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THE BLACK NEUTRON DETECTOR

by

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THE BLACK NEUTRON DETECTOR

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ABSTRACT

A detector has been designed for use as a fast-time-response, absolute-neutron-flux monitor in the fast-energy range. A neutron beam enters a scintillator system through an entrance channel. The neutrons lose most of their primary energy in successive collisions within the scintillator. The sum of the light produced by the recoil hydrogen atoms is detected by several photomultipliers. The response and spectra for incident monoenergetic neutrons are investigated with Monte Carlo calculations. Proper dimensions for a Black Neutron Detector suitable for use of neutrons up to 10 MeV are derived from these calculations.

I. INTRODUCTION

There is a continuing need for a neutron detector with a smooth and flat efficiency over a large energy range. The "Grey Neutron Detector" designed for relative flux measurements in neutron-cross-section experiments¹⁻³ has such a flat and smooth efficiency from 0 to about 1-2 MeV. Above this energy the efficiency is strongly dependent on the knowledge of the leakage of neutrons out of the detector and the γ absorption within the system. An additional disadvantage of the Grey Neutron Detector for the use in fast-neutron cross-section experiments at higher energies is its slow time response. A version with a time resolution of about 0.5 μ sec has been reported.⁴ However, this is still much too slow for a typical time-of-flight experiment in the fast-neutron energy range where a time resolution in the lower nsec range is desired.

The desirable fast time response for the fast-neutron energy range is easily achieved with plastic or liquid scintillators viewed by a photomultiplier. However, for absolute counting, such a system has several severe disadvantages. The carbon scattering cross section influences both the transmission and the secondary effects. The total cross section and especially the angular dependence of the scattering cross section of carbon are not well enough known to warrant a sufficiently accurate calculation of these effects. Due to secondary processes and the noise of the photomultiplier, the spectrum obtained with such a conventional arrangement has a large percentage of low-energy pulses, making it difficult to determine the total count rate.

II. DESIGN AND PRINCIPLE OF THE BLACK NEUTRON DETECTOR

The Black Neutron Detector is designed to maintain the fast time response of a conventional scintillation detector while overcoming its weakness for absolute neutron-flux measurements. The detector consists of a sphere, cube, or cylinder of hydrogenous scintillator material. The neutron beam enters the detector system through a channel which terminates in approximately the center of the detector. The scintillation light of the recoil protons and carbon nuclei is detected with several photomultipliers. The system is sufficiently large so that a neutron undergoes several successive collisions before it falls below a low-energy threshold (E_{thr}), or leaks out of the system. As a result, most of the primary energy of the majority of the neutrons converts to a hydrogen or carbon nuclei

recoil energy and thus to light. The qualitative difference in concept and response of the conventional scintillation detector and the Black Neutron Detector is illustrated in Fig. 1.

Fig. 1. Schematic Comparison of Conventional Scintillation Detector (left) and the Black Neutron Detector (right). ANL Neg. No. 116-911.

The advantage of an additive device is appreciable. The extrapolation to zero pulse height can be carried out with high accuracy because the number of small pulses is very few if the detector system is sufficiently large. The probability for a first collision can be in the range of 99-95% for incident neu-

trons with energies of 1-10 MeV. Due to the small opening angle with little backscattering-escape and the mechanism of multiple collisions, the influence of any involved cross section is expected to be small. However, the use of the detector in absolute-flux measurements of good accuracy requires a precise knowledge of these small cross-section effects and of the optimization of the various detector parameters. For these purposes a Monte Carlo code, "CARLO BLACK," has been developed for a Black Neutron Detector of cylindrical shape with an axial neutron-beam entrance channel surrounded by a lead shield.

III. MONTE CARLO EVALUATION

The parameters of the detector and the orientation of the coordinate system are shown in Fig. 2. The detector cylinder has a height H and

Fig. 2. Detector Geometry and Coordinates.
ANL Neg. No. 116-1155.

radius R and is filled with a scintillator having the hydrogen and carbon atomic densities N_H and N_C . The neutron-beam entrance channel has a radius R_c and a height H_c . The incoming neutron beam is centered and has a circular, homogeneous distribution with a radius R_N . The cylindrical part without the channel is called ZONE 1; the part of the cylinder with the channel is called ZONE 2. A neutron is described by its position parameters X , Y , and Z , its directional parameters U , V , and W , and its energy E . The history of a neutron is followed until it either leaks out of the system, falls below an energy threshold E_{thr} , or exceeds a time threshold T_{thr} before it is lost due to either of the two other reasons. The light produced by the recoil particles or by other charged-particle reaction products during the history of a neutron is summed and recorded at the end of the neutron history. Edge effects of the

charged particles are neglected because of the size of the system. High probabilities for first and second collisions within the detector require a large scintillation system. The size and thus the useful energy range for the application of the Black Neutron Detector are limited by the absorption of light within the scintillator and by the background, which increases with the volume of the detector. In the present considerations, a neutron energy of 10 MeV was chosen as a useful upper energy limit. Some parts of the present problem are extensively described along with their solutions in the general literature dealing with Monte Carlo problems (see, for example, Refs. 5-7). Only a summary description is given here, and more details may be obtained from the above references or secondary references cited therein.

Figure 3 shows the schematic flow diagram for the problem. The frequency of the path a neutron may take in this flow diagram is indicated by the thickness of the lines. To keep evaluation times low, speedy evaluation methods are used along these more frequent paths. The main loop is that in which a neutron has to be followed through successive collisions. The average number of collisions of a neutron before its history is terminated by one of the above limitations is five to eight, depending on the incident energy. Usually two-thirds or more of these collisions involve hydrogen.

Fig. 3. Flow Diagram of "CARLO BLACK." ANL Neg. No. 116-1158 Rev. 1.

About 90% of all collisions take place in ZONE 1 of the detector. Most neutron histories are ended by the neutron falling below E_{thr} . Ten thousand to 20,000 histories usually give sufficiently low statistical errors. This is a computational reflection of the high physical efficiency of the detector ($>90\%$). For spectra evaluations, a larger number of histories is required. However, good spectral distributions are obtained with 50,000-100,000 histories. Outside of the primary calculational paths, straightforward programming is used for simplicity without undue deterioration of computational speed.

A. Neutron Source

The initial parameters of a neutron are, by definition,

$$Z = H_C,$$

$$U = 0.0,$$

$$V = 0.0,$$

$$W = 1.0,$$

and

$$E = E_{Pr} \text{ (primary energy).}$$

X and Y are chosen at random so that a homogeneous distribution on a circular area with the radius R_N is achieved. Two random numbers R_1 and R_2 are selected in the interval $[-1, 1]$. Those for which

$$R_1^2 + R_2^2 \leq 1$$

are retained and $X = R_N R_1$, $Y = R_N R_2$ are evaluated. The efficiency for this trial method is $\pi/4$.

B. Flight Path and Cross Sections

The flight-path length, L , is evaluated by

$$L = - \frac{\ln R}{\Sigma_{tot}},$$

where R is a random number in the interval $[0, 1]$, and Σ_{tot} is the macroscopic total cross section. Σ_{tot} is the sum of the partial cross sections contributing at the present energy of the neutron. Table I gives the reaction types, the Q values, and the first and second thresholds. The latter are defined as those energies in the Laboratory System at which the reaction starts (first threshold) and at which the energy is a unique function of the angle (second threshold). The cross sections have been assumed to be zero below the second thresholds of the applying reactions. This simplifies the evaluations.

TABLE I. Reactions Contributing in the Energy Range 0-10 MeV

Reaction	Q/MeV	First Threshold	Second Threshold
$^1\text{H}(n,n)^1\text{H}$	-	-	-
$^{12}\text{C}(n,n)^{12}\text{C}$	-	-	-
$^{12}\text{C}(n,n'\gamma)^{12}\text{C}$	4.433	4.805	4.840
$^{12}\text{C}(n,\alpha)^9\text{Be}$	5.704	6.183	6.428
$^{12}\text{C}(n,n')^{12*}\text{C}$	7.656	8.299	8.359
$\rightarrow ^8\text{Be} + \alpha$	+0.289		
$\rightarrow 3\alpha$	+0.102		

The hydrogen cross section is known to consist of a triplet and a singlet term⁸

$$\sigma = 3\pi\sigma_t + \pi\sigma_s,$$

where both have the same energy dependence ($i = t, s$)

$$\sigma_i = \left\{ k^2 + \left[\frac{1}{a_i} + \frac{k^2}{2} r_{oi}(1 - 2P_i r_{oi}^2 k^2) \right]^2 \right\}^{-1}.$$

In this equation k^2 in 10^{24} cm^{-2} corresponds to $1.206E$ in MeV. The higher-order terms containing P can be safely neglected. Using recently reported values for a_i , and r_{oi} ,⁹ one obtains (E in MeV)

$$\sigma_H = \frac{2.772}{1 + 0.2395E + 0.0033E^2} + \frac{17.664}{1 + 7.5644E + 0.1534E^2},$$

where σ is in barns. This expression applies in the total energy range and is within the present accuracy of the experimental cross sections (about 0.2-0.8%).

The carbon cross sections are obtained by linear interpolation between values taken from cross-section tables. These tables contain the cross sections in mesh points appropriate to the structure of the carbon total cross section. The elastic scattering cross section of carbon above 4.433 MeV is obtained from

$$\sigma_{n,n} = \sigma_{\text{tot}} - \sum_i \sigma_i,$$

where i stands for the nonelastic cross sections.

C. Geometry

The position of a neutron is described by

$$X' = X + U\ell,$$

$$Y' = Y + V\ell,$$

and

$$Z' = Z + W\ell, \quad 0 \leq \ell \leq L,$$

where ℓ is the length the neutron has traveled since its last collision. The distance from the center axis is given by $F = r^2 = X'^2 + Y'^2$, which is a minimum for $dF/d\ell = 0$. If the neutron flight path reaches in ZONE 2 a point smaller than the channel radius, a channel crossing occurs and the selected path length, L , must be extended by the flight path within the channel. If the entrance and exit points occur in ZONE 2, this flight-path length in the channel is

$$\Delta L = \frac{2}{a} \sqrt{b^2 - a(c - R_c^2)},$$

where $a = U^2 + V^2$, $b = UX + VY$, and $c = X^2 + Y^2$. If one of the crossing points is at the end of the channel ($Z = H_c$), one obtains

$$\Delta L = |t_{1,2} - t_c|,$$

where

$$t_c = \frac{H_c - Z}{W}$$

and

$$t_{1,2} = \frac{-b \pm \sqrt{b^2 - a(c - R_c^2)}}{a}.$$

That t_i for which $Z(t_i) < H_c$ is used. After the flight-path length L has been updated for a possible channel crossing, the new position of the neutron is evaluated by

$$X' = X + UL,$$

$$Y' = X + VL,$$

and

$$Z' = Z + WL,$$

and it is checked for a position outside of ZONE 1 or ZONE 2 (leakage). If the neutron is still inside the system, its flight time is evaluated from

$$T = 0.723L/\sqrt{E},$$

where T is in nsec, L in cm, and E in MeV.

D. Backscattering from the Lead Shield

To reduce the γ background of the detector, a lead shield is used around the detector, leaving openings for the multipliers and the neutron-beam entrance channel. The shield may contain, in addition to lead, some lithium and hydrogenous material to shield against room background neutrons. This shield will cause some backscattering of neutrons initially leaking out of the scintillator. However, only a small number of neutrons return to the scintillator and cause a change in the detector efficiency. Thus a simple approach is used to account for this backscattering. It is assumed that a percentage, R , of the leaking neutrons return with reversed directional parameters $-U$, $-V$, and $-W$ and half of their original energy. It is found that a change of R from 5 to 20% influences the efficiency of the detector by less than 0.2%. Thus these simple assumptions are quite adequate.

