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SAFETY AND ENVIRONMENTAL PROTECTION DIVISION

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INDOSE - PROGRAM FOR CALCULATING RADIAL
ENERGY DEPOSITED DUE TO SCATTERED PARTICLES

M. N. Varma, J. Meo, A. V. Kuehner
and J. W. Baum

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BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

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INDOSE - Program for Calculating Radial Energy
Deposited Due to Scattered Particles

M.N. Varma, J. Meo, A.V. Kuehner and J.W. Baum
Safety and Environmental Protection Division
Brookhaven National Laboratory
Upton, New York 11973

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Abstract

A computer program, INDOSE, is described which was used to calculate energy deposited as a function of radial distance from an ion path for scattered incident particles and scattered target gas atoms. Classical Rutherford scattering theory is used to calculate scattering cross-sections. Linear energy transfer data of Northcliff and Schilling¹ were used for electronic stopping power and Lindhard, et al.² theory was used to estimate nuclear stopping power. Results are given for 2.65 MeV incident ⁴He ions and 41.1 MeV incident ¹⁶O ions.

Introduction

Recent experiments in microdosimetry aimed at increasing our understanding of radiation damage to biological systems have focused on the radial energy deposited around the path of a heavy ion beam in tissue-like material. Our experiments, Baum, et al.,³ Varma, et al.,^{4,5} and Wingate and Baum⁶, employed a variable pressure ionization chamber filled with tissue-equivalent gas into which a beam of monoenergetic heavy ions was directed. Inside this chamber, a movable, mesh ionization chamber (probe) was used to measure ionization at various radial distances from the ion path. The simulated radius in tissue was changed by varying the probe position and/or gas pressure in the chamber. From these measurements energy deposited at a given radial distance was calculated. The measured ionization consists of three components

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(a) secondary electron production, (b) scattered incident ions, and (c) recoil target gas atoms. The contribution due to (a) above has been treated in detail by computer programs developed by Paretzke, et al.⁷, Fain, et al.⁸, and Chatterjee, et al.⁹. A new program described below, INDOSE, was employed to calculate contributions (b) and (c) and thus supplement the programs developed for calculation of energy deposited due to secondary electron production alone. Details concerning the use of the program INDOSE and the theory on which it was based are discussed. A source program and input data format information are also provided.

Theoretical Considerations

The classical Rutherford scattering formula was used to calculate dose due to scattered particles (incident or target). We assume that a particle of mass M_1 with initial energy E_0 collides elastically with a particle of mass M_2 initially at rest and unbound. After the collision, M_1 scatters with energy E_1 at an angle θ (in laboratory coordinates), while M_2 recoils with energy E_2 at an angle ϕ . The Rutherford scattering formula¹⁰ gives the differential cross-section presented by the struck particle M_2 for an energy transfer between E_2 and $E_2 + dE_2$ as

$$d\sigma = \frac{\pi Z_1^2 Z_2^2 e^4 M_1}{M_2 V_0^2} \frac{dE_2}{E_2^2} \quad (1)$$

where Z_1 and Z_2 are incident and target particle charges, e is the fundamental electronic charge, E_2 is energy imparted to the target particle, M_2 is mass of the target particle and V_0 is velocity of the incoming particle. Noting that $E_0 = M_1 V_0^2/2$, we get

$$d\sigma = \frac{\pi Z_1^2 Z_2^2 e^4 M_1}{M_2 E_o} \frac{dE_2}{E_2^2} \quad (2)$$

