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DIRECTIONAL CORRELATION ATTENUATION COEFFICIENTS WITH Ge DETECTORS

George A. Carlson

Davis, California

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I. INTRODUCTION

This work was motivated by the necessity of finding accurate attenuation coefficients for a rectangular Ge detector. These coefficients and the corresponding ones for a cylindrical NaI detector are used in correcting the coefficients in the Legendre polynomial series representing the directional correlation function for the finite solid angles subtended by the detectors.

Because of the now general use of Ge detectors, it was thought that the methods used here might be of value to other workers in the field.

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Directional Correlation Attenuation Coefficients With Ge Detectors

George A. Carlson

January 23, 1967

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II. CALCULATION OF FINITE GEOMETRY CORRECTIONS

For point detectors, the correlation function is written

$$W(\theta') = 1 + A_2 P_2(\cos \theta') + A_4 P_4(\cos \theta')$$

The measured correlation function is a weighted average over the solid angles subtended by the two detectors

$$(1) \quad W(\theta) = \iint E_1(\theta_1, \phi_1) W(\theta') E_2(\theta_2, \phi_2) d\Omega_1 d\Omega_2$$

θ' is the angle between the gamma rays, θ_1, ϕ_1 are the integration angles running over the face of detector number 1 and θ_2, ϕ_2 are the same for detector number 2. The weighting factors, $E(\theta, \phi)$, account for the possibility that the detector efficiency is not constant over the range of θ and ϕ . Reference 2 uses $E = 1$ in its examples but its method is easily generalized. The functional form of E is taken to be that of reference 1,

$$(2) \quad E = 1 - \exp(-\tau l)$$

where l is the length of detector passed through by the gamma ray and τ is the linear absorption efficiency.

For the case of the Ge detector, a rectangular coordinate system is more convenient. Therefore

$$(3) \quad E(x, y) = 1 - \exp[-\tau l(x, y)]$$

on the crystal face and zero otherwise.

Any function of the spherical angles θ and ϕ can be expanded in terms of spherical harmonics

$$(4) \quad E = \sum_{l,m} \left(\frac{2l+1}{4\pi} \right)^{1/2} b_{lm} Y_l^m(\theta, \phi)$$

Solving for the b_{lm} yields:

$$(5) \quad b_{lm} = \left(\frac{4\pi}{2l+1} \right)^{1/2} \int Y_l^m(\theta, \phi) E(\theta, \phi) d\Omega$$

or in terms of x and y ,

$$(6) \quad b_{lm} = \left(\frac{4\pi}{2l+1} \right)^{1/2} \frac{1}{r_0^2} \int_{-b'}^{b'} dy' \int_{-a'}^{a'} \frac{Y_l^m(x', y') E(x', y') dx'}{[1 + x'^2 + y'^2]^{3/2}}$$

where $a' = a/2r_0$, $b' = b/2r_0$, $x' = x/r_0$, $y' = y/r_0$. a and b are the width and height respectively and r_0 is the source to crystal distance.

$I(x, y)$ has three different functional forms depending on where the gamma ray strikes the detector.

Region 1: the gamma ray enters the front face on a line which leaves the back face (figure 1).

Region 2: the gamma ray enters the front face on a line which leaves on one of the sides parallel to the x, r_0 plane (figure 2).

Region 3: the gamma ray enters the front face on a line which leaves on one of the sides parallel to the y, r_0 plane (figure 3).

Case 1:
$$|\tan \alpha_1| \equiv \left| \frac{y}{r_0} \right| \leq \frac{1}{2} \frac{b}{r_0 + t}$$

and
$$|\tan \alpha_2| \equiv \left| \frac{x}{r_0} \right| \leq \frac{1}{2} \frac{a}{r_0 + t}$$

Figure 1. Geometry for case 1.

Figure 2. Geometry for case 2.