E. Type of Collision

The type of collision is chosen by selecting a random number, R , in the interval $[0, 1]$, and checking whether $R\sigma_{\text{tot}} \leq \sigma_H(n,n)$, in which case it is $H(n,n)$; or, if not, whether $R\sigma_{\text{tot}} \leq \sigma_H(n,n) + \sigma_C(n,n)$, in which case it would be $C(n,n)$; etc. The sequence of the test is arbitrary. However, it is fixed during the computation. Checking for the larger cross section first results in the speediest evaluation, thus the sequence $H(n,n)$, $C(n,n)$, $C(n,n')$, $C(n,\alpha)$, $C(n,n'\alpha)$ is used.

F. Hydrogen-collision Kinetics

The differential cross section is assumed isotropic in the CMS. Thus $\cos \psi$ of the CMS is uniformly distributed in the interval $[-1, 1]$. The well-known relations between $\cos \psi$ and the energy, and $\cos \theta$ in the Laboratory System derived from the conservation of energy and momentum are

$$\cos \theta = \frac{1 + A \cos \psi}{\sqrt{1 + 2A \cos \psi + A^2}}$$

and

$$E' = E \frac{1 + 2A \cos \psi + A^2}{(1 + A)^2},$$

where $A = 1$ for hydrogen. With R , a random number in the interval $[0, 1]$, $\cos \psi = 2R - 1$, and one obtains the simple relations

$$\cos \theta = \sqrt{R}$$

and

$$E' = ER.$$

The recoil energy needed for the evaluation of the scintillation light is

$$E_{\text{Rec}} = E - E'.$$

G. Carbon-elastic-collision Kinetics

The elastic neutron scattering cross section of carbon is anisotropic in the CMS. Differential neutron cross sections are usually described in the Laboratory System as an expansion of Legendre polynomials

$$\frac{d\sigma}{d\Omega} = \frac{\sigma}{4\pi} \left(1 + \sum_{i=1}^n \omega_i P_i \right).$$

The coefficients ω_i depend on the energy E and are obtained from fits of the available experimental data.

The selection of the scattering cosine is carried out in a "cross-section-experiment" analogous manner. For this purpose, the above distribution is normalized at $\cos \theta = 1.0$. Thus one obtains

$$F(\cos \theta) = \frac{\sigma(\cos \theta)}{\sigma(1.0)} = \sum_{i=0} \Omega_i P_i.$$

A trial $\cos \theta$ is chosen at random in the interval $[-1, 1]$. Then a random number, R , is chosen in the interval $[0, 1]$. If $F \leq R$, the trial was a "hit" and the energy of the neutron after the collision is evaluated from

$$E' = E \left[\frac{\cos \theta}{A+1} + \sqrt{\frac{A-1}{A+1} + \left(\frac{\cos \theta}{A+1} \right)^2} \right]^2,$$

where $A = 12$ for carbon.

The carbon-recoil energy follows from the energy conservation:

$$E_{\text{Rec}} = E - E'.$$

H. Carbon-inelastic and (n, α)-collision Kinetics

Both carbon-inelastic and (n, α)-collision kinetics are infrequent in the energy range considered here. Thus, for the sake of simplicity, isotropic distribution in the Laboratory System is assumed. The kinetic equations are similar for both reactions. The energy of the neutron or α particle after the collision is

$$E' = E(B + \sqrt{B^2 + C})^2$$

with

$$B = \frac{\cos \theta}{13}$$

and

$$C = \frac{11}{13} - \frac{12}{13} \frac{Q}{E}$$

for inelastic scattering, and

$$B = \frac{2 \cos \theta}{13}$$

and

$$C = \frac{8}{13} - \frac{9}{13} \frac{Q}{E}$$

for the (n, α) reaction.

The energy of the recoil carbon or residual ^9Be nuclei is obtained from the energy conservation:

$$E_{\text{Rec}} = E - E' - Q.$$

I. C(n,n') 3α Kinetics

Only one of two or three levels of ^{12}C contributing to this reaction type are taken into account (see Table I); the thresholds of the neglected levels are too close to 10 MeV to be of significance. Isotropic distribution of the inelastically scattered neutron in the Laboratory System is assumed. The reaction takes place in three steps:

and

The energy of the inelastically scattered neutron is again given by

$$E' = E(B_c + \sqrt{B_c^2 + C_c})^2.$$

The kinetic energy of the excited carbon nucleus is

$$E_c = E - E' - Q.$$

Using this energy, one obtains for the energy of the first α particle and the beryllium recoil energy, E_{Be} ,

$$E_{\alpha_1} = D_1 + \frac{m_\alpha}{m_c} E_c + 2 \sqrt{\frac{m_\alpha}{m_c}} \sqrt{D_1} \sqrt{E_c} \cos \psi$$

with

$$D_1 = \frac{Q_c}{1 + \frac{m_\alpha}{m_{\text{Be}}}},$$

and

$$E_{\text{Be}} = E_c + Q_c - E_{\alpha_1}.$$

Here $\cos \psi$ is given by an isotropic distribution in the CMS and is obtained by choosing a random number in the interval $[-1, 1]$, and $Q_c = 0.289$ MeV. The energies of the two α particles from the decay of ${}^8\text{Be}$ are, accordingly,

$$E_{\alpha_2} = D_2 + \frac{m_\alpha}{m_{\text{Be}}} E_{\text{Be}} + 2 \sqrt{\frac{m_\alpha}{m_{\text{Be}}}} \sqrt{D_2} \sqrt{E_{\text{Be}}} \cos \psi_2$$

and

$$E_{\alpha_3} = E_{\text{Be}} + Q_{\text{Be}} - E_{\alpha_2},$$

where $D_2 = Q_{\text{Be}}/2$ and $Q_{\text{Be}} = 0.102$ MeV.

J. Transformation of Direction Coordinates

The $\cos \theta$ determined by a known microscopic cross section or given by the assumption of an isotropic distribution determines the angle between the previous direction and the direction after the collision. The azimuth, ψ , is distributed at random and its cosine and sine are obtained by Von Neumann's method

Two random numbers, R_1 and R_2 , are selected in the interval $[-1, 1]$ and checked to determine whether they lie within a circle with a radius 1. If

$$R_1^2 + R_2^2 \leq 1.0$$

is not fulfilled, a new pair is chosen. The sine and cosine are obtained from

$$\cos \psi = \frac{R_1^2 - R_2^2}{R_1^2 + R_2^2}$$

and

$$\sin \psi = \frac{2R_1R_2}{R_1^2 + R_2^2}$$

The $A = \cos \theta$, $B = \sin \theta$, $C = \cos \psi$, and $D = \sin \psi$ of the collision process are used to obtain the new directional coordinates U' , V' , and W' from the previous U , V , and W . This is achieved in the transformation

$$U' = \frac{B}{R} (CWU - DV) + AU,$$

$$V' = \frac{B}{R} (CWV + DU) + AV,$$

and

$$W' = -BCR + AW$$

with $R = \sqrt{1 - W^2}$. The source neutrons enter the detector as per the definition of the coordinate system with $W = 1$. In this case, the transformation is simpler:

$$U' = BC,$$

$$V' = BD,$$

and

$$W' = A.$$

This transformation is also used for $|W|$ -values close to 1.

K. Light Pulse-height Distribution

The light produced by a recoil particle in the scintillator is obtained by linear interpolation between values stored in light tables. Only values for light versus energy of protons, alphas, and carbon are incorporated.

The light for beryllium-recoils is assumed to be the same as that for carbon. The light produced during a neutron history is added, and an appropriate count is added at the end of the neutron history to a pulse-height spectrum. For a second spectrum, the attenuation of the light in the system is taken into account by assuming an exponential attenuation of the light with a half-length, $L_{1/2}$, of about 6 cm. The multiplier geometry also is taken into account, assuming a $1/r^2$ law (limited at $1/2$) and a constant portion of the light reaching the multipliers due to wall reflections.

L. Time Distribution

Two different time distributions are recorded. The first is the time at which the light-counter exceeds a given detection threshold, E_c . Thus, this distribution gives the time response of the detector. The second is the time at which the energy falls below the energy limit, E_{thr} , or leaks out of the system. Thus, this distribution gives the lifetime of the neutrons in the detector.

IV. EFFICIENCIES AND SPECTRA

The efficiency of the Black Neutron Detector will depend mainly on the choice of the parameters R , H , R_c , H_c , N_H , and N_C . Detector parameters should be selected such that the efficiency has the least dependence on the accurate knowledge of these parameters. Thus an investigation of the dependence of the efficiency on these parameters is of primary importance.

A. Detector Radius

The detector radius influences only the secondary and higher-order collision leakage probability. A small detector radius will cause a low detection efficiency for those neutrons that had a first collision with carbon. They lose only a small amount of their energy and are most likely to escape. Because of the small size of the carbon light, they remain undetected. Neutrons that had their first collision with hydrogen are unlikely to contribute to a low efficiency for smaller radii because they have produced a sufficiently large amount of light to be observed. The dependence of the efficiency on the detector radius is shown in Fig. 4 for three different incident energies. A radius around 15 cm appears a good choice since the efficiency curves are only slowly increasing beyond this radius.

B. Channel Length

Figure 5 shows the detector efficiency as a function of the neutron-beam entrance-channel length. Though the optimal channel length is a function of the primary neutron energy, the choice of 10-15 cm given by the

higher energy is sufficiently good for the lower energies too. The lower efficiency for short channel lengths is due to the increased backward leakage. The decrease of the efficiency for longer channels is due to the reduced first-collision probability. For higher energies the optimum is a shorter channel due to the larger first-collision average path length, which is given by $1/\Sigma_{tot}$.

Fig. 4. Efficiency as a Function of Detector Radius. ANL Neg. No. 116-1153.

Fig. 5. Efficiency as a Function of Neutron-beam Entrance-channel Length. ANL Neg. No. 116-1149.

C. Channel Radius

The Monte Carlo evaluations show that only about 10% of the collisions take place in ZONE 2 of the detector. This already suggests that the channel radius should not have too strong an influence on the efficiency.

Fig. 6. Efficiency as a Function of Channel Radius. ANL Neg. No. 116-1150.

Figure 6 demonstrates this. However, in the evaluations represented with solid lines, the neutron-beam radius has been kept constant. The dashed lines represent evaluations with a neutron-beam radius essentially the same size as the channel radius. The stronger decrease is due to the influence of the smaller effective detector radius in these cases.

D. Detector Height

Changing the detector height with a constant ratio of channel length to detector height displays mainly the effect of a changing first-collision probability. Figure 7 shows that

Fig. 7 Efficiency as a Function of the Difference between Detector Height and Channel Length. ANL Neg. No. 116-1148.

density improves the first-collision probability. It also causes an improved efficiency because the ratio of collisions with hydrogen to those with carbon in primary and secondary collisions increases. A change of the carbon density by 20% changes the efficiency between 0.2% (1 MeV) and 0.6% (4 MeV) for a constant hydrogen density of 5×10^{22} atoms/cm³. For a higher hydrogen density, the effect is even less.

The low sensitivity of the efficiency to changes of the density reflects the similar insensitivity to uncertainties of the hydrogen and carbon cross sections. An uncertainty in the hydrogen cross section appears as an uncertainty in the detector efficiency reduced by a factor of about 10. Of course, the hydrogen cross section is well enough known, and an advantage of the present detector lies in its insensitivity to the carbon cross section and to parameter changes, and thus to their uncertainties.

F. Detector Cutoff Energy

Any scintillation detector has a lower energy limit, E_C , for the detection of incoming neutrons. This limit varies over a wide range from about 40 to 500 keV, depending on the size of the scintillator, the type of multipliers, and the electronics involved. Figure 9 shows the efficiency as a function of this detector

20 cm is a sufficiently good choice for $\Delta = H - H_C$. For smaller Δ the transmission increases rapidly, especially for higher energies. Only a slight increase in efficiencies can be gained by enlarging Δ above 25 cm.

E. Hydrogen and Carbon Density

The variation of hydrogen and carbon density is limited by the existing scintillator materials. Commercially available scintillators have a carbon atomic density, N_C , of about 4×10^{22} atoms/cm³ and a hydrogen density in the range of 4×10^{22} – 7×10^{22} atoms/cm³. Figure 8 shows the variation of the detector efficiency over this range. A higher hydrogen

Fig. 8. Efficiency as a Function of Hydrogen Atomic Density. ANL Neg. No. 116-1147.

