MONTE CARLO CALCULATION OF MONOCHROMATIC GAMMA-RAYS ENERGY LOSS — APPLICATION FOR NaI(Tl) CRYSTALS

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H.R. Franzen, O.Y. Mafra e F.G. Bianchini

ABSTRACT

A program (GINASB) using the Monte Carlo Method for calculating the energy loss spectra of monoenergetic gamma rays in NaI(Tl) is described, taking into account the following primary interaction effects: Rayleigh, Photoeletric, Compton and Pair Production.

The method can be applied for circular cylinders of various diameters and heights.

This program supplies the energy loss spectra for point sources, broad and collimated parallel beams, and for incident gamma ray of energies from a few keV to 4 MeV.

The experimental resolution effect was taken into account by another program (STRECH).

Both programs were written in Fortran-II-D for the IBM 1620 - II Computer.

In this paper, the lists of the programs, GINASB and STRECH, functions and subroutines are presented.

A comparison between the calculated photo-fraction efficiencies and the energy loss - spectra with the experimental data is also presented.

I - INTRODUCTION

The precise knowledge of the energy loss spectra of gamma radiation is important in various fields of Nuclear Science and Technology, chiefly in Nuclear Spectroscopy.

The theoretical and experimental values of this energy loss are of utmost importance for complex spectra. The program presented in this paper permits the evaluation of the energy loss spectra for any sort of detector, by employing the appropriate cross sections and the various physical constants which are caracteristics of the detector.

In these theoretical calculations, the detector type (scintillators, semiconductors, etc) is not relevant since the physical processes of gamma radiation interaction are the same and do not depend on the nature of the substance considered. This physical process of interaction is simulated by the Monte Carlo Method, the photon history being followed completely inside the detector.

The informations which are obtained through gamma spectrometry are the measurement of the intensities and energies of the gamma rays.

In order to measure the gamma ray intensity it is necessary to know the photofraction and absolute total efficiency of the detector, which can be defined as follows:

i - photofraction - is the fraction of interacting gamma rays that are totally absorbed (including all the secondary particles).

ii - efficiency - is the fraction of emitted source gamma rays that interacts at least once in the crystal.

These factors can be calculated when the energy loss spectra is known.

The program, written in Fortran II-D, can be supplied to a wide range of the basic parameters such as crystal dimensions, source geometries and incident gamma ray energies.

Amongst others, one of the main reasons which led the authors to develop this program were the lack, in the literature available, of calculations with results concerning the various chosen parameters and the fact that there is not a good agreement between the results from different authors[(1)].

The program when utilized for NaI(Tl) crystal is called GINASB without the inclusion of Bremsstrahlung effect because of the insufficiency of the IBM 1620 II cores storage.

That is the reason why GINASB can be used only till 4 MeV, where the Bremsstrahlung effect has a negligible influence. On a computer IBM/360 the inclusion of the Bremsstrahlung effect permits the calculation till 10 MeV.

II - PHOTON HISTORIES

The complete history of an incoming photon and its subsequent secondary radiation is simulated according to the following manner: for an incident photon of a known energy, the initial direction and the point at which it enters the crystal are chosen at random, taking into account the source distribution.

In order to calculate the position of the first collision, a random number (chosen in the interval 0 - 1) which represents the probability of a photon colliding at a distance ℓ from the surface of the crystal, is related to the total cross section of the Sodium Iodide at the initial photon energy. The coordinates of the collision point are calculated and compared with the crystal dimensions. In the case that the collision point will be found to lie outside the crystal boundaries, the photon history ends. A count is placed in the history number counter and a new history is started. If the collision point lies inside the crystal (a count is placed in the interaction counter), a selection is made to choose the type of the event (Rayleigh or Compton scattering, Pair Production or Photoelectric Effect). The type of interaction is determined by a comparison of a random number with the ratio between the photoelectric effect cross section and the total cross section for the photon. If the random number is smaller than this ratio, the event will be a photoelectric effect; in the contrary case, the random number is compared with the ratio of the sum of the cross sections for Compton scattering and photoelectric effect to the total cross section. If the random number is smaller than this ratio, the event will be Compton scattering; in the contrary case it is compared with the ratio of the sum of cross sections due to the photoelectric effect, Compton scattering and pair production to the total cross section. If the random number will be smaller than this ratio, the event will be pair production; in the contrary case it will be a Rayleigh scattering.