Figure 3. Geometry for case 3.

where t is the thickness of the depletion region. From figure 1,

$$l(x, y) = \frac{t}{\cos \beta}$$

where

$$\beta = \tan^{-1} \left(\frac{\sqrt{x^2 + y^2}}{r_0} \right)$$

Case 2:

$$\beta_1 \equiv |\tan^{-1} y/x| > \tan^{-1} b/a$$

and

$$|\tan \alpha_1| \equiv |y/r_0| > \frac{1}{2} \frac{b}{r_0 + t}$$

From figure 2,

$$l(x, y) = \frac{b/2 - |y|}{\sin \beta_1} \frac{1}{\sin \beta}$$

Case 3:

$$\beta_1 = |\tan^{-1} y/x| \leq \tan^{-1} b/a$$

$$|\tan \alpha_2| = |x/r_0| > \frac{1}{2} \frac{a}{r_0 + t}$$

From figure 3,

$$l(x, y) = \frac{a/2 - |x|}{\cos \beta_1} \frac{1}{\sin \beta}$$

Therefore with $E(x, y)$ known, the integrals in equation 6 can be done.

The corresponding geometry correction for a NaI detector is obtained in much the same way.

$$(7) \quad E(\theta, \phi) = \sum_{l, m} \left(\frac{2l+1}{4\pi} \right)^{1/2} C_{lm} Y_l^m(\theta, \phi)$$

and

$$(8) \quad C_{lm} = \left(\frac{4\pi}{2l+1} \right)^{1/2} \int Y_l^m(\theta, \phi) E(\theta, \phi) d\Omega$$

where $E(\theta, \phi)$ is that of reference 1.

$$(9) \quad E(\theta, \varphi) = 1 - \exp[-\tau l(r)]$$

where $l(r) = z \sec \beta$

$$\text{if} \quad 0 \leq \beta \leq \tan^{-1}\left(\frac{R}{h+z}\right) \equiv \beta',$$

$$\text{and*} \quad l(r) = R \csc \beta - h \sec \beta.$$

$$\text{if} \quad \beta' \leq \beta \leq \tan^{-1}\left(\frac{R}{h}\right)$$

$$\text{where} \quad \beta = \tan^{-1}\left(\frac{r}{h}\right) \quad (\text{See figure 4})$$

Due to the symmetry of the NaI detector, only the $m=0$ terms in C_{lm} are non-zero. For these cases,

$$Y_l^m(\theta, \varphi) = \left(\frac{2l+1}{4\pi}\right)^{1/2} P_l(\cos \theta)$$

$$\text{and } C_{10} = 2\pi \int P_l(\cos \theta) E(\theta) \sin \theta d\theta$$

But these integrals are just the familiar J_l 's of reference 1 which are tabulated in many places.

* Notice the misprint in the corresponding equation in reference 1.

Figure 4. Geometry for the NaI detector.

NaI - Ge DIRECTIONAL CORRELATION EXPERIMENTS

Feingold and Frankel show in reference 2 that if the point-point correlation function is

$$(10) \quad W(\theta') = \sum_{l'} \frac{2l'+1}{4\pi} a_{l'} P_{l'}(\cos \theta')$$

then the measured correlation function will be:

$$(11) \quad W(\theta) = \sum_l \frac{2l+1}{4\pi} h_l P_l(\cos \theta)$$

where

$$(12) \quad h_l = \sum_{l', m} (-1)^{m+l+l'} a_{l'} b_{l'm} c_{l'0} g_{m0}^{ll'}$$

The second subscript on c and g is zero because of the $\emptyset$ symmetry of the NaI detector. Also

$$(13) \quad g_{mm'}^{ll'} = \frac{2l+1}{4\pi} \int_{-1}^{+1} d_{mm'}^l(\theta) P_{l'}(\cos \theta) d(\cos \theta)$$

and accounts for the transformation of the Legendre functions in terms of θ' (the angle between the gamma rays) to the angle between the axes of the detectors, θ .