Fig. 9. Efficiency as a Function of Cut-off Energy of the Detector. ANL Neg. No. 116-1154.

cutoff energy. The efficiency decreases with increasing E_c more rapidly for lower values of E_c than for higher values. This is due to the cutoff of those histories due to only collisions with carbon and thus resulting in a very low pulse height.

G. Choice of Detector Parameters

The evaluations shown in Figs. 4-8 suggest the choice of as large a detector as possible. On the other hand, considerations of the background in a large scintillator and the light attenuation in large systems suggest the choice of as small a system as possible. A good compromise can be found by using parameters in a range where the efficiency curve flattens out or shows a maximum. Such values are:

$$N_H = 7.02 \times 10^{22} \text{ atoms/cm}^3,$$

$$N_C = 4.2 \times 10^{22} \text{ atoms/cm}^3,$$

$$H = 40-45 \text{ cm},$$

$$R = 12-18 \text{ cm},$$

$$H_c = 10-15 \text{ cm},$$

and

$$R_c = 1-4 \text{ cm}.$$

The values for N_H and N_C are characteristic of a reasonably priced commercial liquid scintillator. H_c and R_c can be easily varied in a detector by using different channel inserts. The following spectra evaluations have been made for an actual detector built with parameters in the range of the above tabulated values.

H. Efficiency versus Energy

Figure 10 shows the efficiency of a Black Neutron Detector as a function of energy. The energy mesh points used in this evaluation have been chosen to match the structure in the carbon cross section. The statistical accuracy of the computations was between 0.1% at low energies and 0.3% at higher energies. A smooth curve has been drawn through the calculated results. Small-sized structure may have been lost in this procedure. A first glance at the structure in the efficiency curve appears disturbing, if a smooth efficiency is required for the detector. However, the structure is very small and thus of minor practical importance. The uncertainty of the efficiency curve is small due to the insensitivity even to large changes in

the cross sections and parameters of the detector. The change in the carbon cross section around 2.0-2.1 MeV by a factor of 3-4 is reflected in the efficiency only by a change of about 1%.

Fig. 10. Energy Dependence of Detector Efficiency in the 0-9-MeV Range. ANL Neg. No. 116-1151.

With conservative estimates of the uncertainties of the parameters and cross sections, the calculated uncertainty of the detector efficiency is 0.3% at 1 MeV, 0.5% at 2.5 MeV, and 0.7% at 4 MeV.

I. Time Distributions

Figure 11 shows the two different time distributions. The time-resolution curve is mainly determined by the flight-time distribution for the first collision within the system. Though the FWHM is 4 nsec, an appreciable tail extends to about 10-12 nsec. Still, this time resolution is reasonable for most fast-neutron cross-section experiments with monoenergetic neutron beams.

Fig. 11. Time Response and Neutron Lifetime Spectra. ANL Neg. No. 116-1152.

The second curve shows the lifetime of the neutrons in the system in the sense that their life history is terminated by a neutron either leaking out of the system or falling below the threshold E_{thr} . It is of interest that such a curve is similar to that expected for a detector containing ^{10}B or ^6Li of such density that the (n, α) reaction dominates in the keV energy range.

J. Energy Spectra

Pulse-height spectra evaluated for three different primary neutron energies

Fig. 12. Pulse-height Spectra for Three Different Mono-energetic Neutron Beams. ANL Neg. No. 116-1156.

are shown in Fig. 12. The spectra are normalized to the same maximum pulse height. The spectra still show the first-collision hydrogen pulse-height spectra underlying the more complicated sum-spectra which result from the multiple-scattering events. The center of a spectrum lies closer to the maximum pulse height for higher energies than it does for lower energies. The spectra shown in Fig. 12 were calculated under very simplified assumptions about the light attenuation and light reflection as described above. Thus, only the gross structure in the spectra, that is, the peak at larger pulse heights and the minimum for low pulse heights, can be expected to be seen in experimentally obtained pulse-height spectra.

V. EXPERIMENTAL TESTS OF THE DESIGN CONCEPT

The "Black Neutron Detector" shown in Fig. 13 was built to test the expected features of the pulse-height spectrum shown in Fig. 1. The liquid

Fig. 13. The Black Neutron Detector. ANL Neg. No. 116-1180.

scintillator is contained in a 40-cm-high, 13-cm-radius cylinder, surrounded by a 5-cm-thick shield of lead, lithium hydroxide, and water. The liquid scintillator is a mixture of pseudocumene, p-terphenyl, and POPOP and will be replaced with a decalin-based scintillator to improve the hydrogen-to-carbon atomic-density ratio. The scintillation light was viewed by four selected low-noise 58AVP photomultipliers. The fast anode signals were added in pairs of two, and a coincidence between the two added signals was required to reduce noise pulses. A detector threshold was experimentally set at 150 keV by an observation of the time-of-flight peak at successively lower neutron energies. Figure 14 shows the observed pulse-height spectra for 1.5- and 2.5-MeV neutrons. The spectra show the deep minima for low pulse heights, which is one of the major advantages of the present detector for absolute neutron-flux measurements. Figure 15 shows a time-of-flight spectrum for an energy of 2 MeV. The resolution obtained in this measurement is 4 nsec for the prompt γ peak. The width of the neutron peak is 10 nsec.

Fig. 14. Experimental Pulse-height Spectra for 1.5- and 2.5-MeV Neutrons. ANL Neg. No. 116-1159.

Fig. 15
Time-of-flight Spectra
for 2-MeV Neutrons.
ANL Neg. No. 116-1157.

APPENDIX

The Monte Carlo Code "CARLO BLACK"

The Monte Carlo code "CARLO BLACK" is used on a SEL 840 MP/EAU computer with 16K memory. By eliminating the input by console switches and typewriter the code should be operating with any FORTRAN IV compiler.

The code is self-explanatory with the use of the comment cards and mnemonic variable names. A listing of the output of one case is given.

```

C      "CARLO BLACK"                                W.P.PZENITZ,ANL
C
C      MONTE CARLO PROGRAM FOR THE EVALUATION OF SPECTRA AND
C      EFFICIENCIES OF THE BLACK NEUTRON DETECTOR
C
COMMON /BANK1/ L0SE,L0ST,L0SG,LEDC,LEAD,K0LCN0,KTR0B,KT0,N21,N22
COMMON /BANK2/ LITET(128),LITER(128),LEAK(128)
COMMON /BANK3/ K0LC,K0LH,K0LL(100),K0LCC(100),K0LHH(100),NRES(100)
COMMON /CR0S/ KCN,ECN(250),SCN(250),KCIN,ECIN(20),SCIN(20),KCNA,
1ECNA(10),SCNA(10),KC3A,EC3A(5),SC3A(5)
COMMON /CR0SB/ SCB(250),SCIB(20),SCNB(10),SC3B(5)
COMMON /C0M/ K0MEGA,E0MEGA(55),0MEG1(55),0MEG2(55),0MEG3(55),0MEG4
1(55),0MEG0(55)
COMMON /C0S1/ A,B
COMMON /DENS1/ MNH,MNC,SATR,SASI
COMMON /ENER/ E,EREC,EE,EA1,EA2
COMMON /ELCUT/ ECUT,CUTL,NEFF,EFF
COMMON /HIST/ NSAMPL,NHIST,NX,K0LM
COMMON /INDIC/ KANCR,N2ONE
COMMON /INPUT/ ID,0D1,0D2,ID2
COMMON /KANAL/ KANC,KANL
COMMON /LIGHT/ T0LI,RELI,TN0RM,RN0RM
COMMON /LITE/ KLIT,ELIT(125),PLIT(125),CLIT(125),ALIT(125)
COMMON /MATRX/ MATR(25,10)
COMMON /MULT1/ RH(4),HM(4),ALIH
COMMON /PARA/ RT,HT,RC,HC,RT2,RC2
COMMON /P0S1/ X,Y,Z,U,V,W,AL
COMMON /PRIN/ XP,YP,ZP,RP2
COMMON /REFL/ REF
COMMON /REG1/ I,L
COMMON /RES0LU/ NRSU(100)
COMMON /SORTA/ I1,I2,R
COMMON /START/ EST,RN
COMMON /STEN/ MED,E0(50)
COMMON /THRESH/ ETR,TTR
COMMON /TIME/ T
COMMON /WQS/ ST0T,S1,S2,S3,S4,S5

C
C      INTEGER 0D1,0D2
C      INTEGER EA1,EA2
C      INTEGER E,EREC
C      INTEGER ECN,ECIN,ECNA,EC3A,E0MEGA,ELIT,PLIT,CLIT,ALIT
C      INTEGER E0,EST
C
C      DATA ATR,AS1 / 2.772,17.664 /
C
C      SET INPUT / OUTPUT DEVICE
C
C      WRITE(1,666)
C      READ(1,667) ID,ID2

```

```

666 FORMAT(1X,12H)NP DVS(213))
667 FORMAT(213)
      DD1 = 5
      DD2 = 3
C
C      REAL-SKIP RANDOM NUMBERS
C
      WRITE(1,668)
      READ (1,669) NSKIP
      DO 670 K=1,NSKIP
670 R7=RANF(-1)
668 FORMAT(1X,8HSKIP(13))
669 FORMAT(13)
C
C      INITIALIZE ALL CROSS SECTIONS,LIGHT TABLES ETC,
C
      CALL INISH
C
C      READ NW = NUMBER OF CASES
C
      READ ( 10,100 ) NW
100 FORMAT(13)
      DO 220 NX = 1,NW
C
C      READ PARAMETERS AND START ENERGIES FOR ONE CASE
C
      CALL INPUT
C
C      PREEVALUATIONS
C
      RM(1)=RT
      RM(2)=*RT
      RM(3)=RT
      RM(4)=*RT
      HM(1)=0.75*HT
      HM(2)=HM(1)
      HM(3)=0.25*HT
      HM(4)=HM(3)
      ALIH=6.0
      RT2 = RT * RT
      RC2 = RC * RC
      SATR = ATR*HNN
      SASI = ASI*HNN
      DO 40 K = 1,KCN
40 SCN ( K ) = HNC*SCB(K)
      DO 41 K = 1,KCIN
41 SCIN(K) = HNC*SCIB(K)
      DO 42 K = 1,KCNA
42 SCNA(K) = HNC*SCNB(K)
      DO 43 K = 1,KC3A
43 SC3A(K) = HNC*SC3B(K)
C
C      REPEAT FOR DIFFERENT START ENERGIES
C
      DO 221 NEX = 1,NEQ
      EST = E0 (NEX)
C
C      PREEVALUATIONS
C
      EREC = EST
      I=6
      CALL SORT
      RN1 = PLIT(11)

```

```

RN2 = PLIT(I2)
RNORM = RN1 + R * (RN2 - RN1)
TNORM = 120.0/RNORM
RERM=3.0*TNORM
EREC = ECUT
CALL SORT
RN1 = PLIT(I1)
RN2 = PLIT(I2)
CUTL = RN1 + R*(RN2-RN1)
CARB=CUTL
CUTL = CUTL*TNORM
C
C      CLEAR ALL SPECTRA AND COUNTERS
C
      DO 875 M1=1,25
      DO 875 M2=1,10
875  MATR(M1,M2)=0
      DO 1 K=1,128
      LITET(K) = 0
      LITER(K) = 0
      1 LEAK(K) = 0
      DO 2 K = 1,100
      NRSU(K)=0
      NRES(K) = 0
      KOLL (K) = 0
      KOLCC(K) = 0
      2 KOLHH(K) = 0
      LOSE = 0
      LOST = 0
      LOSG = 0
      NZ1=0
      NZ2=0
      NEFF = 0
      LEDC = 0
      KANC = 0
      KANL = 0
      NHIST = 0
      KOLCNO = 0
      KTRBB = 0
C
C      CHECK FOR "CASE COMPLETE"
C
      3 IF(NHIST ,GE. NSAMPL ) GO TO 4
C
C      CHECK FOR FORCED EXIT
C
      CALL SSWTCH(10,KTES)
      IF ( KTES ,EQ. 1 ) CALL OUTPUT
C
C      START ONE HISTORY
C
      NHIST = NHIST + 1
      CALL SOURCE
C
C      CLEAR ALL HISTORY COUNTERS AND RESET INDICATORS
C
      KOLC = 0
      KOLH = 0
      KTB = 0
      TWLI = 0.0
      RELI = 0.0
      LEAD = 0
      KANCX = 0