In the case of a Compton effect, the energy and direction of the secondary photon is calculated according to the Klein-Nishina distribution and this secondary photon is analyzed in the same way as the initial photon. The length of the Compton electron track is calculated by using Wilson's theory[3] and its energy is the difference between the primary and the secondary photon energies. In the Rayleigh effect, the energy loss of the photon is of 1 eV and its new direction is determined by comparing a random number with the critical angle θ_c (which is a function of the incident photon energy) and with another random number with the distribution $dn \cong \exp(-b \cos \theta_c)$. In the pair production effect, the lengths of both the electron and the positron are calculated in order to check whether the whole track length of the particles lies inside the crystal or not. If the positron loses all of its energy inside the crystal, two annihilation gamma rays are produced at the end of the positron track. The direction of one of the gamma rays is chosen at random and, consequently the position of the other gamma ray is unambigously determined at 180^o of the first. Such annihilation gamma rays are considered then in the same way as the initial photons.

In the photoelectric effect, besides the photoelectron (which is analyzed whenever its track lies inside the crystal) there is the production of a characteristic gamma ray whose energy, for the NaI is of approximately 26 keV and has an isotropic distribution. This X-ray is treated in the same way as a initial gamma ray.

The energy loss spectra is presented as a histogram, in which the sub-intervals have a width equal to E_o/n, where E_o is the incoming photon energy and n is the number of channels considered.

III - GENERAL CONSIDERATIONS AND CALCULATION METHODS OF THE GINASB PROGRAM

Transport Mean Free Path

The distance between two collisions of a photon is chosen by hazard following the distribution:

$$\ell = - \frac{1}{\Sigma} \left[\ln (1 - \xi) \right] \quad (1)$$

where

ξ is a random number uniformly distributed in the 0 - 1 interval.

Σ is the total cross section at the photon energy.

As the distributions $(1 - \xi)$ and ξ are the same in the 0 - 1 interval, it follows that:

$$\ell = - \frac{1}{\Sigma} \left[\ln \xi \right] \quad (2)$$

Coordinate Systems at the Crystal Surface (Broad and Collimated Parallel Beams)

Broad beam - It is assumed that the incident gamma rays are uniformly distributed at the crystal surface. The point of impact of the incident gamma ray is determined by selecting a random point on the face of the cylinder.

Collimated parallel beam - The incident gamma ray is sampled in the same manner, except that the point of impact is restricted to an area defined by the radius of collimation

$$x_{initial} = R \cos \theta$$
$$y_{initial} = R \sin \theta \qquad (3)$$
$$z_{initial} = 0$$

where

R is the radial distance from the point of impact at the surface to the crystal center.

This distance R can be calculated by the following expression

$$R = R_{crystal} \sqrt{\xi} \qquad (4)$$

where

$R_{crystal}$ = crystal radius

ξ = random number from 0 to 1

The angle θ is chosen according to the distribution

$$\theta = \pi(2\eta - 1) \qquad (5)$$

where

η is a random number between zero and 1

Therefore, the final expressions for the initial coordinates are:

$$x_{initial} = R_{crystal} \sqrt{\xi} \cos \left[\pi(2\eta - 1)\right]$$
$$y_{initial} = R_{crystal} \sqrt{\xi} \sin \left[\pi(2\eta - 1)\right]$$
$$z_{initial} = 0$$

Calculation of the New Coordinates After Collision

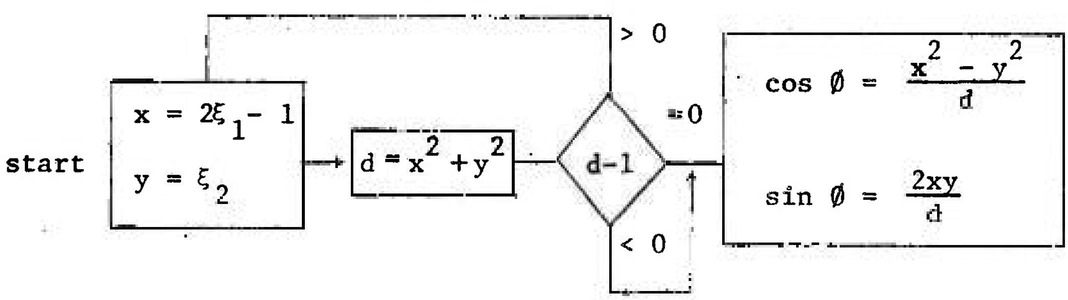
$$x = x_{initial} + |\ell| \cos \alpha$$
$$y = y_{initial} + |\ell| \cos \beta$$
$$z = z_{initial} + |\ell| \cos \gamma$$