If N is number of gas atoms per cm³, then the number of particles per cm³ which originate with energy between E₂ and E₂ + dE₂ and may deposit energy at a radial distance r is given by

$$N d\sigma / 2\pi r \quad (3)$$

and the energy deposited per unit volume is then given by

$$\frac{N d\sigma}{2 \pi r} \cdot \frac{LET_r(E_2)}{\sin \Phi} \quad (4)$$

LET_r(E₂) is the linear energy transfer of scattered particles at distance r originating with energy between E₂ and E₂ + dE₂. Dividing equation (4) by density of the medium and integrating over energy gives dose⁵

$$\text{Dose (rad)} = 1.6 \times 10^{-14} \int_{E_2 \text{ min}}^{E_2 \text{ max}} \frac{N}{r} \frac{1}{\rho} \frac{LET_r(E_2)}{\sin \Phi} \frac{Z_1^2 Z_2^2 e^4 M_1}{M_2 E_o} \frac{dE_2}{E_2^2} \quad (5)$$

A relationship is needed to relate the energy of the particle and the angle of scatter or recoil. For the target particle, solving the classical conservation of energy and momentum equations yields

$$\frac{E_2}{E_o} = \frac{4 M_1 M_2}{(M_1 + M_2)^2} \cdot \cos^2 \Phi \quad (\text{for } \Phi \leq \pi/2) \quad (6)$$

For the scattered incident particle, solution of the classical conservation of energy and momentum equations yields

$$\frac{E_1}{E_o} = \frac{M_1^2}{(M_1 + M_2)^2} \left\{ \cos \theta \pm \left[\left(\frac{M_2}{M_1} \right)^2 - \sin^2 \theta \right]^{1/2} \right\}^2 \quad (7)$$

If $M_1 < M_2$, the + sign is applicable and θ can vary between 0 and π .

If $M_1 > M_2$, the - sign is applicable and θ is restricted by

$$\theta_{\max} = \sin^{-1} \left(\frac{M_2}{M_1} \right) \quad (8)$$

One must set conditions on the limits of integration of equation (5), depending on the relative masses of the particles. If $M_1 < M_2$, then E_1 is a maximum when $\theta = 0$, i.e. $E_{1 \max} = E_0$ which implies that E_2 is a minimum and in this case is zero. Similarly, E_1 is a minimum when $\theta = \pi$ and is given by

$$\frac{E_{1 \min}}{E_0} = \left(\frac{M_2 - M_1}{M_2 + M_1} \right) \quad (\text{for } M_1 < M_2) \quad (9)$$

Since $E_{2 \max} = E_0 - E_{1 \min}$, the maximum energy of recoil for the target particle is given by

$$E_{2 \max} = \frac{4 M_1 M_2}{(M_1 + M_2)^2} E_0 \quad (\text{for } M_1 < M_2) \quad (10)$$

However, if $M_1 > M_2$, then E_1 is a maximum when $\theta = \theta_{\max}$ and is given by

$$E_{1 \max} = \left(\frac{M_1 - M_2}{M_1 + M_2} \right) E_0 \quad (\text{for } M_1 > M_2) \quad (11)$$

$$\text{and } E_{2 \min} = E_0 - E_{1 \max}$$

$$= \frac{2 M_2}{M_1 + M_2} E_0 \quad (\text{for } M_1 > M_2) \quad (12)$$

INDOSE - Program Structure and Functions

INDOSE is a general program that is used to calculate dose due to scattered incident and target particles at various radial distances for a

given initial energy of the incident particle by numerically integrating equation (5). The program is structured in a modular fashion, using external user created functions to calculate angle of scattering, cross-section, path length energy and LET at end of path length.

For the target particle, the upper energy limit is calculated from equation (10), while the lower energy limit is determined by the ratio M_2/M_1 . If $M_1 < M_2$, the lower energy limit is set to an arbitrarily small value (5 eV), since setting $\Phi = 0$ will cause a singularity in equation (5). If $M_1 > M_2$, the lower limit of integration is determined by equation (12). Linear energy transfer (LET) for the incident particle and the target particle as a function of energy are provided as input data. LET data for the incident particle are stored on the first plane (x) of a two dimensional array while LET data for the target particle are stored on the second plane. The number of radii and the radii values are read next as input parameters.

