMULATES THE COMPTON SCATTERING OF A GAMMA OF ENERGY EGAM BY AN
C ELECTRON. FOR NTRY=0, CMPSCT RETURNS ONLY THE TOTAL COMPTON CROSS-
C SECTION SIGT (BARNS) PER ELECTRON AT ENERGY EGAM. IF NTRY IS NONZERO
C CMPSCT ALSO CHOOSES BY MONTE CARLO THE RECOIL ELECTRON ENERGY EEL,
C THE NEW GAMMA ENERGY EGAMP, AND THE COSINE COSGAM OF THE LAB SCAT-
C TERING ANGLE OF THE GAMMA. SEE THE PROGRAM DESCRIPTION FOR MORE DETAI
C
C COMPUTE TOTAL CROSS SECTION

EPS=.001
G=EGAM/.5110
G4=(G*G)**2
A=1.02.*G
TM=2.*G/A
B=(1.0G)/G**2
S=B*(2.*(1.0G)/A -ALOG(A)/G) &ALOG(A)*.5/G -(1.03.*G)/A**2
SIGT=.4989*S
IF (NTRY .EQ. 0) RETURN

C
C CHOOSE THE RECOIL ELECTRON ENERGY BY MONTE CARLO.
C P IS THE INTEGRAL DISTRIBUTION OF THE ELECTRON ENERGY E (IN UNITS
C OF THE ELECTRON REST MASS). THE EQUATION $P(E)-U=0$ IS SOLVED BY
C ITERATION, WHERE U IS A UNIFORMLY-DISTRIBUTED RANDOM VARIABLE.

C
U=UNIRND(X)
C=0.
D=TM
6 D=.5*D
E=C&D
F=G/(G-E)
FL=ALOG(F)/G
P=(B*(B*.5*E-FL) &.5*FL &.5*E*(F-E*G*.5)/G4)/S
IF (ABS(U-P)-EPS) 20,20,10
10 IF (U-P) 6,20,12
12 C=E
GO TO 6

SUBROUTINE CMPSCT (NTRY,EGAM,SIGT,EEL,EGAMP,COSGAM)

PAGE 2

```
20 EEL=.5110*E
   EGAMP=EGAM-EEL
   COSGAM=1.-(EGAM/EGAMP-1.)/G
   IF (COSGAM .GT. 1.0) COSGAM=1.
   RETURN
   END
```

SUBROUTINE NALPHA(E,ELT)

PAGE 1

SUBROUTINE NALPHA(E,ELT)

```
C
C SIMULATE THE REACTION N&C--ALPHA &9BE
C ISOTROPIC TWO-BODY REACTION ASSUMED.
C
  REAL M1,M2,M3,M4
  DATA M1,M2,M3,M4 /940. ,11280. ,3760. ,8465.71 /
C
  C=-1.02.*UNIRND(Y)
  CALL KINNR(M1,M2,M3,M4,E,C,VB,WCM,PCM,CSL,T)
C (KINNR IS THE KINEMATICS ROUTINE)
  ELT=EEQAL(T)
C (EEQAL GIVES THE LIGHT OUTPUT FOR ALPHA OF ENERGY T)
  RETURN
  END
```

SUBROUTINE NN3AL(E,EN,COSL,ELT)

PAGE 1

SUBROUTINE NN3AL(E,EN,COSL,ELT)

C
C SIMULATES THE REACTION N&C--N&THREE ALPHAS
C PHASE SPACE ENERGY DISTRIBUTION OF OUTGOING NEUTRON ASSUMED.
C

DATA EMN,EMC,QQ /940. ,11280. ,-7.26 /
COMMON /ENG/U
EXTERNAL ENGDIS
WCM=E*.923&QQ
IF (WCM) 2,2,4
2 EN=E
COSL=1.
ELT=0.
RETURN

C
C MAXIMUM NEUTRON ENERGY IN CM
4 TM=.923*WCM

C
C SIMULATE PHASE SPACE DISTRIBUTION FOR OUTGOING NEUTRON.
C SEE ENGDIS LISTING FOR DETAILS.
C

U=UNIRND(Y)
X=.01
IF (U .LE. .01) GO TO 3
CALL RTNI(X,FN,DV,ENGDIS,.5,.001,20,IER)
C (THE SUBROUTINE RTNI INVERTS THE EQUATION ENGDIS(E)=U .SEE LISTING.)
IF (IER .NE. 0) WRITE (1,1) IER,X,FN,DV
1 FORMAT (8HERRNN3AL,I3,3E12.4)
3 T=TM*X
IF (T .LE. 0.) T=0.

C
C FIND THE LAB ENERGY EN AND COSINE COSL OF THE LAB SCATTERING ANGLE
C FOR THE OUTGOING NEUTRON
C

PCM=SQRT(2.*EMN*T)
VB=SQRT(2.*EMN*E)/(EMN&EMC)

C
C ISOTROPIC CM ANGULAR DISTRIBUTION OF THE NEUTRON IS ASSUMED.

SUBROUTINE NN3AL(E,EN,COSL,ELT)

PAGE 2

```
COSCM=-1.82.*UNIRND(Y)
EN= T &PCM*VB*COSCM &.5*EMN*VB**2
IF (EN .LE. 0. ) EN=0.
PN=SQRT(2.*EMN*EN)
COSL=(PCM*COSCM &EMN*VB)/PN
```

```
C
C
C TRI S THE LAB ENERGY REMAINING TO THE THREE ALPHAS.
C ASSUME ENERGY OF FIRST ALPHA IS UNIFORMLY DISTRIBUTED BETWEEN 0 AND
C THE REMAINING ENERGY FROM NEUTRON RECOIL.ENERGY OF SECOND ALPHA
C IS UNIFORMLY DISTRIBUTED IN REMAINING ENERGY,ETC.
C ADD UP THE LIGHT OUTPUT OF THE ALPHAS.THE LIGHT OUTPUT OF AN
C ALPHA OF ENERGY E IS EEQAL(E).
```

```
C
C
C TR=E-EN -7.26
C ELT=0.
C DO 15 IA=1,2
C TA=TR*UNIRND(Y)
C ELT=EEQAL(TA)&ELT
15 TR=TR-TA
C ELT=EEQAL(TR)&ELT
```

```
C
C
C RETURN
C END
```

