A UNITED STATES DEPARTMENT OF COMMERCE PUBLICATION

NBS TECHNICAL NOTE 499

Multiple Scattering Corrections for the Associated-Particle Neutron Time-of-Flight Technique

U.S. DEPARTMENT OF COMMERCE
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NBS TECHNICAL NOTE 499

ISSUED OCTOBER 1969

Nat. Bur. Stand. (U.S.), Tech. Note 499, 68 pages (Oct. 1969)
CODEN: NBTNA

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Abstract

The computer code, MAGGIE, for the calculation of multiple scattering and sample attenuation in neutron differential cross-section measurements, has been revised and corrected. The particular case of the scattering geometry required by the associted-particle time-of-flight is considered in detail.

Key words: associated-particle, cross-section, Monte Carlo, multiple scattering, neutron, time-of-flight

MULTIPLE SCATTERING CORRECTIONS FOR THE ASSOCIATED-PARTICLE NEUTRON TIME-OF-FLIGHT TECHNIQUE

Allan C. B. Richardson

I. INTRODUCTION

Measurements of fast neutron elastic and inelastic differential cross sections have, for many years now, usually been done using one of two time-of-flight techniques. The first of these requires a pulsed source of neutrons, and energy separation of the various neutron groups is then achieved by time correlation of the scattered neutrons with the incident neutron pulse. This technique has the advantage of flexibility of incident neutron energy and intensity, and the disadvantages of a relatively high time-correlated background and a low duty cycle. The other, and less commonly used, technique utilizes the detection of a charged particle from the neutron source reaction to tag the incident neutrons in time and direction. Energy separation of the various scattered neutron groups is then achieved by time correlation with the incident neutrons. This "associated-particle technique" has the advantages of very small time-correlated background, inherent absolute determination of the incident correlated neutron flux, and high duty cycle; but it suffers from limitations on the available neutron intensity and energy. However, at energies and intensities where this technique is applicable, it is the method of choice, since it is capable of yielding results of high accuracy without the ambiguities introduced by the time-correlated backgrounds and the massive shielding required by pulsed source techniques. The source reactions eligible for this method are those involving very light nuclei, and therefore capable of producing a light (and thus energetic) stable recoil nucleus. The $T(d,n)^4He$ reaction, producing 14-15 MeV neutrons at 90° over a rather wide range of incident particle energies, is most commonly used; other reactions that have been employed are $D(d,n)^3He$ and $T(p,n)^3He$, both of which produce lower energy neutrons. We will confine the discussion here to the $T(d,n)^4He$ case, although the method described is more generally applicable.

The associated-particle technique has scattering sample requirements that are quite different from those for a pulsed source. Instead of a relatively uniform incident neutron flux across the sample, the correlated neutron beam is highly directional. The angular distribution about the neutron beam line is usually well approximated by

$$I = I_o e^{-\left(\frac{\theta}{\theta_o}\right)^2} ,$$

with θ_o typically only a few degrees [1]. This property can be very useful [2]. It provides a high degree of neutron collimation without the need for massive collimators, which, in the case of 14 MeV neutrons, can produce substantial degradation of the initially monoenergetic neutron beam. However, it forces the use of scattering samples of uniform thickness so that the cylindrical or spherical samples commonly used to simplify multiple scattering corrections are immediately ruled out. Otherwise a detailed knowledge of the neutron beam shape and extremely accurate alignment of this beam with respect to the scattering sample is needed. This alignment problem is further complicated because the center of the neutron beam slowly moves back as the neutron producing target ages with use. In measuring angular distributions of scattered neutrons it is of course also desirable to reduce the amount of scattering sample not directly in the neutron beam, so as to minimize multiple scattering.

A scattering sample in the form of a truncated cone, axis lying along the neutron beam, best satisfies all of these requirements. The origin of this cone is taken sufficiently far behind the source to allow for finite spot size on the neutron producing target, to provide some flexibility in alignment, and also to make allowance for changes due to target aging during a run. In order to make best use of the available neutron intensity, one must also use the thickest sample possible. The limit is set by either the angular resolution required at 90° or the time resolution required. A typical geometry is shown in figure 1.

In either case the resulting samples are sufficiently thick to require a careful multiple scattering correction. None of the analytical techniques [3], useful at energies up to a few MeV, are adequate at 14 MeV, the energy most commonly used for measurements of this type, since at energies above 6-7 MeV the diffraction peaks in the elastic angular distributions become too numerous. The only method of sufficient generality is the Monte Carlo technique. A survey of existing Monte Carlo codes revealed none for this particular geometry, but it was immediately apparent that the code "MAGGIE," developed by Parker, Towle, Sams, et al. at Aldermaston [4,5] contained all of the other elements important to such a calculation. For example, this code easily accommodates the neutron source distribution specified above. In addition, MAGGIE calculates an energy spectrum at each angle, so that false peaks due to double scattering can easily be identified. This sophistication is often useful, for example: the measurement of inelastic scattering from the very weakly excited 7.66 MeV 0^+ level in ^{12}C is easily confused by double scattering from the more easily excited 4.43 MeV 2^+ level in this nucleus.

A corollary need of any Monte Carlo neutronic calculation is an easily accessible, but at the same time sufficiently general, file program for the nuclear data required. This was available in a companion code to MAGGIE, entitled MOULD [6]. We have therefore modified the code MAGGIE so that it now handles the geometry required for associated-particle time-of-flight measurements. During the course of this modification we also corrected a few coding errors found in the original version, and made several additional modifications, principally updating the code to current computer syntax and capabilities.

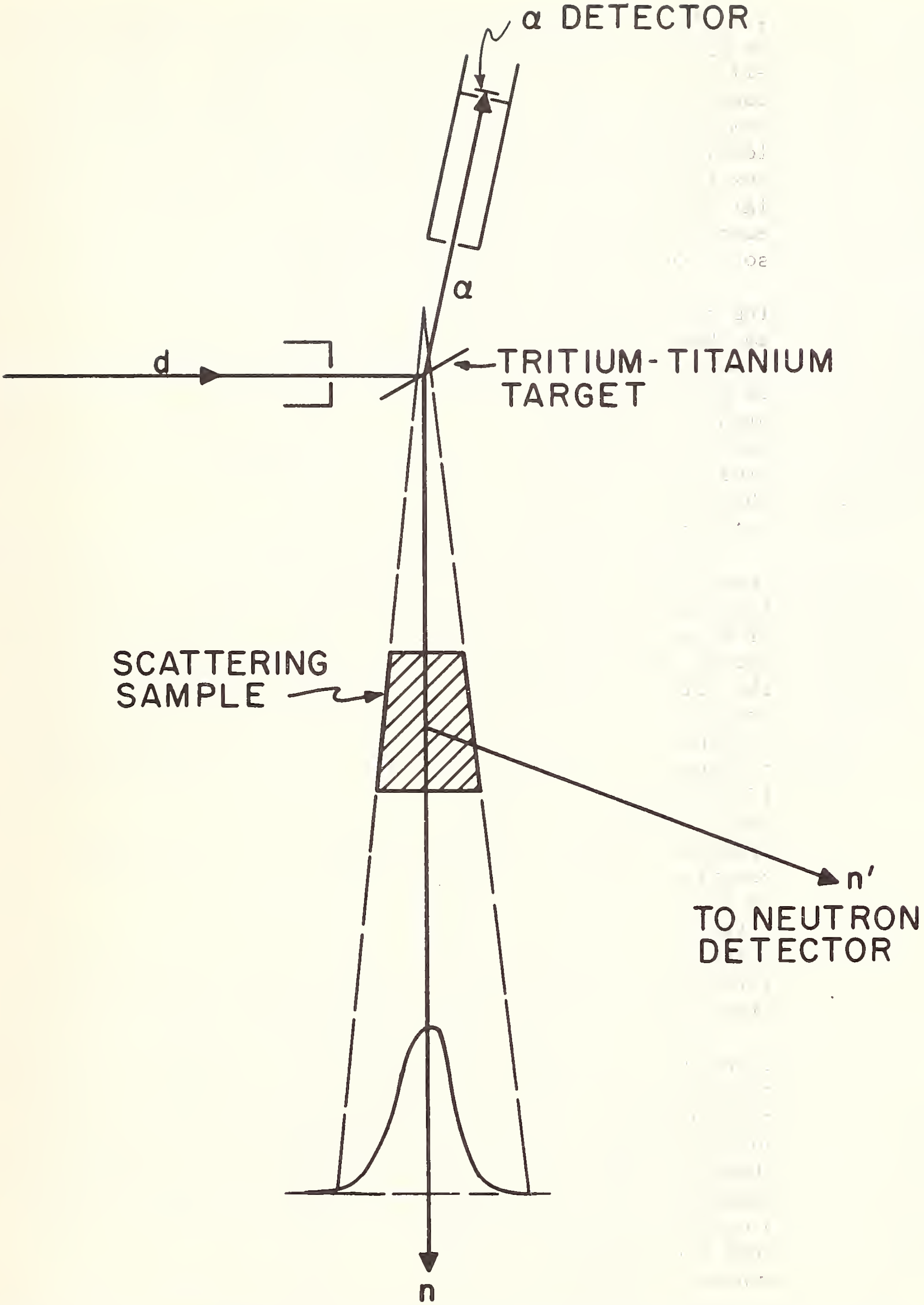

Fig. 1. The experimental geometry for associated-particle measurements at 14 MeV. The associated neutron intensity profile is indicated at the bottom of the figure.

Although a complete description of the code would be out of place here (see references 4 and 5 for details), a general overview of the program will facilitate later discussion of specific details. The point of view adopted is first to sample the scattering sample geometry and the available nuclear interactions using straightforward Monte Carlo techniques. Then, at each collision point, the weighted probability of scattering and escape to each of 33 detector positions (angles) in a half-plane lying to one side of the neutron beam axis is computed using the experimental data for elastic events and each of those inelastic processes of interest. The use of weighted probabilities of scattering to each of the detector positions at the final collision in the sample in place of a completely Monte Carlo approach results in a greatly reduced computation time. This is because the small solid angle subtended by each of the detectors (typically 10^{-3}) makes a final Monte Carlo scattering particularly inefficient. The output angular distributions obtained from applying this procedure to, typically, 1000 interacting neutrons are then reflected about the experimental input data and used as input for a second iteration. Two or three iterations are usually sufficient to obtain a convergent result.

In section II we give a description of the changes made in the code. First, the new coding for the scattering geometry used in the associated particle technique is described. Next we discuss a number of coding errors in the original version. Finally some changes are described that simplify the code and adopt it to FORTRAN V syntax. In section III we give some results obtained using data from the scattering of 14 MeV neutrons on natural carbon. A listing of those subroutines entirely rewritten or having extensive changes is given in Appendix A. In figure 2 the calling sequence for all of the components of the program is shown. A brief description of all of these subroutines appears in Appendix B.

II. DESCRIPTION OF MODIFICATIONS TO THE MONTE CARLO CODE MAGGIE

A. Changes Due to the New Scattering Sample Shape

Four subroutines are affected by changing the shape of the scattering sample. These are: 1) subroutine INPUT - those sections where scatterer parameters are read in and the flux attenuation factor is calculated are affected. The flux attenuation factor is defined as the ratio of incident flux along the axis of the sample to average flux in the entire sample. 2) CRNEU, the subroutine that creates incident neutrons at the entrance face of the scatterer by random sampling of the incident neutron spatial distribution. 3) TRACK, the tracking subroutine. 4) FPATH, the subroutine for calculating the probability of neutron escape from the sample in the direction of each of the assumed detector positions, for each collision point arrived at in TRACK.

It is worth noting here, although not necessary to what follows, that the data used for a) the neutron track lengths in the Monte Carlo sampling of the sample shape from subroutine EGMV, and b) the Monte Carlo sampling of reaction type and angular distribution at each collision by subroutine

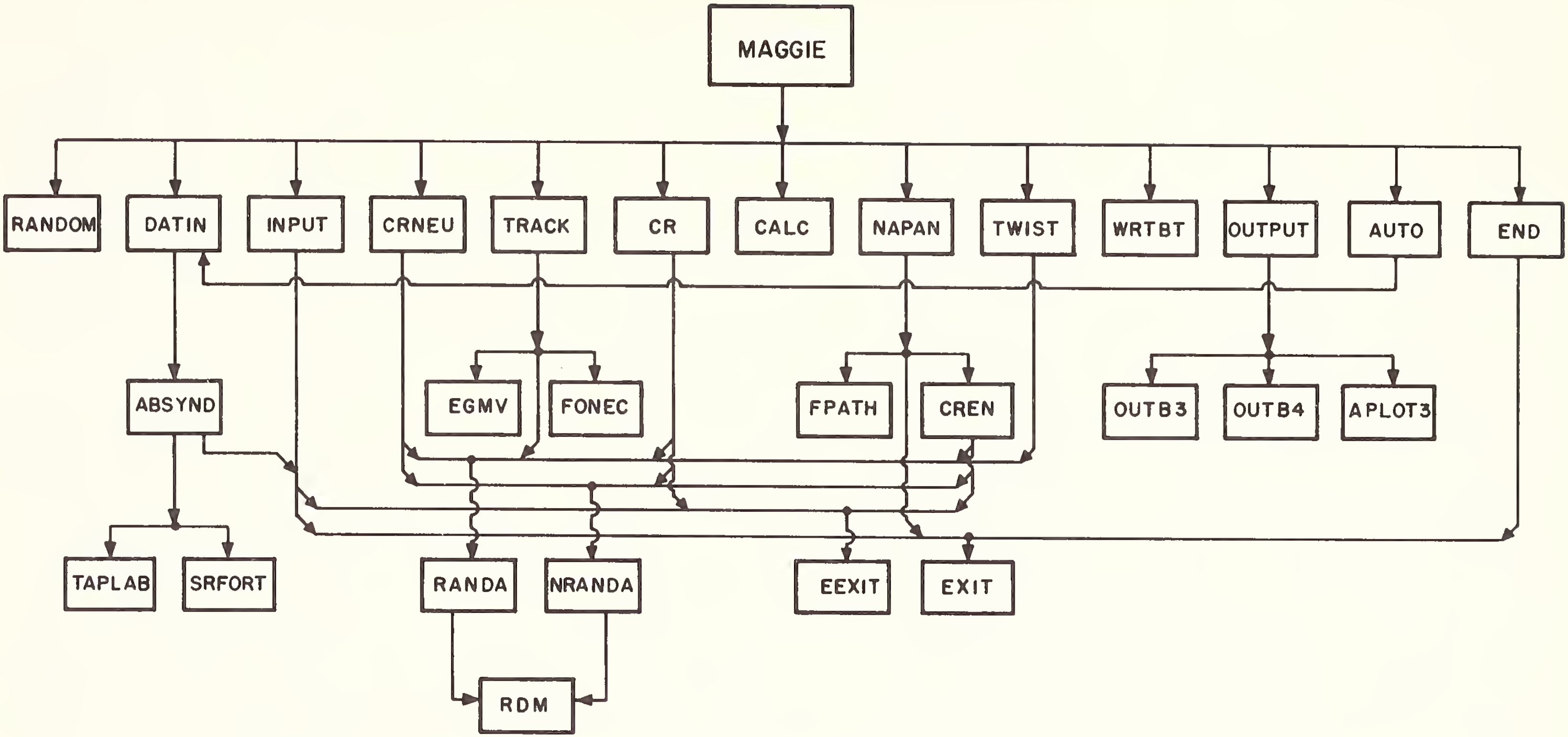

Fig. 2. The calling hierachy for the present version of code MAGGIE.

CR, as well as c) the transmission probabilities in the direction of the detectors used in subroutines FPATH and NAPAN, are all drawn from the MOULD nuclear data file tape and not from input experimental data. The only experimental data employed are angular distributions used for the calculation of the scores for the relative probability of scattering to the various assumed detector positions in subroutine NAPAN. The elastic angular distribution (for the incident neutron energy only) used here is also automatically updated after each iteration by the subroutine AUTO. Thus it may be necessary to update the angular distributions on the MOULD file tape before and during the course of data-processing.

We now describe the changes due to the new scattering geometry in some detail for each of the subroutines affected.