There are restrictions on m, l, and l' which severely limit the number of terms in the sum in equation 12. These are proved in reference 2 and only stated here. They are:

- 1) $g = 0$ for $(l + l' + m)$ odd
- 2) $g = \delta_{ll'}$ for $m = m' = 0$

- 3) $g_{mm', l'l'} = g_{-m, -m', l'l'}$
- 4) $b_{l'm} = 0$ for m odd
- 5) $b_{l'm} = 0$ for $m > l'$
- 6) l' summed over even values only ($A_{l'} = 0$ for l' odd)

Therefore l has only even values by 1) and 4). Feingold and Frankel give a table of $g_{mm', l'l'}$ for more than enough cases to suffice for this work. Using these values and the restrictions on the sum, the h_l 's in equation 12 are:

$$h_0 = (b_{00} c_{00}) a_0$$

$$h_2 = (b_{20} - \frac{2}{\sqrt{6}} b_{22}) c_{20} a_2$$

$$h_4 = \left(\frac{6}{\sqrt{10}} b_{22} c_{20} \right) a_2 + \left(b_{40} - 2\sqrt{\frac{2}{5}} b_{42} + \frac{2}{\sqrt{70}} b_{44} \right) c_{40} a_4$$

Finally

$$(14) \quad W(\theta) = (b_{00} c_{00}) A_{00} + (b_{20} - \frac{2}{\sqrt{6}} b_{22}) c_{20} A_{22} P_2(\cos \theta) + \left[\left(\frac{54}{5\sqrt{10}} b_{22} c_{20} \right) A_{22} + \left(b_{40} - 2\sqrt{\frac{2}{5}} b_{42} + \frac{2}{\sqrt{70}} b_{44} \right) c_{40} A_{44} \right] P_4(\cos \theta)$$

where

$$A_{22} = A_2(L_1 L'_1 I_i I) A_2(L_2 L'_2 I_s I)$$

and

$$A_{44} = A_4(L_1 L'_1 I_i I) A_4(L_2 L'_2 I_s I)$$

as defined in reference 3, chapter XIXA.

IV. LINEAR ABSORPTION COEFFICIENTS

The linear absorption coefficients for NaI and Ge posed a special problem. In a NaI detector, the full energy peak is greater than expected from just a consideration of photoelectric events only because of multiple interactions. Therefore, a linear absorption

coefficient based on the photoelectric cross section would be incorrect. The method used here is to multiply the linear absorption coefficient for the total interaction cross section by the photopeak efficiency for 3" X 3" NaI detectors as calculated by the Monte Carlo method. These efficiencies are tabulated in appendix 9 of reference 3 and are shown here in figure 5. Table I summarizes the values used.

<u>Energy</u>	<u>Total Absorption Coefficient</u>	<u>Photopeak Efficiency</u>	<u>Linear Absorption Coefficient used</u>
427 kev	.347 cm ⁻¹	.510	.191 cm ⁻¹
702	.257	.335	.0861

Table I

The Ge detector was small enough so that the assumption was made that multiple interactions contributed a negligible amount to the full energy peak. Therefore the linear absorption coefficient used was just the photoelectric coefficient. Figure 6 shows the linear absorption coefficients for Ge over the range of interest. These values were calculated from the corresponding values for copper (reference 3, appendix 1). The conversion was made by the formula (ref 4, eq 1.5, Ch 24)

$$\tau_1 = \tau_2 \rho \frac{A_2}{A_1} \left(\frac{Z_1}{Z_2} \right)^n$$

where Z_1 and Z_2 are the atomic numbers

A_1 and A_2 are the atomic mass numbers

ρ is the density

n is an energy dependent number found in reference 4, figure 1.7, ch. 24.

($n = 4.30$ for a 405 kev gamma-ray)

Figure 5. Full energy peak efficiency for a 3" X 3" NaI detector.

Figure 6. Linear photoelectric absorption coefficient for Ge.