```

```

NZONE = 1
T = 0.0
NT = 0
ISET=0
C
C      CHECK FOR MAX NUMBER OF COLLISIONS
C
15 IF ( KTO .LT. KOLM ) GO TO 65
    CALL BANKER
    GO TO 3
C
C      EVALUATE PRESENT CROSS SECTIONS
C
65 CALL EVACRO
C
C      SELECT FLIGHT PATH AND EVALUATE TENTATIVE POSITION
C
R1 = RANF ( -1 )
AL =      = ALOG ( R1 ) / STOT
XP = X + U*AL
YP = Y + V*AL
ZP = Z + W*AL
RP2 = XP*XP + YP*YP
C
C      FIND COLLISION ZONE AND ACT ACCORDINGLY
C
CALL ZONE
IF ( 1 .EQ. 1 ) NZ1 = NZ1 + 1
IF ( 1 .EQ. 2 ) NZ2 = NZ2 + 1
GO TO ( 5,6,7 ), I
C
C      COLLISION WAS IN ZONE 1
C
5 IF ( NZONE .EQ. 1 ) GO TO 21
    CALL CHANX
    CALL ZONE
    GO TO ( 17,20,7 ), I
17 NZONE = 1
    GO TO 21
C
C      COLLISION WAS IN ZONE 2
C
6 CALL CHANX
    CALL ZONE
    GO TO ( 17,19,7 ), I
19 NZONE = 2
    GO TO 21
C
C      COLLISION WAS OUTSIDE OF SCINTILLATOR
C
7 CALL LEADR
  NZONE = 3
  IF ( L .GT. 0 ) GO TO 36
  LOSG = LOSG + 1
  N=(E*120)/EST+1
  LEAK(N)=LEAK(N)+1
10 CALL BANKER
  GO TO 3
36 LEAD = 1
  GO TO 15
C
C      ADD TO TIME AND CHECK FOR LIMIT

```

```

C
21 X = XP
   Y = YP
   Z = ZP
   T1 = 23.151 * AL / SQRT(EE)
   T = T + T1
38 IF ( T ,LT, TTR ) GO TO 8
   LOST = LOST + 1
   CALL BANKER
   GO TO 3

C
C       IRREGULARITY COUNTER
C
20 KTR00 = KTR00 + 1
   GO TO 3

C
C       FIND COLLISION TYPE
C
8 CALL TYPE
  IF ( L ,EQ, 0 ) GO TO 20

C
C       BRANCH ACCORDING TO TYPE AND EVALUATE NEW DIRECTION,
C       ENERGY AND LIGHT
C
  GO TO ( 11,12,13,14,16 ), L

C
C       REACTION H(N,N)H
C
11 K0LH = K0LH + 1
   KT0 = KT0 + 1
   R = RANF (-1)
   EN = EE * R
   ER = EE - EN
   EREC = ER
   EE = EN
   E = EN
   A = SQRT ( R )
   B = SQRT ( 1.0 - R )
37 CALL LIGHT
   IF ( ISET ,GT, 0 ) GO TO 95
   IF ( T0L1 ,LT, CAR0 ) GO TO 95
   N = T
   N = N + 1
   IF ( N ,GT, 100 ) N = 100
   NRSU(N) = NRSU(N) + 1
   ISET = 5

C
C       CHECK FOR LOWER ENERGY LIMIT
C
95 IF ( EE ,GT, ETR ) GO TO 45
   LOSE = LOSE + 1
   CALL BANKER
   GO TO 3
45 CALL TRANS
   GO TO 15

C
C       REACTION C(N,N)C
C
12 K0LC = K0LC + 1
   KT0 = KT0 + 1
   CALL CARBON
   GO TO 37

```

```

C
C      REACTION C(N,N)N GAMMA)C
C
13 K0LCN0 = K0LCN0 + 1
   KT0 = KT0 + 1
   CALL C1NEL
   GO TO 37

C
C      REACTION C(N,ALPHA)
C
14 K0LCN0 = K0LCN0 + 1
   KT0 = KT0 + 1
   CALL CNAL
   CALL LIGHT
   CALL BANKER
   GO TO 3

C
C      REACTION C(N,N)N 3 ALPHA)
C
16 K0LCN0 = K0LCN0 + 1
   KT0 = KT0 + 1
   CALL CN3A
   GO TO 37
4 CALL OUTPUT
221 CONTINUE
220 CONTINUE
   STOP
   END

```

SUBROUTINE INISH

```

C
C      INITIALIZE CARBON CROSS SECTIONS, LIGHT TABLES, AND ANG. DISTR.
C      AND COPY TO PRINTER
C
COMMON /CR05/ KCN,ECN(250),SCN(250),KCIN,ECIN(20),SCIN(20),KCNA,
1ECNA(10),SCNA(10),KC3A,EC3A(5),SC3A(5)
COMMON /CR06/ SCB(250),SCIB(20),SCNB(10),SC3B(5)
COMMON /COM/ K0MEGA,E0MEGA(55),0MEG1(55),0MEG2(55),0MEG3(55),0MEG4
1(55),0MEG0(55)
COMMON /INOUT/ ID,0D1,0D2,ID2
COMMON /LITE/ KLIT,ELIT(125),PLIT(125),CLIT(125),ALIT(125)
C
INTEGER ECN,ECIN,ECNA,EC3A,E0MEGA,ELIT,PLIT,CLIT,ALIT
INTEGER 0D1,0D2
C
READ CARBON ELASTIC C S
C
READ ( ID,100 ) KCN
READ ( ID,101 ) ( ECN(K),SCB(K),K = 1,KCN)
100 FORMAT (I4)
101 FORMAT(I6,2X,E12.6)
C
READ CARBON INELASTIC C S
C
READ ( ID,100 ) KCIN
READ ( ID,102 ) ( ECIN(K),SCIB(K),K = 1,KCIN )
102 FORMAT(I6,2X,F5,2)
C
READ CARBON N, ALPHA
C
READ ( ID,100 ) KCNA
READ ( ID,102 ) ( ECNA(K),SCNB(K),K = 1,KCNA )
C
READ CARBON N,N3ALPHA
C
READ (ID,100) KC3A
READ ( ID,102 ) ( EC3A (K),SC3B(K),K = 1,KC3A )
C
READ LIGHT TABLE
C
READ ( ID,100 ) KLIT
READ ( ID,103 ) ( ELIT(K),PLIT(K),CLIT(K),ALIT(K),K=1,KLIT)
DO 1 K =1,KLIT
1 PLIT(K) = 10*PLIT(K)
103 FORMAT(I6,1X,I6,1X,I6,1X,I7)
C
READ CARBON LEG. COEF.
C
READ (ID,100) K0MEGA
READ (ID,104) (E0MEGA(K),0MEG0(K),0MEG1(K),0MEG2(K),0MEG3(K),
10MEG4(K),K=1,K0MEGA)
115 FORMAT(1H1,
1 10X,5HE/KEV,5X,3H0M0,9X,3H0M1,9X,3H0M2,9X,3H0M3,9X,3H0M4//)
114 FORMAT(1H1,1X, 5HE/KEV,3X,7HSIGMA/B,10X,7HC(N,N)C//)
105 FORMAT(1H1,1X,5HE/KEV,3X,7HSIGMA/B,10X,8HC(N,N')C//)
106 FORMAT(1H0, 2X,5HE/KEV,3X,7HSIGMA/B,10X,8HC(N,A)BE//)
107 FORMAT(1H0, 2X,5HE/KEV,3X,7HSIGMA/B,10X,7HC(N,3A)///)
108 FORMAT(1H1,1X,5HE/KEV,3X,5HPLITE,4X,5HCLITE,4X,5HALITE///)
109 FORMAT(I6,3I9)
104 FORMAT(10X,I6,5E12.4)
CALL SSWTCH(12,N12)
GO TO (8,9),N12

```



```

9 WRITE ( DD1 ,114 )
  WRITE ( DD1,101)(ECN(K),SCB(K),K=1,KCN)
  WRITE ( DD1,105 )
  WRITE ( DD1,101 ) (ECIN(K),SCIB(K),K=1,KCIN)
  WRITE ( DD1,106 )
  WRITE ( DD1,101 ) (ECNA(K),SCNB(K),K=1,KCNA)
  WRITE ( DD1,107 )
  WRITE ( DD1,101 ) (EC3A(K),SC3B(K),K=1,KC3A)
  WRITE ( DD1,108 )
  WRITE ( DD1,109 ) (ELIT (K),PLIT (K),CLIT (K),ALIT (K),K=1,KLIT)
  WRITE(DD1,115)
  WRITE(DD1,104)(EOMEGA(K),OMEGU(K),OMEG1(K),OMEG2(K),OMEG3(K),
10MEG4(K),K=1,KOMEGA)
8 RETURN
END

```

```

SUBROUTINE INPUT
C
C      INPUT OF PARAMETER SETS
C
COMMON /DENS1/ HNH,HNC,SATR,SASI
COMMON /ELCUT/ ECUT,CUTL,NEFF,EFF
COMMON /HIST/ NSAMPL,NHIST,NX,KOLM
COMMON /INPUT/ ID,ØD1,ØD2,ID2
COMMON /PARA/ RT,HT,RC,HC,RT2,RC2
COMMON /REFL/ REF
COMMON /STEN/ NEO,EØ( 50 )
COMMON /START/ EST,RN
COMMON /THRESH/ ETR,TTR

C      INTEGER ØD1,ØD2
C      INTEGER EØ,EST

      ID=ID2
      READ (ID,100 ) RT,HT,RC,HC,RN
      READ ( ID,101 ) HNH,HNC
      READ ( ID,102 ) NSAMPL
      READ (ID,103) KOLM
      READ (ID,103 ) NEO
      READ (ID,104 ) (EØ(K),K = 1,NEØ)
      READ(ID,105) ETR,TTR,ECUT
      READ (ID,106)REF
100 FORMAT (SF6.2 )
101 FORMAT ( 2E12.6)
102 FORMAT (I8)
103 FORMAT (I3)
104 FORMAT (I5)
105 FORMAT (3F10.4)
106 FORMAT(F5.2)
      CALL SSWTCH(12,N12)
      GO TO (8,9),N12
      9 WRITE ( ØD1,110 )
110 FORMAT(1H1,10HPARAMETERS///)
      WRITE (ØD1,100 ) RT,HT,RC,HC,RN
      WRITE (ØD1,101 ) HNH,HNC
      WRITE ( ØD1,102 ) NSAMPL
      WRITE (ØD1,103) KOLM
      WRITE (ØD1,103 )NEØ
      WRITE (ØD1,104) (EØ(K),K=1,NEØ)
      WRITE (ØD1,105) ETR,TTR,ECUT
      WRITE(ØD1,106)REF
      8 RETURN
      END