1. INPUT

a. Cards 0207-0226 are changed to eliminate parameters required for samples consisting of concentric cylindrical shells, with common axes perpendicular to the beam axis, and to substitute those needed to characterize a truncated cone sample, axis lying along the neutron beam, and origin behind the neutron source. The new variables are HITE, FRAD, and ANGLE; the height, entrance face radius, and half-angle of the sample, respectively. HITE is immediately redefined as HITE/2, a more convenient quantity in subsequent calculations.

b. Card 0245, the calculation of the maximum angle subtended by the scattering sample at the neutron source, is changed to conform to the new geometry.

c. Cards 0301-0303 have been replaced. The correct expression for the flux attenuation factor for the new geometry is

$$\frac{F_o}{F} = \frac{K(o)}{\overline{K}} \cdot \frac{C}{N\lambda} \cdot \frac{h(r_1^2+r_1\Delta r+\Delta r^3/3)}{(1-\cos\theta_m)\, d^2} ,$$

where h is the half-length of the scattering sample, r_1 the radius of its entrance face, Δr the difference in radii of the entrance and exit faces, and d the distance from the source to the entrance face of the sample. The remaining symbols are defined as in the original.

d. The original version of MAGGIE utilized a sample which was not symmetric about the axis of the incident neutron flux. Thus the experimental sampling of scattered neutrons in the detector plane was not truly representative of the scattering into 4π, which is employed in the program to calculate the flux attenuation factors and which are used in turn to infer the integrated cross-sections. This necessitated a small correction which was calculated with the help of a classification of the outgoing

Monte Carlo tracks vs. energy and the angle with respect to the scattering sample axis. Since the present scattering sample is symmetric about the incident neutron flux the experimental sampling of scattered neutrons in the detector plane is representative, and no correction is required. Accordingly, cards 0331-0338 in INPUT, cards 1544-1548 in DATIN, and cards 1735-1743 in MAGGIE are deleted. Card 1734 of MAGGIE is replaced by the statement

```
20 CONTINUE
```

The output of this table, by cards 3695-3715 of subroutine OUTB3, is also deleted.

2. CRNEU

Cards 3117-3119, 3140-3141, 3143-3147 and 3151 are replaced as shown in the listing. The new coding creates neutrons randomly scattered over the face of the conical scattering sample, in accordance with the specified spatial distribution. The old reference to multiple materials is not deleted, but the sample is now designated "material one." Similarly, the register containing neutrons which miss the sample is retained, although for this geometry misses occur with very low frequency.

3. TRACK

The entire subroutine has been replaced. The geometry is illustrated in figure 3. The subroutine is entered with the starting point (x_o, y_o, z_o) and the direction cosines $(\cos\theta_x, \cos\theta_y, \cos\theta_z)$ already defined. A random sampling of the neutron mean free path establishes the track length to the next possible collision. The track vector is then extended until it intersects the plane determined by the endface of the sample in the direction of travel of the neutron, and the path length from the starting point to this intersection is computed. A comparison of this intersection point with the radius of the endface establishes whether the track is in the direction of the endface or the curved surface of the sample, and the program branches accordingly. If the track passes through the endface, the path length calculated above is compared with the Monte Carlo track length to the next collision and the coordinates of collision or escape from the surface of the sample as well as the time elapsed along the track are computed in a straight-forward way.

We consider now the procedure used for a neutron headed toward a curved surface of the scattering sample. The coordinates of the endpoint of the previously determined Monte Carlo track length are first found. These are used to calculate the projected distance, perpendicular to the symmetry axis, of this endpoint from the symmetry axis, as well as the length of the radius of the sample lying along this projection. Comparison of these quantities determines whether a collision occurs within the sample or not. If so, the coordinates are already known and the time elapsed along the track is all that remains to be calculated. If not, it is necessary to calculate the coordinates of the neutron's exit from

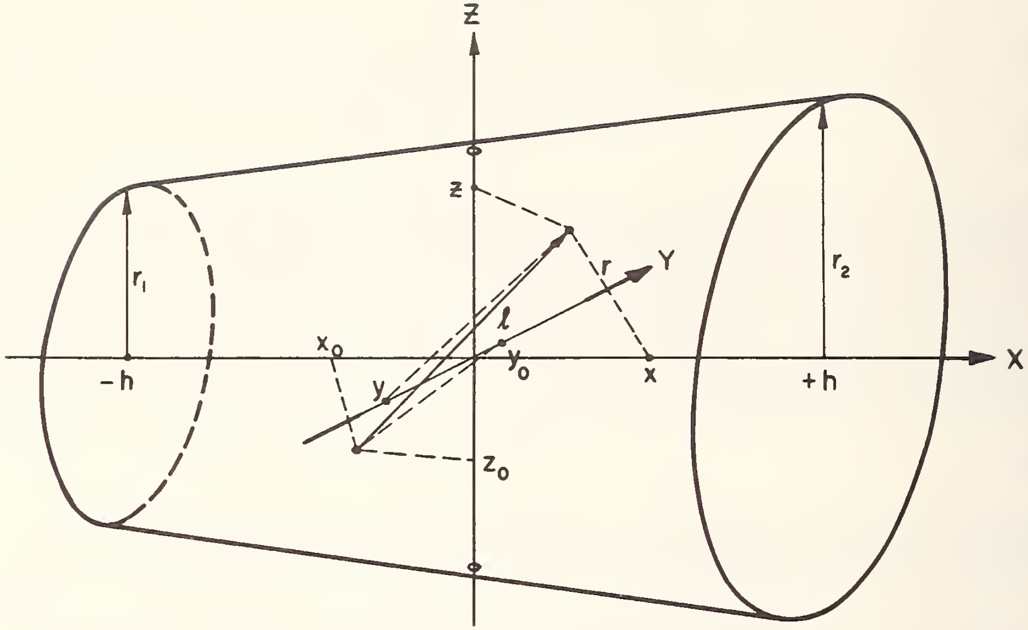

Fig. 3. The geometry for subroutine TRACK. The trajectory shown is that of a neutron which, after collision at point x_o, y_o, z_o escapes from the curved surface of the sample at point x, y, z.

the surface of the cone. Designate ℓ the path length to the surface and x, y, z the coordinates of the intersection of the track with the surface. We have, referring to figure 3,

$$x - x_o = \ell\cos\theta_x$$

$$y - y_o = \ell\cos\theta_y$$

$$z - z_o = \ell\cos\theta_z \quad ,$$

so that the projected distance, r, from the symmetry axis of the cone to the point (x, y, z) is given by

$$r^2 = y^2 + z^2$$

$$= \ell^2 \sin^2\theta_x + 2\ell(y_o\cos\theta_y + z_o\cos\theta_z) + y_o{}^2 + z_o{}^2 \quad , \qquad (1)$$

where we have used the identity

$$\cos^2\theta_x + \cos^2\theta_y + \cos^2\theta_z = 1 \ .$$

Since we know the parameters of the cone we can also calculate r from the x coordinate (again see figure 3.):

$$r = r_1+(h+x)\tan\theta_o \quad , \qquad (2)$$

where θ_o is the half-angle of the cone. Eliminating r from eq'ns. (1) and (2) and arranging the terms as a quadratic in ℓ, we obtain

$$\ell^2\left[1-\cos^2\theta_x(1+\tan^2\theta_o)\right]$$

$$+ 2\ell\left[y_o\cos\theta_y+z_o\cos\theta_z-\cos\theta_x(r_1\tan\theta_o+h+x_o)\tan^2\theta_o)\right]$$

$$+ \left[y_o{}^2+z_o{}^2 - (r_1+(h+x_o)\tan\theta_o)^2\right] = 0. \qquad (3)$$

The positive root of this equation is the required path length to the surface, and the subroutine FONEC is then called to provide the x, y, and

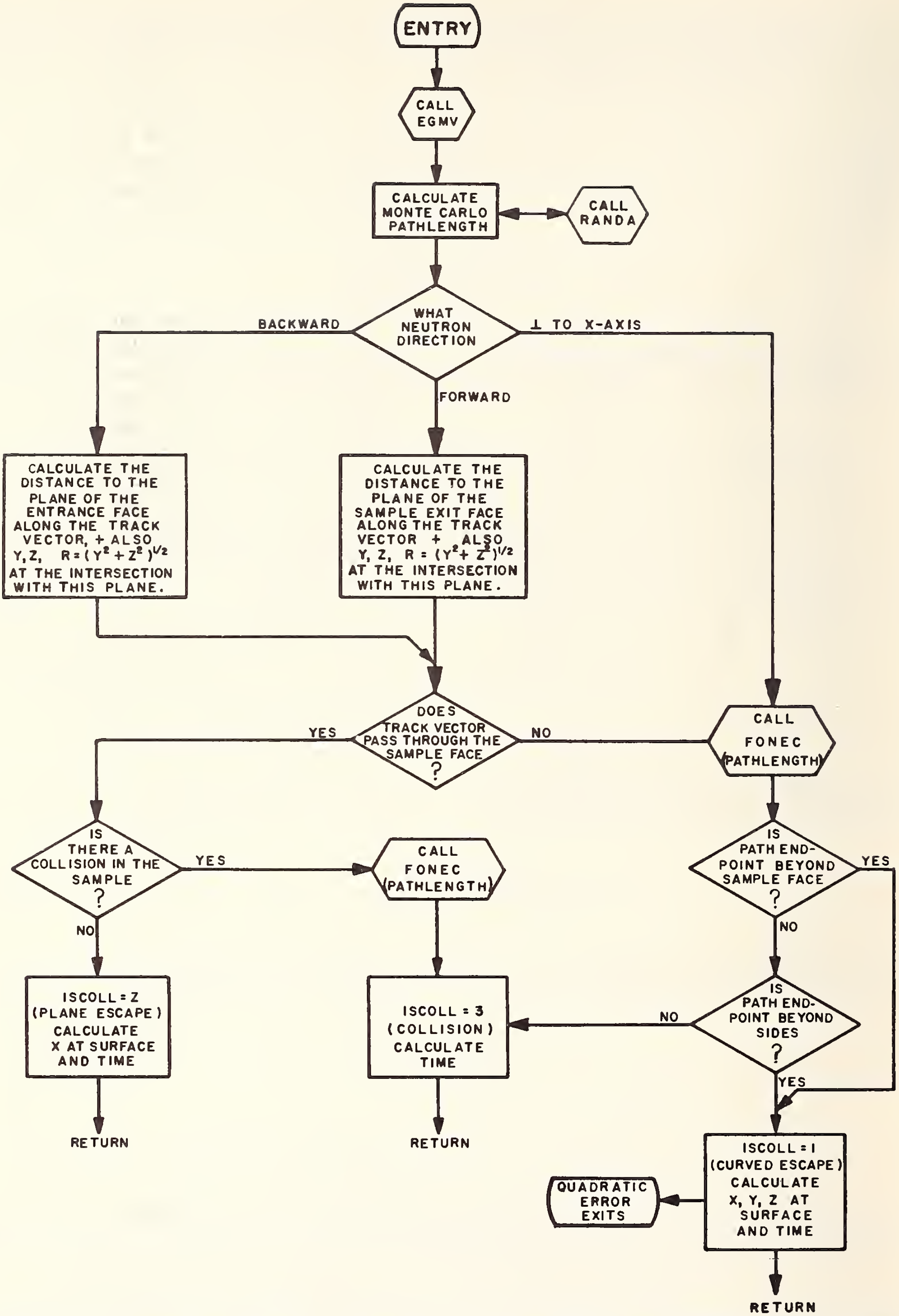

Fig. 4. Subroutine TRACK. The subroutines EGMV and FONEC return the neutron mean free path and the coordinates at the end of a track, respectively. RANDA returns a random number.

z coordinates. Error prints are provided for the cases of two positive, two negative, imaginary, or indeterminate roots as solutions to eq. (3). However none of these situations has occurred in many tens of thousands of tracks, although at least some of them are mathematically possible. Once ℓ has been calculated, determination of the coordinates of escape and the track time are straightforward. The subroutine also returns an index that indicates the fate of the neutron, i.e., curved escape, plane escape, or collision. A block diagram is shown on figure 4.

4. FPATH

This subroutine has also been entirely replaced. The same simplifying assumption is made as in the original coding--that is, the dimensions of the scattering sample are considered to be negligible compared to the flight path to the detector. This has the effect that the angle and flight path to any particular detector position may be considered to be the same from any scattering point in the sample. The quantities to be calculated are the neutron path length, p, in the sample from any point (x, y, z) to the surface of the sample and the scattering angle, θ_d, in the direction of a particular detector, at the angle ψ. The geometry is shown in figures 5 and 6. All paths are assumed to be parallel to the x-y plane, and all detector positions satisfy the condition $y \geq 0$.

We note that the locus of the intersection of a cone with a plane parallel to its axis is an hyperbola, and write, using the notation shown in figure 5,

$$\frac{X^2}{a^2} - \frac{Y^2}{b^2} = 1 \quad ,$$

$$\text{or} \qquad Y^2 = X^2 \tan^2\theta - z \quad , \tag{4}$$

$$\text{since} \qquad b = z \quad \text{and} \quad a = z/\tan\theta .$$

Now, referring to figure 6, we may also write

$$Y = p \sin\psi + y$$

$$\text{and} \qquad X = p \cos\psi + x' \quad , \tag{5}$$

$$\text{where} \qquad x' = R + h + x = \frac{r_1}{\tan\theta} + h + x .$$

Again we reduce the problem to a quadratic in path length, p, after

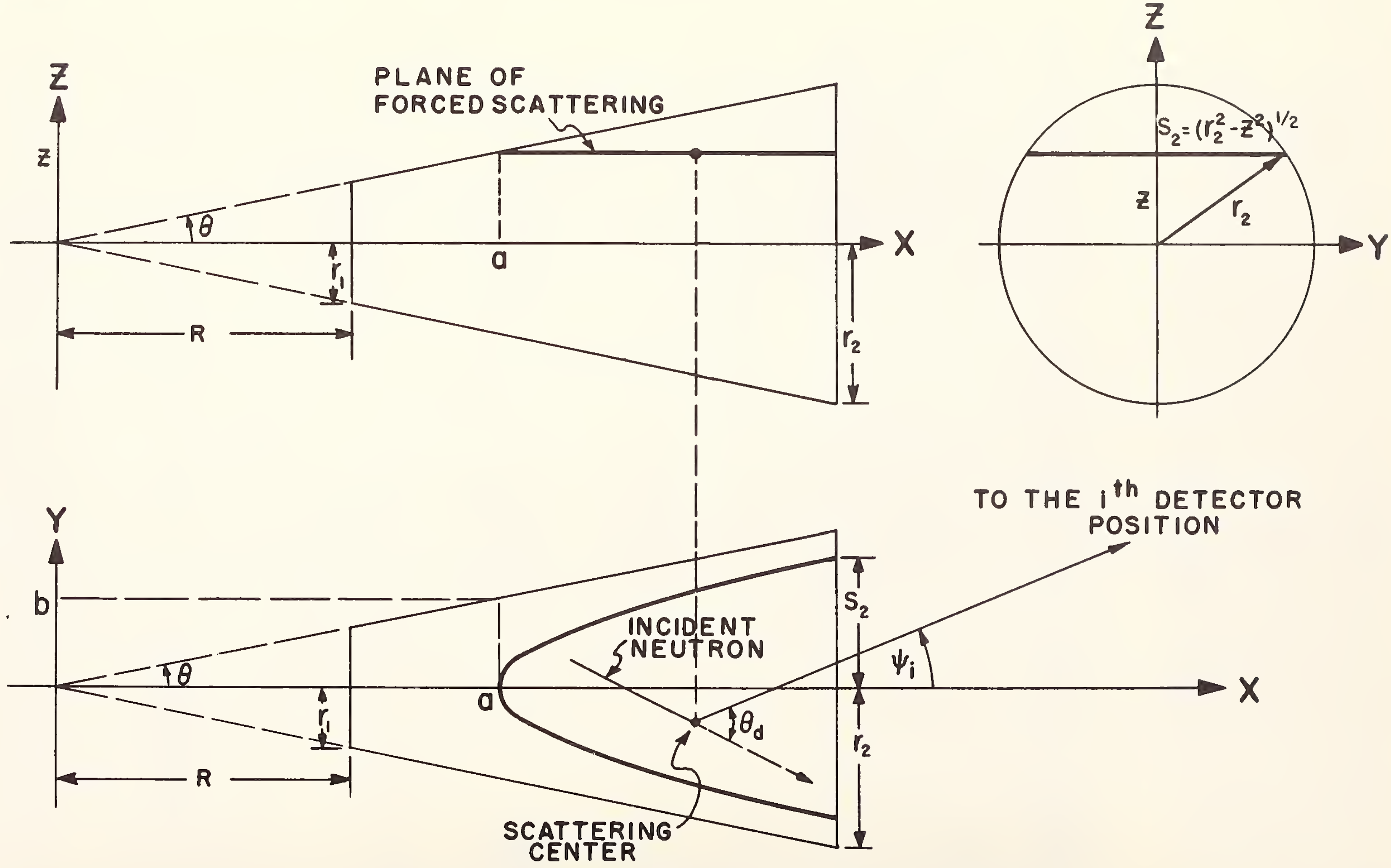

Fig. 5. The geometry for subroutine FPATH. The plane of forced scattering is located at a height $r_1 < z < r_2$ in this instance. The track of the incident neutron does not, in general, lie in this plane as shown.