For copper,

$$Z_2 = 29$$

$$A_2 = 63.54$$

$$\tau_2 \text{ is in } \text{cm}^2/\text{g}$$

For Germanium,

$$Z_1 = 32$$

$$A_1 = 72.59$$

$$\rho_1 = 5.35 \text{ g/cc}$$

$$\tau_1 \text{ is in } \text{cm}^{-1}$$

V. EXAMPLES

Some of the coefficients for particular cases are presented here

NaI

<u>E(mev)</u>	<u>T(cm⁻¹)</u>	<u>R(cm)</u>	<u>T(cm)</u>	<u>H(cm)</u>	<u>l</u>	<u>C_l/c₀</u>	<u>Q_l*</u>
.427	.91	3.81	7.62	10.16	0	1.0	1.0
					2	.93187	.931
					4	.78559	.783
.702	.0861				0	1.0	1.0
					2	.93534	.935
					4	.79601	.796

* From figure 7

Figure 7. Attenuation factors Q_2 and Q_4 for a 3" X 3" NaI detector at 10 cm from the source. (Reference 3, appendix 9)

<u>E(Mev)</u>	<u>(cm⁻¹)</u>	<u>A</u>	<u>B</u>	<u>T</u>	<u>Ro</u>	<u>l</u>	<u>m</u>	<u>B_{lm}</u>
1.25	.165	.85	.85	.45	1.88	0	0	.2377 X 10 ⁻¹
						2	0	.2345 X 10 ⁻¹
						2	2	.1409 X 10 ⁻⁴
						4	0	.2273 X 10 ⁻¹
						4	2	.2936 X 10 ⁻⁴
						4	4	-.7772 X 10 ⁻⁶
.405	.0346					0	0	.7688 X 10 ⁻²
						2	0	.7618 X 10 ⁻²
						2	2	.1830 X 10 ⁻⁵
						4	0	.7457 X 10 ⁻²
						4	2	.3652 X 10 ⁻⁵
						4	4	-.3652 X 10 ⁻⁶

VI. THE PROGRAM

The computer program designed to perform these integrals is divided into three parts:

1. J_1 and $Q_1 = J_1/J_0$ are calculated for the NaI detector by the method just described. In this case, the first input data card is left blank ($N = 0$). The second input data card contains the following information in an 8F10.0 format:

TAU = the linear absorption coefficient for NaI in cm^{-1} .

H = source to detector distance in cm.

R = detector radius in cm.

T = detector length in cm.

DA = angular integration increment.

GMEV = gamma ray energy in Mev.

2. B_{lm} are calculated for the Ge detector also by the method just described. The first input data card has $N = 1$ in the first column. The second input data card contains the following information in an 8F10.0 format.

A = length of the Ge detector in the x-direction in cm

ie: (in the plane of the correlation measurement)

B = length of the Ge detector in the y-direction in cm

RO = source to detector distance in cm

TAUI = linear absorption coefficient for Ge in cm^{-1} .

DX = integration step in x

DY = integration step in y

T = thickness of the depletion region in cm

EGAMI = gamma ray energy in Mev

The third card contains:

NX = number of x integration steps

NY = number of y integration steps

These are in an 8I10 format.

3. The J_l and Q_l are calculated when $E(\theta)$ is an empirical curve obtained by measuring the counting rate as a function of angle from a collimated beam of gamma-rays. In this case, the first input data card is $N = 2$ in column 1. The second input data card reads:

JJ = number of points in $E(\theta)$, I3 format

Next comes a group of JJ input data cards with $E(K)$ $K = 1, JJ$ in an F10.0 format. These are followed by the last input data card with 8F10.0 format:

AMAXX = angle of first data point from the axis in degrees.