SUBROUTINE NPB(E,ELT)

PAGE 1

SUBROUTINE NPB(E,ELT)

```
C
C SIMULATE THE REACTION N&C--P&12B.
C PHASE SPACE ENERGY DISTRIBUTION OF PROTON ASSUMED
C
  DATA EMN,EMC,QQ /940.,11280.,-12.59 /
  COMMON /ENG/U
  EXTERNAL ENGDIS
C
  WCM=E*.923&QQ
  IF (WCM) 2,2,4
2  ELT=0.
  RETURN
C
C MAXIMUM PROTON ENERGY IN CM
  4 TM=.923*WCM
C
C SIMULATE PHASE SPACE DISTRIBUTION FOR OUTGOING PROTON.
C SEE ENGDIS LISTING FOR DETAILS.
C
  U=UNIRND(Y)
  X=.01
  IF (U .LE. .01 ) GO TO 3
  CALL RTNI(X,FN,DV,ENGDIS,.5,.001,20,IER)
C (THE SUBROUTINE RTNI INVERTS THE EQUATION ENGDIS(E)=U .SEE LISTING.)
  IF (IER .NE. 0 ) WRITE (1,1) IER,X,FN,DV
  1 FORMAT ( 8HERR NPB ,I3,3E12.4)
  3 T=TM*X
  IF (T .LE. 0. ) T=0.
C
C FIND LAB ENERGY OF PROTON
C
  PCM=SQRT(2.*EMN*T)
  VB=SQRT(2.*EMN*E)/(EMN&EMC)
C
C ISOTROPIC ANGULAR DISTRIBUTION IN CM ASSUMED.
  COSCM=-1.&2.*UNIRND(Y)
  EN= T &PCM*VB*COSCM &.5*EMN*VB**2
```

SUBROUTINE NPB(E,ELT)

PAGE 2

IF (EN .LE. 0.) EN=0.

ELT=EEQUIV (EN)

C EEQUIV RETURNS LIGHT OUTPUT FOR PROTON OF ENERGY EN

RETURN

END

SUBROUTINE KINNR (EM1,EM2,EM3,EM4,T1,CSCM,VB,WCM,PCM,CSL,T3)

PAGE 1

SUBROUTINE KINNR (EM1,EM2,EM3,EM4,T1,CSCM,VB,WCM,PCM,CSL,T3)

C
C NONRELATIVISTIC 2-BODY KINEMATICS
C
C LET A PARTICLE OF MASS EM1 AND KINETIC ENERGY T1 COLLIDE WITH A
C PARTICLE OF MASS EM2 AT REST, PRODUCING OUTGOING PARTICLES OF
C MASSES EM3 AND EM4 .THE COSINE OF THE CENTER OF MASS (CM) SCATTERING
C ANGLE BETWEEN PARTICLES 1 AND 3 IS CSCM.
C
C KINNR RETURNS VB,THE VELOCITY OF THE CM WCM,THE TOTAL KINETIC
C ENERGY OF THE OUTGOING PARTICLES IN THE CM PCM,THE CM MOMENTUM OF
C EITHER OUTGOING PARTICLE CSL,THE COSINE OF THE LAB ANGLE BETWEEN
C PARTICLES 1 AND 3 AND T3,THE LAB KINETIC ENERGY OF PARTICLE 3.
C
C P1 IS THE LAB MOMENTUM OF PARTICLE 1.
C $P1 = \sqrt{2 * EM1 * T1}$
C $Q = EM1 * EM2 - EM3 - EM4$
C FI IS THE REDUCED MASS OF THE INCIDENT PARTICLES.
C $FI = EM1 * EM2 / (EM1 + EM2)$
C FF IS THE REDUCED MASS OF THE OUTGOING PARTICLES.
C $FF = EM3 * EM4 / (EM3 + EM4)$
C WI IS THE TOTAL CM KINETIC ENERGY OF THE INCIDENT PARTICLES.
C $WI = FI * T1 / EM1$
C $VB = P1 / (EM1 + EM2)$
C $WCM = WI * Q$
C IF (WCM .LE. 0.) GO TO 10
C $PCMS = 2 * WCM * FF$
C $PCM = \sqrt{PCMS}$
C $T3 = PCMS * .5 / EM3 + PCM * VB * CSCM + .5 * EM3 * VB * VB$
C P3 IS THE LAB MOMENTUM OF PARTICLE 3.
C $P3 = \sqrt{2 * EM3 * T3}$
C $CSL = (PCM * CSCM + EM3 * VB) / P3$
C IF (CSL .GT. 1.) CSL=1.
C IF (CSL .LT. -1.) CSL=-1.
C RETURN
10 WCM=0.
PCM=0.
T3=0.

SUBROUTINE KINN (EM1,EM2,EM3,EM4,T1,CSCM,VB,WCM,PCM,CSL,T3)

PAGE

CSL=1.
RETURN
END

SUBROUTINE ANGDIS(X,F,DF)

PAGE 1

SUBROUTINE ANGDIS(X,F,DF)

C
C POLYNOMIAL ANGULAR DISTRIBUTIONS FOR USE WITH THE NEWTON'S
C METHOD SUBROUTINE RTNI.
C
C F&V IS THE INTEGRAL DISTRIBUTION, DF IS ITS DERIVATIVE.
C A,B,C ARE ARBITRARY COEFFICIENTS. V IS A RANDOM NUMBER BETWEEN 0 AND 1
C

COMMON /COEF/A,B,C,V
XS=X**2
F= X*(A& XS*(B&C*XS))-V
DF=A&XS*(3.*B&XS*5.*C)
IF (DF .EQ. 0.) DF=.0001
RETURN
END

SUBROUTINE ENGDIS(X,F,DF)

SUBROUTINE ENGDIS(X,F,DF)