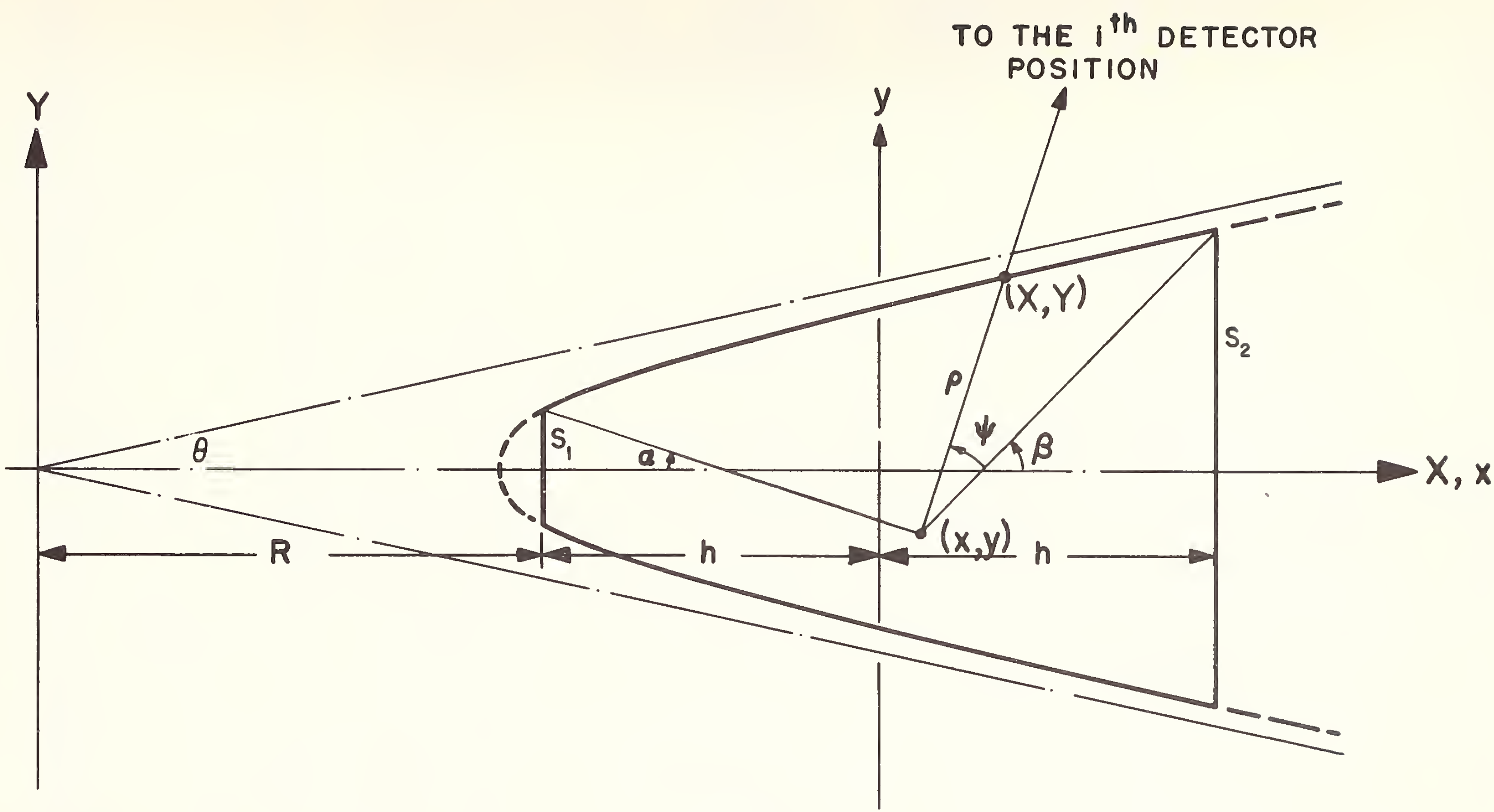

Fig. 6. A section through the scattering sample at height $z<r_1$. The upper case quantities refer to the axes X and Y, whose origin is that of hyperbola defined by the intersection of the plane (x,y) with the surface of the scattering sample.

combining eq's (4) and (5) to eliminate the variables X and Y to obtain:

$$p^2(\sin^2\psi - \cos^2\psi \tan^2\theta)$$

$$+ 2p(y\sin\psi - x'\cos\psi\tan^2\theta)$$

$$+ (y^2 - x'^2\tan^2\theta + z^2) = 0 \, . \qquad (6)$$

For each value of z there will be a pair of angles, α and β (see figure 6 , which define the limits of the hyperbolic curve. These angles are given by

$$\tan\alpha = \frac{(r_1^2 - z^2)^{1/2} - y}{h + x}$$

$$\tan\beta = \frac{(r_2^2 - z^2)^{1/2} - y}{h - x} \, . \qquad (7)$$

The subroutine is diagrammed in figure 7. After testing for the special case of exit perpendicular to the beam axis, the program tests, using eq's (7), for exit through the endfaces vs. the curved sides for the exit angle, ψ, and branches accordingly. The path length in the former case is a straightforward calculation, and for curved escape is the positive root of eq. (6). It should be noted that in the limiting case of cylinder ($\tan\theta=0$) this subroutine, unlike all of the others, does not work. A modified subroutine for a cylindrical sample is given in the Appendix following the listing of FPATH for a truncated cone.

B. Correction of Coding Errors [7]

1. INPUT

a. Statements resulting in LGR=0 in the table look-up for the mean free path (following card 0308) have all been changed to give LGR=1. LGR=0 references not a mean free path, but instead the last tabular value of collision probability in the previous MOULD table. The revised look-up supplies the mean free path at the lowest tabulated energy for any neutron at or below that energy.

b. On the card following statement 5001, LRG has been replaced by the correct variable, LGR.

c. Card 0441 is replaced by

IMINM = IMAXM+1 .

This change yields sequential storage of supplementary ranges of experimental angular distributions, and thus avoids loss of needed storage space in the array SUPVAL (I,J).

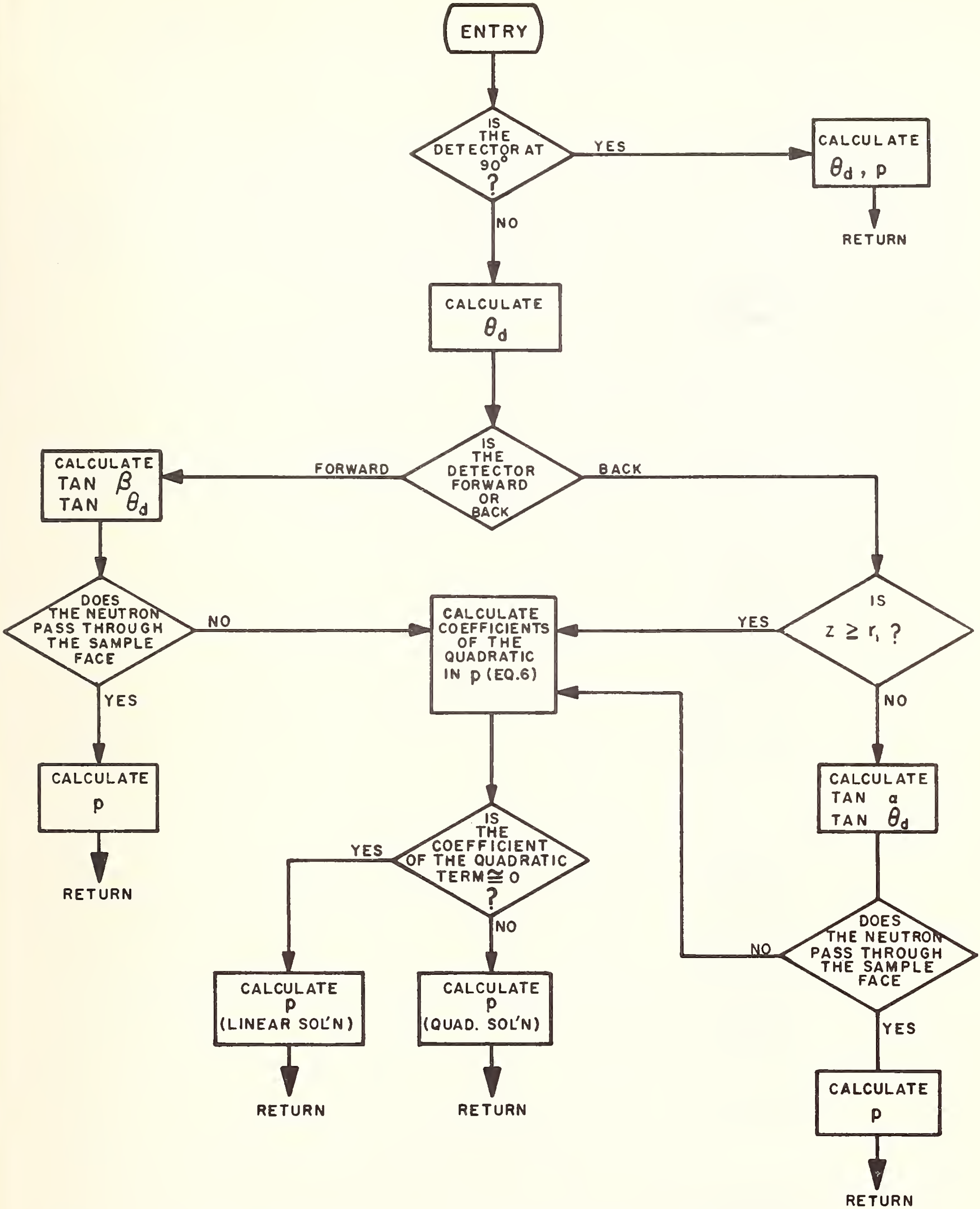

Fig. 7. Subroutine FPATH, for a truncated cone. The subroutine for a cylinder is similar.

2. EGMV

LGROUP=0 has been eliminated for the reason given in 1a. above.

3. NAPAN

a. The angle used for the interpolation of the experimental distributions, as well as for calculation of the neutron energy after collision is the laboratory angle, calculated in the subroutine FPATH. For this reason the experimental angular distributions must be read in at laboratory angles. Also the center-of-mass energy calculation on cards 3494 and 3497-3501 (in the case of center-of-mass MOULD angular distribution tables) is in error. This has been changed to a calculation in laboratory coordinates by replacing card 3494 by

```
GO TO (36,11,11,11,11,11,11,11,36,11,11,11,11,11,11,11) NFORM
```

and deleting cards 3497-3501.

b. The sequence of cards 3502-3512, which picks the appropriate experimental angular distribution values, does not refer to the correct angular distributions, nor to the correct neutron energy--that before collision. It has been replaced by the sequence:

```
11      IF(IMAX(J).LE.0) GO TO 15
        IMINM=IMIN(J)
        IMAXM=IMINM+IMAX(J)-1
        DO 50 JJ=IMINM,IMAXM
        IF(EIN-ENVAL(J,JJ))50,51,52
50      CONTINUE
51      KK=JJ
        GO TO 19
52      IF(JJ.LE.IMINM) GO TO 15
        KK=JJ-1
```

c. On the card following statement 5001, LRG has been replaced by the correct variable, LGR.

d. LGR=0 has been eliminated for the reason given in 1a. above.

e. The option that provides for suppression of printout of various scores, through setting the indicators IANALA, IANALB, IANALC, and IANALD negative, should not suppress storage of these scores by NAPAN. The time saved is negligible and the elastic scores, DEB(I,L), are required by the automatic iteration scheme, AUTO. Cards 3528-43 have been revised to eliminate the dependence on these printout indicators.

4. ABSYND

LGROUP=0 has been eliminated for the reason given in 1a. above.

5. CREN

For the same reason set out in section 3a. above, the center-of-mass energy calculation (cards 2960-66) has been replaced by a calculation in laboratory coordinates by deleting cards 2961-66 and replacing card 2960 with

880 GO TO 800 .

6. OUTPUT, OUTB3, OUTB4

The sum over energy, at each detector angle, stored in the vector DES(J,33) is required by subroutine AUTO. So as to allow calculation of this quantity in subroutine OUTB4, even when no B4 printout is requested, a print indicator, IFPR, has been added to the call for subroutine OUTB4. This is accomplished by the changes shown in the listing for cards 3721, 3808A, 3873, and 3975-4002.

7. AUTO

a. The quantity "chi-squared," on card 2084, should be

$$\chi^2 = \sum_{1}^{33} \frac{\left(\sigma(\theta)_{exp} - \sigma(\theta)_{calc}\right)^2}{\sigma(\theta)_{exp}} ,$$

and not as formerly written, with the denominator squared.

b. It should be noted that the normalization of the Monte Carlo output on cards 2065-2068 and 2088 is not, in general, correct; but only holds for detectors positioned at equal increments of $\cos\theta$ between -1 and +1. For this reason, if subroutine AUTO is used, the input detector positions must satisfy this criterion.

8. FPATH

The original version of this subroutine contained two errors. These do not apply to the new version of FPATH reported here, but are listed for completeness. Card 3356 of the original should read

SINOM = SQRT(1-COSOM**2) ,

card 3358 be deleted, and a new card inserted following card 3359:

FP1 = WORK16**2+WORK17**2-FP2**2 .

C. Other Modifications

1. General

a. Common storage assignments have been handled by combining all common statements into one package, processed by the UNIVAC 1108 "Procedure Definition Processor" using the assembler directive FCOPY (Fortran copy). This package, designated CINC1, is then included at the time of assembly in all subroutines making use of common variables by means of the statement

INCLUDE CINC1

placed immediately following the subroutine name definition. This process, which effects a considerable economy in the size of the source deck and listing, is characteristic of the UNIVAC 1108 Assembler and FORTRAN V; however, equivalent procedures are often available to other systems. In some subroutines dimension statements still appear for those few variables not in common storage. A block of common storage has been specifically assigned to the subroutine ABSYND variables DATA and IDATA. This carries the dummy label BLANK. The details of these changes in memory storage allotment will be obvious upon examination of the listings.

b. The size of many modern computers obviates the need for linkage. We have deleted references to CHAIN(I,J) and incorporated the balance of subroutine PRELUDE into the main program MAGGIE. Similarly, references to CHAIN(I,J) in subroutines DATIN and AUTO have been replaced by the appropriate CALL and/or RETURN statements.

c. The final F in the names of all library functions (such as SIN, COS, EXP, MIN) has been deleted, as it is not compatible with FORTRAN V. In addition, such functions as FLOAT and INT have been eliminated by using the mixed expressions allowed by FORTRAN V.

d. Disc storage read and write statements have been modified in the main program MAGGIE and subroutine WRTBT to conform to 1108 FORTRAN V usage.

e. A number of formats have been altered. Some of the changes are merely different spacing options, but others are required by the new scattering geometry. A list of card numbers of the affected statements follows:

0226	0226A	0226B
0249	0258	0345
0410	0450	0451
1719	1963	1972
2111	2115	3638
3639	3828	3833

On card 2735 in subroutine CR the variable N has been replaced by the correct variable NSECS.

f. A new random number generator, subroutine RANDOM, entry RDM, has been incorporated, and the required changes in the functions RANDA and NRANDA are shown in the listings.

2. MAGGIE

a. All of the subroutine PRELUDE, except for calls to subroutines CLOCK and CHAIN, has been inserted following card 1654. A call to subroutine RANDOM immediately following the read-in of OCT, the starting value of the random number generator, initializes this generator. OCT is printed out following the call to subroutine INPUT.

b. All references to subroutine CLOCK have been deleted.

c. Card 0530 is eliminated by changing cards 1776, 1778, 1787, 1789, and 1792 to read

GO TO 1 .