DA = angular spacing of data in degrees

H = source to detector distance in cm

R = detector radius in cm

T = detector length in cm

GMEV = gamma ray energy in Mev

Several cases can be run in succession since the program returns to the first READ command to look for more data when the preceeding case is completed.

```

$IBFTC MAIN
1  READ(5,100)N
C
C  N=0  NAI DETECTOR      ROSE METHOD
C  N=1  GERMANIUM DETECTOR
C  N=2  NAI DETECTOR      EMPIRICAL METHOD
C
      IF(N.EQ.1)GO TO 2
      IF(N.EQ.2)GO TO 3
      CALL EPS0
      GO TO 4
2  CALL GERM
      GO TO 4
3  CALL EPS1
4  GO TO 1
100 FORMAT(I1)
      END

```


\$IBFTC EPS1

SUBROUTINE EPS1

DIMENSION E(100)

COMMON/COM1/ N,C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,J,P1
*,P2,P3,A,BP,GAM,EFAC1,EFAC2,EFAC3,M,TAU,T,DA,R,H,AMAX,E,I,R1,R2,F1
*,F2,F3,Q0,Y0

READ(5,120)JJ

READ(5,121)(E(K),K=1,JJ)

READ(5,121)AMAXX,DA,H,R,T,GMEV

DA=DA*3.1415927/180.

AMAX=AMAXX*3.1415927/180.

R1=1.-SQRT(.5)

R2=1.+SQRT(.5)

J=1

C1=1.5

C2=.5

C3=35./8.

C4=15./4.

C5=3./8.

C6=231./16.

C7=315./16.

C8=105./16.

C9=5./16.

C10=6435./128.

C11=3003./32.

C12=3465./64.

C13=315./32.

C14=35./128.

40 A=-AMAX

Y0=0.

Q0=0.

M=0

I=1

41 CALL ERQUT

CALL INTEG

IF(M.EQ.0)GO TO 41

GO TO (42,43,44,45,46),J

42 J=2

Z0=Y0

GO TO 40

43 J=3

Z1=Y0

GO TO 40

44 J=4

Z2=Y0

GO TO 40

45 J=5

Z3=Y0

GO TO 40

46 EJ2=Z1/Z0

EJ4=Z2/Z0

EJ6=Z3/Z0

EJ8=Y0/Z0

WRITE(6,124)

WRITE(6,125)GMEV,R,T

WRITE(6,126)H,AMAXX

WRITE(6,127)Z0,Z1,Z2,Z3,Y0,EJ2,EJ4,EJ6,EJ8

RETURN

```

120  FORMAT(I3)
121  FORMAT(8F10.0)
124  FORMAT(1H1,108HATTENUATION COEFFICIENTS FOR ANGULAR DISTRIBUTIONS
1    USING EXPERIMENTALLY DETERMINED ANGULAR EFFICIENCY CURVES)
125  FORMAT(1HL,19HGAMMA RAY ENERGY = ,F10.6,3HMEV,5X,17HCRYSTAL RADIUS
1    1 = ,F10.6,3H CM    ,5X,17HCRYSTAL LENGTH = ,F10.6,3H CM    )
126  FORMAT(1HK,29HSOURCE TO CRYSTAL DISTANCE = ,F10.6,3H CM    ,5X,13HH
1    1ALF ANGLE = ,F10.6,7HDEGREES)
127  FORMAT(1HL,5H J0 =,E15.7/5H J2 =,E15.7/5H J4 =,E15.7/5H J6 =,E15.7
1    1/5H J8 =,E15.7/5H Q2 =,E15.7/5H Q4 =,E15.7/5H Q6 =,E15.7/5H Q8 =,E
1    215.7)
      END

```

\$IBFTC EPS0

SUBROUTINE EPS0

COMMON/COM1/ N,C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,J,P1
*,P2,P3,A,BP,GAM,EFAC1,EFAC2,EFAC3,M,TAU,T,DA,R,H,AMAX,E,I,R1,R2,F1
*,F2,F3,Q0,Y0

READ(5,110)TAU,H,R,T,DA,GMEV

BP=ATAN(R/(H+T))

GAM=ATAN(R/H)

GAM1=GAM*180./3.1415927

J=1

DA=DA*3.1415927/180.

R1=1.-SQRT(.5)

R2=1.+SQRT(.5)

C1=1.5

C2=.5

C3=35./8.

C4=15./4.

C5=3./8.

C6=231./16.

C7=315./16.