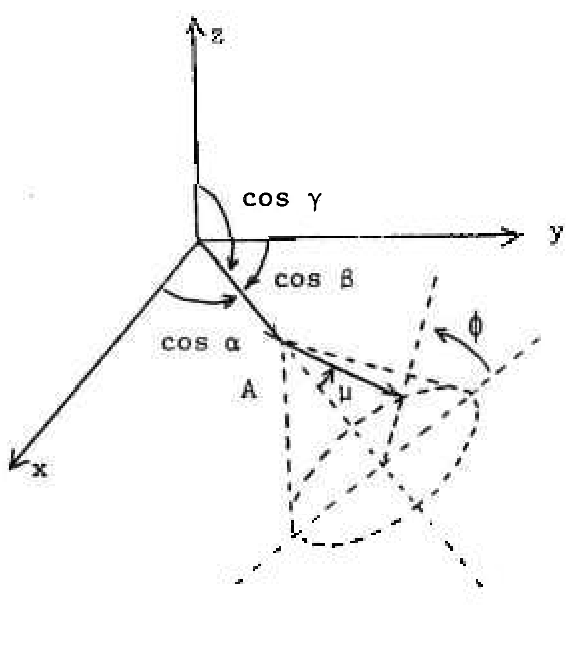
where

ℓ is the mean free path and cos α, cos β, cos γ the direction cosines of the scattering direction.

Von Neumann's Technique for Selecting a Uniformly Distributed Azimuthal Angle

If Ø is the azimuthal angle and ξ_1 and ξ_2 two random numbers uniformly distributed at the 0 — 1 interval, we can select sin Ø and cos Ø through the following block diagram



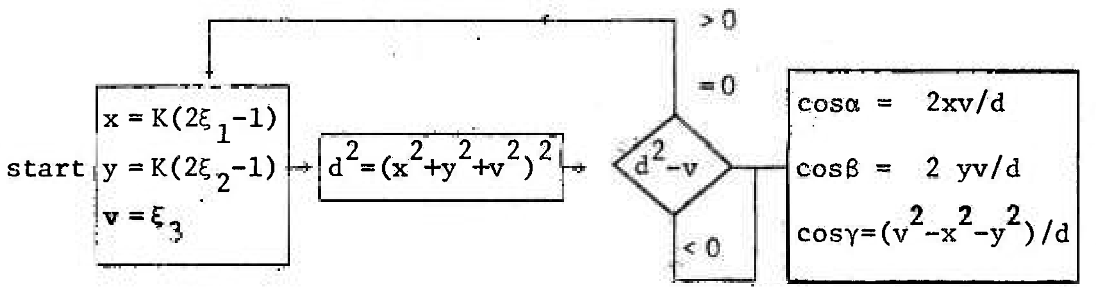


μ = cos Ø

A - first collision

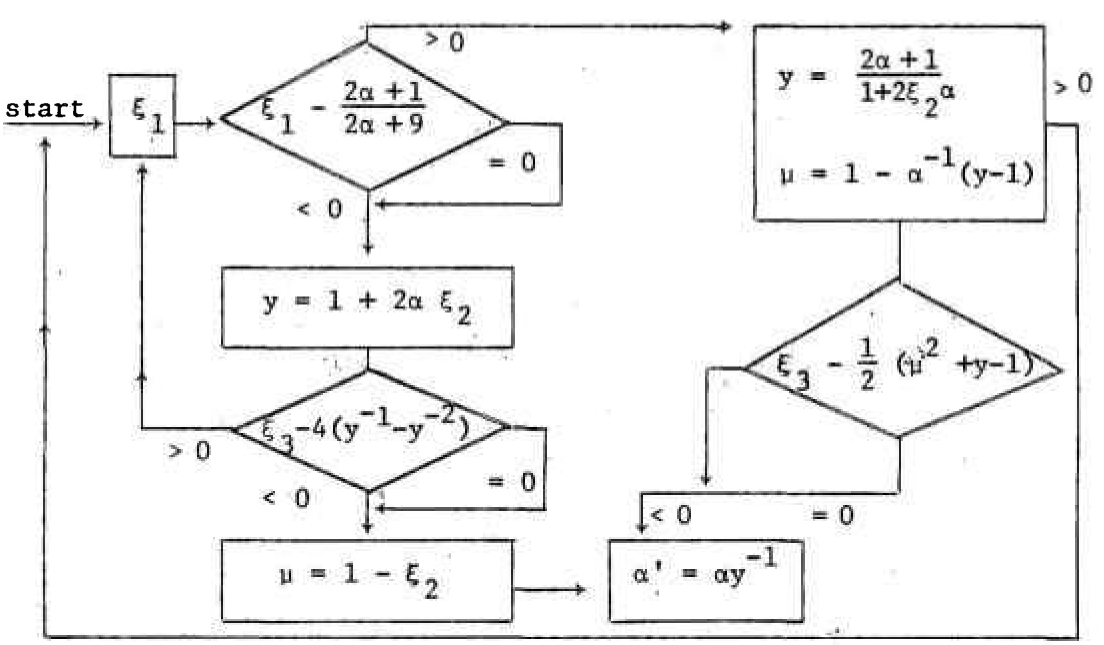
Coveyou's Method for Selecting a Random Isotropic Direction