3. ABSYND

a. Card 0525, which assigns the logical tape unit carrying the MOULD nuclear data tape, now reads

NUCDAT=9 .

On cards 0525, 0530, and 1394 the variable name TAPE has been changed to ATAPE to avoid confusing the compiler. These changes may not be required by other installations.

b. Cards 0553 and 0554 set all storage for the variables DATA and IDATA to zero before each ABSYND run.

c. Card 1398 is modified so as to print only those action numbers processed.

4. CR

The variable names NACT and Q have been changed to NACTV and QV, so as to avoid conflict with the array names NACT(I) and Q(I). Similarly, the variable name COS is changed to COZ, so as to make the library function COS available.

5. CREN

a. The variable names NACT and Q have been changed to NACTV and QV, for the reason given above.

b. Cards 2832-2837, 2878-2881, and 2911-2915 have been deleted, since they are not needed. In order to accomodate these deletions card 2910 has been amended to read

```
IF(NVCOS.LT.1) GO TO 208        ,
```

and card 2916 to read

```
P = (AS+SQRT(AS**2+A*QV*(1+A)/EIN+A**2-1))/(1+A) .
```

6. AUTO

a. The multiple elastic sums are not required, and so cards 2069-2072 are deleted.

b. The quantity RATIO is not used, and has been eliminated from cards 2077 and 2078.

c. The do-loop 2083-2085 is redundant, since ELM2(J) is also set at card 2097. Cards 2083-2085 are therefore deleted, and card 2080 is modified to reflect this change.

d. The three do-loops in the sequence 2087-2098 have been combined into a single loop.

e. The variable name EXP(J) has been changed to EZP(J) to avoid conflict with the library function EXP.

f. Often it is desirable to separate an iteration procedure into two or more consecutive runs. Cards 2073-2082 have been modified to allow a run to be made using the partially corrected output of a previous run as input, instead of the experimental data. When this option is to be used the second field of the input card specifying the number of iterations, NTERM, should be non-zero. This is then followed by the cards specifying the experimental values for the angular distribution, FCVAL, which are removed from their usual position and replaced by the partially corrected output of the previous run.

g. In the case of rapidly varying angular distributions such as at 14.1 MeV, the usual iteration procedure is not as rapidly convergent as the "physical" method. For this method the calculated multiple scattering is first subtracted from the experimental input, and then the balance of the iteration (sample attenuation) is performed as usual by reflecting the output for single scattered neutrons about the input. The new coding on cards 2091-2097 reflects this change. For the first two iterations the iteration improves only the multiple scattering, the correction being applied both times to the experimental input. After two iterations multiple scattering is well enough known to allow the iterative procedure full play, so the correction is applied each time to the previous input, instead of the experimental values. This procedure yields much more rapid convergence, three iterations providing better convergence than six of the previous method.

III. AN APPLICATION TO 14.1 MeV NEUTRON SCATTERING

The code has been applied to a typical associated-particle scattering geometry for 14.1 MeV neutrons on carbon. The scattering sample was a truncated cone of half-angle seven degrees, length 3.193 cm., and entrance face radius 2.059 cm., with its center located 20 cm from the neutron source. The experimental input used was simulated using published results for carbon at this energy. The results of a typical run are shown in Table 1, and on figures 8 and 10. The cross-section data used for the Monte Carlo scattering were those of Slaggie and Reynolds [8]. In Table 1 the quantity $\sigma(\theta)$ represents the true angular distribution, and the total and multiple outputs are the results calculated using it and the specified sample shape. The code varies $\sigma(\theta)$ until the total elastic output matches the experimental input to the accuracy required. The calculated angular distribution for neutrons undergoing multiple scattering is shown in figure 8. It can be seen that the result converges quite rapidly. Further iterations resulted only in statistical variations about the values obtained after three iterations; in fact, the largest change after two iterations, that at $\cos\theta = 0.625$, represents only a 1.5% change in the cross section.

In figure 9 we show the part of the correction, exclusive of multiple scattering, that depends upon sample shape. Also displayed for comparison is a calculation of the effect expected due to attenuation in the sample for an isotropic angular distribution. As can be seen, this correction is not independent of the input angular distribution. The quantity plotted, $\Delta\sigma/\sigma$, is the difference between the singly scattered output and the input, divided by the input, for each angle. This geometrical correction is contributed to about equally by varying path length in the sample and the change in the total neutron cross section with energy as a function of the neutron scattering angle. The correction varies from a few percent to about ten percent, and is directly dependent upon the accuracy with which the total neutron cross section is known over the range of energy exhibited by the neutron recoil. On the other hand, the correction for multiple scattering is larger, ranging from about 50% at the backward minimum to 4% at zero degrees, but depends mainly upon the experimental input data. Over most of the practical angular range of measurement it is a quite appreciable 15-20%. Figure 10 shows the input distribution used and the corrected output distribution obtained after three iterations of approximately 2000 interacting neutrons each. The total correction is, of course, largest in regions where the cross section exhibits minima. It varies from a few percent to a maximum of only twenty percent at measurable angles, since the geometrical and multiple scattering corrections tend to be in opposite directions, except at the extreme backward angles. Several examples of spectra showing elastic-inelastic and multiple inelastic effects in the energy spectra are given in the original references [4, 5]; the present version of MAGGIE also yields similar results.

TABLE 1

The scores for a typical Monte Carlo run for carbon at 14.1 MeV.

COUNTER NUMBER	Cos θ	σ(θ)	TOTAL ELASTIC OUTPUT	MULTIPLE ELASTIC OUTPUT	EXPERIMENTAL INPUT
1	-1.0000	.023	.044	.021	.044
2	-.9375	.075	.092	.022	.093
3	-.8750	.093	.111	.024	.111
4	-.8125	.100	.120	.026	.121
5	-.7500	.110	.131	.028	.131
6	-.6875	.127	.148	.030	.148
7	-.6250	.152	.170	.031	.171
8	-.5625	.176	.190	.033	.191
9	-.5000	.202	.212	.034	.212
10	-.4375	.225	.231	.035	.232
11	-.3750	.240	.246	.036	.246
12	-.3125	.248	.253	.037	.254
13	-.2500	.245	.251	.037	.251
14	-.1875	.233	.240	.038	.241
15	-.1250	.216	.225	.038	.226
16	-.0625	.192	.205	.038	.205
17	.0000	.173	.183	.038	.183
18	.0625	.145	.155	.037	.155
19	.1250	.125	.135	.037	.135
20	.1875	.114	.125	.037	.125
21	.2500	.107	.123	.039	.122
22	.3125	.110	.127	.041	.126
23	.3750	.124	.142	.044	.140
24	.4375	.154	.170	.049	.167
25	.5000	.203	.215	.055	.212
26	.5625	.281	.285	.063	.281
27	.6250	.412	.404	.074	.400
28	.6875	.628	.605	.087	.600
29	.7500	.969	.929	.104	.925
30	.8125	1.486	1.435	.125	1.435
31	.8750	2.274	2.218	.151	2.219
32	.9375	3.451	3.380	.181	3.387
33	1.0000	5.197	5.045	.216	5.062

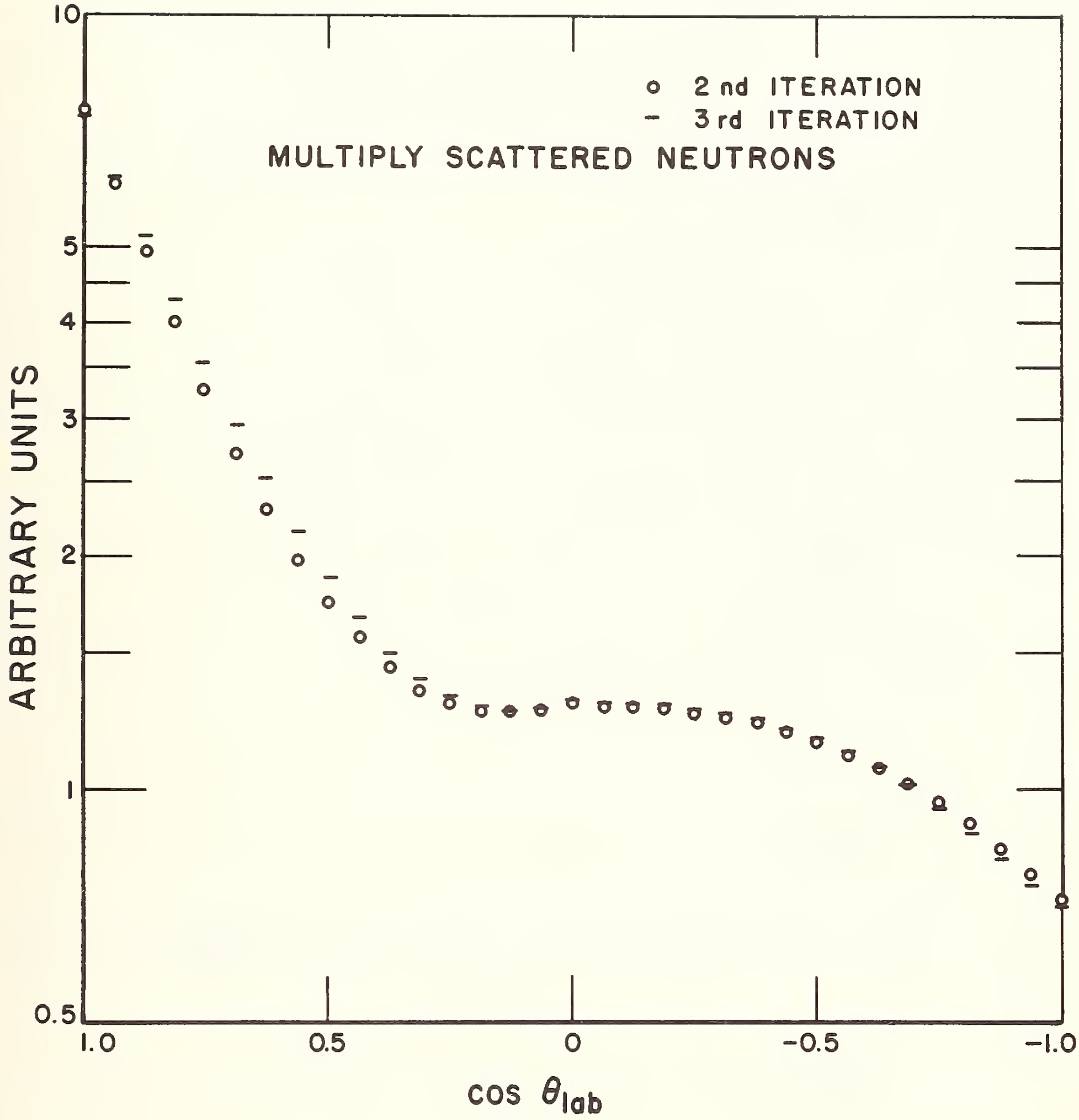

Fig. 8. The angular distribution of multiply scattered neutrons on carbon at 14.1 MeV for two successive iterations. The data for the third iteration are also given in Table 1, after suitable normalization.

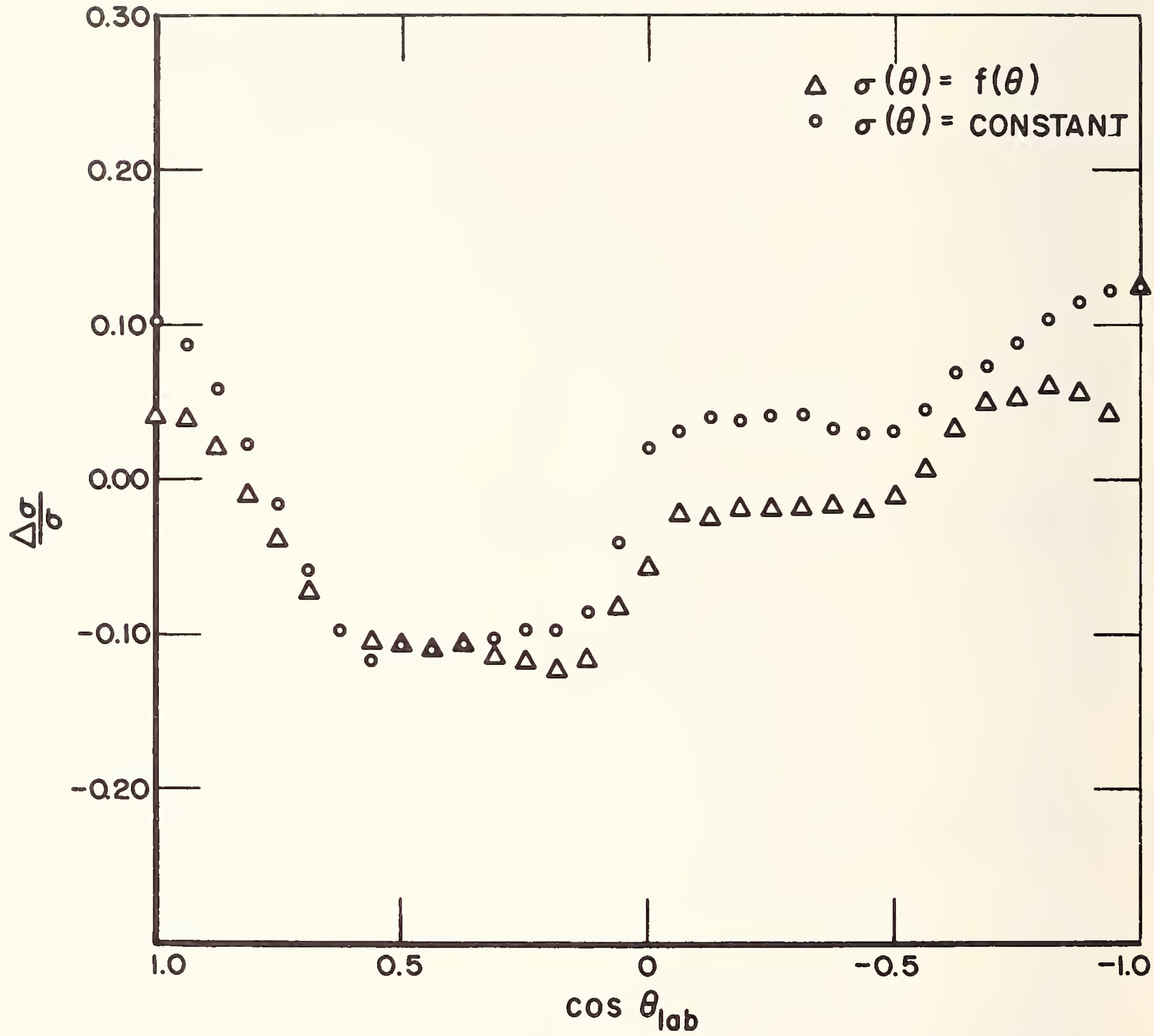

Fig. 9. The correction due to sample shape. The quantity $\Delta\sigma/\sigma$ is the change in the normalized angular distribution after subtracting multiple scattering.