C8=105./16.

C9=5./16.

C10=6435./128.

C11=3003./32.

C12=3465./64.

C13=315./32.

C14=35./128.

10 A=0.

Y0=0.

Q0=0.

M=0

11 CALL XROUT

CALL INTEG

IF(M.EQ.0)GO TO 11

GO TO(12,13,14,15,16),J

12 J=2

Z0=Y0

GO TO 10

13 J=3

Z1=Y0

GO TO 10

14 J=4

Z2=Y0

GO TO 10

15 J=5

Z3=Y0

GO TO 10

16 EJ2=Z1/Z0

EJ4=Z2/Z0

EJ6=Z3/Z0

EJ8=Y0/Z0

WRITE(6,114)

WRITE(6,115)GMEV,R,T

WRITE(6,116)H,GAM1

WRITE(6,117)Z0,Z1,Z2,Z3,Y0,EJ2,EJ4,EJ6,EJ8

RETURN

110 FORMAT(8F10.0)

114 FORMAT(1H1,93HATTENUATION COEFFICIENTS FOR ANGULAR DISTRIBUTIONS U

```

1SING THEORETICAL ANGULAR EFFICIENCY CURVE)
115  FORMAT(1HL,19HGAMMA RAY ENERGY = ,F10.6,3HMEV,5X,17HCRYSTAL RADIUS
1    = ,F10.6,3H CM    ,5X,17HCRYSTAL LENGTH = ,F10.6,3H CM    )
116  FORMAT(1HK,29HSOURCE TO CRYSTAL DISTANCE = ,F10.6,3H CM    ,5X,13HH
1    ALF ANGLE = ,F10.6,7HDEGREES)
117  FORMAT(1HL,5H J0 =,E15.7/5H J2 =,E15.7/5H J4 =,E15.7/5H J6 =,E15.7
1    /5H J8 =,E15.7/5H Q2 =,E15.7/5H Q4 =,E15.7/5H Q6 =,E15.7/5H Q8 =,E
2    215.7)
      END

```

```

$IBFTC XROUT
SUBROUTINE XROUT
COMMON/COM1/ N,C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,J,P1
*,P2,P3,A,BP,GAM,EFAC1,EFAC2,EFAC3,M,TAU,T,DA,R,H,AMAX,E,I,R1,R2,F1
*,F2,F3,Q0,Y0
IF(A.LE.BP) GO TO 21
IF(A.LE.GAM)GO TO 22
EFAC1=0.
EFAC2=0.
EFAC3=0.
M=1
GO TO 23
21 EFAC1=1.-EXP(-TAU*T/COS(A))
EFAC2=1.-EXP(-TAU*T/COS(A+DA/2.))
EFAC3=1.-EXP(-TAU*T/COS(A+DA))
GO TO 23
22 EFAC1=1.-EXP(-TAU*(R/SIN(A)-H/COS(A)))
EFAC2=1.-EXP(-TAU*(R/SIN(A+DA/2.)-H/COS(A+DA/2.)))
EFAC3=1.-EXP(-TAU*(R/SIN(A+DA)-H/COS(A+DA)))
23 RETURN
END

```

```

$IBFTC EROUT
  SUBROUTINE EROUT
    DIMENSION E(100)
    COMMON/COM1/ N,C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,J,P1
    *,P2,P3,A,BP,GAM,EFAC1,EFAC2,EFAC3,M,TAU,T,DA,R,H,AMAX,E,I,R1,R2,F1
    *,F2,F3,Q0,Y0
    IF(A.LE.AMAX)GO TO 51
    EFAC1=0.
    EFAC2=0.
    EFAC3=0.
    M=1
    GO TO 59
51  EFAC1=E(I)
    EFAC2=E(I+1)
    EFAC3=E(I+2)
    I=I+1
59  RETURN
    END