C PHASE SPACE ENERGY DISTRIBUTION FOR USE WITH THE NEWTON'S
 C METHOD SUBROUTINE RTNI.
 C
 C F & U IS THE INTEGRAL PHASE SPACE DISTRIBUTION, AND DF ITS DERIVATIVE.
 C U IS A RANDOM NUMBER BETWEEN 0 AND 1.
 C

COMMON /ENG/U

IF (X .LE. .01) GO TO 2

XR=SQRT(X)*6.562

XS=X*X

DF=XR*(1.-X)**2

F=XR*X*(.6667-.8*X+.2857*XS) -U

RETURN

2 DF=.6431

F=.016DF*(X-.01)-U

RETURN

END

SUBROUTINE SCATTR (C,COSTH,PHI,CNEW)

PAGE 1

SUBROUTINE SCATTR (C,COSTH,PHI,CNEW)

C
C GIVEN A PARTICLE MOVING IN A DIRECTION SPECIFIED BY DIRECTION COSINES
C C(I), I=1 TO 3, WHICH SCATTERS BY ANGLES $\arccos(\text{COSTH})=\text{TH}$ AND PHI WITH
C RESPECT TO THE INITIAL DIRECTION. SCATTR FINDS THE NEW DIRECTION
C COSINES CNEW(I) AS FOLLOWS --

C
C THE OLD DIRECTION OF THE PARTICLE MAY BE DESCRIBED BY THE ANGLES
C T AND P, MEASURED FROM THE POSITIVE Z- AND X-AXES RESPECTIVELY.
C THEN $\text{CT}=\cos(\text{T})=\text{C}(3)$, $\text{SP}=\sin(\text{P})=\text{C}(2)/\sin(\text{T})$, $\text{CP}=\cos(\text{P})=\text{C}(1)/\sin(\text{T})$.
C NOW CONSIDER A COORDINATE SYSTEM WHICH HAS ITS POSITIVE Z-AXIS ALONG
C THE ORIGINAL DIRECTION OF THE PARTICLE AND ITS X-AXIS ALONG THE
C X-AXIS OF THE MAIN COORDINATE SYSTEM. IN THIS FRAME THE NEW DIRECTION
C COSINES AFTER THE SCATTER ARE $\text{CXP}=\sin(\text{TH})*\cos(\text{PHI})$,
C $\text{CYP}=\sin(\text{TH})*\sin(\text{PHI})$, $\text{CZP}=\cos(\text{TH})$. ROTATING BY THE ANGLES T AND P
C WILL PUT THE NEW DIRECTION COSINES BACK INTO THE MAIN COORDINATE
C SYSTEM.

C
C DIMENSION C(3),CNEW(3)
C SI(X)=SQRT(1.-X**2)
C PROTECT THE ANGLES
C CT=C(3)
C IF (CT-1.)6,4,2
C 2 CT=1.
C 4 ST=0.
C SP=0.
C CP=1.
C GO TO 30
C 6 IF (-CT-1.)20,4,8
C 8 CT=-1.
C GO TO 4
C 20 ST=SI(CT)
C CP=C(1)/ST
C IF (CP .GT. 1.) CP=1.
C IF (CP .LT. -1.) CP=-1.
C SP= C(2)/ST
C IF (SP .GT. 1.) SP=1.
C IF (SP .LT. -1.) SP=-1.

SUBROUTINE SCATTR (C,COSTH,PHI,CNEW)

PAGE 2

```
30 IF (COSTH .GT. 1.) COSTH=1.  
   IF (COSTH .LT. -1.) COSTH=-1.  
   S=SI(COSTH)  
   CXP= S*COS(PHI)  
   CYP= S*SIN(PHI)  
   CZP=COSTH  
   CNEW(1)=CXP*CT*CP-CYP*SP& CZP*ST*CP  
   CNEW(2)=&CXP*CT*SP&CYP*CP &CZP*ST*SP  
   CNEW(3)=-CXP*ST &CZP*CT  
   RETURN  
   END
```

FUNCTION EEQUIV(E)

PAGE 1

FUNCTION EEQUIV(E)

C
C FINDS ENERGY OF ELECTRON GIVING SAME AMT OF LIGHT AS PROTON OF ENGY E
IF (E) 2,2,1
1 E EQUIV = -10.68*(1.-EXP(-.07*E**0.89))0.929*E
IF(EEQUIV)2,3,3
3 RETURN
2 EEQUIV=0.
RETURN
END

FUNCTION EEQAL(E)

PAGE 1

FUNCTION EEQAL(E)

C
C LIGHT OUTPUT FOR AN ALPHA OF ENERGY E
EEQAL= $0.046 \times E \& 0.007 \times E^2$
RETURN
END

FUNCTION IBNSH (A,B,N)

PAGE 1

FUNCTION IBNSH (A,B,N)

C
C BINARY SEARCH FOR AN ELEMENT L OF ARRAY B SUCH THAT
C A .GE. B(I) AND A .LT. B(I&1).
C NOTE-DIMENSION N OF B MUST BE A POWER OF 2.
C

DIMENSION B(2)
4 J=0
K=N
6 K=K/2
L=K&J
IF (A-B(L)) 6,20,10
10 IF (A-B(L&1)) 20,12,12
12 J=L
GO TO 6
20 IBNSH=L
RETURN
END

.....

SUBROUTINE RTNI

PURPOSE

TO SOLVE GENERAL NONLINEAR EQUATIONS OF THE FORM $F(X)=0$
BY MEANS OF NEWTON-S ITERATION METHOD.

USAGE

CALL RTNI (X,F,DERF,FCT,XST,EPS,IEND,IER)
PARAMETER FCT REQUIRES AN EXTERNAL STATEMENT.