```

SUBROUTINE EVACR0

```

C
C      EVALUATION OF TOTAL AND PARTIAL CROSS SECTIONS
C
COMMON /CR0S/ KCN,ECN(250),SCN(250),KCIN,ECIN(20),SCIN(20),KCNA,
1ECNA(10),SCNA(10),KC3A,EC3A(5),SC3A(5)
COMMON /DENS1/ MNH,MNC,SATR,SAS1
COMMON /ENER/ E,EREC,EE,EA1,EA2
COMMON /REG1/ I,L
COMMON /SORTA/ I1,I2,R
COMMON /NQS/ ST0T,S1,S2,S3,S4,S5

C
INTEGER E,EREC
INTEGER EQ1,EQ2,EQ3
INTEGER EA1,EA2
INTEGER ECN,ECIN,ECNA,EC3A,EOmega,ELIT,PLIT,CLIT,ALIT

C
DATA EQ1,EQ2,EQ3 /4845,8430,8365/
DATA BT1,BT2 / 0.2395E-03,0.0033E-06 /
DATA BS1,BS2 /7.5644E-03,0.1534E-06 /

C
E2 = EE*EE
D1 = BT2*E2 + BT1*EE + 1.0
D2 = BS2*E2 + BS1*EE + 1.0
S1 = SATR / D1 + SAS1 / D2
I = 1
CALL SORT
S2 = SCN ( I1 ) + R*( SCN(I2) - SCN(I1) )
IF (E ,LE, EQ1) GO TO 1
I = 2
CALL SORT
S3 = SCIN (I1) + R*(SCIN(I2) - SCIN(I1) )
S2 = S2 - S3
IF (E ,LE, EQ2) GO TO 2
I = 3
CALL SORT
S4 = SCNA(I1) + R*( SCNA(I2) - SCNA(I1) )
S2 = S2 + S4
IF (E ,LE, EQ3) GO TO 3
I = 4
CALL SORT
S5 = SC3A (I1) + R*(SC3A(I2) - SC3A(I1) )
S2 = S2 + S5
GO TO 4
1 S3 = 0.0
2 S4 = 0.0
3 S5 = 0.0
4 ST0T = S1 + S2 + S3 + S4 + S5
RETURN
END

```

SUBROUTINE SORT

C
C
C
CFIND CLOSEST HIGHER AND LOWER ENERGY GROUP, AND
DETERMINE INTERPOLATION FACTOR

```

COMMON /CRBS/ KCN,ECN(250),SCN(250),KCIN,ECIN(20),SCIN(20),KCNA,
1ECNA(10),SCNA(10),KC3A,EC3A(5),SC3A(5)
COMMON /COM/ K0MEGA,E0MEGA(55),0MEG1(55),0MEG2(55),0MEG3(55),0MEG4
1(55),0MEG0(55)
COMMON /ENER/ E,EREC,EE,EA1,EA2
COMMON /LITE/ KLIT,ELIT(125),PLIT(125),CLIT(125),ALIT(125)
COMMON /REG1/ I,L
COMMON /SORTA/ I1,I2,R

```

C

```

INTEGER ECN,ECIN,ECNA,EC3A,E0MEGA,ELIT,PLIT,CLIT,ALIT
INTEGER EA1,EA2
INTEGER E,EREC
INTEGER E1,EM
INTEGER EW

```

C

```

KU = 1
EW=E
QE=EE
GO TO ( 11,12,13,14,15,16 ),I
11 E1 = ECN(1)
EM = ECN(KCN)
KM = KCN
GO TO 17
12 E1 = ECIN(1)
EM = ECIN(KCIN)
KM = KCIN
GO TO 17
13 E1 = ECNA(1)
EM = ECNA(KCNA)
KM = KCNA
GO TO 17
14 E1 = EC3A(1)
EM = EC3A(KC3A)
KM = KC3A
GO TO 17
15 E1 = E0MEGA(1)
EM = E0MEGA(K0MEGA)
KM = K0MEGA
GO TO 17
16 E1 = ELIT(1)
EM = ELIT(KELIT)
KM = KELIT
EW=EREC
QE=EREC
17 IF(EW,LT, E1 ,OR, EW,GT, EM ) GO TO 5
4 KH = (KM - KU ) / 2
M = 1
KT = KU + KH
GO TO ( 21,22,23,24,25,26 ),I
21 NER = ECN (KT)
GO TO 27
22 NER = ECIN (KT)
GO TO 27
23 NER = ECNA (KT)
GO TO 27
24 NER = EC3A (KT)
GO TO 27
25 NER = E0MEGA (KT)

```

```

      GO TO 27
26  NER = ELIT (KT)
27  IF ( KM,LT, 1 ) M = 2
      IF ( NER = EW) 1,2,3
      1  KU = KT
      GO TO ( 4,5), M
      2  I1 = KT
      I2 = XT
      R = 0.0
      RETURN
      3  KM = KT
      GO TO ( 4,5), M
      5  I1 = KU
      I2 = KM
      GO TO ( 31,32,33,34,35,36 ), I
31  ER1 = ECN (I1)
      ER2 = ECN (I2)
      GO TO 37
32  ER1 = ECIN (I1)
      ER2 = ECIN (I2)
      GO TO 37
33  ER1 = ECNA (I1)
      ER2 = ECNA (I2)
      GO TO 37
34  ER1 = EC3A (I1)
      ER2 = EC3A (I2)
      GO TO 37
35  ER1 = EOMEGA (I1)
      ER2 = EOMEGA (I2)
      GO TO 37
36  ER1 = ELIT (I1)
      ER2 = ELIT (I2)
37  R = (OE-ER1) / (ER2-ER1)
      RETURN
      END

```

SUBROUTINE SOURCE

```

C
C      SETTING AND SELECTION OF START COORDINATES
C
COMMON /ENER/ E,EREC,EE,EA1,EA2
COMMON /PARA/ RT,HT,RC,HC,RT2,RC2
COMMON /POSI/ X,Y,Z,U,V,W,AL
COMMON /START/ EST,RN

C
INTEGER E,EREC,EST
INTEGER EA1,EA2

C
Z = HC
U = 0.0
V = 0.0
W = 1.0
E = EST
EE=EST
1 R1 = RANF ( -1 )
  R2 = RANF ( -1 )
  R1 = 2.0*R1 - 1.0
  R2 = 2.0*R2 - 1.0
  RSQ = R1*R1 + R2*R2
  IF ( RSQ .GT. 1.0 ) GO TO 1
  X = RN*R2
  Y = RN*R1
  RETURN
END

```

```

SUBROUTINE ZONE
C
C      FIND COLLISION ZONE,
C
COMMON /PARA/ RT,HT,RC,HC,RT2,RC2
COMMON /PRIN/ XP,YP,ZP,RP2
COMMON /REG1/ I,L
C
IF ( RP2 .GT. HT2 ) GO TO 3
IF ( ZP .LT. 0.0 .OR. ZP .GT. HT ) GO TO 3
IF ( ZP .LT. HC ) GO TO 2
1 * 1
RETURN
2 1 * 2
RETURN
3 1 * 3
RETURN
END

```

```

SUBROUTINE CHANX
C
C      CHECK FOR CHANNEL XING,EVALUATE PATH IN CHANNEL AND
C      UPDATE AL,XP,YP,AND ZP
C
COMMON /INDIC/ KANCR,NZONE
COMMON /PARA/ RT,HT,RC,HC,RT2,RC2
COMMON /POSI/ X,Y,Z,U,V,W,AL
COMMON /PRIN/ XP,YP,ZP,RP2
C
  A = U*U + V*V
  IF ( A .EQ. 0.0 ) GO TO 5
  B = U*X + V*Y
  C = X*X + Y*Y
  B2 = B*B
  D = B2 - A*( C - RC2 )
  IF ( D .LE. 0.0 ) RETURN
  T0 = SQRT ( D )
  T1 = ( -B + T0 ) / A
  T2 = ( -B - T0 ) / A
  Z1 = Z + W*T1
  Z2 = Z + W*T2
  IF (Z1 .GT. HC) GO TO 1
  IF (Z2 .GT. HC) GO TO 2
  DT=2.0*T0/A
  GO TO 3
1 IF ( Z2 .GT. HC ) RETURN
  TE = (HC - Z) / W
  DT = ABS (T2 - TE)
  GO TO 3
2 TE = (HC - Z) / W
  DT = ABS (T1 - TE)
3 AL = AL + DT
  KANCR = 1
4 XP = X + U*AL
  YP = Y + V*AL
  ZP = Z + W*AL
  RP2 = XP*XP + YP*YP
  RETURN
5 IF(W .GT. 0.0) RETURN
  C=X*X+Y*Y
  IF(C .GT. RC2) RETURN
  AL = AL+HC
  GO TO 4
END

```



```

SUBROUTINE TYPE
C
C      SELECT TYPE OF COLLISION
C
COMMON /REGI/ I,L
COMMON /WQS/ STOT,S1,S2,S3,S4,S5
C
R = RANF ( -1 )
R = R*STOT
IF ( R .GT. S1 ) GO TO 2
L = 1
RETURN
2 S2 = S2 + S1
IF ( R .GT. S2 ) GO TO 3
L = 2
RETURN
3 S3 = S2 + S3
IF ( R .GT. S3 ) GO TO 4
L = 3
RETURN
4 S4 = S3 + S4
IF ( R .GT. S4 ) GO TO 5
L = 4
RETURN
5 S5 = S4 + S5
IF ( R .GT. S5 ) GO TO 6
L = 5
RETURN
6 L = 0
RETURN
END

```

SUBROUTINE LEADR

```

C
C      REFLECTION FROM LEAD SHIELD
C
COMMON /ENER/ E,EREC,EE,EA1,EA2
COMMON /PARA/ RT,HT,RC,HC,RT2,RC2
COMMON /POS1/ X,Y,Z,U,V,W,AL
COMMON /REFL/ REF
COMMON /REG1/ I,L
COMMON /TIME/ T

C
INTEGER EA1,EA2
INTEGER E,EREC

C
I = 0
L = 0
R = RANF ( -1 )
IF ( R ,GT, REF ) RETURN
L = 1
AL = AL + 5.0
PP = U*U + V*V
IF (PP ,EQ, 0.0) GO TO 1
P = (U*X + V*Y)/PP
Q = (X*X + Y*Y - RT2)/PP
P2 = P*P - Q
TQ = SQRT (P2)
ZQ = Z + W*TQ
IF(ZQ ,GT, HT) GO TO 2
IF(ZQ ,LT, 0.0) GO TO 3
X = X + U*TQ
Y = Y + V*TQ
GO TO 4
1 Z = HT
GO TO 4
2 TQ = (HT-Z)/W
X = X + U*TQ
Y = Y + V*TQ
GO TO 1
3 TQ = -Z/W
GO TO 5
4 U = -U
V = -V
W = -W
T1=23.151*AL/SQRT(EE)
T = T + T1
EE = 0.5*EE
E = EE
RETURN
END

```

SUBROUTINE CARBON

```

C
C      SELECT SCATTERING ANGLE, EVALUATE NEW NEUTRON ENERGY
C      AND CARBON RECOIL ENERGY
C
      COMMON /CJM/ K0MEGA, E0MEGA(55), 0MEG1(55), 0MEG2(55), 0MEG3(55), 0MEG4
1(55), 0MEG0(55)
      COMMON /COSI/ A, B
      COMMON /ENER/ E, EREC, EE, EA1, EA2
      COMMON /REGI/ I, L
      COMMON /SORTA/ I1, I2, R
C
      INTEGER E0MEGA
      INTEGER E, EREC
      INTEGER EA1, EA2
C
      I = 5
      CALL SORT
1 A = RANF(-1)
  A = 2.0*A - 1.0
  R2 = A*A
  R7= RANF ( -1 )
  P2 = 1.5*R2 - 0.5
  P3 = 2.5*A*R2 - 1.5*A
  P4 = 4.375*R2*R2-4.75*R2+0.375
  P5 = RANF(-1)
  IF( R5 .GT. R ) GO TO 2
  F2=0MEG0(I1)+0MEG1(I1)*A+0MEG2(I1)*P2+0MEG3(I1)*P3+0MEG4(I1)*P4
  GO TO 4
2 F2=0MEG0(I2)+0MEG1(I2)*A+0MEG2(I2)*P2+0MEG3(I2)*P3+0MEG4(I2)*P4
4 IF (R7.GT. F2 ) GO TO 1
  B = SQRT (1.0 - A*A )
  AA=(A+SQRT(143.*R2))/13.
  EN = EE-AA*AA
  ER = EE - EN
  EREC = ER
  EE = EN
  E = EN
  RETURN
  END