If ξ_1, ξ_2, ξ_3 are three random numbers uniformly distributed in the 0 — 1 interval and, if $K = \sqrt{3} / \sqrt[3]{16}$, the direction cosines can be obtained from the following block diagram:



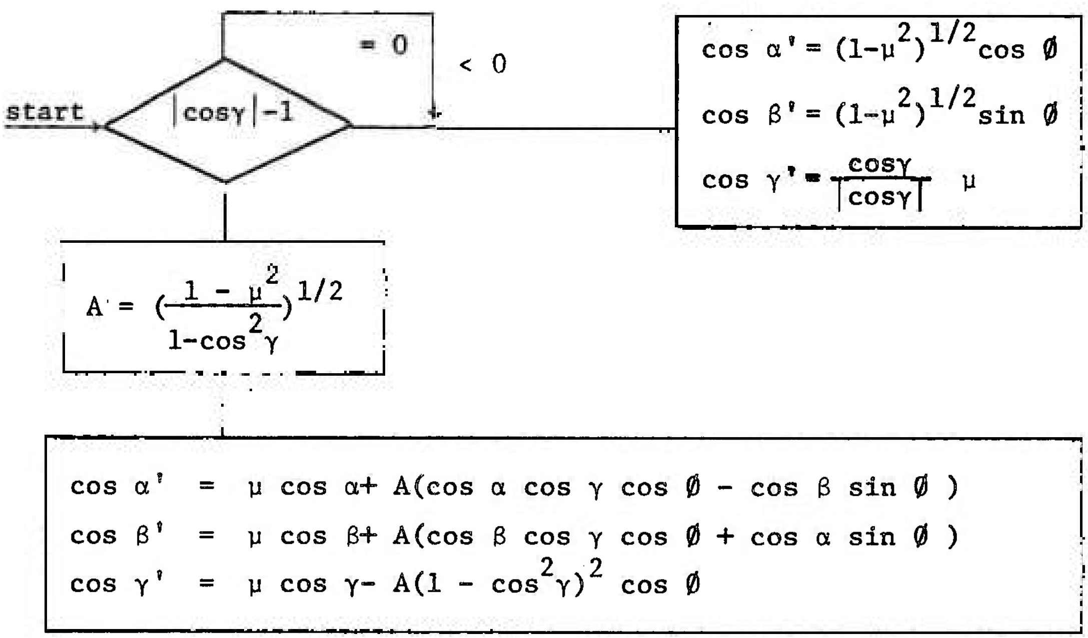
Kahn's Method for Randomly the Cosine of the Polar Angle of Scattering

If $\alpha = E/.511$ (where E is the photon energy in MeV) and ξ_1, ξ_2, ξ_3 are random numbers, the cosine of the polar angle of the scattering gamma ray, μ, is obtained through the following diagram



Rotation of the Coordinates. Choice of New Direction Cosines

If cos α, cos β, cos γ are the new direction cosines of the incident photon, Ø the azimuthal angle, and μ the cosine of the polar angle, the new scattering direction will be given by the direction cosines, cos α', cos β' and cos γ' by means of the following diagram:



Point Source - Forced Collisions

The direction of the initial photon is chosen by hazard, uniformly distributed in a solid angle, subentended by the source height and the crystal diameter.

If D is the distance from the point source to the crystal surface, R the crystal radius, ξ_1 a random number uniformly distributed in the 0 — 1 interval, the direction cosine of the z axis is calculated from the following block diagram

$$\xi_1 \longrightarrow \cos\gamma = \xi_1 \left(1 - \frac{D}{R}\right) - 1$$

The other direction cosines can be obtained by

$$\theta = \pi(2\,\xi_2 - 1)$$

$$\downarrow$$

$$R_i = D\,\frac{\sqrt{1-(\cos\gamma)^2}}{\cos\gamma}$$

$$\downarrow$$

$$x_i = R_i \cos\theta \qquad y_i = R_i \sin\theta \qquad z_i = 0$$

$$\longrightarrow \quad \cos\beta = \frac{y_i}{\sqrt{x_i^2 + y_i^2 + D^2}} \qquad \cos\alpha = \frac{x_i}{\sqrt{x_i^2 + y_i^2 + D^2}}$$

where x_i, y_i, z_i are the incidence coordinates at the crystal surface.