DESCRIPTION OF PARAMETERS

X - RESULTANT ROOT OF EQUATION $F(X)=0$.
F - RESULTANT FUNCTION VALUE AT ROOT X.
DERF - RESULTANT VALUE OF DERIVATIVE AT ROOT X.
FCT - NAME OF THE EXTERNAL SUBROUTINE USED. IT COMPUTES
TO GIVEN ARGUMENT X FUNCTION VALUE F AND DERIVATIVE
DERF. ITS PARAMETER LIST MUST BE X,F,DERF.
XST - INPUT VALUE WHICH SPECIFIES THE INITIAL GUESS OF
THE ROOT X.
EPS - INPUT VALUE WHICH SPECIFIES THE UPPER BOUND OF THE
ERROR OF RESULT X.
IEND - MAXIMUM NUMBER OF ITERATION STEPS SPECIFIED.
IER - RESULTANT ERROR PARAMETER CODED AS FOLLOWS
IER=0 - NO ERROR,
IER=1 - NO CONVERGENCE AFTER IEND ITERATION STEPS,
IER=2 - AT ANY ITERATION STEP DERIVATIVE DERF WAS
EQUAL TO ZERO.

REMARKS

THE PROCEDURE IS BYPASSED AND GIVES THE ERROR MESSAGE IER=2
IF AT ANY ITERATION STEP DERIVATIVE OF $F(X)$ IS EQUAL TO 0.
POSSIBLY THE PROCEDURE WOULD BE SUCCESSFUL IF IT IS STARTED
ONCE MORE WITH ANOTHER INITIAL GUESS XST.

SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED

THE EXTERNAL SUBROUTINE FCT(X,F,DERF) MUST BE FURNISHED
BY THE USER.

METHOD

SOLUTION OF EQUATION $F(X)=0$ IS DONE BY MEANS OF NEWTON-S
ITERATION METHOD, WHICH STARTS AT THE INITIAL GUESS XST OF
A ROOT X. CONVERGENCE IS QUADRATIC IF THE DERIVATIVE OF
 $F(X)$ AT ROOT X IS NOT EQUAL TO ZERO. ONE ITERATION STEP
REQUIRES ONE EVALUATION OF $F(X)$ AND ONE EVALUATION OF THE
DERIVATIVE OF $F(X)$. FOR TEST ON SATISFACTORY ACCURACY SEE
FORMULAE (2) OF MATHEMATICAL DESCRIPTION.
FOR REFERENCE, SEE R. ZURMUEHL, PRAKTISCHE MATHEMATIK FUER
INGENIEURE UND PHYSIKER, SPRINGER, BERLIN/GOETTINGEN/
HEIDELBERG, 1963, PP.12-17.

.....
SUBROUTINE RTNI(X,F,DERF,FCT,XST,EPS,IEND,IER)

PREPARE ITERATION

IER=0

X=XST

TOL=X

CALL FCT(TOL,F,DERF)

TOLF=100.*EPS

START ITERATION LOOP

DO 6 I=1,IEND

IF(F)1,7,1

EQUATION IS NOT SATISFIED BY X

1 IF(DERF)2,8,2

ITERATION IS POSSIBLE

2 DX=F/DERF

X=X-DX

C

```
TOL=X  
CALL FCT(TOL,F,DERF)
```

C

C

```
TEST ON SATISFACTORY ACCURACY  
TOL=EPS  
A=ABS(X)  
IF(A-1.)4,4,3  
3 TOL=TOL*A  
4 IF(ABS(DX)-TOL)5,5,6  
5 IF(ABS(F)-TOLF)7,7,6  
6 CONTINUE
```

C

C

C

C

```
END OF ITERATION LOOP
```

```
NO CONVERGENCE AFTER IEND ITERATION STEPS. ERROR RETURN.
```

```
IER=1
```

```
7 RETURN
```

C

C

```
ERROR RETURN IN CASE OF ZERO DIVISOR
```

```
8 IER=2
```

```
RETURN
```

```
END
```

C FUNCTION GAUSS

C FUNCTION GAUSS

C PURPOSE

C COMPUTES A NORMALLY DISTRIBUTED RANDOM NUMBER WITH MEAN= μ .
C AND STANDARD DEVIATION=1.

C METHOD

C USES 12 UNIFORM RANDOM NUMBERS TO COMPUTE NORMAL RANDOM
C NUMBERS BY CENTRAL LIMIT THEOREM. THE RESULT IS THEN
C ADJUSTED TO MATCH THE GIVEN MEAN AND STANDARD DEVIATION.
C THE UNIFORM RANDOM NUMBERS COMPUTED WITHIN THE SUBROUTINE
C ARE FOUND BY THE POWER RESIDUE METHOD.

CC

C FUNCTION GAUSS(T)

A=-6.

DO 50 I=1,12

50 A=A&UNIRND(X)

GAUSS=A

RETURN

END

C SSWTCH

PAGE 1

C SSWTCH

C

C PURPOSE

C

C TO SIMULATE SENSE SWITCHES

C

SUBROUTINE SSWTCH(I,J)

COMMON/SWBLK/NSW(6)

J=NSW(I)

RETURN

END

C UNIRND

PAGE 1

C UNIRND

C

C PURPOSE

C TO RETURN A PSEUDO-RANDOM NUMBER UNIFORMLY DISTRIBUTED BETWEEN
C 0. AND 1.
C

FUNCTION UNIRND(X)

DATA IX/1234567/

CALL RANDU (IX,IY,YFL)

IF (YFL .LT. 0. .OR. YFL .GE. 1.) GO TO 1

2 UNIRND=YFL

IX=IY

RETURN

1 WRITE (6,100) IX

YFL=0.5

GO TO 2

100 FORMAT (I12,6H RANDU)

END

Appendix II: Data Deck Listing

This Appendix contains a listing of the data deck used by the program, containing the "tuned" values of the cross-sections. The last 9 cards in the deck specify the simulation of the counter calibrated in Ref. 6; the last card specifies an incident neutron energy interval of 20 to 25 MeV. The output generated by the program from this data deck is given in Appendix III.