```

```

      SUBROUTINE TRANS
C
C      TRANSFORMATION OF DIRECTION PARAMETERS U,V,W
C
      COMMON /CDS1/ A,B
      COMMON /PDS1/ X,Y,Z,U,V,W,AL
C
1  R1=RANF(-1)
   R2=RANF(-1)
   R1=2.0*R1-1.0
   R11=R1*R1
   R22=R2*R2
   RR= R11+R22
   IF(RR .GE. 1.0) GO TO 1
   C=(R11-R22)/RR
   D=2.0*R1*R2/RR
   IF ( ABS(W) .GT. 0.999995) GO TO 2
   R = SQRT (1.0 - W*W)
   BR = B/R
   CW = C*W
   Q = BR*(CW*U + D*V) + A*U
   V = BR*(CW*V + D*U) + A*V
   U = Q
   W = A*W + B*C*R
   RETURN
2  U = B*C
   V = B*D
   W = A*W
3  RETURN
   END

```

SUBROUTINE CNAL

C
C
C

FOR N,ALPHA AT CARBON

```

COMMON /COSI/ A,B
COMMON /ENER/ E,EREC,EE,EA1,EA2
INTEGER E,EREC,EST
INTEGER EA1,EA2
DATA QC,C1,C2 /3949.8,0.61495,0.04767/
DATA Q / 6200.0 /
R1 = RANF ( *1)
A = 2.0*R1 - 1.0
A2 = A*A
BB=0.1538*A
CC=0.6154-3930.0/EE
CB2=8*SQRT(BB*BB+CC)
EN=EE*CB2*CB2
ER =EE - EN - Q
EA1 = EN
EREC = ER
B = SQRT(1.0 - A2)
RETURN
END

```

```

SUBROUTINE CINEL
C
C   .   FOR INEL. SCATTERING AT CARBON
C
COMMON /COSI/ A,B
COMMON /ENER/ E,EREC,EE,EA1,EA2
C
INTEGER EA1,EA2
INTEGER E,EREC,EST
C
R1 = RANF ( -1 )
A = 2.0*R1 - 1.0
A2 = A*A
CC=0.8461+4090.0/EE
BB=A/13.0
BC=BB*BB*CC
BDB=BB+SQR1(BC)
EN=EE*BDB*BDB
ER=EE-EN+4432.0
E = EN
EE = EN
EREC = ER
B = SQR1 (1.0 - A2 )
RETURN
END

```

```

C
C
C      SUBROUTINE CN3A
          FOR N,3ALPHA AT CARBON

COMMON /ENER/ E,EREC,EE,EA1,EA2
COMMON /C0SI/ A,b
INTEGER E,EREC,EST
INTEGER EA1,EA2
R1 = RANF(-1)
A = 2.0*R1 - 1.0
CC=0.8461-7067.0/EE
BB=A/13.0
BC=BB*BB*CC
BDB=BB*SQRT(BC)
EN=EE*BDB*BDB
EC=EE-EN-7655.0
E = EN
EE = EN
B = SQRT(1.0-AZ)
R2=RANF(-1)
R2=2.0*R2-1.0
ER=193.0+0.3336*EC+16.1*R2*SQRT(EC)
EREC=ER
EBE=EC+289.0-ER
R3=RANF(-1)
R3=2.0*R3-1.0
EAA1=51.0+0.4999*EBE+10.0*R3*SQRT(EBE)
EA1=EAA1
EAA2=EBE+102.0-EAA1
EA2=EAA2
RETURN
END

```

```

SUBROUTINE LIGHT
C
C      OBTAIN LIGHT FROM TABLE USING RECOIL ENERGY
C
COMMON /ENER/ E,EREC,EE,EA1,EA2
COMMON /LIGHT/ TOLI,RELI,TNORM,RNORM
COMMON /LITE/ KLIT,ELIT(125),PLIT(125),CLIT(125),ALIT(125)
COMMON /MULTI/ RM(4),HM(4),ALIH
COMMON /POSI/ X,Y,Z,U,V,W,AL
COMMON /PAHA/ RT,HT,RC,HC,RT2,RC2
COMMON /REGI/ I,L
COMMON /SORTA/ I1,I2,R

INTEGER ECN,ECIN,ECNA,EC3A,EOMEGA,ELIT,PLIT,CLIT,ALIT
INTEGER E,EREC
INTEGER EA1,EA2

C
  ALIG = 0.0
  I=6
  CALL SORT
  GO TO ( 1,2,2,4,5),L
1  ALI=PLIT(I1)
  BLI = PLIT(I2)
3  ALIG=ALIG+ALI+R*(BLI-ALI)
  TOLI=TOLI+ALIG
  RELI=RELI+0.25*ALIG
  DO 10 K=1,4
    D22=Y*Y+(RM(K)+X)**2
    D2=SQRT(D)
    D2=ABS(2-HM(K))
    AL22=D2*D2+D22
    AL1=SQRT(AL22)
    IF(AL1 .GT. 0.01) GO TO 11
    BM=0.5
  GO TO 12
11 BM=0.0*ABS(RM(K)+X)/(AL22*AL1)
  IF(BM .GT. 0.5) BM=0.5
12 BM=BM*EXP (-AL1/ALIH)
10 RELI=RELI+ALIG*BM
  RETURN
2  ALI=CLIT(I1)
  BLI=CLIT(I2)
  GO TO 3
4  ALI=CLIT(I1)
  BLI=CLIT(I2)
6  ALIG = ALIG+ALI+R*(BLI-ALI)
  EREC = EA1
  CALL SORT
  ALI=ALIT(I1)
  BLI=ALIT(I2)
  GO TO 3
5  ALI = ALIT(I1)
  BLI = ALIT(I2)
  ALIG=ALIG+ALI+R*(BLI-ALI)
  EREC =EA2
  CALL SORT
  ALI =ALIT(I1)
  BLI=ALIT(I2)
  GO TO 6
END

```


SUBROUTINE BANKER

C
C
C

TAKES CARE OF ACCOUNTING

COMMON /BANK1/ L0SE,L0ST,L0SG,LEDC,LEAD,K0LCN0,KTR08,KT0,NZ1,NZ2
 COMMON /BANK2/ LITET(128),LITER(128),LEAK(128)
 COMMON /BANK3/ K0LC,K0LH,K0LL(100),K0LCC(100),K0LHH(100),NRES(100)
 COMMON /ELCUT/ ECUT,CUTL,NEFF,EFF
 COMMON /INDIC/ KANCR,NZONE
 COMMON /KANAL/ KANC,KANL
 COMMON /LIGHT/ T0LI,RELI,TN0RM,RN0RM
 COMMON /MATRX/ MATR(25,10)
 COMMON /TIME/ T

C

J1=K0LH+1
 J2=K0LC+1
 IF (J1 .GT. 25) J1=25
 IF (J2 .GT. 10) J2=10
 MATR(J1,J2)=MATR(J1,J2)+1
 IF (K0LC .EQ. 0) GO TO 2
 IF (K0LC .GT. 100) K0LC = 100
 K0LCC(K0LC)=K0LCC(K0LC) + 1
 2 IF (K0LH .EQ. 0) GO TO 3
 IF (K0LH .GT. 100) K0LH=100
 K0LHH(K0LH)=K0LHH(K0LH) + 2
 3 LEDC=LEDC + LEAD
 KANC = KANC + KANCR
 F = T0LI*TN0RM
 IF (F .GT. CUTL) NEFF =NEFF + 1
 N = F
 IF (N .GT. 127) N = 127
 LITET(N+1) = LITET(N+1) + 1
 F = RELI*RN0RM
 N = F
 IF (N .GT. 127) N = 127
 LITER(N+1) = LITER(N+1) + 1
 6 IF (KT0 .EQ. 0) GO TO 4
 IF (KT0 .GT. 100)KT0 = 100
 K0LL(KT0)=K0LL(KT0) + 1
 4 N = T
 N = N+ 1
 IF (N .GT. 99) N = 99
 NRES(N) = NRES(N) +1
 RETURN
 END

SUBROUTINE OUTPUT

OUTPUT PARAMETERS AND RESULTS

```

COMMON /BANK1/ L0SE,L0ST,L0SG,LEDC,LEAD,K0LCN0,KTR0B,KT0,NZ1,NZ2
COMMON /BANK2/ LITET(120),LITER(120),LEAK(120)
COMMON /BANK3/ K0LC,K0LM,K0LL(100),K0LCC(100),K0LHH(100),NRES(100)
COMMON /DENS1/ HNH,HNC,SATR,SAS1
COMMON /ELCUT/ ECUT,CUTL,NEFF,EFF
COMMON /HIST/ NSAMPL,NHIST,NX,K0LM
COMMON /INOUT/ ID,0D1,0D2,ID2
COMMON /KANAL/ KANC,KANL
COMMON /MATRX/ MATR(25,10)
COMMON /PARA/ RT,HT,RC,HC,RT2,RC2
COMMON /REFL/ REF
COMMON /RESOLU/ NRSU(100)
COMMON /START/ EST,RN
COMMON /THRESH/ ETR,TTR

```

```

INTEGER 0D1,0D2
INTEGER EST

```

PARAMETER PART

```

WRITE ( 0D1,1)
WRITE ( 0D1,100 ) NX
WRITE ( 0D1, 137 )
WRITE ( 0D1,115 ) RT
WRITE ( 0D1,116 ) HT
WRITE ( 0D1,117 ) RC
WRITE ( 0D1,118 ) HC
WRITE ( 0D1,119 ) RN
WRITE ( 0D1,125 ) ETR,TTR
WRITE ( 0D1, 140 ) ECUT
WRITE ( 0D1,112 ) HNH
WRITE ( 0D1,113 ) HNC
WRITE ( 0D1,114 ) REF
WRITE ( 0D1,101 ) EST
WRITE ( 0D1,102 ) NSAMPL
WRITE ( 0D1, 135 ) NHIST
WRITE ( 0D1,126 ) K0LM

```

RESULT PART

```

WRITE ( 0D1, 136 )
WRITE ( 0D1,103 ) L0SE
WRITE ( 0D1,104 ) L0ST
WRITE ( 0D1,105 ) L0SG
WRITE ( 0D1,106 ) LEDC
WRITE ( 0D1,107 ) KANC
KT0H = 0
KT0C = 0
DO 2 K=1,100
KT0C=KT0C+K*K0LCC(K)
2 KT0H=KT0H+K*K0LHH(K)
WRITE ( 0D1,108 ) KT0H
WRITE ( 0D1,109 ) KT0C
WRITE ( 0D1,129 ) NZ1
WRITE ( 0D1,130 ) NZ2
WRITE ( 0D1,110 ) KTR0B
WRITE ( 0D1,120 ) K0LCN0
KAV = 0
DO 3 K=1,100