The other input data required in the program are energy, charge and mass of the incident particle, and charge and mass of the target particle. First, the probability of (both incident and target) for scattering through an angle θ and energy E is calculated, and then the energy loss of these particles is followed as a function of distance, until it reaches the specified radial distance. At this point information about the energy of the particle, its LET at the energy and the probability is stored and is used to calculate the energy deposited (dose) at that radius. To accomplish this, the program employs several subroutines and functions which are explained below.

FUNCTION ANGL: This function is used to calculate the angle θ of the scattered incident particle, given its energy E. This is done by employing

a subroutine called INTANG, which interpolates through the table of energy vs. angle generated in the program. Note that this angle is limited by the length of the chamber and the radial distance in question. The IF statement following the function call statement takes care of this.

FUNCTION ANGL 2: This function is used to calculate angle of scattered target particle for a given energy from equation (6).

FUNCTION XNBR: This function is used to calculate the cross-section for collisions by evaluating the indefinite integral of equation (2) between $E_2 + dE_2$ and $E_2 - dE_2$. Note that the cross-section for the incident particle of energy $E_1 = E_0 - E_2$ should be the same as that for the target particle of energy E_2 .

FUNCTION XLNGTH: This function is used to calculate length of the path that a particle (incident or target) must travel at the angle in question in order to reach the radial distance at which dose is calculated.

FUNCTION EATXL: This function is used to calculate energy of the particle (originating at energy E) at the radial distance r by dividing distance into 100 (this number can be changed) equal segments, and calculating the average LET over each increment. This is multiplied by the segment length and subtracted from E to give energy left after traversing a distance r .

FUNCTION GETLET: This function is used to calculate LET of the particle at radial distance r by interpolating or extrapolating LET vs.

energy data for the particle. Subroutin INTERP is called for this purpose.

FUNCTION GETN: This function is used to provide values for nuclear stopping power for the particle at low energies. These values were calculated using the Lindhard, et al.² theory.

This program has been used to calculate the contribution to energy deposition due to incident ion scattering and gas atom scattering. Figure 1 shows a plot of energy deposited as a function of radial distance in tissue of unit density for both scattered incident particles and scattered gas atoms for 2.6 MeV incident ^4He ions. Figure 2 shows the same information for 41.1 MeV ^{16}O ions. Appendix 1 gives the detail about INPUT DATA and Appendix 2 gives the complete INDOSE computer code.

Appendix 1

Input-data format details

1. Card #1. Contains incident and target masses M_1 and M_2 in units of amu, incident and target atomic numbers Z_1 and Z_2 , incident particle initial energy E_0 and the angle increments (INCR) in degrees desired for the table of energy vs. θ .

Columns 1-20 contain M_1 , M_2 , Z_1 and Z_2 in F5.2 format.

Columns 21-30 contain E_0 in E10.3 format.

Columns 31-35 contain INCR, in F5.2 format.

2. LET vs. ENERGY Data. Two sets of data cards are required, the first for the incident particle, and the second for the target particle. Columns 1-10 of each card contain energy in MeV in F10.4 format. Columns 11-20 contain LET in eV/Å or MeV·cm²/gm in F10.4 format. These values can be converted to the desired units by multiplying by the appropriate conversion factor, as shown in the program source list. A single digit, non-zero integer punched in column 22 signals the end of a data set, and must appear at the end of data for both incident and target particle.

3. Number of Radii. The number of radii to be considered is punched in I5 format on a separate card following the set of LET data cards.
4. Radii. The radii values are punched on separate cards in E10.3 format. The units should be in cm. They can always be converted later if desired. Each radii value is punched on a separate card.