IV - RESOLUTION EFFECTS - "STRECH"

In the calculation of the energy loss spectra by the GINASB, no account was taken of the resolution effects accompanying light collection within the crystal and its amplification through the photomultiplier system. In this chapter, those effects are included in the calculations.

The function used to correct the resolution effects is a Gaussian curve in the form:

$$G(E, E') = \frac{1}{k\,\sigma} \exp\left[-\frac{1}{2}(E - E')^2 / \sigma^2\right]$$

whose half width is determined experimentally.

The resolution used for a NaI(Tl) 3" x 3" crystal was taken as $R = A\,E^{-1/2} + B$, where A and B are parameters determined experimentally[5].

V - RESULTS AND COMPARISON WITH EXPERIMENTAL DATA

Some calculations of photofraction and intrinsic efficiency were made. In order to allow a comparison with the data available other authors, the crystal dimensions and geometries were chosen accordingly. These comparisons are presented in the tables of the figures 2 and 3.

The errors signed correspond only to the statistic fluctuations intrinsic of the Monte Carlo Method; therefore, the systematic errors, due to the choosen model or to the values of the cross section employed, are not taken into account.

In figure 4 we present a comparison of the photofraction curve with theoretical[1] data obtained also by the Monte Carlo Method; it refers to point source, 10 cm far away from the NaI(Tl) crystal 3" x 3".

Our results for the photofraction and efficiency can be considered satisfactory because of the reasonable agreement with the experimental[4] data, as can be observed in figure 5.

A further comparison was made between the calculated histogram, the results obtained after the resolution correction by the STRECH program and the experimental data[4] (figure 6).

The lack of agreement between the theoretical and the experimental response function can be attributed to the experimental background. The fact that the experimental photopeak considered in the STRECH program, is a perfect Gaussian and not a modified one are responsible for the disagreement; more correct approach should give rise to a deeper valley before the photopeak.

VI - GINASB PROGRAM, SUBROUTINE AND FUNCTIONS FOR IBM 1620 (Printer Unit 144 Positions)

Function ACC	random number generation.
Function POLSC	gives the total cross section NaI(Tl) crystal.
Function REPOL	gives the relation between the individual to total cross sections.
Function NEUMAN	cosine and sine of the azimuthal angle Φ.
Subroutine GERAL	calculates the energy loss inside the crystal, direction cosines and verifies if the electrons, positrons, gamma rays and X rays are or not inside the detector.
Program GINASB	selects the interaction type, kinetic energies and performs the distribution of energy loss in the corresponding channel.

Number of Core Storage Positions Required

ACC	342
POLSC	596
REPOL	2320
GERAL	8094
NEUMAN	680
GINASB	14730

Restriction

a) maximum number of channels : 128

b) the control card *FANDK1010 must be used in all functions, subroutine and main program

c) the random number used to begin a complete calculation must have an 1, 3, 7 or 9 in the unit position.

Sense Switch Conditions

To interrupt the program whenever required turn on sense switch 2. After the program interruption, 15 cards will be punched. These cards contain the necessary data to a next processing.

To study the point source case, the switch number 3 must be mantained on during the running.

End of Processing

The processing finishes when the total number of interactions in the spectra reaches 10.000.

Equivalence

RCRIST	crystal radius (cm)	Format F7.3
HCRIST	crystal height (cm)	Format F7.3
RFEIXE	beam radius (cm)	Format F7.3
DP	distance from point source (cm)	Format F7.3
IMP	always zero to begin a complete calculation	Format F7.3
INTERV	interval between the impression of partial results	Format I6
NI	interactions number	Format I6
NH	histories number	Format I6
NC	Compton events number	Format I6

NP	pair production events number	Format I6
NR	Rayleigh events number	Format I6
NF	Photoelectric events number	Format I6
IU	random number	Format I10
KANAL	counts per channel	Format I8

VII - MODIFICATIONS OF GINASB PROGRAM, SUBROUTINE AND FUNCTIONS FOR IBM/360 COMPUTER (Model 44)

a) In all functions, subroutines and main program, replace LOG by ALOG.

b) The random number IU must contain only 9 digits and must end with any odd digit.

c) Remove all cards *FANDK1010 of the functions, subroutine and main program, and also the cards LDISK.

d) The variable IDENT in the READ instruction substitutes the sense switch conditions (see list).

e) Function ACC must be replaced by a new function ACC (see list).