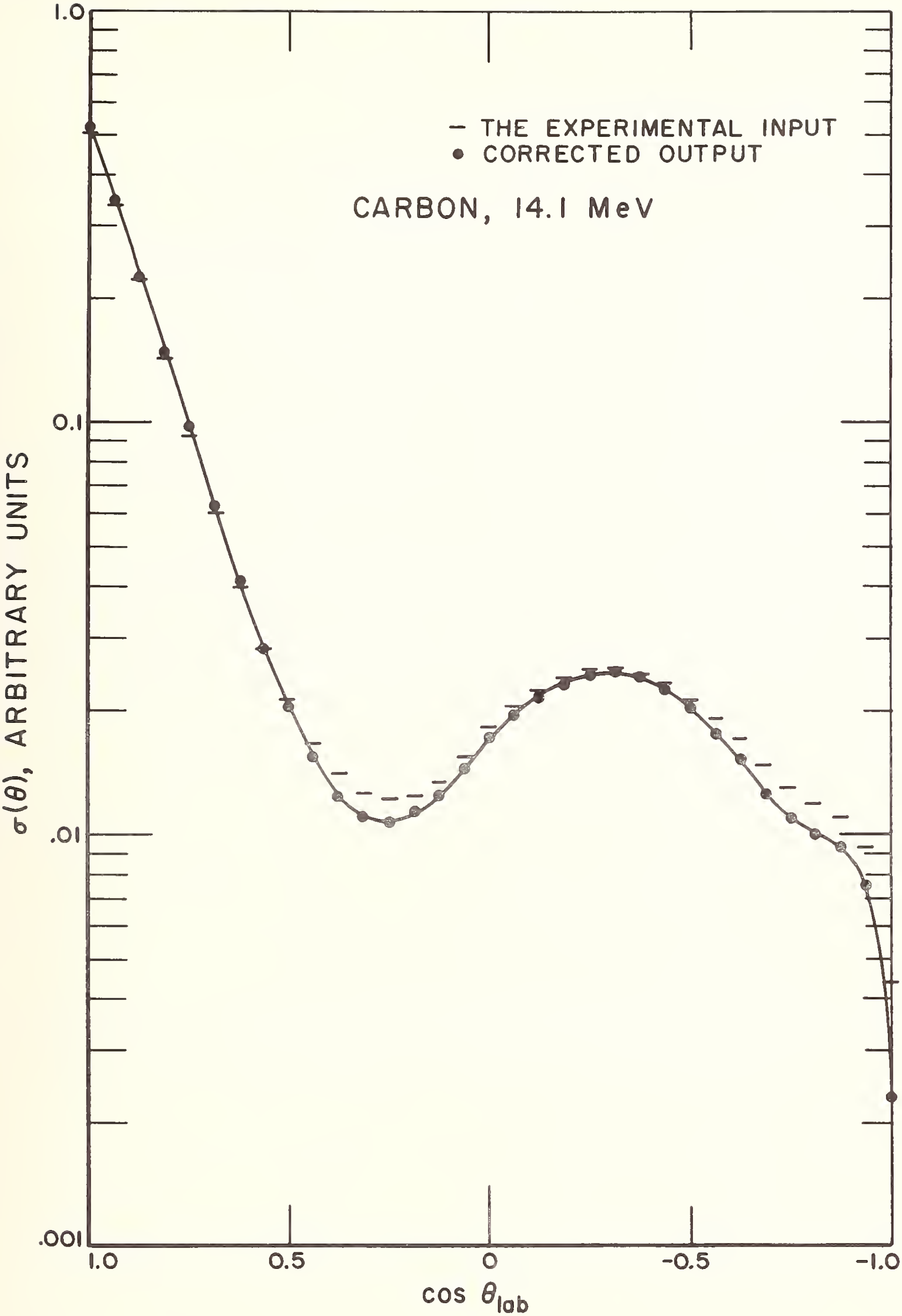

Fig. 10. The experimental input and corrected output for carbon at 14 MeV.

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4. Parker, J. B., Towle, J. H., Sams, D., and Jones, P. G., Nucl. Instr. and Meth. 14, 1 (1961).

5. Parker, J. B., et al, Nucl. Instr. and Meth. 30, 77 (1964).

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7. Some of these coding errors have also been previously noted in private communications. We are indebted to J. B. Parker, Aldermaston, for noting the substitution of REDEN for EIN in subroutine NAPAN, as well as the errors in subroutine FPATH. H. Horstmann and H. Schmid, Geel, have noted, in addition, the difficulty involving the center of mass calculation of neutron recoil energy in subroutines NAPAN and CREN.

8. Slaggie, E. L., and Reynolds, J. T., KAPL-3099, (1966).

APPENDIX A

Listings of new and extensively revised coding.