APPENDIX 2

```

PROGRAM INDOSE(INPUT,OUTPUT,DEBUG=OUTPUT)
REAL M1,M2,INCP,NUM
COMMON/BI/PSI(180),ENERGY(180),M1,M2
COMMON/B2/X(2,75),Y(2,75),NN(2),ICOUNT
DIMENSION RADIUS(20)

```

```

C *** PROGRAM TO CALCULATE DOSE CONTRIBUTIONS DUE TO INCIDENT AND TARGET

```

```

C *** ATOM SCATTERING AT RADIAL DISTANCES TO AN ION TRACK IN TISSUE

```

```

C *** EQUIVALENT GAS.

```

```

C *** PROGRAMMER - JOSEPH MEO

```

```

C *** INPUT PARAMETER RUNDOWN .....

```

```

C *** CARD-1 ... M1,M2 - INCIDENT AND TARGET MASSES (AMU)

```

```

C *** 71,72 - INCIDENT AND TARGET CHARGE NUMBERS

```

```

C *** E0 - INCIDENT PARTICLE INITIAL ENERGY (EV)

```

```

C *** INCR - INCREMENTAL ANGLE (DEGREES) FOR GENERATION OF TABLE OF ENERGY

```

```

C *** VS. ANGLE OF SCATTER OF INCIDENT PARTICLES.

```

```

HEAD 67,M1,M2,71,72,E0,INCR

```

```

67 FORMAT(4F5.2,E10.3,F5.2)

```

```

PRINT 46

```

```

46 FORMAT(1H1,5X,* INITIAL PARAMETERS*)

```

```

PRINT 48

```

```

48 FORMAT(1H0,3X,*M1*,7X,*M2*,7X,*Z1*,7X,*Z2*,7X,*E0*)

```

```

PRINT 49,M1,M2,Z1,Z2,E0

```

```

49 FORMAT(1X,4(F6.2,3X),E10.3)

```

```

C *** GENERATE A TABLE OF ENERGY VS. ANGLE OF SCATTER FOR THE INCIDENT PARTICLE.

```

```

C *** THIS TABLE WILL BE INTERPOLATED THRU WHEN CALCULATING DOSE.

```

```

C *** INDEX IS THE NUMBER OF TIMES LOOP IS TO BE EXECUTED.

```

```

C *** DPST IS THE INCREMENTAL ANGLE IN RADIAN.

```

```

INDEX=180./INCR

```

```

DPST=INCR*3.1415926/180.

```

```

PSI(1)=0

```

```

ENMAX=0

```

```

C *** NUM IS THE NUMBER OF GAS ATOMS PER GRAM .

```

```

NUM=6.02E+23/M2

```

```

RATM=M2/M1

```

```

PSMAX=3.1415926

```

```

C *** IF M1 IS GREATER THAN OR EQUAL TO M2, SET CONDITION PN PSI.

```

```

IF(M1.GE.M2) PSMAX=ASIN(RATM)

```

```

PRINT 22

```

```

22 FORMAT(1H0,2X,*PSI*,9X,*ENERGY*)

```

```

C *** GENERATE THE TABLE. ENMIN AND ENMAX WILL HOLD THE MINIMUM AND MAXIMUM

```

```

C *** VALUES OF ENERGY, RESPECTIVELY.

```

```

DO 50 I=1,INDEX

```

```

IF(M1.GT.M2) GO TO 30

```

```

ENERGY(I)=E0*((M1/(M1+M2))**2)*(COS(PSI(I)) +

```

```

Y((RATM)**2-(SIN(PSI(I))**2)**.5)**2

```

```

GO TO 40

```

```

30 ENERGY(I)=E0*((M1/(M1+M2))**2)*(COS(PSI(I)) - ((RATM)**2 -

```

```

X(SIN(PSI(I))**2)**.5)**2

```

```

IF(I.EQ.1) ENMIN=ENERGY(I)

```

```

40 IF(ENERGY(I).GT.ENMAX) ENMAX=ENERGY(I)

```

```

IF(M1.GT.M2) GO TO 55

```

```

IF(I.EQ.1) ENMIN=ENMAX

```

```

IF(ENERGY(I).LT.ENMIN) ENMIN=ENERGY(I)

```

```

55 PRINT 70,PSI(I),ENERGY(I)

```

```

70 FORMAT(1X,E10.3,2X,E10.3)

```

```

PSI(I+1)=PSI(I)+DPST

```

```

IF(M1.GE.M2.AND.PSI(I+1).GT.PSMAX) GO TO 100

```

FUNCTION GETN(E)

C *** RETURNS A NUCLEAR STOPPING COEFFICIENT.