VIII - "STRECH" PROGRAM

The resolution effect applied to the final results of GINASB program can be obtained by the STRECH program written in Fortran II-D. The counts N(K) in a channel K can be obtained by the following expression:

$$N(K) = \sum_{i=1}^{N} \frac{\omega_i\, I(\xi_i)}{\sqrt{2\pi}\,\sigma_i}\; e^{-(E_i-E_k)^2/2\sigma_i^2}$$

where

N = number of analyzed channels

$I(\xi_i)$ = counts in the i^{th} channel (results of the GINASB program)

σ_i = $BE + A(E_i)^{1/2}$ where A and B are constants and E_i the energy of i channel

E_i, E_k = channel energy i and k

$N(K)$ = final counts of k channel

ω_i = 1 if $i \neq 0$ and

ω_i = 1/2 if i = first or last channel

Sense Switch Conditions

Sense switch 1 - ON - to interrupt the program.

Sense switch 2 - ON - to check the number of the channel being processed.

Core Storage Positions Required

10418

Restrictions

Maximum number of channels: 145

The program must contain the control card *FANDK1008

Equivalence

A,B	constants in the expression $A(E)^{1/2} + BE$	Format 2E14.8
E128	energy of the 128 channel	Format E14.8
N	number of channels	Format I4

RESUMO

Neste trabalho apresenta-se o programa GINASB escrito em FORTRAN-II-D, para o computador IBM 1620, modêlo II. Êste programa permite efetuar, através do método de Monte Carlo um estudo da distribuição da perda de energia em cristais de iodeto de sódio, para radiação gama monoenergética, isto é, da função de resposta do cristal.

Os efeitos de interação da radiação gama com a matéria considerados no programa são: Rayleigh, foto-elétrico, Compton e produção de pares.

Podem ser efetuados com êste programa cálculos da perda de energia para fontes pontuais ou feixes, para várias dimensões de cristal e para energias dos raios gama incidentes variando desde alguns keV até aproximadamente 4 MeV.

Para o estudo da influência da resolução no espectro de linhas fornecido pelo programa GINASB, foi desenvolvido um outro programa - STRECH.

Neste trabalho são apresentadas as listas dos programas, funções e sub-rotinas utilizadas, e, também as modificações para o processamento do GINASB no computador IBM / 360.

São apresentadas ainda comparações entre a foto-fração calculada pelo GINASB e valôres teóricos e experimentais de outros autores, assim como uma comparação entre o espectro calculado corrigido para resolução e o experimental.

RÉSUMÉ

Le GINASB est un programme écrit en langage FORTRAN-II-D, pour le computateur IBM 1620, modèle II. Le programme utilize la méthode de Monte Carlo pour étudier la distribution de la perte d'énergie dans les cristaux d'iodure de sodium, pour des radiations gamma monochromatiques.

Les effets de l'interation de la radiation gamma avec la matière considerés sont: Rayleigh, photoéléctrique, Compton et production de paires.

Le programme permet calculer pour des cristaux de différentes dimensions, la perte d'energie des rayons gamma provenant de sources ponctuelles ou de faisceaux d'énergies comprises entre quelques keV jusqu'à 4 MeV.

Le rôle de la résolution dans le spectre de raies donné par le GINASB est étudié avec l'aide du programme STRECH.

Les listes des programmes, fonctions et subroutines utilizées sont ici presentées ainsi que les modifications pour leur utilisation dans l'IBM/360.

La comparaison entre la photofraction calculée par le GINASB, et quelques valeurs théoriques et expérimentales prouvées dans la littérature est faite. Nous avons calculé aussi le spectre affecté par la resolution et comparé avec les donnés expérimentales.

ACKNOWLEDGEMENTS

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(2) Methods in Computational in Physics - Berni Alder.

(3) W.F. Miller, W.J. Snow - ANL 6318.

(4) R.L. Heath - IDO 16880 - vol. 1.

(5) C.D. Zerby, H.S. Moran - ORNL 3169.

LIST OF FIGURES

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Figure 3 - Table presenting a comparison of the efficiency data for NaI(Tl) crystal 2 inch x 2 inch broad beam.

Figure 4 - Comparison between theoretical curves of photofraction against the incident gamma ray energy for crystal 3 inch x 3 inch point source 10 cm for away.

Figure 5 - Comparison of our photofraction data with experimental data.