```

```

3 KAV=KAV+K*KOLL(K)
  IF ( NHIST ,ED. 0 ) GO TO 999
  KOLAY = KAV/NHIST
  WRITE ( 0D1,111 ) KOLAY
  QEF = NHIST
  REQ = NEFF
  EFF = REQ/QEF
  WRITE ( 0D1,144 ) EFF
  CALL SSWTCH(14,N14)
  GO TO (999,17),N14
17 WRITE(0D1,246)
  WRITE(0D1,248)
  DO 247 K=1,25
    M=K+1
247 WRITE(0D1,249)M,(MATR(K,J),J=1,10)
246 FORMAT(1H1,16HC0LL[SI0N MATR]X//)
248 FORMAT(3X,5HH/C ,2X,1H0,5X,1H1,5X,1H2,5X,1H3,5X,1H4,5X,1H5,5X,
1 1H6,5X,1H7,5X,1H8,5X,1H9//)
249 FORMAT(15,10I6)
999 CALL SSWTCH(11,KTES)
  IF (KTES ,EQ. 1 ) RETURN
  WRITE (0D1,121)
  DO 23 K= 1,100
23 WRITE ( 0D1,124 ) K,LITET(K),LITER(K),LEAK(K),KOLL(K),KOLCC(K),
1 KOLHH(K),NRES(K),NRSU(K)
  DO 22 K = 101,128
22 WRITE ( 0D1,122 ) K,LITET(K),LITER(K),LEAK(K)
1 FORMAT(1H1,20X,11HCARLO BLACK//)
100 FORMAT ( 7HCASE NO,5X,13/// )
101 FORMAT ( 16HSTART ENERGY/KEV,16X,17 )
102 FORMAT ( 19HNUMBER OF HISTORIES,13X,17 )
103 FORMAT ( 26HNUMBER OF LOSSES BELOW ETR,6X,17 )
104 FORMAT ( 26HNUMBER OF LOSSES BELOW TTR,6X,17 )
105 FORMAT ( 7HLEAKAGE,25X,17 )
106 FORMAT ( 22HNUMBER OF LEAD RETURNS,10X,17 )
107 FORMAT ( 23HNUMBER OF CHANNEL XINGS,9X,17 )
108 FORMAT ( 22HTOTAL COLLISIONS ON H,10X,17 )
109 FORMAT ( 22HTOTAL COLLISIONS ON C,10X,17 )
110 FORMAT ( 27HNUMBER OF TROUBLE HISTORIES,5X,17 )
111 FORMAT ( 31HAVERAGE COLLISIONS PER NEUTRON,1X,17/// )
112 FORMAT ( 16HHYDROGEN DENSITY,9X,E12.6 )
113 FORMAT ( 14HCARBON DENSITY,11X,E12.6 )
114 FORMAT ( 22HLEAD REFLECTION FACTOR,3X,E12.6/// )
115 FORMAT( 15HDETECTOR RADIUS,10X,E12.6 )
116 FORMAT( 15HDETECTOR HEIGHT,10X,E12.6 )
117 FORMAT( 14HCHANNEL RADIUS,11X,E12.6 )
118 FORMAT( 14HCHANNEL LENGTH,11X,E12.6 )
119 FORMAT( 19HNEUTRON BEAM RADIUS,6X,E12.6 )
120 FORMAT(22HNNELASTIC COLLISSI0NS,10X,17)
121 FORMAT(1H1,2X,2HKX,7X,4HLITE,4X,8HRED,LITE,2X,4HLEAK,5X,4HC0L,,
1 3X,5HC0L,C,3X,5HC0L,H,5X,3HRES,5X,4HTRES//)
122 FORMAT(15,3X,4I8)
124 FORMAT(15,3X,8I8)
125 FORMAT(11HETR AND TTR,14X,2E12.6 )
126 FORMAT(22HNUMB. OF C0L. F0LL0WED,10X,17///)
129 FORMAT (28HT0T. NUMB. OF C0L. IN ZONE 1,4X,17)
130 FORMAT (28HT0T. NUMB. OF C0L. IN ZONE 2,4X,17)
135 FORMAT(28HNUMBER OF HISTORIES F0LL0WED,4X,17)
136 FORMAT(15X,7HRESULTS//)
137 FORMAT(15X,10HPARAMETERS//)
140 FORMAT(22HCUT-OFF FOR EFFICIENCY,3X,E12.6)
144 FORMAT(10HEFFICIENCY,10X,E12.6///)
  RETURN
  END

```

Cross-section Tables

		C(N,MC			
E/KEV	SIGMA/B	E/KEV	SIGMA/B	E/KEV	SIGMA/B
0	.492400E 01	3019	.119900E 01	6239	.157500E 01
0	.475300E 01	3029	.115000E 01	6259	.207500E 01
99	.439800E 01	3039	.116100E 01	6279	.262500E 01
199	.408900E 01	3099	.145000E 01	6299	.255000E 01
299	.381600E 01	3199	.188800E 01	6319	.190000E 01
399	.357300E 01	3299	.227500E 01	6339	.155000E 01
500	.335600E 01	3399	.257200E 01	6349	.145000E 01
599	.315900E 01	3439	.264700E 01	6359	.136000E 01
699	.298200E 01	3479	.269200E 01	6379	.122000E 01
799	.282000E 01	3519	.270600E 01	6399	.112500E 01
899	.267200E 01	3559	.269200E 01	6500	.102500E 01
1000	.253700E 01	3599	.265500E 01	6539	.925000E 00
1099	.241300E 01	3669	.254800E 01	6579	.640000E 00
1199	.229800E 01	3799	.228600E 01	6599	.720000E 00
1299	.219300E 01	3899	.208100E 01	6639	.800000E 00
1399	.209500E 01	4000	.189400E 01	6699	.850000E 00
1500	.200500E 01	4099	.175400E 01	6739	.850000E 00
1599	.192200E 01	4139	.175000E 01	6899	.770000E 00
1699	.184600E 01	4159	.177900E 01	7000	.745000E 00
1799	.177500E 01	4179	.184200E 01	7099	.735000E 00
1899	.171000E 01	4199	.194600E 01	7139	.750000E 00
2000	.164700E 01	4239	.219900E 01	7179	.815000E 00
2039	.162600E 01	4259	.226000E 01	7199	.870000E 00
2059	.166900E 01	4279	.225200E 01	7239	.102500E 01
2069	.205200E 01	4299	.219800E 01	7259	.113000E 01
2071	.241000E 01	4349	.202000E 01	7279	.132500E 01
2073	.320800E 01	4399	.187400E 01	7299	.152500E 01
2075	.487000E 01	4449	.176800E 01	7319	.167000E 01
2076	.576300E 01	4500	.164000E 01	7339	.172000E 01
2077	.599500E 01	4649	.145000E 01	7359	.174000E 01
2078	.542000E 01	4849	.126800E 01	7379	.175000E 01
2079	.456000E 01	4899	.118200E 01	7399	.175000E 01
2081	.327600E 01	4919	.120600E 01	7500	.172000E 01
2083	.262900E 01	4933	.137500E 01	7599	.165000E 01
2085	.229500E 01	4935	.241400E 01	7639	.168000E 01
2087	.210500E 01	4936	.247700E 01	7659	.182000E 01
2089	.198800E 01	4936	.231400E 01	7679	.192000E 01
2099	.176200E 01	4937	.197500E 01	7699	.212500E 01
2109	.169500E 01	4939	.165700E 01	7719	.224000E 01
2119	.166300E 01	4941	.153900E 01	7739	.232000E 01
2139	.163100E 01	4943	.148200E 01	7759	.224000E 01
2199	.158600E 01	4947	.142700E 01	7779	.214000E 01
2299	.154700E 01	4959	.131700E 01	7799	.206500E 01
2339	.153600E 01	4979	.126200E 01	7859	.187000E 01
2399	.152500E 01	5000	.124300E 01	7959	.181000E 01
2500	.152100E 01	5199	.111000E 01	8000	.182000E 01
2599	.154400E 01	5299	.108000E 01	8039	.185000E 01
2699	.161000E 01	5319	.108500E 01	8079	.182000E 01
2799	.176700E 01	5339	.124000E 01	8119	.171000E 01
2849	.192600E 01	5359	.177000E 01	8199	.135000E 01
2899	.223400E 01	5379	.165000E 01	8279	.118000E 01
2909	.233200E 01	5399	.131000E 01	8359	.111000E 01
2919	.245100E 01	5419	.122000E 01	8399	.118500E 01
2929	.259600E 01	5459	.112500E 01	8439	.107000E 01
2939	.277000E 01	5500	.108500E 01	8479	.106000E 01
2949	.296900E 01	5599	.106000E 01	8799	.103000E 01
2959	.315800E 01	5699	.105000E 01	9000	.106500E 01
2964	.321900E 01	5799	.106000E 01	9119	.126000E 01
2969	.322900E 01	6000	.108000E 01	9199	.131000E 01
2974	.316000E 01	6099	.111500E 01	9399	.126500E 01
2979	.299300E 01	6159	.116000E 01	9599	.120000E 01
2989	.240100E 01	6199	.123500E 01	9799	.119000E 01
3000	.177200E 01	6219	.137500E 01	10000	.116500E 01
3009	.137400E 01				

C(N,N')C

E/KEY	SIGMA/B	E/KEY	SIGMA/B
4910	.000000E 00	7330	.270000E 00
5160	.400000E-01	7700	.290000E 00
5430	.600000E-01	8100	.370000E 00
5700	.900000E-01	8510	.470000E 00
6000	.150000E 00	8950	.520000E 00
6300	.240000E 00	9000	.430000E 00
6630	.220000E 00	10000	.480000E 00
6970	.170000E 00		

C(N,A)BE

E/KEY	SIGMA/B	E/KEY	SIGMA/B
7330	.000000E 00	8200	.700000E-01
7400	.400000E-01	8300	.600000E-01
7500	.500000E-01	8510	.500000E-01
7700	.600000E-01	9000	.300000E-01
8000	.800000E-01	10000	.300000E-01

C(N,3A)

E/KEY	SIGMA/B	E/KEY	SIGMA/B
8100	.000000E 00	9000	.100000E-01
8510	.000000E 00	10000	.400000E-01

Light Tables

E/KEY	PLITE	CLITE	ALITE	E/KEY	PLITE	CLITE	ALITE
0	0	0	0	320	26800	2650	5270
1	350	22	30	340	29000	2793	5640
10	1030	226	285	360	31300	2926	6010
12	1150	250	321	380	33800	3056	6380
14	1270	272	355	400	36500	3191	6750
16	1400	294	388	440	42200	3433	7510
17	1460	305	404	480	48300	3676	8300
18	1520	316	420	520	54500	3919	9120
19	1580	327	426	560	60900	4140	9960
20	1640	338	452	600	67800	4361	10800
22	1760	360	484	660	78600	4692	12100
24	1880	381	516	720	91000	5023	13500
26	2000	402	548	780	104000	5254	15000
28	2120	422	580	840	117500	5686	16560
30	2240	443	610	920	136700	6127	18760
32	2360	462	640	1000	156200	6569	21000
34	2480	482	670	1100	182500	7093	24000
36	2600	500	700	1200	209500	7604	27000
38	2720	519	730	1300	238500	8128	30200
40	2850	537	758	1400	269000	8639	33700
44	3090	571	814	1500	299500	9163	36900
48	3340	607	870	1600	332000	9660	40400
52	3570	640	926	1700	366000	10157	44100
56	3820	673	982	1800	400000	10667	48000
60	4070	707	1040	1900	436000	11150	52000
66	4460	756	1130	2000	472500	11647	56200
72	4840	806	1220	2200	548000	12641	65200
78	5220	856	1310	2400	625000	13634	73000
84	5620	905	1400	2600	703000	14628	85700
92	6150	972	1520	2800	783000	15622	97500
100	6710	1038	1640	3000	866000	16615	110000
110	7400	1115	1790	3200	952000	17664	123000
120	8120	1192	1940	3400	1042000	18713	136500
130	8860	1270	2090	3600	1135000	19762	150500
140	9620	1347	2240	3800	1230000	20810	165500
150	10400	1424	2400	4000	1327000	21859	181500
160	11220	1501	2560	4400	1521000	23957	216500
170	12070	1573	2720	4800	1718000	26054	255500
180	12920	1643	2880	5200	1915000	28152	300000
190	13770	1717	3040	5600	2112000	30250	350500
200	14650	1788	3200	6000	2310000	32347	407000
220	16450	1932	3520	7200	2630000	35549	500000
240	18380	2076	3860	7800	2950000	38750	607000
260	20350	2219	4200	8400	3280000	41952	727000
280	22450	2363	4540	9200	3620000	45154	870000
300	24600	2506	4900	10000	4080000	49570	1090000