C DATA DECK

PAGE 1

C DATA DECK

SENSE SWITCH SETTINGS AND NUMBER OF EVENTS TO DUMP (6I1,I4)
222222 100

DENSITY (GM/CM**3) AND RATIO OF H TO C ATOMS (10F8.3)
1.02 1.10

BIAS FOR TIMING STUDY (MEVEE), BIN WIDTHS FOR TIMING(NSEC), POSITION(IN.) (10F8.3)
1.0 .20 .20

TOTAL CROSS-SECTION DATA. FIRST READ NUMBER OF CARDS TO FOLLOW (I3)
71

ENERGY(MEV) AND CROSS-SECTION(BARNS) IN EACH OF 7 CHANNELS (8F5.3)

.0	.20	4.90
.25	8.65	4.05
.50	6.19	3.40
.80	4.80	2.96
1.0	4.25	2.58
1.21	3.85	2.34
1.48	3.40	2.08
1.72	3.16	1.89
2.00	2.90	1.65
2.10	2.84	2.20
2.21	2.75	1.61
2.56	2.50	1.60
2.69	2.42	1.60
2.83	2.35	2.00
2.97	2.28	2.85
3.13	2.20	1.15
3.29	2.14	2.05
3.46	2.07	2.30
3.82	1.93	2.10
4.02	1.89	1.87
4.23	1.82	1.95
4.44	1.75	1.75
4.67	1.71	1.36
4.91	1.65	1.20
5.16	1.59	1.11 .04
5.43	1.53	1.18 .06
5.70	1.48	.997 .093
6.00	1.425	.917 .153

PAGE 2

[illegible]

200. .042 .015 .020 .004 .027 .150 .160
 251. .037 .015 .020 .004 .019 .146 .130
 316. .034 .015 .020 .004 .019 .146 .100
 398. .034 .015 .020 .004 .019 .146 .080
 1000. .033 .015 .020 .004 .019 .146 .040

COEFFICIENT ARRAY FOR NC NONDIFFRACTIVE ELASTIC SCATTERING, READ NO. CARDS (13)
 20

READ ENERGY(MEV) AND 5 COEFFICIENTS (10F8.3) .THREE MORE ARE CALCULATED.

0.	390.	390.	0.	390.	0.
1.0	210.	210.	0.	210.	0.
1.50	140.	210.	.20	180.	-.40
1.66	130.	220.	.300	190.	-.30
2.20	105.	205.	.250	180.	-.30
2.65	70.	240.	.250	240.	-.25
2.84	50.	300.	.15	340.	-.15
2.95	50.	580.	.20	620.	-.20
3.05	80.	140.	.30	210.	-.30
3.25	30.	350.	.30	370.	-.20
3.76	70.	520.	.40	500.	-.35
4.10	50.	450.	.55	320.	-.30
4.70	120.	600.	.50	120.	0.
5.00	60.	350.	.60	60.	0.
5.6	50.	200.	.40	170.	.20
6.30	80.	400.	.70	80.	0.
7.0	30.	100.	.40	30.	0.
7.60	30.	60.	.40	100.	0.
9.00	30.	60.	.40	30.	0.
999.	30.	60.	.40	30.	0.

SCINTILLATOR BOUNDARIES(INCHES), IGEO, IRANP (3F6.2, 2I2)

6.0 6.0 11.26 2 0

TWO VALUES OF ONE-PHOTOELECTRON LEVEL(MEV) FOR RESOLUTION SIMULATION (3F6.2)

0.5 1.0

FOR EACH SET OF HISTORIES DESIRED, READ INITIAL POSITION VECTOR, INITIAL DIRECTION COSINES, INITIAL ENERGY LIMITS, NO. OF HISTORIES TO RUN, BIN WIDTH FOR PULSE HEIGHT HISTOGRAMS (IN MEV ELECTRON EQUIVALENT) (3F5.2, 3F7.4, 2F8.3, I8, F8.3)

COUNTER OF CRABB ET AL (NE102A)

0.0 0.0 0.0 0.0 0.0 1.0 20.0 25.0 10000 .100

Appendix III. Sample Output

The following output is produced by the data deck listed in Appendix II, except that only the first 13 of the 100 individual histories that were dumped are included.

DUMP OF INDIVIDUAL HISTORIES
 THE FOLLOWING VARIABLES ARE DUMPED AT EACH INTERACTION
 (SEE FOLNUT LISTING FOR DEFINITION)
 E,EL(7),MS,FLT,(X(I),I=1,3),(C(I),I=1,3),COSL,PHI,TIME