GETN=0

IF (E.LT.4000) GETN=4.E+07

IF (E.LT.400) GETN=8.E+07

RETURN

END

FUNCTION GETLET(EL)

C *** RETURNS LET AT END OF PATHLENGTH.

COMMON/B2/X(2,75),Y(2,75),N(2),IC

CALL INTERP(X,Y,N,IC,EL,XLET)

GETLET=XLET

RETURN

END

SUBROUTINE INTERP(X,Y,N,IC,A,B)

C *** INTERPOLATES OR EXTRAPOLATES TABLES OF ENERGY AND LET.

DIMENSION X(2,75),Y(2,75),N(2)

I=2

IF (A.GT.X(IC,I)) GO TO 2

B=Y(IC,I)+((Y(IC,I)-Y(IC,I-1))/(X(IC,I)-X(IC,I-1)))*(A-X(IC,I-1))

RETURN

2 IF (A-X(IC,I)) 5,4,3

3 I=I+1

IF (I.LT.N(IC)) GO TO 2

B=Y(IC,N(IC))+((Y(IC,N(IC))-Y(IC,N(IC)-1))/(X(IC,N(IC))-

X(IC,N(IC)-1)))*(A-X(IC,N(IC)))

RETURN

4 B=Y(IC,I)

RETURN

5 B=Y(IC,I-1)+((Y(IC,I)-Y(IC,I-1))/(X(IC,I)-X(IC,I-1)))*(A-X(IC,

XI-1))

RETURN

END

```

X*FENERGY INC*,3X,*ANGLE(RAD)*,3X,*XN(SQ.CM)*,4X,*XL(CM)*,7X,
X*FXL(EV)*,6X,*XLET(EV/CM)*

```

```

LINES=0

```

```

1 N=N+1

```

```

C *** INTEGRATION STEP SIZE TAKEN AS 2**N, CAN BE CHANGED AS THE INTEGRATION

```

```

C *** PROCEEDS WITH AN APPROPRIATE IF STATEMENT.

```

```

DE=2**N

```

```

C *** INCREMENT E TO GET TO MIDPOINT OF INTERVAL

```

```

E=E+DE/2

```

```

C *** CHECK FOR ENERGY INTERVAL EXCEEDING MAXIMUM ENERGY.

```

```

IF(E+DE/2.GE.ECIM) GO TO 200

```

```

IF(ICOUNT.EQ.1) A=ANGL(E)

```

```

IF(ICOUNT.EQ.2) A=ANGL2(E,M1,M2,E0)

```

```

C *** CHECK FOR ANGLE LESS THAN SMALLEST POSSIBLE ANGLE.

```

```

IF(ICOUNT.EQ.1.AND.A.LT.5.7*3.1415926/180.) GO TO 6

```

```

E1=E

```

```

C *** CROSS SECTION FOR E1 AND E2=F0-E1 MUST BE THE SAME.

```

```

IF(ICOUNT.EQ.1) E1=E0-E

```

```

99 XN=XN9R(E1,DE,F0,M1,M2,Z1,Z2,NUM)

```

```

XL=XLNGTH(A,R)

```

```

EXL=EATXL(E,XL)

```

```

XLET=GETLET(EXL)

```

```

C *** CALCULATE DOSE, CONVERT TO ERGS/GRAM.