A complete listing is available by request from the Center for Radiation Research, Neutron Physics Section, National Bureau of Standards, Washington, D. C. 20234.

```
CINC1* FCOPY                                                              NBS
C                                                                         EU.
C      COMMON STORAGE ALLOCATION.                                         EU.
C                                                                         EU.
      COMMON LOC,OCT                                                      NBS
      DIMENSION DATA(1),IDATA(1)                                          EU.
      EQUIVALENCE (DATA,IDATA)                                            EU.
      COMMON IDATA,INIT,NEGS,UMAX,XLYMIN,IXMAT,IDICE,NMATS,EMC(257),      NBS
     1       PATH,SPEED,MAT,EIN,UIN,LGROUP,ROOTE,WIN,WOUT,NSECS,          NBS
     2       COSPHI(100),EOUT(100),UOUT(100),ISORAN(100) ,NOLAW(100),     NBS
     3       NONUC(100),NOACT(100),NREACT(100),NORNGE(100),ALF,           NBS
     4       ALFP(20),WMIN,WMAX                                           NBS
C                                                                         EU.
C      MAGGIE NUCLEAR DATA AIDS.                                          EU.
C                                                                         EU.
      COMMON NUCLID,NAC,AS,ENER,NFORM,QV,ATOM1(24),Q(24),PART1(24),       NBS
     1       IXACT1(24),IXNUC1,FNEGS,NUCS,NUCL(24),NACT(24),NAC1(24),     NBS
     2       NANAL,NENSP,NOCOU,NOGR,LAWREV(50),LWNO(50),NLWREV            NBS
C                                                                         EU.
C      BIRTH STORES AND REGISTERS.                                        EU.
C                                                                         EU.
      COMMON BIRTH(5500),IBIRTH(1500)                                     NBS
C                                                                         EU.
C      GENERAL WORK STORES.                                               EU.
C                                                                         EU.
      COMMON IWORK1,IWORK2,WORK3,WORK4,WORK5,WORK6,WORK7,WORK8,WORK9,     NBS
     1       WORK10,WORK11,WORK12,WORK13,WORK14,WORK15,WORK16,WORK17,     NBS
     2       WORK18,WORK19,ISCOLL                                         NBS
C                                                                         EU.
C      DIMENSIONS ETC.                                                    EU.
C                                                                         EU.
      COMMON HITE,FRAD,BRAD,ANGLE,TANGLE,DIST,STRTE,CNPHI(64),FLTPTH      NBS
C                                                                         EU.
C      CONTROL PARAMETERS.                                                EU.
C                                                                         EU.
      COMMON IRECRG,IRGRA,IRGRB,JOBFIN,NOSAMP,SAMPLE,ANEUNO,NSENSE,IFB4 NBS
```

```
C                                                                         EU.
C     ANALYSIS AND AIDS TO ANALYSIS.                                      EU.
C                                                                         EU.
      COMMON HEAD(12),ONCOL(31),DEGENE(30),DEGENI(30),EDGEN(30),          NBS
     1       ICOLL(100),AMISS,PESC,CESC,ANOCOL,ALLEL,EVDGEN,FCCOS(33),    NBS
     2       FCCOSD(33),FCER(24,15),FCVAL(24,33),SUPVAL(24,33),           NBS
     3       ENVAL(24,24),IMAX(24),IMIN(24),ENSP(33),COUNT(33),           NBS
     4       TOCOL(5,5),                                  DEA(33,33),     NBS
     5       DEB(33,33),DEC(33,33),DED(33,33),IANALA,IANALB,IANALC,       NBS
     6       IANALD,FLUXFT,ALAM(32),ITMAG,ITER,EZP(33),NTERM,SAMP(10)     NBS
C                                                                         NBS
C     ABSYND IDATA AND DATA STORAGE                                       NBS
C                                                                         NBS
      COMMON BLANK(15000)                                                 NBS
      END                                                                 NBS
```

```
C     MAGGIE 3A                                                          1566
C     20.7.64 A.D.PURNELL                                                1570
C     9.68 MODIFIED NBS VERSION FOR FORTRAN V, A.C.B.RICHARDSON       NBS1570A
C     FOR TRUNCATED CONE SCATTERING SAMPLE, INCLUDING AUTOMATIC ELASTIC NBS1571
C     SCATTERING CALCULATION AND GRAPHS.                              NBS1571A

      INCLUDE CINC1                                                   NBS
      DIMENSION LAWTP(100)                                               1653
      ITER=1                                                             1654
      INIT = 16719                                                    NBS
      READ(5,51)OCT                                                   NBS
      CALL RANDOM(OCT)                                                NBS
   51 FORMAT(O12)                                                     NBS
      READ(5,200)(HEAD(I),I=1,12)                                     NBS
      WRITE(6,200)(HEAD(I),I=1,12)                                    NBS
  200 FORMAT(12A6)                                                    NBS
      CALL DATIN                                                      NBS
      CALL INPUT                                                         1656
      WRITE(6,52)OCT                                                  NBS
   52 FORMAT(55H0THE STARTING VALUE FOR THE RANDOM NUMBER GENERATOR IS ,NBS
     1O12)                                                            NBS
  103 NOSAMP=0                                                           1658
      IRECRG=0                                                           1659
      IRGRA=0                                                            1660
      IRGRB=0                                                            1661
      ANEUNO=0.0                                                         1662
      THERM=0.25000001E-7                                                1663
1     IF(IRGRA)2,7,4                                                     1664
2     PRINT 3,ANEUNO                                                     1665
3     FORMAT(1H1,47HERROR CONDITION-BIRTH REGISTER NEGATIVE ANEUNO=,F6.0 1666
     2)                                                                  1667
      IRGRA=0                                                            1668
      IRGRB=0                                                            1669
      GO TO 7                                                            1670
4     IRGRA=IRGRA-11                                                     1671
      IRGRB=IRGRB-3                                                      1672
```

```
      IWORK1=IBIRTH(IRGRB+1)
      MAT=IBIRTH(IRGRB+2)
      IWORK2=IBIRTH(IRGRB+3)
      EIN=BIRTH(IRGRA+1)
      WORK3=BIRTH(IRGRA+2)
      WORK4=BIRTH(IRGRA+3)
      WORK5=BIRTH(IRGRA+4)
      WORK6=BIRTH(IRGRA+5)
      WORK7=BIRTH(IRGRA+6)
      WORK8=BIRTH(IRGRA+7)
      WORK19=BIRTH(IRGRA+8)
      UIN=BIRTH(IRGRA+9)
      WIN=BIRTH(IRGRA+10)
      WORK11=BIRTH(IRGRA+11)
      IF(IRGRA-550)13,5,13
5     IF(IRECRG)13,13,6
6     IRECRG=IRECRG-11
      LOC=LOC-5600
      READ(37)IRECRG,(BIRTH(I),I=551,4950),(IBIRTH(I),I=151,1350)
      IRGRA=IRGRA+4400
      IRGRB=IRGRB+1200
      GO TO 13
7     IF(ANEUNO-SAMPLE)10,8,8
8     NOSAMP=NOSAMP+1
      ANEUNO=0.0
      CALL OUTPUT
      IF(ITMAG-1)81,82,81
   81 IF(NOSAMP-JOBFIN)10,9,9
   82 IF(NAC1(1)-2) 9,84,9
   84 IF(NOCOU-33)9,85,9
   85 CALL AUTO
      IF(ITER-10) 103,9,9
    9 CONTINUE
      CALL END
10    CALL CRNEU
      IF(NSENSE)11,13,11
```

```
11    PRINT 12                                                          1718
12    FORMAT(120H0SERIAL  STEP   EN     LETH    WT    L      M      N   NBS1719
     2   X        Y       Z        TIME     FATE  ISO.  ACT.  RAN. LAW  NSECS)   1720
13    IF(NSENSE)14,15,14                                                1721
14    PRINT                 33,ANEUNO,IWORK1,EIN,UIN,WIN,WORK3,WORK4,WORK5   1722
     2,WORK6,WORK7,WORK8,WORK19                                         1723
15    CALL TRACK                                                        1724
      WORK1=WIN                                                         1725
      ISCOLM=ISCOLL                                                     1726
      GO TO (17,16,22),ISCOLM                                           1727
16    PESC=PESC+WORK1                                                   1728
      GO TO 18                                                          1729
17    CESC=CESC+WORK1                                                   1730
18    IF(NSENSE)19,20,19                                                1731
19    PRINT                  34,ANEUNO,IWORK1,EIN,UIN,WIN,WORK3,WORK4,WORK   1732
     25,WORK16,WORK17,WORK18,WORK19,ISCOLM                              1733
   20 CONTINUE
505   IF(IWORK1)506,506,507                                             1744
506   ANOCOL=ANOCOL+WORK1                                               1745
      GO TO 1                                                        NBS1746
  507 IF(IWORK1-1)1,508,509                                          NBS1747
508   I=ICOLL(1)                                                        1748
      ONCOL(I)=ONCOL(I)+WORK1                                           1749
      GO TO 1                                                        NBS1750
509   NOIN=0                                                            1751
      DO 511 I=1,IWORK1                                                 1752
      IF(ICOLL(I)-2)511,511,510                                         1753
510   NOIN=NOIN+1                                                       1754
      LAWTP(NOIN)=LAWTP(I)                                              1755
511   CONTINUE                                                          1756
      IF(NOIN-2)518,512,518                                             1757
512   IF(LAWTP(1)-LAWTP(2))513,514,514                                  1758
513   I=LAWTP(2)                                                        1759
      J=LAWTP(1)                                                        1760
      GO TO 515                                                         1761
514   I=LAWTP(1)                                                        1762
```

```
      J=LAWTP(2)                                                       1763
  515 IF(I-5)516,516,518                                               1764
  516 IF(J-5)517,517,518                                               1765
  517 TOCOL(I,J)=TOCOL(I,J)+WORK1                                      1766
  518 IF(ICOLL(1)-2)524,519,519                                        1767
  519 J=ICOLL(1)-1                                                     1768
      NOIN = 0                                                         1769
      DO 521 I=1,IWORK1                                                1770
      IF(ICOLL(I)-2)521,520,520                                        1771
  520 NOIN=NOIN+1                                                      1772
  521 CONTINUE                                                         1773
      IF(NOIN-1)522,522,523                                            1774
  522 DEGENE(J)=DEGENE(J)+WORK1                                        1775
      GO TO 1                                                       NBS1776
  523 DEGENI(J)=DEGENI(J)+WORK1                                        1777
      GO TO 1                                                       NBS1778
  524 NOIN=0                                                           1779
      DO 526 I=1,IWORK1                                                1780
      IF(ICOLL(I)-2)526,525,525                                        1781
  525 NOIN=NOIN+1                                                      1782
      NOIN1=ICOLL(I)                                                   1783
  526 CONTINUE                                                         1784
      IF(NOIN-1)527,529,528                                            1785
  527 ALLEL=ALLEL+WORK1                                                1786
      GO TO 1                                                       NBS1787
  528 EVDGEN=EVDGEN+WORK1                                              1788
      GO TO 1                                                       NBS1789
  529 J=NOIN1-1                                                        1790
      EDGEN(J)=EDGEN(J)+WORK1                                          1791
      GO TO 1                                                       NBS1792
                                                                       1794
C     COLSN                                                            1795
                                                                       1796
   22 IWORK1=IWORK1+1                                                  1797
      CALL CR                                                          1798
      IF(IFB4)23,24,23                                                 1799
```

```
23    CALL CALC
      CALL NAPAN
24    WORK1=WOUT
      IF(IWORK1-100)25,25,26
25    IF(NREACT(1)-2)532,531,532
531   ICOLL(IWORK1)=1
      IF(IWORK1-1)26,5310,26
5310  ALAM(1)=ALAM(1)+WORK1
      GO TO 26
532   IF(NREACT(1)-16)534,533,533
533   ICOLL(IWORK1)=2
      IF(IWORK1-1)26,5330,26
5330  ALAM(2)=ALAM(2)+WORK1
      GO TO 26
534   DO 535 I=1,NLWREV
      IF(NOLAW(1)-LAWREV(I))535,536,535
535   CONTINUE
      ICOLL(IWORK1)=3
      LAWTP(IWORK1)=1
      IF(IWORK1-1)26,5350,26
5350  ALAM(3)=ALAM(3)+WORK1
      GO TO 26
536   ICOLL(IWORK1)=LWNO(I)+3
      LAWTP(IWORK1)=LWNO(I)+1
      IF(IWORK1-1)26,5360,26
5360  ALAM(I+3)=ALAM(I+3)+WORK1
26    IF(NSECS)32,507,27
27    WORK10=WOUT
      DO 31 I=1,NSECS
      WORK12=EOUT(I)
      WORK9=UOUT(I)
      IF(WORK12-THERM)28,29,29
28    WORK12=THERM
      WORK9=LOG (THERM/0.25E-7)
29    ANGLE=COSPHI(I)
      CALL TWIST(ANGLE)
```

```
      CALL WRIBT
      IF(NSENSE)30,31,30
30    PRINT                    34,ANEUNO,IWORK1,EOUT(I),UOUT(I),WOUT,WORK13,
     2WORK14,WORK15,WORK16,WORK17,WORK18,WORK19,ISCOLM,NONUC(I),NOACT(I)
     3,NORNGE(I),NOLAW(I),NSECS
31    CONTINUE
32    GO TO 1
33    FORMAT(1H0,F7.0,I4,9F7.3,F10.4,I5,3I6,I5,I7)
34    FORMAT(1X,F7.0,I4,9F7.3,F10.4,I5,3I6,I5,I7)
      END
```

```
      SUBROUTINE INPUT                                                  0123
C                                                                       0204
C     GENERAL INPUT FOR TRUNCATED CONE, INCIDENT NEUTRONS ALONG THE AXISNBS0205
C                                                                       0206
      INCLUDE CINC1                                                    NBS
      DIMENSION STDIST(25),ANGS(25),AREA(25),NOACA(24)                 NBS0207
      READ(5,201)IFB4,NSENSE                                           NBS0219
      READ(5,202)HITE,FRAD,ANGLE                                       NBS0224
      WRITE(6,204)HITE,FRAD,ANGLE                                      NBS0225
  204 FORMAT(46HOTHE SCATTERER IS A TRUNCATED CONE OF LENGTH =,F7.3,   NBS0226
     127HCMS, ENTRANCE FACE RADIUS =,F7.3,21HCMS, AND HALF ANGLE =,    NBS0226A
     2F7.5,8HRADIANS.)                                                 NBS0226B
      HITE=HITE/2.                                                     NBS0226C
      READ(5,201)JOBFIN,ITMAG                                           0227
      READ(5,202)            SAMPLE                                     0228
      WRITE(6,2040)             JOBFIN,SAMPLE                           0229
 2040 FORMAT(14HOTHERE WILL BE,I3,16H SAMPLES EACH OF,F8.0,10H NEUTRONS. 0230
     2)                                                                 0231
      IF(ITMAG-1)2043,2042,2043                                         0232
 2042 WRITE(6,2041)                                                     0233
 2041 FORMAT(1H ,31H AUTOMATIC ITERATION REQUESTED.,10X,17H ONE SAMPLE O 0234
     1NLY.)                                                             0235
      JOBFIN=1                                                          0236
 2043 READ(5,202)STRTE                                                  0237
      IF(STRTE)205,206,205                                              0238
205   WRITE(6,207)            STRTE                                     0239
207   FORMAT(21HOSTARTING ENERGY IS =,F8.3,4H MEV)                      0240
      GO TO 208                                                         0241
206   WRITE(6,209)                                                      0242
209   FORMAT(41HOSTARTING ENERGY IS FROM FISSON SPECTRUM.)              0243
208   READ(5,202)            DIST                                       0244
      THETAM=COS(ATAN(FRAD/(-DIST-HITE)))                              NBS0245
      WRITE(6,210)THETAM,DIST                                           0247
210   FORMAT(71HOCOSINE OF SEMI-VERTICAL ANGLE OF THE CONE JUST ENCLOSIN 0248
     2G THE SAMPLE  =,F8.6,12H FROM SOURCE,F6.2,22H CMS ALONG THE X AXISNBS0249
     3.)                                                                0250
```

```
      READ(5,201)NSTDP
      READ(5,202)(ANGS(I),STDIST(I),I=1,NSTDP)
      WRITE(6,2010)(ANGS(I),STDIST(I),I=1,NSTDP)
 2010 FORMAT(31H0START DISTRIBUTION PROVIDED IS /9(6F10.4/))
 201  FORMAT(6I10)
 202  FORMAT(6F10.4)
C     DEFINE START DISTRIBUTION TO INCLUDE THE MINIMUM ANGLE WHICH WILL
C     JUST ENCLOSE THE SAMPLE (USUALLY ABOUT 10-16 DEGREES) BY UP TO 25 NBS
C     POINTS.
      DO 211 I=1,NSTDP
      ANGS(I)=COS (ANGS(I)/57.295828)                                  NBS
 211  CONTINUE
      DO 212 I=1,NSTDP
      IF(THETAM-ANGS(I))212,213,213
 212  CONTINUE
      WRITE(6,2120)
 2120 FORMAT(41HINSUFFICIENT START DISTRIBUTION PROVIDED.)
      CALL EEXIT
 213  AREA(1)=0.0
      STDIST(I)=STDIST(I-1)-(STDIST(I-1)-STDIST(I))*(ANGS(I-1)-THETAM)/(
     2ANGS(I-1)-ANGS(I))
      ANGS(I)=THETAM
      L=I-1
      LI=I-1
      DO 214 K=1,L
      AREA(K+1)=AREA(K)+((STDIST(K+1)+STDIST(K))/2.0)*(ANGS(K)-ANGS(K+1)
     2)
 214  CONTINUE
      DO 215 K=1,64
      AI=K
      SEG=(AREA(I)*(2.0*AI-1.0))/128.0
      DO 216 L=1,I
      IF(AREA(L)-SEG)216,217,218
 216  CONTINUE
      WRITE(6,2160)
 2160 FORMAT(63H1ERROR IN INPUT. PARTIAL SUM LRSS THAN THE TOTAL.  CALL
```

```
     2EXIT.   )                                                          0287
      CALL EExIT                                                         0288
 217  CNPHI(K)=ANGS(L)                                                   0289
      GO TO 215                                                          0290
 218  GRAD=(STDIST(L)-STDIST(L-1))/(ANGS(L)-ANGS(L-1))                   0291
      IF(GRAD)300,301,300                                                0292
 300  CNPHI(K)=ANGS(L-1)-(STDIST(L-1)-SQRT ((STDIST(L-1)*STDIST(L-1))-2.NBS0293
     20*GRAD*(SEG-AREA(L-1))))/GRAD                                      0294
      GO TO 215                                                          0295
 301  CNPHI(K)=ANGS(L)+(AREA(L)-SEG)/STDIST(L)                           0296
 215  CONTINUE                                                           0297
      WRITE(6,219)(CNPHI(I),I=1,64)                                      0298
 219  FORMAT(55H064 EQUI-PROBABLE COSINES OF THE START DISTRIBUTION ARE/ 0299
     2(8F14.6))                                                          0300
      TANGLE=TAN(ANGLE)                                                 NBS0301
      RINC=HITE*TANGLE*2.                                               NBS0301A
      BRAD=FRAD+RINC                                                    NBS0301B
      FLUXFT=(HITE*(FRAD**2+FRAD*RINC+(RINC**2)/3))/(((DIST+HITE)**2)*  NBS0302
     1(1-THETAM))                                                       NBS0303
      M1=IXMAT+2*NMATS                                                   0304
      FNEGS=NEGS-1.0                                                     0305
      N=M1+4*NMATS                                                       0307
      MISSM=IDATA(N)                                                     0308
      UIN=LOG (STRTE/0.25E-7)                                           NBS
      S=STRTE                                                           EU.
      LGR=1                                                             EU.
      IF(S-EMC(1))5000,5000,4999                                        EU.NBS
 4999 IF(NEGS-128)4001,4001,5001                                        EU.
 5001 M=129                                                             EU.
      LGR=M                                                             EU.NBS
      IF(S-EMC(M))5002,5000,5003                                        EU.
 5002 M=M-64                                                            EU.
      GO TO 4020                                                        EU.
 5003 M=M+64                                                            EU.
      GO TO 4020                                                        EU.
 4001 M=65                                                              EU.
```

```
4020 LGR=M                                                     EU.
     IF(S-EMC(M))4030,5000,4040                                EU.
4030 M=M-32                                                    EU.
     GO TO 4050                                                EU.
4040 M=M+32                                                    EU.
4050 LGR=M                                                     EU.
     IF(S-EMC(M))4060,5000,4070                                EU.
4060 M=M-16                                                    EU.
     GO TO 4080                                                EU.
4070 M=M+16                                                    EU.
4080 LGR=M                                                     EU.
     IF(S-EMC(M))4090,5000,4100                                EU.
4090 M=M-8                                                     EU.
     GO TO 4110                                                EU.
4100 M=M+8                                                     EU.
4110 LGR=M                                                     EU.
     IF(S-EMC(M))4120,5000,4130                                EU.
4120 M=M-4                                                     EU.
     GO TO 4140                                                EU.
4130 M=M+4                                                     EU.
4140 LGR=M                                                     EU.
     IF(S-EMC(M))4150,5000,4160                                EU.
4150 M=M-2                                                     EU.
     GO TO 4170                                                EU.
4160 M=M+2                                                     EU.
4170 LGR=M                                                     EU.
     IF(S-EMC(M))4180,5000,4190                                EU.
4180 M=M-1                                                     EU.
     GO TO 4200                                                EU.
4190 M=M+1                                                     EU.
4200 LGR=M                                                     EU.
     IF(S-EMC(M))4210,5000,5000                                EU.
4210 LGR=M-1                                                   EU.
5000 M2=IDATA(M1)+LGR-MISSM                                    EU.
     AVPATH=DATA(M2)                                             0313
     FLUXFT=FLUXFT/AVPATH                                        0314
```

```
      AVCOS=(CNPHI(32)+CNPHI(33))/2.0                                      0315
      DO 2150 I=1,LI                                                       0316
      IF(ANGS (I+1)-AVCOS)2151,2152,2150                                   0317
 2150 CONTINUE                                                             0318
      I=LI                                                                 0319
 2151 FACT=STDIST(I)-(STDIST(I)-STDIST(I+1))*((ANGS (I)-AVCOS)/(ANGS (I)   0320
     2-ANGS (I+1)))                                                        0321
      GO TO 2153                                                           0322
 2152 FACT=STDIST(I)                                                       0323
 2153 FLUXFT=FLUXFT*STDIST(1)/FACT                                         0324
      READ(5,201)NLWREV                                                    0325
      READ(5,220)(LAWREV(I),LWNO(I),I=1,NLWREV)                            0326
      WRITE(6,2193)                                                        0327
 2193 FORMAT(38H0LAW REFERENCE NUMBER  M.C.LAW NUMBER.)                    0328
      WRITE(6,2194)(LAWREV(I),LWNO(I),I=1,NLWREV)                          0329
 2194 FORMAT(I10,10X,I10)                                                  0330
      IF(IFB4)2192,234,2192                                                0339
 2192 READ(5,201)IANALA,IANALB,IANALC,IANALD                               0340
      READ(5,201)NANAL                                                     0341
      READ(5,220)           (NUCL(I),NAC1(I),I=1,NANAL)                    0342
 220  FORMAT(2I10)                                                         0343
      WRITE(6,221)NANAL                                                    0344
 221  FORMAT(15H0B4 ANALYSIS ON,I3,10H ACTIONS. )                       NBS0345
      WRITE(6,222)             (NUCL(I),I=1,NANAL)                         0346
 222  FORMAT(15H0NUCLIDE NOS.  ,24I4)                                      0347
      WRITE(6,223)             (NAC1(I),I=1,NANAL)                         0348
 223  FORMAT(16H0K.P.ACTION NOS.,I3,23I4)                                  0349
      M3=M1-NMATS                                                          0350
      IXNUC1=IDATA(M3)                                                     0351
      M4=M3+4*NMATS                                                        0352
      NUCS=IDATA(M4)                                                       0353
      DO 3 I=1,NANAL                                                       0354
      M5=IXNUC1+NUCL(I)                                                    0355
      M6=8*NUCS+M5                                                         0356
      NOACA(I)=IDATA(M6)                                                   0357
      IXACT1(I)=IDATA(M5)                                                  0358
```

```
      MMM=2*NOACA(I)+IXACT1(I)
      K=1
      NOACA1=NOACA(I)
      DO 4 J=1,NOACA1
      L=MMM+K
      IF(IDATA(L)-NAC1(I))7,5,7
 7    K=K+1
 4    CONTINUE
      WRITE(6,6)             NAC1(I)
      CALL EXIT
 5    NACT(I)=K
 3    CONTINUE
 6    FORMAT(18H K.P.ACTION NUMBER,I4,29H DOES NOT APPEAR IN THE DATA.)
      WRITE(6,224)               (NACT(I),I=1,NANAL)
 224  FORMAT(15HOM.C.ACTION NO.,24I4)
      READ(5,202)(FCCOS(I),I=1,33)
C     33 COSINES WITH 33 VALUES OF THE ANGULAR DISTRIBUTION MUST BE
C     SUPPLIED, WITH MONOTONICALLY INCREASING VALUES OF THE COSINE.
      DO 225 J=1,NANAL
      READ(5,202)(FCVAL(J,I),I=1,33)
      AREB=0.0
      DO 228 I=1,32
      AREB=AREB+ABS (FCCOS(I+1)-FCCOS(I))*((FCVAL(J,I)+FCVAL(J,I+1))/2.0
     2)
 228  CONTINUE
      IA=1
      IB=15
 2280 WRITE(6,226)(FCCOS(I),I=IA,IB)
 226  FORMAT(15HOCOSINES        ,15F7.3)
      WRITE(6,227)(FCVAL(J,I),I=IA,IB)
 227  FORMAT(15H DISTRIBUTION  ,15F7.3)
      DO 229 I=IA,IB
      FCVAL(J,I)=FCVAL(J,I)/AREB
 229  CONTINUE
      WRITE(6,230)(FCVAL(J,I),I=IA,IB)
 230  FORMAT(15H DIFF. X SECT. ,15F7.3)
```

```
      IF(IA-1)2300,2300,2301
 2300 IA=16
      IB=30
      GO TO 2280
 2301 IF(IA-16)2302,2302,225
 2302 IA=31
      IB=33
      GO TO 2280
 225  CONTINUE
      IMINM=1
      DO 252 L=1,NANAL
      IMIN(L)=IMINM
      READ(5,250)IMAX(L)
 250  FORMAT(I10)
      PRINT 251,IMAX(L),L
 251  FORMAT(10HUTHERE ARE,I2,46H SUPPLEMENTARY RANGES ASSOCIATED WITH A
     2NALYSIS,I2)
      IF(IMAX(L))252,252,253
 253  IMAXM=IMAX(L)-1+IMINM
      DO 254 I=IMINM,IMAXM
      READ(5,202)ENVAL(L,I)
      READ(5,202)(SUPVAL(I,K),K=1,33)
      AREB=0.0
      DO 258 J=1,32
      AREB=AREB+ABS (FCCOS(J+1)-FCCOS(J))*((SUPVAL(I,J)+SUPVAL(I,J+1))/2
     2.0)
 258  CONTINUE
      IA=1
      IB=15
 259  WRITE(6,2580)ENVAL(L,I)
 2580 FORMAT(25H0THIS RANGE APPLIES BELOW,F7.4,5H MEV.)
      WRITE(6,226)(FCCOS(J),J=IA,IB)
      WRITE(6,227)(SUPVAL(I,J),J=IA,IB)
      DO 260 J=IA,IB
      SUPVAL(I,J)=SUPVAL(I,J)/AREB
 260  CONTINUE
```

```
      WRITE(6,230)(SUPVAL(I,J),J=IA,IB)                                0431
      IF(IA-1)261,261,262                                              0432
261   IA=16                                                            0433
      IB=30                                                            0434
      GO TO 259                                                        0435
262   IF(IA-16)263,263,254                                             0436
263   IA=31                                                            0437
      IB=33                                                            0438
      GO TO 259                                                        0439
254   CONTINUE                                                         0440
      IMINM=IMAXM+1                                                 NBS0441
      IF(IMAXM-24)252,252,256                                          0442
256   WRITE(6,257)                                                     0443
257   FORMAT(27H1IMAX HAS EXCEEDED 24-HALT.)                           0444
      CALL EEXIT                                                       0445