EVENT	1	INITIAL ENERGY	23.389 MEV						
EVENT	2	INITIAL ENERGY	21.337 MEV						
EVENT	3	INITIAL ENERGY	24.588 MEV						
EVENT	4	INITIAL ENERGY	24.296 MEV						
4.3	1.46	5	1.46	0.0	0.0	0.11	-0.01	0.73	-0.69
									-0.6854 1.5897 0.0396
EVENT	5	INITIAL ENERGY	24.6F3 MEV						
24.5	0.00	2	0.00	0.0	0.0	1.84	0.28	-0.16	0.95
8.7	8.68	1	8.67	0.22	-0.13	2.60	-0.50	-0.53	0.69
7.3	9.01	1	0.33	-0.19	-0.56	3.16	-0.19	-0.78	0.59
1.7	11.27	1	2.26	-0.31	-1.04	3.52	-0.54	-0.16	0.30
0.3	11.60	1	0.33	-1.68	-1.27	3.55	-0.30	0.49	0.82
0.1	11.62	1	0.02	-1.72	-1.21	4.05	0.56	-0.11	0.82
									0.4519 3.6386 4.3339
EVENT	6	INITIAL ENERGY	21.119 MEV						
21.0	0.00	2	0.00	0.0	0.0	3.88	0.10	-0.20	0.97
19.2	0.03	2	0.03	0.11	-0.21	4.92	0.88	0.24	0.42
0.0	0.43	4	0.39	3.55	0.73	6.55	0.88	0.24	0.42
									0.9749 5.1866 1.5519
									0.4475 1.4704 1.9801
									1.0000 1.3278 3.6295
EVENT	7	INITIAL ENERGY	20.784 MEV						
0.6	1.18	5	1.18	0.0	0.0	0.84	0.90	-0.00	0.43
0.4	1.19	1	0.00	0.07	-0.60	0.87	0.99	0.13	-0.06
0.1	1.23	1	0.04	0.66	0.07	0.93	0.41	0.28	0.87
									0.4274 6.2779 0.3371
									0.8689 0.2694 0.5223
									0.3934 2.8989 2.1561
EVENT	8	INITIAL ENERGY	21.455 MEV						
EVENT	9	INITIAL ENERGY	22.338 MEV						
EVENT	10	INITIAL ENERGY	24.803 MEV						
23.7	0.02	2	0.02	0.0	0.0	3.26	-0.35	-0.58	0.73
0.0	0.43	6	0.41	-2.54	-4.21	8.57	-0.35	-0.58	0.73
									0.7341 4.1703 1.2044
									1.0000 3.7629 3.9388
EVENT	11	INITIAL ENERGY	24.028 MEV						
EVENT	12	INITIAL ENERGY	24.302 MEV						
24.1	0.00	2	0.00	0.0	0.0	0.01	-0.11	-0.31	0.94
15.1	4.15	1	4.15	-0.57	-1.60	4.86	-0.62	0.05	0.78
5.9	4.26	5	0.11	-1.66	-1.52	6.25	0.11	0.24	0.96
2.3	5.50	1	1.24	-1.21	-0.55	10.18	0.04	-0.61	0.79
1.7	5.51	2	0.01	-1.19	-0.74	10.43	0.55	0.66	-0.51
1.4	5.52	2	0.01	-1.15	-0.69	10.39	-0.88	0.46	0.08
0.5	5.71	1	0.19	-2.72	0.14	10.52	-0.12	0.58	0.16
0.4	5.71	1	0.0	-2.80	0.81	10.64	-0.31	0.94	0.14
0.2	5.72	1	0.01	-2.87	1.02	10.67	-0.15	0.55	0.82
0.2	5.72	1	0.0	-2.89	1.07	10.74	0.17	0.27	0.95
									0.9436 4.3736 0.0054
									0.7931 4.5358 1.9313
									0.6979 3.4920 2.7698
									0.6261 3.5342 5.8572
									-0.7836 1.8702 6.2287
									-0.2133 1.5317 6.3362
									0.5720 4.5648 9.1054
									0.9812 1.4779 10.9704
									0.6812 3.1740 11.5874
									0.8988 3.7174 11.9219
EVENT	13	INITIAL ENERGY	23.808 MEV						
23.8	0.00	2	0.00	0.0	0.0	1.93	-0.04	0.12	0.99
23.6	0.00	2	0.00	-0.01	0.02	2.11	-0.07	0.39	0.92
1.7	13.25	1	13.25	-0.03	0.16	2.44	-0.91	-0.25	0.33
0.2	13.63	1	0.30	-4.15	-0.96	3.93	-0.60	0.80	-0.04
0.2	13.63	1	0.0	-4.30	-0.77	3.92	-0.44	0.87	0.22
0.1	13.63	1	0.0	-4.46	-0.45	4.00	-0.03	0.76	0.65
0.1	13.63	1	0.0	-4.47	-0.26	4.17	-0.60	0.34	0.73
									0.9925 1.9124 0.7267
									0.9581 6.0518 0.7980
									0.2693 1.7884 0.9308
									0.3401 4.8878 7.2915
									0.9486 3.7418 8.2858
									0.8169 3.7080 9.8512
									0.7519 2.0595 11.2153

CYLINDRICAL SCINTILLATOR WITH DIMENSIONS (INCHES) 11.260 CFEP BY 6.000 IN RADIUS

COUNTER OF CRABG ET AL (NE102A)

DENSITY= 1.020 GM/CM**3 H/C RATIO= 1.100

10000 NEUTRONS OF ENERGY 20.00 TO 25.00 MEV
INCIDENT AT X,Y,Z= 0.0 0.0 0.0 INCHES DIRECTION COSINES= 0.0 0.0 1.0000

DIFFERENTIAL PULSE HEIGHT SPECTRA

LIGHT OUTPUT IN MEV ELECTRON EQUIVALENT

CHANNEL 1 ONLY				BIN WIDTH 0.100				4886 EVENTS											
213	144	116	114	86	91	75	71	58	51	57	48	53	45	50	35	38	38	45	36
36	31	35	37	49	28	27	21	35	31	30	25	26	26	21	21	20	35	29	24
25	27	17	27	19	19	31	23	25	22	29	25	26	28	21	30	22	24	17	27
21	20	23	27	22	32	15	31	18	19	25	13	15	32	27	21	23	23	31	29
23	36	31	25	37	31	30	28	32	41	36	30	50	40	40	29	40	29	36	49
35	37	43	40	44	37	38	36	36	36	37	42	25	40	26	38	31	22	28	34
37	39	26	33	25	21	22	21	18	18	20	21	8	19	19	12	17	14	9	9
10	2	8	9	7	11	6	10	1	9	2	2	3	2	1					
CHANNEL 2 ONLY				BIN WIDTH 0.100				6671 EVENTS											
657	92																		
CHANNEL 3 ONLY				BIN WIDTH 0.100				316 EVENTS											
4	3	5	2	2	4	3	4	4	4	5	3	5	4	6	4	6	1	4	2
6	5	4	5	4	6	3	7	4	5	9	4	2	6	2	6	14	6	12	11
16	29	25	38	0	0	0	0	0	1	0	0	0	0	1	1	0	0	1	0
0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1
0	0	0	2	0	2				0	0	0	0	0	0	0	0	0		
CHANNEL 4 ONLY				BIN WIDTH 0.100				158 EVENTS											
7	12	5	7	11	10	11	12	8	9	8	8	4	6	3	12	5	4	2	7
3	1	0	2	0	0	1													
CHANNEL 5 ONLY				BIN WIDTH 0.100				1327 EVENTS											
4	22	42	70	85	112	117	124	124	132	106	97	72	58	53	28	29	24	7	9
2	1	4	2	1	1	1													
CHANNEL 6 ONLY				BIN WIDTH 0.100				1414 EVENTS											
124	106	110	99	74	87	88	65	66	71	65	64	40	43	30	43	36	19	19	25
16	20	12	12	11	12	6	5	10	10	5	1	4	6	3	1	1	1	0	0
0	2	0	0	1	1														