```

```

DOSE=XN*XLET*1.6E-12/(SIN(A)*6.28*R)+DOSE

```

```

PRINT 87,R,DOSE,E,DE,A,XN,XL,EXL,XLET

```

```

87 FORMAT(1H,1X,9(E10.3,3X))

```

```

LINES=LINES+1

```

```

C *** INCREMENT E TO GET TO END OF INTERVAL.

```

```

6 E=E+DE/2

```

```

IF(LINES.GT.58) GO TO 72

```

```

GO TO 1

```

```

200 ICOUNT=ICOUNT+1

```

```

IF(ICOUNT.EQ.3) GO TO 300

```

```

GO TO 13

```

```

300 CONTINUE

```

```

END

```

```

50 CONTINUE
100 PRINT 105,ENMIN,ENMAX
105 FORMAT(1H0,*,MINIMUM ENERGY =*,E10.3,5X,*,MAXIMUM ENERGY =*,E10.3)
RECLIM=4*F0*M2*M1/((M1+M2)**2)
PRINT 106,RECLIM
106 FORMAT(1H0,*,RECOIL PARTICLE MAXIMUM ENERGY = *,E10.3)
C *** READ TABLE OF ENERGY AND LET FOR INCIDENT AND TARGET PARTICLE.
C *** UNITS USED BY THE PROGRAM ARE ENERGY IN EV AND LET IN EV/CM.
C *** THESE ARE STORED IN THE TWO-DIMENSIONAL ARRAYS X AND Y.
C *** IF K=1, READ INCIDENT PARTICLE ENERGY AND LET. IF K=2 READ TARGET
C *** PARTICLE ENERGY AND LET. CONVERT TO CORRECT UNITS BY MULTIPLYING BY THE
C *** APPROPRIATE FACTORS FOR EACH VALUE OF K IF NEEDED.
DO 59 K=1,2
NN(K)=1
56 READ 57,X(K,NN(K)),Y(K,NN(K)),MARK
57 FORMAT(2F10.4,1X,I1)
C *** CONVERT TO EV
X(K,NN(K))=X(K,NN(K))*1.E6
C *** CONVERT TO EV/CM
IF(K.EQ.1) Y(K,NN(K))=Y(K,NN(K))*1.E8
IF(K.EQ.2) Y(K,NN(K))=Y(K,NN(K))*1.E9
NN(K)=NN(K)+1
IF(NN(K).GT.75) GO TO 58
IF(MARK.EQ.0) GO TO 56
58 NN(K)=NN(K)-1
59 CONTINUE
C *** READ NUMBER OF RADIAL DISTANCES AND THE DISTANCES (CM)
READ 80,NR
DO 85 K=1,NR
READ 205,RADIUS(K)
85 CONTINUE
80 FORMAT(I5)
205 FORMAT(E10.3)
C *** LOOP TO CALCULATE DOSE DUE TO INCIDENT AND TARGET PARTICLES.
C *** IF ICOUNT=1, INCIDENT PARTICLE IS CALCULATED.
C *** IF ICOUNT=2, TARGET PARTICLE IS CALCULATED.
DO 300 L=1,NR
ICOUNT=1
R=RADIUS(L)
C *** FOR INCIDENT PARTICLE, START INTEGRATION AT MINIMUM ENERGY.
E=ENMIN
ELIM=ENMAX
IF(ICOUNT.EQ.1) GO TO 27
C *** FOR TARGET PARTICLE, START AT 5 EV (ARBITRARILY SMALL VALUE)
13 E=5.0
ELIM=RECLIM
C *** IF M1 BIGGER THAN M2, SET CONDITION ON MINIMUM RECOIL ENERGY.
IF(M1.GT.M2) E=RECLIM*(M1+M2)/(2*M1)
27 DOSE=0
A=0
72 IF(ICOUNT.EQ.1) PRINT 74
IF(ICOUNT.EQ.2) PRINT 75
74 FORMAT(1H1,36X,*,SCATTERED (INCIDENT) PARTICLE*)
75 FORMAT(1H1,36X,*,RECOIL (TARGET) PARTICLE*)
C PRINT OUTPUT PARAMETER HEADINGS
76 PRINT 77
77 FORMAT(1H,4X,*,RADIUS(CM)*,3X,*,DOSE(ERG/G)*,2X,*,ENERGY(EV)*,3X,