252   CONTINUE                                                         0446
      READ(5,201)NOCOU                                                 0447
      READ(5,202)             (COUNT(I),I=1,NOCOU)                     0448
      WRITE(6,232)              NOCOU,(COUNT(I),I=1,NOCOU)             0449
232   FORMAT(10H0THERE ARE,I3,56H COUNTERS LOCATED AROUND THE EQUATOR OFNBS0450
     2 THE SCATTERER AT/(10F9.4))                                   NBS0451
      READ(5,201)             NENSP                                    0452
      READ(5,202)             (ENSP(I),I=1,NENSP)                      0453
      WRITE(6,233)              (ENSP(I),I=1,NENSP)                    0454
233   FORMAT(48H0THE ENERGY SPECTRA OF THE B4 ANALYSIS CELLS ARE/(10F9.3 0455
     2))                                                               0456
234   DO 2340 K=1,32                                                   0457
      FCCOSD(K)=FCCOS(K+1)-FCCOS(K)                                    0458
2340  CONTINUE                                                         0459
      RETURN                                                           0460
      END                                                              0463
```

```
      SUBROUTINE CRNEU                                                  3036
C
C     TRUNCATED CONE SCATTERING SAMPLE, INCIDENT NEUTRONS ALONG THE AXISNBS
C
      INCLUDE CINC1                                                     NBS
      DIMENSION TEMP(10),TRIG(4)                                        3116
   61 ITEMP=NRANDA(64)                                               NBS3121
      WORK3=CNPHI(ITEMP)                                                3122
   62 TEMP(1)=RANDA(-1)                                              EU.3124
      TEMP(2)=RANDA(-2)                                              EU.3126
      TEMP(3)=TEMP(1)*TEMP(1)                                           3127
      TEMP(4)=TEMP(2)*TEMP(2)                                           3128
      TEMP(5)=TEMP(3)+TEMP(4)                                           3129
      IF(TEMP(5))62,62,63                                               3130
 63   IF(TEMP(5)-1.0)64,62,62                                           3131
 64   TRIG(1)=(TEMP(3)-TEMP(4))/TEMP(5)                                 3132
      TRIG(2)=(2.0*TEMP(1)*TEMP(2))/TEMP(5)                             3133
      TRIG(3)=SQRT (1.0-WORK3*WORK3)                                 NBS3134
      WORK4=TRIG(1)*TRIG(3)                                             3135
      WORK5=TRIG(2)*TRIG(3)                                             3136
C                                                                       3137
C     DOES THE NEUTRON HIT THE TARGET                                   3138
C                                                                       3139
      TEMP(1)=FRAD+(DIST+HITE)*TRIG(3)/WORK3                         NBS3140
      IF(TEMP(1))67,67,65                                               3142
   65 TEMP(2)=-(DIST+HITE)/WORK3                                     NBS3143
   66 WORK6=-HITE                                                    NBS3145
      WORK7=WORK4*TEMP(2)                                            NBS3146
      WORK8=WORK5*TEMP(2)                                            NBS3147
      ANEUNO=ANEUNO+1.0                                                 3148
      EIN=STRTE                                                         3149
      UIN=LOG (EIN/0.25E-7)                                          NBS3150
      MAT=1                                                          NBS3151
      IWORK1=0                                                          3152
      WORK19=0.0                                                        3153
      WIN=1.0                                                           3154
```

```
      WORK11=0.0
      IWORK2=0
      RETURN
   67 AMISS=AMISS+1.0
      GO TO 61
      END
```

```
      SUBROUTINE TRACK
C     TRACKS NEUTRONS IN A TRUNCATED CONE WITH AXIS LYING ALONG THE NEUTRON BEAM
      INCLUDE CINC1
      CALL EGMV
      PATHL=(-(LOG(RANDA(1))))*PATH
      IF(WORK3)1,6,2
    1 TRS=-(HITE+WORK6)/WORK3
      RAD2=FRAD**2
      GO TO 3
    2 TRS=(HITE-WORK6)/WORK3
      RAD2=BRAD**2
    3 WORK17=WORK7+TRS*WORK4
      WORK18=WORK8+TRS*WORK5
      TRR2=WORK17**2+WORK18**2
      IF(RAD2.LT.TRR2)GO TO 6
      IF(TRS.GT.PATHL)GO TO 13
      ISCOLL=2
      IF(WORK3.GT.0)GO TO 4
      WORK16=-HITE
      GO TO 5
    4 WORK16=HITE
    5 WORK19=WORK19+TRS/SPEED
      RETURN

    6 CALL FONEC(PATHL)
      IF(HITE.LE.ABS(WORK16))GO TO 7
      TRA2=WORK17**2+WORK18**2
      RAD2=(FRAD+(HITE+WORK16)*TANGLE)**2
      IF(RAD2.GT.TRA2)GO TO 14
    7 ISCOLL=1
      NRTS=0
      RAD=FRAD+(HITE+WORK6)*TANGLE
      TA=1.-WORK3**2*(1.+TANGLE**2)
      TB=WORK7*WORK4+WORK8*WORK5-WORK3*TANGLE*RAD
```

```
      TC=WORK7**2+WORK8**2-RAD**2
      IF(ABS(TA).GT.1.E-30)GO TO 8
      IF(ABS(TB).LT.1.E-30)GO TO 21
      TR=-TC/(2.*TB)
      GO TO 12
    8 TD=TB*TB-TA*TC
      IF(TD)15,10,9
    9 TE=-TB+SQRT(TD)
      IF(TE.LT.0)GO TO 10
      NRTS=1
      TR=TE/TA
   10 TE=-TB-SQRT(TD)
      IF(TE.LT.0)GO TO 11
      NRTS=NRTS+1
      TR=TE/TA
   11 IF(NRTS-1)17,12,19
   12 CALL FONEC(TR)
      WORK19=WORK19+TR/SPEED
      RETURN

   13 CALL FONEC(PATHL)
   14 ISCOLL=3
      WORK19=WORK19+PATHL/SPEED
      RETURN

C     ERROR EXITS

   15 WRITE(6,16)
   16 FORMAT(24H IMAGINARY ROOT IN TRACK)
      GO TO 23
   17 WRITE(6,18)
   18 FORMAT(26H NO POSITIVE ROOT IN TRACK)
      GO TO 23
   19 WRITE(6,20)
   20 FORMAT(28H TWO POSITIVE ROOTS IN TRACK)
      GO TO 23
```

```
21 WRITE(6,22)
22 FORMAT(28H INDETERMINATE ROOT IN TRACK)
23 WRITE(6,24)WORK3,WORK4,WORK5,WORK6,WORK7,WORK8,PATHL
24 FORMAT(7F10.3)
   CALL EEXIT
   END
```

```
      SUBROUTINE NAPAN                                                  3371
      INCLUDE CINC1                                                     NBS
      DIMENSION FACT(33),PATHLL(33),ANGLEE(33),KL(33)                   NBS3451
      NENSP1=NENSP-1                                                    3453
      M1=IXMAT+NMATS+MAT                                                3454
      N=M1+4*NMATS                                                      3455
      MISSM=IDATA(N)                                                    3456
      M2=IDATA(M1)-MISSM                                                3457
      DO 1 I=1,NOCOU                                                    3458
      COSOM=COUNT(I)                                                    3459
      CALL FPATH(COSOM,PATHL,ANGLEF)                                    NBS3460
      DO 2 K=1,32                                                       3461
      IF(FCCOS(K+1)-ANGLEF)2,3,3                                        NBS3462
    2 CONTINUE                                                          3463
      K=32                                                              3464
    3 AFCOS=FCCOS(K)                                                    3465
      FACT(I)=(ANGLEF-AFCOS)/FCCOSD(K)                                  NBS3466
      PATHLL(I)=PATHL                                                   3467
      ANGLEE(I)=ANGLEF                                                  NBS3468
      KL(I)=K                                                           3469
    1 CONTINUE                                                          3470
      DO 7 J=1,NANAL                                                    3471
      NFORM=0                                                           3472
      NAC=NAC1(J)                                                       3473
      NUCLID=NUCL(J)                                                    3474
      PART=PART1(J)                                                     3475
      ATOM=ATOM1(J)                                                     3476
      WSQ=ATOM*ATOM-1.0                                                 3477
      DO 6 I=1,NOCOU                                                    3478
      K=KL(I)                                                           3479
      AS=ANGLEE(I)                                                      3480
      FACTOR=FACT(I)                                                    3481
      PATHL=PATHLL(I)                                                   3482
      ASQ=AS*AS                                                         3483
      IF(PART)7,7,8                                                     3484
```

```
8     IF(NAC-2)9,10,9                                                     3485
10    X=SQRT (ASQ+WSQ)                                                 NBS3486
      P=((AS+X)/(ATOM+1.0))*((AS+X)/(ATOM+1.0))                           3487
      REDEN=EIN*P                                                         3488
      GO TO 11                                                            3489
9     IF(NFORM)34,34,35                                                   3490
34    CALL CREN                                                           3491
      REDEN=ENER                                                          3492
      IF(REDEN)38,11,11                                                   3493
35    GO TO (36,11,11,11,11,11,11,11,36,11,11,11,11,11,11,11),NFORM    NBS3494
36    P=(AS+SQRT (ASQ+ATOM*QV*(1.0+ATOM)/EIN+WSQ))/(1.0+ATOM)          NBS3495
      REDEN=EIN*P*P                                                       3496
   11 IF(IMAX(J).LE.0)GO TO 15                                         NBS3503
      IMINM=IMIN(J)                                                    NBS3504
      IMAXM=IMINM+IMAX(J)-1                                            NBS3505
      DO 50 JJ=IMINM,IMAXM                                             NBS3506
      IF(EIN-ENVAL(J,JJ))50,51,52                                      NBS3507
   50 CONTINUE                                                         NBS3508
   51 KK=JJ                                                            NBS3509
      GO TO 19                                                         NBS3510
   52 IF(JJ.LL.IMINM)GO TO 15                                          NBS3511
      KK=JJ-1                                                          NBS3512
      GO TO 19                                                            3513
15    SIGMA=(FCVAL(J,K+1)-FCVAL(J,K))*FACTOR+FCVAL(J,K)                   3514
      GO TO 16                                                            3515
19    SIGMA=(SUPVAL(KK,K+1)-SUPVAL(KK,K))*FACTOR+SUPVAL(KK,K)             3516
16    DO 20 L=1,NENSP1                                                    3517
      IF(ENSP(L+1)-REDEN)20,21,21                                         3518
20    CONTINUE                                                            3519
      L=NENSP1                                                            3520
 21   S=REDEN                                                          EU.
      LGR=1                                                            EU.
      IF(S-EMC(1))5000,5000,4999                                       NBS EU.
4999  IF(NEGS-128)4001,4001,5001                                       EU.
5001  M=129                                                            EU.
      LGR=M                                                            EU.NBS
```

```
      IF(S-EMC(M))5002,5000,5003                                 EU.
 5002 M=M-64                                                     EU.
      GO TO 4020                                                 EU.
 5003 M=M+64                                                     EU.
      GO TO 4020                                                 EU.
 4001 M=65                                                       EU.
 4020 LGR=M                                                      EU.
      IF(S-EMC(M))4030,5000,4040                                 EU.
 4030 M=M-32                                                     EU.
      GO TO 4050                                                 EU.
 4040 M=M+32                                                     EU.
 4050 LGR=M                                                      EU.
      IF(S-EMC(M))4060,5000,4070                                 EU.
 4060 M=M-16                                                     EU.
      GO TO 4080                                                 EU.
 4070 M=M+16                                                     EU.
 4080 LGR=M                                                      EU.
      IF(S-EMC(M))4090,5000,4100                                 EU.
 4090 M=M-8                                                      EU.
      GO TO 4110                                                 EU.
 4100 M=M+8                                                      EU.
 4110 LGR=M                                                      EU.
      IF(S-EMC(M))4120,5000,4130                                 EU.
 4120 M=M-4                                                      EU.
      GO TO 4140                                                 EU.
 4130 M=M+4                                                      EU.
 4140 LGR=M                                                      EU.
      IF(S-EMC(M))4150,5000,4160                                 EU.
 4150 M=M-2                                                      EU.
      GO TO 4170                                                 EU.
 4160 M=M+2                                                      EU.
      IF(S-EMC(M))4180,5000,4190                                 EU.
 4170 LGR=M                                                      EU.
 4180 M=M-1                                                      EU.
      GO TO 4200                                                 EU.
 4190 M=M+1                                                      EU.
```

```
4200 LGR=M                                                               EU.
     IF(S-EMC(M))4210,5000,5000                                          EU.
4210 LGR=M-1                                                             EU.
5000 M3=M2+LGR                                                           EU.
     PATHB=(-DATA(M3))                                                     3524
     QU=Q(J)                                                               3525
     PTH=PATHL/PATHB                                                       3526
     ADD=QU*SIGMA*EXP (PTH)                                                3527
     DEA(I,L)=DEA(I,L)+ADD                                              NBS3529
     IF(NAC.NE.2)GO TO 24                                               NBS3530
     IF(IWORK1.LE.1)GO TO 23                                            NBS3531
     III=IWORK1-1                                                       NBS3532
     DO 22 II=1,III                                                     NBS3533
     IF(ICOLL(II).NE.1)GO TO 24                                         NBS3534
  22 CONTINUE                                                           NBS3535
  23 DEB(I,L)=DEB(I,L)+ADD                                              NBS3537
     IF(IWORK1.LE.1)GO TO 6                                             NBS3539
     DED(I,L)=DED(I,L)+ADD                                              NBS3540
     GO TO 6                                                               3541
  24 DEC(I,L)=DEC(I,L)+ADD                                              NBS3543
6    CONTINUE                                                              3544
7    CONTINUE                                                              3545
     GO TO 40                                                              3546
38   PRINT 39,REDEN                                                        3547
39   FORMAT(1H0,F10.4,32HNEGATIVE ENERGY COMPUTED IN CREN)                 3548
     CALL EXIT                                                             3549
40   RETURN                                                                3550
     END                                                                   3551
```

```
      SUBROUTINE FPATH(COSOM,PATHL,ANGLEF)

C     PATHLENGTH AND ANGLE FOR B4 ANALYSIS, FOR TRUNCATED CONE SAMPLE.
C     AXIS ALONG THE INCIDENT NEUTRON BEAM.

      INCLUDE CINC1

C     NEUTRON OUT AT 90 DEGREES.
      IF(ABS(COSOM).GE.1.E-5)GO TO 1
      ANGLEF=WORK4
      TSQ=TANGLE**2
      XPR=FRAD/TANGLE+HITE+WORK16
      PATHL=SQRT(XPR*XPR*TSQ-WORK18**2)-WORK17
      RETURN

C     NEUTRON OUT ENTRANCE FACE
    1 SINOM=SQRT(1.-COSOM**2)
      ANGLEF=COSOM*WORK3+SINOM*WORK4
      IF(COSOM.GT.0)GO TO 2
      IF(FRAD.LT.ABS(WORK18))GO TO 3
      FTAN=(SQRT(FRAD**2-WORK18**2)-WORK17)/(HITE+WORK16)
      TANOM=SINOM/COSOM
      IF(FTAN+TANOM.LT.0)GO TO 3
      PATHL=-(HITE+WORK16)/COSOM
      RETURN

C     NEUTRON OUT EXIT FACE
    2 BTAN=(SQRT(BRAD**2-WORK18**2)-WORK17)/(HITE-WORK16)
      TANOM=SINOM/COSOM
      IF(BTAN.LT.TANOM)GO TO 3
      PATHL=(HITE+WORK16)/COSOM
      RETURN

C     NEUTRON OUT THE SIDE, BUT NOT AT 90 DEGREES, NORMAL SOLUTION.
    3 TSQ=TANGLE**2
      XPR=FRAD/TANGLE+HITE+WORK16
```

```
      PA=SINOM**2-(COSOM**2)*TSQ
      PB=WORK17*SINOM-XPR*COSOM*TSQ
      PC=WORK17**2-(XPR**2)*TSQ+WORK18**2
      IF(ABS(PA).LT.1.E-30)GO TO 4
      PATHL=(SQRT(PB**2-PA*PC)-PB)/PA
      RETURN
C     LINEAR SOLUTION
    4 PATHL=-PC/(2.*PB)
      RETURN
      END
```

```
      SUBROUTINE FPATH(COSOM,PATHL,ANGLEF)
C
C     PATHLENGTH AND ANGLE FOR THE B4 ANALYSIS, FOR A CYLINDRICAL SAMPLE
C     WITH ITS AXIS ALONG THE INCIDENT NEUTRON BEAM.
C
      INCLUDE CINC1
      PATHL=SQRT(FRAD**2-WORK18**2)-WORK17
      IF(ABS(COSOM).GT.1E-5)GO TO 1
      ANGLEF=WORK4
      GO TO 3
    1 SINOM=SQRT(1-COSOM**2)
      TANOM=SINOM/COSOM
      ANGLEF=COSOM*WORK3+SINOM*WORK4
      IF(COSOM.GT.1E-5)GO TO 2
      FTAN=PATHL/(HITE+WORK16)
      IF((FTAN+TANOM).LT.1E-5)GO TO 3
      PATHL=-(HITE+WORK16)/COSOM
      RETURN
    2 FTAN=PATHL/(HITE-WORK16)
      IF(FTAN.LT.TANOM)GO TO 3
      PATHL=(HITE+WORK16)/COSOM
      RETURN
    3 PATHL=PATHL/SINOM
      RETURN
      END
```

```
      SUBROUTINE OUTPUT                                                 3878
C     OUTPUTS RESULTS AT THE END OF EACH SAMPLE.                        3879

      INCLUDE CINC1                                                  NBS
      DIMENSION P(33)                                                   3958
      PRINT             1,(HEAD(I),I=1,12)                              3960
    1 FORMAT(12A6)                                                      3961
      PRINT             2,NOSAMP                                        3962
    2 FORMAT(1H0,52X,13HSAMPLE NUMBER,I3)                               3963
      PRINT             3,SAMPLE                                        3964
    3 FORMAT(1H0,40X,F8.0,33H NEUTRONS STARTED IN EACH SAMPLE.)         3965
      PART =NOSAMP                                                      3966
      TOT=PART*SAMPLE                                                   3967
      PRINT             5,TOT                                           3968
    5 FORMAT(1H0,39X,F9.0,35H NEUTRONS HAVE BEEN TRACKED SO FAR.)       3969
      PRINT             4,PESC,CESC                                     3970
    4 FORMAT(24H0PLANE SURFACE ESCAPES =,F11.3/24H0CURVED SURFACE ESCAPE 3971
     2S=,F11.3)                                                         3972
      CALL OUTB3                                                        3973
      I1=NENSP-1                                                        3974
      IF(IFB4.EQ.0)GO TO 7                                           NBS3975
      CALL OUTB4(DEA,1,IANALA)                                       NBS3937
      IF(IANALA.LE.0)GO TO 8                                         NBS3978
      DO 6 I=1,I1                                                    NBS3979
    6 P(I)=DEA(IANALA,I)                                             NBS3980
      CALL APLOT3(P,I1,ENSP,IANALA)                                     3982
    8 CALL OUTB4(DEB,2,IANALB)                                       NBS3984
      IF(IANALB.LE.0)GO TO 10                                        NBS3985
      DO 9 I=1,I1                                                    NBS3986
    9 P(I)=DEB(IANALB,I)                                             NBS3987
      CALL APLOT3 (P,I1,ENSP,IANALB)                                    3989
   10 CALL OUTB4(DEC,3,IANALC)                                       NBS3991
      IF(IANALC.LE.0)GO TO 12                                        NBS3992
      DO 11 I=1,I1                                                   NBS3993
   11 P(I)=DEC(IANALC,I)                                             NBS3994
      CALL APLOT3 (P,I1,ENSP,IANALC)                                    3996
```

```
12    CALL OUTB4(DED,4,IANALD)                                   NBS3998
      IF(IANALD.LE.0)GO TO 7                                     NBS3999
      DO 13 I=1,I1                                               NBS4000
13    P(I)=DED(IANALD,I)                                         NBS4001
      CALL APLOT3 (P,I1,ENSP,IANALD)                                4003
7     RETURN                                                        4004
      END                                                           4005
```

```
      SUBROUTINE AUTO                                                   1977
C
C  TO ALLOW AUTOMATIC ITERATION UNDER THE FOLLOWING CONDITIONS.         1978
C          NUMBER OF COUNTERS AND INPUT POINTS = 33.                    1979
C          ONE NUCLIDE  ONLY.                                           1980
C          ELASTIC CORRECTION ONLY.                                     1981
C     PHYSICAL ITERATION.
C     (DELTA SIGMA)/(SIGMA) IS THE CHANGE IN THE CROSS SECTION EXCLUDING
C     MULTIPLE SCATTERING.
C
      INCLUDE CINC1                                                   NBS
      DIMENSION TOTEL(33),CHI(33),ELM2(33),XIP3(33)                   NBS2062
      SUMEL=(DEB(1,33)+DEB(33,33))/32.0                                  2065
      DO 4 J=2,32                                                        2066
      SUMEL=SUMEL+DEB(J,33)/16.0                                         2067
    4 CONTINUE                                                           2068
      IF(ITER.NE.1)GO TO 300                                          NBS2073
      READ(5,101)NTERM,IFCONT                                         NBS2077
  101 FORMAT(2I10)                                                    NBS2078
      NTERM1=NTERM-1                                                     2079
      IF(IFCONT.EQ.0)GO TO 100                                        NBS
      READ(5,104)(EZP(I),I=1,33)                                      NBS
  104 FORMAT(6F10.4)                                                  NBS
      SUMEZP=(EZP(1)+EZP(33))/32                                      NBS
      DO 107 J=2,32                                                   NBS
  107 SUMEZP=SUMEZP+EZP(J)/16                                         NBS
      DO 108 J=1,33                                                   NBS
  108 EZP(J)=EZP(J)/SUMEZP                                            NBS
      GO TO 102                                                       NBS
  100 DO 105 I=1,33                                                      2074
      EZP(1)=FCVAL(1,I)                                               NBS2075
  105 CONTINUE                                                           2076
  102 IF(NTERM.LE.1)GO TO 300                                         NBS2080
  106 READ(5,103)(SAMP(I),I=1,NTERM)                                  NBS2081
  103 FORMAT(6F10.2)                                                     2082
  300 CHISQ=0.0                                                          2086
```

```
      DO 303 J=1,33                                                     NBS2087
      TOTEL(J)=DEB(J,33)/SUMEL                                             2088
      CHI(J)=((TOTEL(J)-EZP(J))**2)/EZP(J)                              NBS2089
      CHISQ=CHISQ+CHI(J)                                                   2090
      DEDNJ=DED(J,33)/SUMEL                                             NBS
      ELM2(J)=FCVAL(1,J)                                                   2097
      FACTOR=(TOTEL(J)-DEDNJ)/ELM2(J)                                   NBS
      IF(ITER.GT.2)GO TO 302                                            NBS
      XIP3(J)=(EZP(J)-DEDNJ)/FACTOR                                     NBS
      GO TO 303                                                         NBS
  302 XIP3(J)=FCVAL(1,J)/FACTOR                                         NBS
  303 CONTINUE                                                             2098
  214 SUM=(XIP3(1)+XIP3(33))/32.0                                          2099
      DO 207 J=2,32                                                        2100
      SUM=SUM+XIP3(J)/16.0                                                 2101
  207 CONTINUE                                                             2102
      DO 208 I=1,33                                                        2103
      FCVAL(1,I)=(XIP3(I))/SUM                                             2104
  208 CONTINUE                                                             2105
      DO 220 I=1,33                                                     NBS
  220 XIP3(I)=DEB(I,33)-DED(I,33)                                       NBS
      SUMSEL=(XIP3(1)+XIP(33))/32                                       NBS
      DO 221 I=2,32                                                     NBS
  221 SUMSEL=SUMSEL+XIP3(I)/16                                          NBS
      DO 222 I=1,33                                                     NBS
  222 XIP3(I)=(XIP3(I)/SUMSEL-ELM2(I))/ELM2(I)                          NBS
      PRINT 209,ITER                                                       2106
  209 FORMAT(1H1,20H AFTER ITERATION NO.,I3,49H . NORMALISATION IS UNIT    2107
     1AREA FOR ELASTIC EVENTS.)                                            2108
  216 ITER1=ITER+1                                                         2109
      PRINT 210,ITER,ITER,ITER,ITER1                                       2110
  210 FORMAT(1H0,7HCOUNTER,4X,6HCOSINE,11X,3HEXP,7X,10HOUTPUT NO.,I2,4X,   2111
     13HNO.,I2,5H CHI ,7X,3HNO.,I2,11X,3HNO.,I2,4X,11HDELTA SIGMA,2X,   NBS2112
     27HCOUNTER/2X,6HNUMBER,5X,5HANGLE,10X,5HINPUT,7X,11HALL ELASTIC,6X,   2113
     37HSQUARED,8X,5HINPUT,11X,5HINPUT,9X,6H/SIGMA,2X,6HNUMBER)         NBS2114
      PRINT 111,(J,COUNT(J),EZP(J),TOTEL(J),CHI(J),ELM2(J),FCVAL(1,J),  NBS2115
```

```
     1XIP3(J),J,J=1,33)                                                NBS2116
 111 FORMAT(I4,7F15.6,I4)                                                 2117
     PRINT 112,CHISQ                                                      2118
 112 FORMAT(1H0,8HCHISQ = ,F10.6)                                         2119
 997 IF(ITER-NTERM)415,416,416                                            2120
 415 SAMPLE=SAMP(ITER)                                                    2121
     ITER=ITER+1                                                          2122
     GO TO 999                                                            2123
 416 ITER=10                                                              2124
     GO TO 998                                                            2125
 999 CALL DATIN                                                           2126
 998 RETURN                                                               2129
     END                                                                  2130
```

```
      SUBROUTINE RANDOM(ISTART)                                         NBS

      DATA MASK/0377777777777/,MULTA/30517578125/,C/.29103830E-10/      NBS
      IR=ISTART                                                         NBS
      RETURN                                                            NBS
      ENTRY RDM(R)                                                      NBS
      IR=AND(MASK,IR*MULTA)                                             NBS
      R=C*(FLOAT(IR))                                                   NBS
      RETURN                                                            NBS
      END                                                               NBS



      FUNCTION RANDA(I)                                                 EU.4009

      CALL RDM(R)                                                       NBS4010
      RANDA=R                                                           NBS4010A
      IF(I)1,1,3                                                        EU.4011
    1 RANDA=RANDA*2.-1.                                                 EU.4012
    3 RETURN                                                            EU.4013
      END                                                               EU.4014



      FUNCTION NRANDA(I)                                                EU.0002

      CALL RDM(XRAND)                                                   NBS0003
      IF(XRAND)10,10,1                                                  EU.0004
    1 IF(XRAND-1.)20,30,30                                              EU.0005
   10 NRANDA=1                                                          EU.0006
      GO TO 40                                                          EU.0007
   20 NRANDA=XRAND*I+1                                                  EU.0008
      GO TO 40                                                          EU.0009
   30 NRANDA=I                                                          EU.0010
   40 RETURN                                                            EU.0011
      END                                                               EU.0012
```