Normalized Legendre Coefficients of Carbon

E/KEY	0M0	0M1	0M2	0M3	0M4
0	.8632E 00	.1597E 00	-.1937E-01	-.3521E-02	.0000E 00
99	.8632E 00	.1597E 00	-.1937E-01	-.3521E-02	.0000E 00
119	.8511E 00	.1560E 00	.2919E-04	-.7169E-02	.0000E 00
156	.8231E 00	.1617E 00	.4450E-02	.1080E-01	.0000E 00
206	.7999E 00	.1911E 00	.4164E-02	.4779E-02	.0000E 00
256	.7685E 00	.2087E 00	.9376E-02	.1340E-01	.0000E 00
306	.7932E 00	.2233E 00	-.1141E-01	-.5062E-02	.0000E 00
329	.7823E 00	.2189E 00	.2940E-02	-.4181E-02	.0000E 00
356	.7751E 00	.2144E 00	.1711E-01	-.6559E-02	.0000E 00
406	.7555E 00	.2234E 00	.2065E-01	.5077E-03	.0000E 00
429	.7435E 00	.2223E 00	.1714E-01	.1711E-01	.0000E 00
431	.7717E 00	.2277E 00	-.4903E-02	.5476E-02	.0000E 00
456	.7652E 00	.2243E 00	-.5413E-03	.1105E-01	.0000E 00
506	.7321E 00	.2258E 00	.2152E-01	.2056E-01	.0000E 00
529	.7163E 00	.2436E 00	.3062E-01	.9477E-02	.0000E 00
629	.7060E 00	.2517E 00	.3088E-01	.1138E-01	.0000E 00
729	.6911E 00	.2531E 00	.2995E-01	.2581E-01	.0000E 00
829	.6747E 00	.2522E 00	.4480E-01	.2634E-01	.0000E 00
929	.6573E 00	.2610E 00	.5286E-01	.2883E-01	.0000E 00
1039	.6400E 00	.2512E 00	.5781E-01	.5094E-01	.0000E 00
1139	.6599E 00	.2594E 00	.6154E-01	.1918E-01	.0000E 00
1239	.6522E 00	.2558E 00	.6241E-01	.2959E-01	.0000E 00
1339	.6542E 00	.2489E 00	.6241E-01	.3449E-01	.0000E 00
1439	.6485E 00	.2475E 00	.7439E-01	.2959E-01	.0000E 00
1539	.6567E 00	.2364E 00	.7210E-01	.3484E-01	.0000E 00
1649	.6474E 00	.2333E 00	.8649E-01	.3281E-01	.0000E 00
1750	.6393E 00	.2221E 00	.9737E-01	.4122E-01	.0000E 00
1849	.6481E 00	.2066E 00	.9825E-01	.4706E-01	.0000E 00
1949	.6662E 00	.1909E 00	.1072E 00	.3573E-01	.0000E 00
2250	.5933E 00	.1281E 00	.2142E 00	.6443E-01	.0000E 00
2299	.5848E 00	.1116E 00	.1957E 00	.1079E 00	.0000E 00
2399	.5989E 00	.8139E-01	.2524E 00	.1186E 00	-.5119E-01
2500	.8262E 00	-.2688E-02	.4237E 00	-.2157E-01	-.2256E 00
2599	.7222E 00	-.3099E-01	.4633E 00	.2010E-01	-.1746E 00
2699	.6144E 00	-.3058E-01	.5922E 00	.3846E-01	-.2144E 00
2799	.4434E 00	.4519E-01	.5277E 00	.1095E 00	-.1258E 00
2899	.3377E 00	.3739E-01	.6039E 00	.4208E-01	-.2105E-01
3000	.3785E 00	.1619E 00	.1727E 00	.1615E 00	.1254E 00
3199	.5211E 00	-.6045E-01	.6170E 00	.3908E-01	-.1167E 00
3399	.3593E 00	.8264E-02	.5900E 00	.9810E-01	-.5570E-01
4000	.3218E 00	.1255E-01	.4292E 00	.1097E 00	.1268E 00
4209	.3003E 00	.1700E 00	.3162E 00	.1288E 00	.8468E-01
4699	.3164E 00	.2407E 00	.2034E 00	.1455E 00	.9396E-01
5000	.1952E 00	.2162E 00	.2073E 00	.2069E 00	.1745E 00
5439	.2323E 00	.2277E 00	.1975E 00	.1961E 00	.1464E 00
5579	.2173E 00	.2051E 00	.1877E 00	.2647E 00	.1252E 00
6000	.2391E 00	.1810E 00	.1814E 00	.2912E 00	.1073E 00
6299	.2663E 00	.1182E 00	.1310E 00	.3286E 00	.1558E 00
6439	.2860E 00	.2634E 00	.1753E 00	.2752E 00	.0000E 00
7029	.4014E 00	.3344E 00	.2369E+01	.2071E 00	.3332E-01
7539	.1354E 00	.1531E 00	.3116E 00	.2624E 00	.1375E 00
8039	.1171E 00	.1946E 00	.2902E 00	.2291E 00	.1690E 00
10000	.1171E 00	.1946E 00	.2902E 00	.2291E 00	.1690E 00

Output Example

CARLO BLACK

CASE NO 1

PARAMETERS

DETECTOR RADIUS	,130000E 02	
DETECTOR HEIGHT	,400000E 02	
CHANNEL RADIUS	,126000E 01	
CHANNEL LENGTH	,150000E 02	
NEUTRON BEAM RADIUS	,800000E 00	
ETR AND TTR	,200000E 02	,100000E 03
CUT-OFF FOR EFFICIENCY	,200000E 03	
HYDROGEN DENSITY	,703600E-01	
CARBON DENSITY	,419300E-01	
LEAD REFLECTION FACTOR	,200000E 00	

START ENERGY/KEV	2500
NUMBER OF HISTORIES	10000
NUMBER OF HISTORIES FOLLOWED	10000
NUMB. OF COL. FOLLOWED	50

RESULTS

NUMBER OF LOSSES BELOW ETR	9386
NUMBER OF LOSSES BELOW TTR	0
LEAKAGE	614
NUMBER OF LEAD RETURNS	136
NUMBER OF CHANNEL XINGS	598
TOTAL COLLISIONS ON H	53303
TOTAL COLLISIONS ON C	14576
TOT. NUMB. OF COL. IN ZONE 1	62983
TOT. NUMB. OF COL. IN ZONE 2	4945
NUMBER OF TROUBLE HISTORIES	0
NONELASTIC COLLISIONS	0
AVERAGE COLLISIONS PER NEUTRON	6

EFFICIENCY	,993200E 00
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KX	LITE	RED,LITE	LEAK	CBL.	CBL,C	CBL,H	RES	TRES
1	39	43	18	91	3069	202	70	3026
2	18	23	33	327	2064	552	119	2139
3	14	14	29	660	1133	1119	181	1497
4	12	15	17	1033	496	1686	252	1021
5	9	10	19	1332	232	1932	298	712
6	10	8	17	1453	85	1719	411	506
7	8	7	14	1425	25	1253	461	411
8	5	9	9	1150	8	771	524	285
9	4	11	14	897	3	420	472	132
10	5	15	9	642	2	184	587	71
11	10	15	8	469	0	82	565	45
12	14	10	7	244	0	27	569	42
13	9	11	7	122	0	7	566	15
14	13	13	12	83	0	2	496	10
15	3	23	7	36	0	0	495	6
16	10	19	17	21	0	0	474	6
17	9	29	8	9	0	0	443	5
18	10	23	5	5	0	1	386	1
19	14	37	7	0	0	0	371	0
20	21	36	12	0	0	0	286	1
21	16	36	7	0	0	0	287	0
22	25	42	5	1	0	0	259	1
23	17	45	7	0	0	0	215	0
24	23	42	3	0	0	0	182	0
25	32	58	4	0	0	0	175	0
26	28	56	4	0	0	0	133	0
27	28	63	3	0	0	0	124	0
28	26	81	7	0	0	0	89	0
29	34	83	3	0	0	0	88	0
30	34	101	6	0	0	0	79	0
31	35	96	4	0	0	0	56	0
32	41	108	5	0	0	0	40	0
33	54	112	7	0	0	0	36	0
34	41	119	5	0	0	0	22	0
35	55	115	5	0	0	0	35	0
36	68	130	8	0	0	0	24	0
37	64	145	4	0	0	0	17	0
38	64	172	8	0	0	0	22	0
39	78	176	7	0	0	0	15	0
40	68	173	5	0	0	0	10	0
41	80	190	5	0	0	0	6	0
42	86	219	3	0	0	0	5	0
43	90	184	4	0	0	0	5	0
44	90	185	5	0	0	0	3	0
45	98	233	8	0	0	0	8	0
46	92	256	1	0	0	0	2	0
47	99	249	5	0	0	0	3	0
48	107	246	4	0	0	0	3	0
49	136	228	4	0	0	0	1	0
50	129	234	5	0	0	0	2	0
51	132	233	2	0	0	0	2	0
52	138	230	5	0	0	0	0	0
53	126	248	6	0	0	0	1	0
54	161	192	1	0	0	0	1	0
55	187	217	4	0	0	0	1	0
56	127	233	3	0	0	0	1	0
57	142	224	5	0	0	0	3	0
58	166	221	2	0	0	0	3	0
59	189	198	3	0	0	0	2	0
60	204	190	4	0	0	0	0	0
61	172	197	2	0	0	0	2	0
62	188	176	5	0	0	0	0	0
63	191	131	1	0	0	0	1	0

64	170	173	4	0	0	0	1	0
65	189	137	6	0	0	0	1	0
66	156	142	3	0	0	0	0	0
67	190	99	4	0	0	0	0	0
68	191	127	1	0	0	0	0	0
69	174	125	4	0	0	0	1	0
70	155	97	1	0	0	0	0	0
71	151	124	3	0	0	0	2	0
72	175	91	2	0	0	0	0	0
73	178	100	2	0	0	0	0	0
74	183	103	5	0	0	0	1	0
75	161	95	2	0	0	0	0	0
76	155	83	5	0	0	0	0	0
77	158	91	6	0	0	0	1	0
78	141	92	2	0	0	0	1	0
79	158	96	3	0	0	0	0	0
80	127	82	4	0	0	0	1	0
81	131	77	6	0	0	0	1	0
82	106	85	5	0	0	0	0	0
83	115	79	0	0	0	0	0	0
84	122	79	3	0	0	0	0	0
85	101	80	4	0	0	0	0	0
86	98	62	6	0	0	0	0	0
87	93	60	4	0	0	0	0	0
88	98	93	2	0	0	0	0	0
89	95	74	3	0	0	0	0	0
90	87	68	1	0	0	0	0	0
91	74	87	4	0	0	0	0	0
92	93	54	2	0	0	0	0	0
93	82	6	1	0	0	0	0	0
94	68	0	4	0	0	0	0	0
95	82	0	2	0	0	0	0	0
96	80	0	5	0	0	0	0	0
97	67	0	3	0	0	0	0	0
98	66	0	1	0	0	0	0	0
99	69	0	4	0	0	0	1	0
100	71	0	0	0	0	0	0	0
101	65	0	6	0	0	0	0	0
102	67	0	4	0	0	0	0	0
103	74	0	3	0	0	0	0	0
104	65	0	4	0	0	0	0	0
105	67	0	3	0	0	0	0	0
106	54	0	1	0	0	0	0	0
107	54	0	4	0	0	0	0	0
108	70	0	1	0	0	0	0	0
109	60	0	2	0	0	0	0	0
110	60	0	2	0	0	0	0	0
111	59	0	1	0	0	0	0	0
112	55	0	0	0	0	0	0	0
113	40	0	0	0	0	0	0	0
114	63	0	1	0	0	0	0	0
115	62	0	0	0	0	0	0	0
116	56	0	0	0	0	0	0	0
117	54	0	0	0	0	0	0	0
118	61	0	0	0	0	0	0	0
119	65	0	1	0	0	0	0	0
120	41	0	1	0	0	0	0	0
121	0	0	0	0	0	0	0	0
122	0	0	0	0	0	0	0	0
123	0	0	0	0	0	0	0	0
124	0	0	0	0	0	0	0	0
125	0	1	0	0	0	0	0	0
126	0	0	0	0	0	0	0	0
127	0	0	0	0	0	0	0	0
128	0	0	0	0	0	0	0	0

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