```

\$IBFTC INTEG

```
SUBROUTINE INTEG
COMMON/COM1/ N,C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,J,P1
*,P2,P3,A,BP,GAM,EFAC1,EFAC2,EFAC3,M,TAU,T,DA,R,H,AMAX,E,I,R1,R2,F1
*,F2,F3,Q0,Y0
CALL LEGPOL
F1=P1*EFAC1*SIN(ABS(A))
F2=P2*EFAC2*SIN(ABS(A)+DA/2.)
F3=P3*EFAC3*SIN(ABS(A)+DA)
G1=DA*F1
Y1=Y0+.5*(G1-2.*Q0)
G2=DA*F2
Q1=Q0+3.*(1.5*(G1-2.*Q0)-.5*G1)
Y2=Y1+R1*(G2-Q1)
G3=DA*F3
Q2=Q1+3.*(R1*(G2-Q1))-R1*G2
Y3=Y2+R2*(G3-Q2)
G4=DA*F3
Q3=Q2+3.*(R2*(G3-Q2))-R2*G3
Y0=Y3+(G4-2.*Q3)/6.
Q0=Q3+3.*((G4-2.*Q3)/6.)-.5*G4
A=A+DA
RETURN
END
```

\$IBFTC LEGPOL

SUBROUTINE LEGPOL

COMMON/COM1/ N,C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,J,P1
*,P2,P3,A,BP,GAM,EFAC1,EFAC2,EFAC3,M,TAU,T,DA,R,H,AMAX,E,I,R1,R2,F1
*,F2,F3,Q0,Y0

U=COS(A)

V=COS(A+DA/2.)

W=COS(A+DA)

GO TO (31,32,33,34,30),J

30 P1=C10*U**8-C11*U**6+C12*U**4-C13*U*U+C14

P2=C10*V**8-C11*V**6+C12*V**4-C13*V*V+C14

P3=C10*W**8-C11*W**6+C12*W**4-C13*W*W+C14

GO TO 35

31 P1=1.

P2=1.

P3=1.

GO TO 35

32 P1=C1*U*U-C2

P2=C1*V*V-C2

P3=C1*W*W-C2

GO TO 35

33 P1=C3*U**4-C4*U*U+C5

P2=C3*V**4-C4*V*V+C5

P3=C3*W**4-C4*W*W+C5

GO TO 35

34 P1=C6*U**6-C7*U**4+C8*U*U-C9

P2=C6*V**6-C7*V**4+C8*V*V-C9

P3=C6*W**6-C7*W**4+C8*W*W-C9

35 RETURN

END


```

$IBFTC GERM
SUBROUTINE GERM
COMMON /COM2/TH,L,WHY,PI,M,PHI,N
READ(5,100)A,B,RO,TAU1,DX,DY,T,EGAM1
READ(5,110)NX,NY
C
C      ECHO CHECK
C
WRITE(6,200)
WRITE(6,201)A,B,T,RO,EGAM1,TAU1,NX,NY
PI=3.1415927
BL=B/(2.*RO)
AL=A/(2.*RO)
ANG=ATAN(B/A)
DO4LM=1,5
L=LM-1
GO TO (11,11,12,12,13),LM
11  NUML=1
    GO TO 14
12  NUML=2
    GO TO 14
13  NUML=3
14  DO3 N=1,NUML
    SUM=0.
    Y=-B/2.*DY/2.
    DO2 I=1,NY
    X=-A/2.*DX/2.
    DO1 J=1,NX
    PHI=ATAN2(Y,X)
    W=SQRT(X*X+Y*Y)
    AY=ABS(Y)
    AX=ABS(X)
    TH=ATAN2(X,RO)
    TN1=ABS(Y/RO)
    TN2=ABS(X/RO)
    BETA=ATAN(W/RO)
    BB=B/(2.*(RO+T))
    AA=A/(2.*(RO+T))
    IF(TN1.LE.BB)GO TO 20
    GO TO 30
20  IF(TN2.LE.AA)GO TO 21
    GO TO 30
21  ELXY=T/COS(BETA)
    GO TO 50
30  IF(ANG.LE.B1)GO TO 35
    GO TO 40
35  ELXY=(B/2.-AY)*W/(AY*SIN(BETA))
    GO TO 50
40  ELXY=(A/2.-AX)*W/(AX*SIN(BETA))
50  CALL WYE
    E=1.-EXP(-TAU1*ELXY)
    XP=X/RO
    YP=Y/RO
    ROOT=SQRT(1.+XP*XP+YP*YP)
    SUM=SUM+WHY*E/ROOT**3
    X=X+DX
1  CONTINUE
    Y=Y+DY