LIGHT OUTPUT FROM ALL CHANNELS ,										ONE PHOTOELECTRON LEVEL AT										0.0 MEV	
BIN WIDTH 0.100 MEV										8974 EVENTS											
2345	183	149	142	121	137	178	135	122	144		162	163	162	148	143	141	133	112	100	108	
86	79	77	64	74	61	36	43	50	42		50	28	35	44	26	25	31	43	37	27	
33	40	30	53	29	21	34	26	21	29		31	18	32	32	21	27	23	21	21	28	
22	19	21	29	18	34	14	31	27	19		25	15	14	32	26	25	23	24	33	29	
26	30	32	31	34	34	30	33	27	44		38	35	44	41	45	29	42	30	35	49	
35	36	45	41	46	31	40	40	39	35		37	45	29	37	27	40	35	23	28	31	
38	43	27	33	26	24	20	20	20	20		20	22	9	19	21	12	18	13	11	9	
10	3	8	9	6	11	7	10	1	8		3	2	3	2	1						

LIGHT OUTPUT FROM ALL CHANNELS ,										ONE PHOTOELECTRON LEVEL AT										0.500 MEV	
BIN WIDTH 0.100 MEV										7494 EVENTS											
345	359	334	288	223	203	166	140	145	142		133	128	115	107	106	96	114	83	81	85	
80	82	65	72	59	60	46	77	63	62		54	41	43	38	35	37	37	34	42	53	
20	38	39	26	21	26	28	33	31	34		32	23	32	27	24	23	33	38	38	21	
22	25	34	21	35	38	30	33	16	37		29	20	42	35	29	36	19	28	38	33	
27	27	30	30	27	25	24	22	23	27		35	27	32	28	25	24	23	33	25	37	
32	35	28	36	20	25	37	36	28	35		29	24	27	25	22	24	29	16	34	24	
25	24	26	14	17	23	16	23	25	21		15	18	15	14	14	19	6	13	14	22	
6	8	7	8	12	22	7	11	10	7		10	15	4	13	10	7	13	6	8	6	
3	6	4	7	3	7	3	2	2	5		2	4	5	1	2	3	2	2	0	2	
1	3	2	3	0	2	3	0	1	0		2	1	0	0	0	0	0	0	1	5	

LIGHT OUTPUT FROM ALL CHANNELS ,										ONE PHOTOELECTRON LEVEL AT										1.000 MEV	
BIN WIDTH 0.100 MEV										7179 EVENTS											
225	206	223	195	192	198	198	157	173	150		127	137	124	111	112	116	78	98	91	96	
74	79	66	65	74	71	66	67	57	66		47	56	53	62	53	38	41	59	29	38	
37	38	47	31	31	49	39	47	36	30		27	32	36	33	11	30	38	26	31	22	
37	26	17	24	42	22	23	36	27	38		29	22	25	34	30	32	29	25	28	27	
27	25	26	25	31	28	25	21	24	31		38	23	13	28	32	25	33	25	26	26	
28	30	34	25	25	22	32	30	17	29		24	22	19	23	24	27	18	27	24	15	
30	24	24	28	21	14	8	21	15	21		21	17	17	14	18	12	20	11	16	10	
14	5	17	10	14	20	13	9	12	11		5	12	11	12	9	13	8	6	4	4	
5	5	5	9	5	4	5	3	4	6		4	4	5	3	6	4	3	3	2	6	
0	3	1	1	2	0	5	0	2	3		1	0	2	3	2	0	0	3	2	35	

LIGHT OUTPUT IN MEV ELECTRON EQUIVALENT

[illegible][illegible][illegible]

FIRST SCATTERED DATA

BIAS	CH.1	CH.2	CH.3	CH.4	CH.5	CH.6			
BIAS	0.25		2225	0	129	48	716	711	
BIAS	0.50		2153	0	126	47	652	570	
BIAS	1.00		2043	0	116	38	334	341	
BIAS	2.00		1823	0	101	6	9	91	
BIAS	4.00		1458	0	48	0	0	2	

SECOND SCATTER DATA

BIAS	CH.1	CH.2	CH.3	CH.4	CH.5	CH.6		
BIAS	0.25		43	1619	62	0	1	0
BIAS	0.50		65	1484	53	0	22	0
BIAS	1.00		77	1165	44	0	68	0
BIAS	2.00		104	847	39	0	35	0
BIAS	4.00		106	639	31	0	2	0

HISTOGRAMS OF TIME DELAY AND X-COORD. DRIFT BEFORE BIAS OF 1.000 MEV IS ATTAINED

TIMING 0.200 NSEC/BIN

[illegible]

POSITION C.200 INCH/BIN

[illegible]

Appendix IV: Additional Features of the Program.

The four functions described below are not essential to the efficiency calculation but were found to be useful. They may be deleted if time or core is limited.

1) First- and second- scatter bookkeeping. This feature was useful for tuning cross-sections and for making comparisons with the Kurz program. The following information is provided: a) The number of histories in which the first interaction in the scintillator produced a light output above a given fixed bias, in each of the six reaction channels. This is done for five values of the bias: 0.25, 0.5, 1.0, 2.0 and 4.0 MeV electron equivalent. Thus the first-order efficiency contribution of each channel is monitored. b) The number of histories in which the summed light output from the first and second interactions exceeded each of the five bias levels; the reaction channel incremented is that of the first interaction. What is being measured here is the contribution to the efficiency from those secondary neutrons from the first interaction which are detected in the second interaction. No resolution smearing is applied. The coding appears in the MAIN routine.