```

ION XNRR 76/76 OPT=0 TRACE DEBUG

FTN 4.2+383

08/19/75

FUNCTION XNRR(F,DE,E0,M1,M2,Z1,Z2,NUM)

C *** RETURNS COLLISION CROSS SECTION IN SQUARE CM.

REAL M1,M2,NUM

C *** CONSTANT $\pi^2 \cdot (FUND. CHARGE)^4 / (1.6E-12)^2$

$XNRR = ((NUM * 6.513E-14 * M1 * (Z1 * Z2)^2) / (M2 * E0))$

$X * ((1 / (E - .5 * DE)) - (1 / (E + .5 * DE)))$

RETURN

END

ION XLNGTH 76/76 OPT=0 TRACE DEBUG

FTN 4.2+383

08/19/75

FUNCTION XLNGTH(A,R)

C *** FINDS PATH LENGTH TRAVERSED BY PARTICLE FOR RADIUS IN QUESTION.

$XLNGTH = R / \sin(A)$

RETURN

END

ON EATXL 76/76 OPT=0 TRACE DEBUG

FTN 4.2+383

08/19/75

FUNCTION EATXL(E,XL)

C *** RETURNS ENERGY AT END OF PATH LENGTH

FL=E

DL=XL*.01

DO 10 I=1,100

$EATXL = EL - (GFTLFT(EL) + GETN(EL)) * DL$

EL=EATXL

IF (FL.LT.0) GO TO 40

10 CONTINUE

RETURN

40 EATXL=0

RETURN

END

ON ANGL

76/76

OPT=0

TRACE DEBUG

FTN 4.2+383

08/19/75

FUNCTION ANGL(E,ENMIN)

C *** INTERPOLATES TABLE OF ANGLE VS. PSI, RETURNS ANGLE.

C *** STOPS IF ENERGY LESS THAN MINIMUM POSSIBLE.

IF(E.LT.ENMIN) STOP

CALL INTANG(E,ANG)

ANGL=ANG

RETURN

END

ON ANGL2

76/76

OPT=0

TRACE DEBUG

FTN 4.2+383

08/19/75

FUNCTION ANGL2(E,M1,M2,E0)

REAL M1,M2

C *** CALCULATES ANGLE FROM ENERGY OF RECOIL PARTICLE.

 $ANGL2 = \arccos(((M1+M2)/2) * \sqrt{E/(M1*M2*E0)})$

RETURN

END

C *** SUBROUTINE INTANG(EN,AN)
INTERPOLATION ROUTINE -- DOES NOT EXTRAPOLATE

COMMON/81/PSI(180),ENERGY(180),M1,M2

REAL M1,M2

I=1

34 IF(M1.GT.M2) GO TO 88

IF(ENERGY(I)-EN)5,4,3

C *** NOT FOUND YET

3 I=I+1

GO TO 34

C *** EQUAL -- RETURN PSI(I)

4 AN=PSI(I)

RETURN

C *** FOUND ENERGY LESS, INTERPOLATE

5 $AN = PSI(I) + (EN - ENERGY(I)) * (PSI(I-1) - PSI(I)) / (ENERGY(I-1) - ENERGY(I))$

RETURN

88 IF(ENERGY(I)-EN)3,4,5

END

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Figure 1: Plot of Energy deposited (Ergs/gm) vs. radial distance in tissue of unit density for 2.65 MeV incident ^4He ions.

Figure 2: Plot of Energy deposited (Ergs/gm) vs. radial distance in tissue of unit density for 41.1 MeV incident ^{16}O ions.