APPENDIX B

A Brief Description of the Components of MAGGIE

1. MAGGIE (Main Program). This program calls the various subroutines required for the analysis, retrieves neutrons from disc storage when required, outputs track parameters if desired, and records the various fates of tracked neutrons.

2. RANDOM (and RDM). This subroutine contains the random number generator, RDM, as a separate entry. RANDOM is called at the beginning of program MAGGIE to enter the starting value for RDM.

3. DATIN serves to set all of the output arrays to zero, and calls ABSYND.

4. ABSYND reads the required nuclear data from the MOULD tape and puts it in encoded sequential storage in the array DATA-IDATA for use during the Monte Carlo tracking.

5. INPUT reads and processes samples and experimental angular distribution data from card input and calculates most of the flux attenuation factor.

6. CRNEU creates random incident neutrons at the entrance face of the sample, in accordance with the input source distribution.

7. TRACK tracks neutrons in the sample, specifying coordinates of collision or escape.

8. EGMV. This subroutine computes the mean free path, velocity, and lethargy group number.

9. FONEC calculates coordinates at the end of a track from initial position, direction cosines, and track length.

10. CR. This subroutine, using random sampling of the information stored by ABSYND from the MOULD data tape, determines all of the parameters of a collision.

11. CALC determines some constants used in subroutine NAPAN.

12. NAPAN. This subroutine calculates and scores the probability of detection at each detector for each collision in the sample.

13. FPATH calculates the path length in the direction of each detector for each collision.

14. CREN is an abbreviated version of CR used by NAPAN that determines only the neutron energy.

15. TWIST chooses new direction cosines after a collision.

16. WRIBT stores any secondary neutrons produced, for recall at the end of the current tracking.

17. OUTPUT, OUTB3, OUTB4 and APLOT3. These subroutines print the results of the calculation.

18. AUTO performs the calculations required for iterative correction of the elastic angular distribution, prints the current output, and calls DATIN to begin the next iteration.

19. END, and its entries EXIT and EEXIT designate normal vs. error exit conditions.

20. TAPLAB returns the tape logical unit label.

21. SRFORT is a subroutine for skipping tape records.

Input requirements for MAGGIE-NBS

	FORMAT	VARIABLE	COMMENTS
1.	O12	OCT	Octal starting value for RDM.
2.	12A6	HEAD(I)	Arbitrary heading. Column one should be a 1.
3.	I10	NMATS	The number of materials in the sample. This is always = 1.
4.	I10, E10.4	IDATA(MAT5)	Number of different nuclides in the material.
		DATA(MAT4)	Density of the material.
5.	I10, E10.4	IDATA(K2)	Nuclide reference number (i.e. position on the MOULD tape: see output of MOULD for this).
		DATA(K4)	Proportion of this nuclide in the material. This card is repeated for each nuclide in the material.
6.	2I10	IFB4	Positive for B4 output.
		NSENSE	Positive for track print.
7.	3F10.4	HITE	Length of the samples, in cm.
		FRAD	Entrance radius of same, in cm.
		ANGLE	Half-angle of same, in radians.
8.	2I10	JOBFIN	Number of independant samples (= 1 if ITMAG > 0).
		ITMAG	Positive for automatic iteration.
9.	F10.4	SAMPLE	Number of neutrons in each sample.
10.	F10.4	STRTE	Starting energy in MeV. If the starting energy is set = 0 a fission spectrum is assumed.
11.	F10.4	DIST	Distance from the center of the sample to the source (negative), in cm.
12.	I10	NSTDP	No. of start distribution points to be read in (≤25).
13.	6F10.4	ANGS(I)	Three pairs to a card, the angle and start distribution for that angle. The start distribution need not be normalized, and this card is repeated until NSTDP pairs are read in.

14.	I10	NLWREV	The number of Law Reference numbers for inelastic scatter, i.e. the number of Law Reference numbers to different angular distributions on the MOULD output (P.C.N.'s* 4-15 only) (NLWREV ≤ 50).
15.	2I10	LAWREV(I) LWNO(I)	One pair per card, the above Law Reference numbers and the monotonically increasing "Monte Carlo" law numbers allocated. Any inelastic law not given here will be printed in the B3 section results under Law zero.

NOTE: The following cards are not required if IFB4 ≤ 0.

16.	4I10	IANALA IANALB IANALC IANALD	Four markers, for the tables: A) Complete multiple scatter analysis. B) Elastic events only. C) Inelastic events only. D) Multiple elastic events only. A negative marker suppresses the table. A positive marker = N produces, in addition to the table, a graph for the Nth counter.
17.	I10	NANAL	Number of actions (index I below) (i.e. different neutron processes, such as elastic, inelastic from the 1st excited state, etc.) to be processed by the subroutine NAPAN.
18.	6F10.4	NUCL(I) NAC1(I)	The nuclide reference number (as in card 5), and the P.C.N.* for each action. There are NANAL such pairs.
19.	6F10.4	FCCOS(J)	Thirty-three values of cosine, including -1 and +1, monotonically increasing.
20.	6F10.4	FCVAL(I,J)	Thirty-three values of the angular distribution (index J) corresponding to the above values of cosines. Repeat for each action (index I) in the same order as in 18.

NOTE: The following three items are repeated, as a group, for each action.

21.	I10	IMAX(I)	Number (index L) of supplementary ranges for this action (even if zero).

*The "P.C.N.'s (Particular Classification Numbers) are listed starting on p.8 of AWRE report no. O 70/63, "The Aldermaston Nuclear Data Library as at May, 1963", K. Parker.

NOTE: The following two items are repeated for each supplementary range. If, for any action, there is no supplementary range these items are omitted.

22.	F10.4	ENVAL(I, L)	Upper limit of the range in MeV. These must be listed in order of decreasing value.
23.	6F10.4	SUPVAL(L, J)	Thirty-three values (index J) of the distribution (range L) at the cosine values FCCOS(J).
24.	I10	NOCOU	Number of counters (≤33).
25.	6F10.4	COUNT(I)	Cosines of counter locations.
26.	I10	NENSP	Number of output energy points (≤33). The output will be classified into the bins formed by these points.
27.	6F10.6	ENSP(I)	Values of output energy points in MeV.
28.	2I10	NTERM IFCONT	Number of iterations (≤10). If this is a continuation of a previous run, for further iterations this should be non-zero (see Section II.c.6.f).
29.	6F10.4	SAMP(I)	Number of neutrons for each iteration, <u>except</u> the first.

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