Figure 6 - Comparison for Cs^{137} between response function obtained from GINASB (with and without the correction for the resolution effect) and the experimental one.

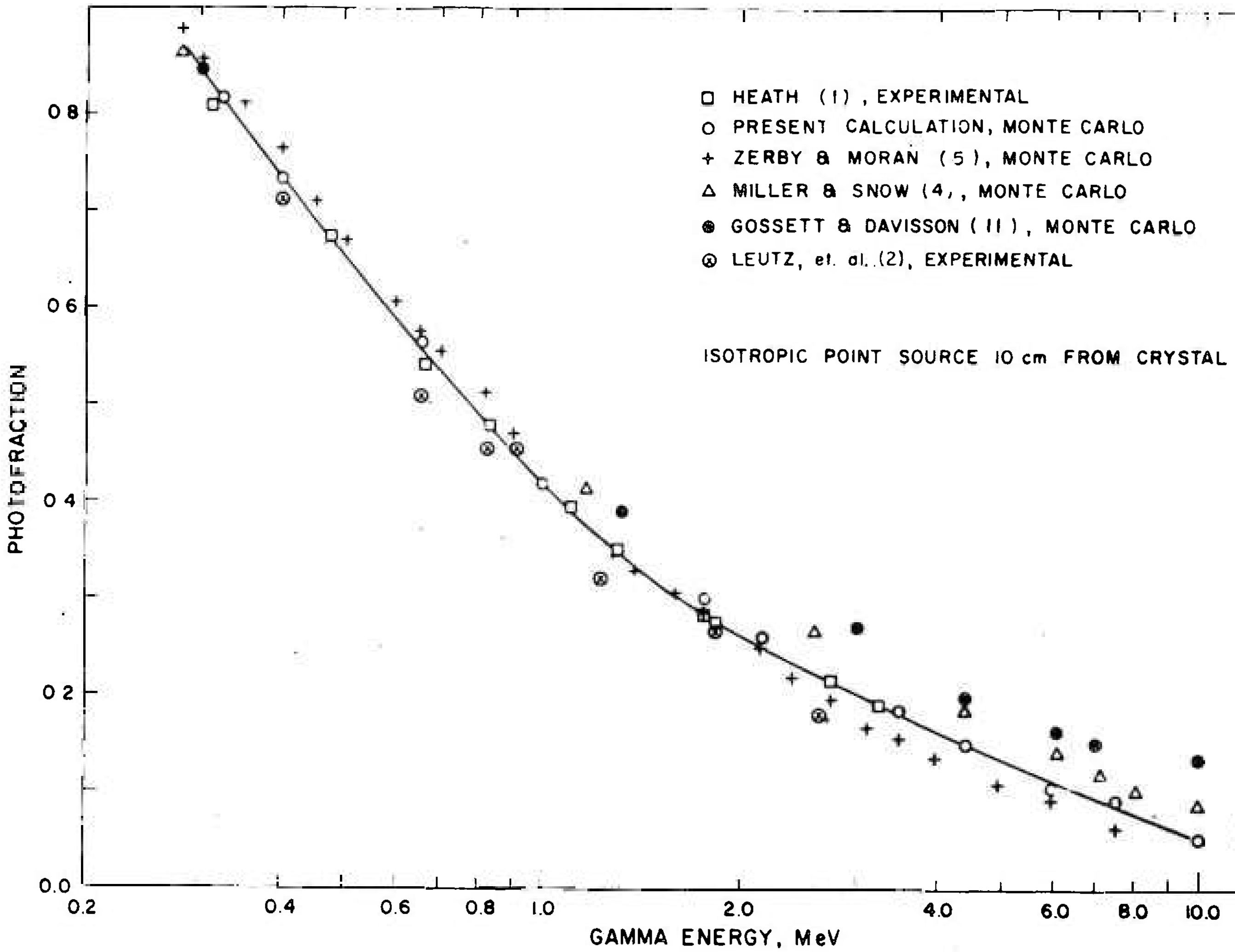


Fig. 1. Photofraction vs energy for 3″ × 3″ solid crystal.