2) Timing Information. Since neutron counters are often used as part of a time-of-flight system for determining the neutron velocity, it may be significant that low-energy neutrons often have two or more interactions before supplying a total light output above a given bias. For this reason the total time elapsing in each history between the incidence and detection of each neutron is monitored, and an accumulated histogram is printed out. ("Detected" here means producing total light output above a specified fixed bias.)

3) Position Drift Information. It is sometimes desirable to find the point of impact of each neutron by measuring the time difference between signals from photomultipliers at each end of a counter. One contribution to the error in this measurement comes from the detection of neutrons which have already scattered one or more times and thus no longer have their original transverse coordinates. In order to study the effect, the program monitors the difference in x-coordinate between the incident and detected neutron and prints out the accumulated histogram. The bookkeeping for functions (2) and (3) is done in subroutine FOLNUT and is documented there.

4) Dump of Individual Histories. To understand what a Monte Carlo program is doing, it is often useful to look at a number of histories in detail. For this reason, an option has been provided (the coding is in FOLNUT) to print out the following information for each history:

- a) The event number and the energy of the incident neutron E .
- b) For each interaction which occurs:
 - The new neutron energy E .
 - The light output from the interaction, $EL(7)$.
 - The reaction channel number MS .
 - The total light output for this history ELT .
 - The position vector $C(I)$, $I = 1$ to 3.
 - The new direction cosines $C(I)$, $I = 1$ to 3.
 - The lab cosine of the neutron scattering angle $COSL$.
 - The neutron azimuth PHI .
 - The elapsed time since the neutron entered the scintillator $TIME$ (nanoseconds).

Every history will be dumped as long as sense switch 2 is on; if sense switch 2 is off, the first MDUMP events will be dumped, where MDUMP is read in from the data deck.

5) Sense Switch Options. This program was originally written for a computer (DDP-24) having six sense switches available to the user; these were interrogated by the subroutine SSWTCH(I,J), where I = switch number, and SSWTCH returns J = 1 if switch is on, J = 2 if switch is off. For use on other computers a dummy routine SSWTCH is provided which always returns J = NSW(I), where NSW(I) is read in from a card in the data deck. One would ordinarily have NSW(I) = 2 for all I. For completeness, however, the sense switch options are listed below:

Setting sense switch 1 on causes termination of the current set of histories and transfers control to the output section of MAIN;

Setting sense switch 2 on causes the printout of individual histories described in (4) above;

Setting sense switch 5 on causes the number of the current history (variable IN in MAIN) and the number of neutrons which interacted (NDET) to be printed out.

Appendix V: Scintillator Geometry and Coordinate System.

The function INBND (X) decides whether the position vector $X(1)$ is inside or outside the scintillator. The present version of INBND will handle a scintillator which is either a rectangular prism (variable IGE0 = 1) or cylinder (IGE0 = 2); in the latter case the neutrons are assumed incident on a flat face. (This scheme may be readily extended to other geometries, including "dead" regions which scatter but give no light). All charged particles are assumed to stop in the scintillator. The origin of the right-handed coordinate system is at the center of the front face of the counter, with the positive z-axis ($I=3$) pointing into the counter.

The direction of the neutron is described by the three direction cosines $C(I)$. After each interaction the new direction cosines are found by subroutine SCATTER from θ and ϕ , the laboratory polar and azimuthal angles of the scatter, with θ measured from the positive z-axis and ϕ from the positive x-axis.

SCATTER finds the new direction cosines as follows: let C_x, C_y, C_z be the old direction cosines. Then the old neutron direction may be described by the angles T and P , measured from the positive z- and x-axes respectively, where $\cos(T) = C_z$, $\sin(P) = C_y/\sin(T)$, $\cos(P) = C_x/\sin(T)$. Now consider a coordinate system which has its positive z-axis along the original direction of the neutron, and its x-axis along the x-axis of the main coordinate system. In this frame the new direction cosines after the scatter are $C'_x = \sin\theta\cos\phi$, $C'_y = \sin\theta\sin\phi$, $C'_z = \cos\theta$. Rotating by the angles T and P will put them back into the main

coordinate system. The new direction cosines are then

$$C_{xn} = C'_x \cos(T) \cos(P) - C'_y \sin(P) + C'_z \sin(T) \cos(P)$$

$$C_{yn} = C'_x \cos(T) \sin(P) + C'_y \cos(P) + C'_z \sin(T) \sin(P)$$

$$C_{zn} = C'_x \sin(T) + C'_z \cos(T)$$

Appendix VI: Some Examples of the Monte Carlo Method

Briefly, the idea behind a Monte Carlo calculation is this: Suppose the variable x obeys a normalized probability distribution $p(x)$, so that $p(x)$ is the probability of finding x between x and $x + dx$. If x_1 and x_2 are the minimum and maximum allowed values of x , then

$$\int_{x_1}^{x_2} p(x') dx' = 1, \text{ and } \int_{x_1}^x p(x') dx' = R(x) \text{ where } R(x) \text{ is distributed uni-}$$

formly between 0 and 1. To simulate the distribution $p(x)$, let u be a number between 0 and 1 drawn randomly from a uniform distribution; if the equation $R(x) = u$ is solved for x for each value of u so chosen, these values of x will obey the distribution $p(x)$.

The values of u are supplied by a random number generator (in this case, the function UNIRND). Solving $R(x) = u$ for x is trivial for simple distributions. For example, an isotropic angular distribution (x uniform between -1 and +1) is simulated by $x = -1 + 2u$, while the exponential distribution $p(x)dx = ae^{-ax}dx$ is simulated by $x = -\frac{1}{a} \ln(1-u)$.

For some applications in this program (for example, the polynomial angular distributions used by NCNCGM and the energy distributions used by NN3AL and NPB) it is not convenient to solve explicitly for x in

$R(x) = u$. For these cases the subroutine RTNI (see listing) is used to perform the inversion by Newton's iteration method. RTNI requires an external subroutine which supplies $R(x)$ and its derivative (which is $p(x)$) at any point x . This requirement is met by the subroutine ANGDIS (for polynormal angular distributions) and ENGDIS (for phase space energy distributions).