```

```

2   CONTINUE
    PL=L
    NSQ=NX*NY
    SQN=NSQ
    BLM=SQRT(4.*PI/(2.*PL+1.))*SUM*A*B/(SQN*RO*RO)
    WRITE(6,210)L,M,BLM
3   CONTINUE
4   CONTINUE
    RETURN
100  FORMAT(8F10.0)
110  FORMAT(8I10)
200  FORMAT(1H1,32HBLM COEFFICIENTS FOR GE DETECTOR)
201  FORMAT(1HL,15HDIMENSIONS ARE ,E13.7,3HBY ,E13.7,3HBY ,E13.7,14H TH
1ICK (IN CM)/21HKSOURCE TO CRYSTAL = ,E13.7,3H CM/16HKGAMMA ENERGY
2= ,E13.7,4H MEV/26HKABSORPTION COEFFICIENT = ,E13.7,3H/CM/33HKNUMB
3ER OF X INTEGRATION STEPS = ,15/33HKNUMBER OF Y INTEGRATION STEPS
4= ,15/1HK,10X,1HL,20X,1HM,20X,3HBLM)
210  FORMAT(1HK,10X,11,20X,11,10X,E13.7)
    END

```

\$IBFTC WYE

```
SUBROUTINE WYE
COMMON /COM2/TH,L,WHY,PI,M,PHI,N
STH=SIN(TH)
CTH=COS(TH)
IF(L.EQ.0)GO TO 300
IF(L.EQ.1)GO TO 301
IF(L.EQ.2)GO TO 302
IF(L.EQ.3)GO TO 303
GO TO 304
300 WHY=SQRT(1./(4.*PI))
M=0
RETURN
301 WHY=.5*SQRT(3./PI)*CTH
M=0
RETURN
302 IF(N.EQ.1)GO TO 310
IF(N.EQ.2)GO TO 311
310 WHY=.25*SQRT(5./PI)*(3.*CTH*CTH-1.)
M=0
RETURN
311 WHY=.25*SQRT(7.5/PI)*STH*STH*COS(2.*PHI)
M=2
RETURN
303 IF(N.EQ.1)GO TO 320
IF(N.EQ.2)GO TO 321
320 WHY=.25*SQRT(7./PI)*(5.*CTH*CTH-3.)*CTH
M=0
RETURN
321 WHY=.25*SQRT(52.5/PI)*STH*STH*CTH*COS(2.*PHI)
M=2
RETURN
304 IF(N.EQ.1)GO TO 330
IF(N.EQ.2)GO TO 331
IF(N.EQ.3)GO TO 332
330 WHY=3./16.*SQRT(1./PI)*(35.*CTH**4-30.*CTH*CTH+3.)
M=0
RETURN
331 WHY=15./8.*SQRT(1./(30.*PI))*STH*STH*(7.*CTH*CTH-1.)*COS(2.*PHI)
M=2
RETURN
332 WHY=105./16.*SQRT(1./(70.*PI))*STH**4*COS(4.*PHI)
M=4
RETURN
END
```

\$IBSYS

REFERENCES

1. M. E. Rose, Phys. Rev. 91, 610 (1953).
2. Feingold and Frankel, Physics Rev. 97, 1025 (1955).
3. Alpha-, Beta- and Gamma-Ray Spectroscopy, K. Siegbahn Ed. (North Holland Publishing Company, Amsterdam).
4. R. D. Evans, The Atomic Nucleus, McGraw-Hill Book Company, 1955.