PHOTOFRACTION

BROAD BEAM - CRYSTAL : NaI 2" x 2"

E(MeV)	GINASB	ANL-6318	ANL-5902
.279	.831 ± .001	.829	.855
.661	.476 ± .001	.470	.481
1.33	.295 ± .005	.297	.286
2.62	.166 ± .001	.189	.199
4.45	.121 ± .001	.11	.141

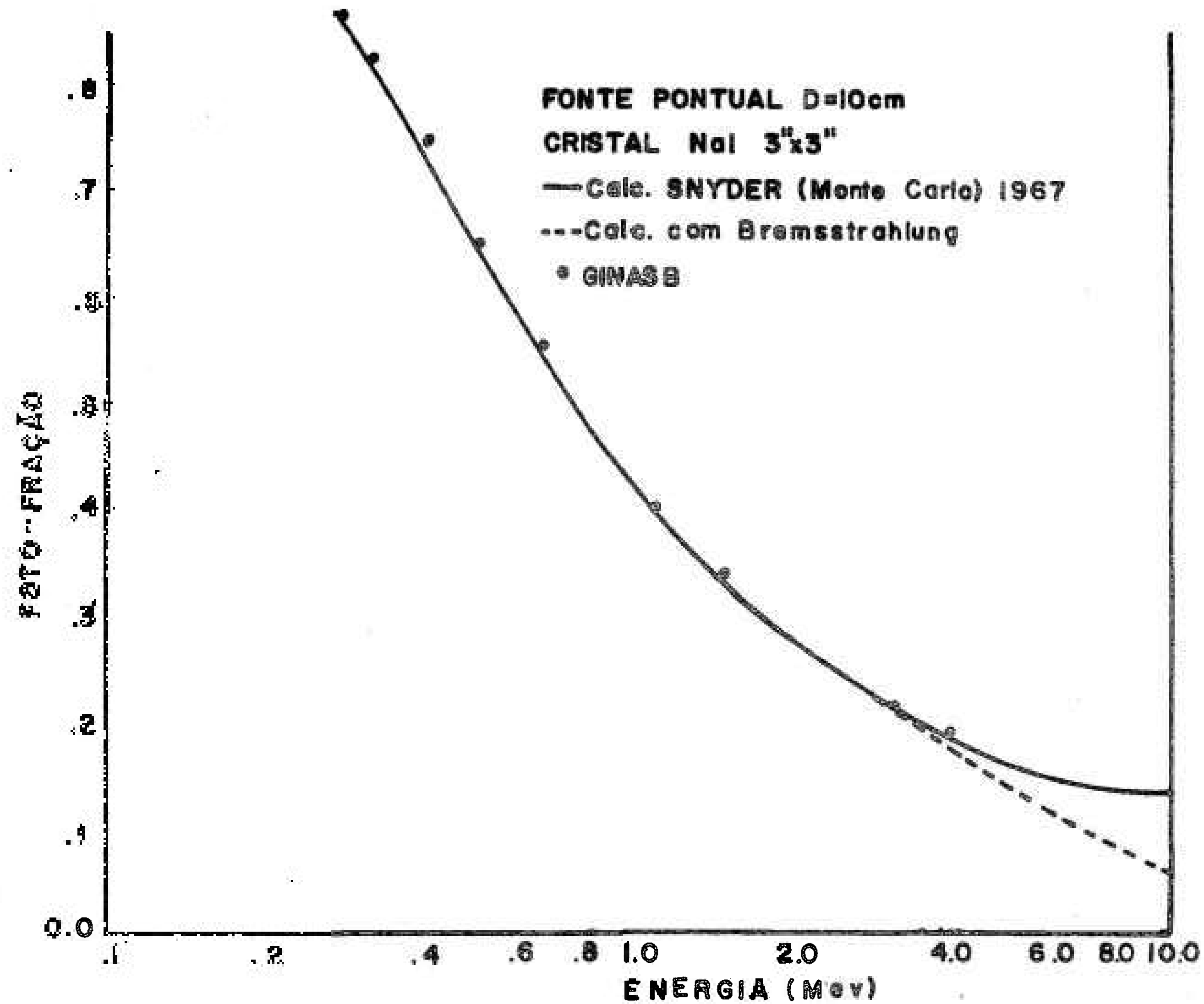
Fig. 2

EFFICIENCY

BROAD BEAM - CRYSTAL : 2" x 2"

E(MeV)	GINASB	ANL-6318	ANL-5902
.279	.966	.966	.957 ± .004
.661	.764	.754	.749 ± .005
1.33	.612	.602	.613 ± .005
2.62	.501	.495	.509 ± .003
4.45	.477	.471	.484 ± .002

Fig. 3


FONTE PONTUAL D=10cm
CRISTAL NaI 3"x3"
—Calc. SNYDER (Monte Carlo) 1967
---Calc. com Bremsstrahlung
• GINASB
FOTO - FRAÇÃO
.8
.7
.4
.3
.2
.1
0.0
.1
.2
.4
.6
.8
1.0
2.0
4.0
6.0
8.0
10.0
ENERGIA (Mev)
Fig. 4

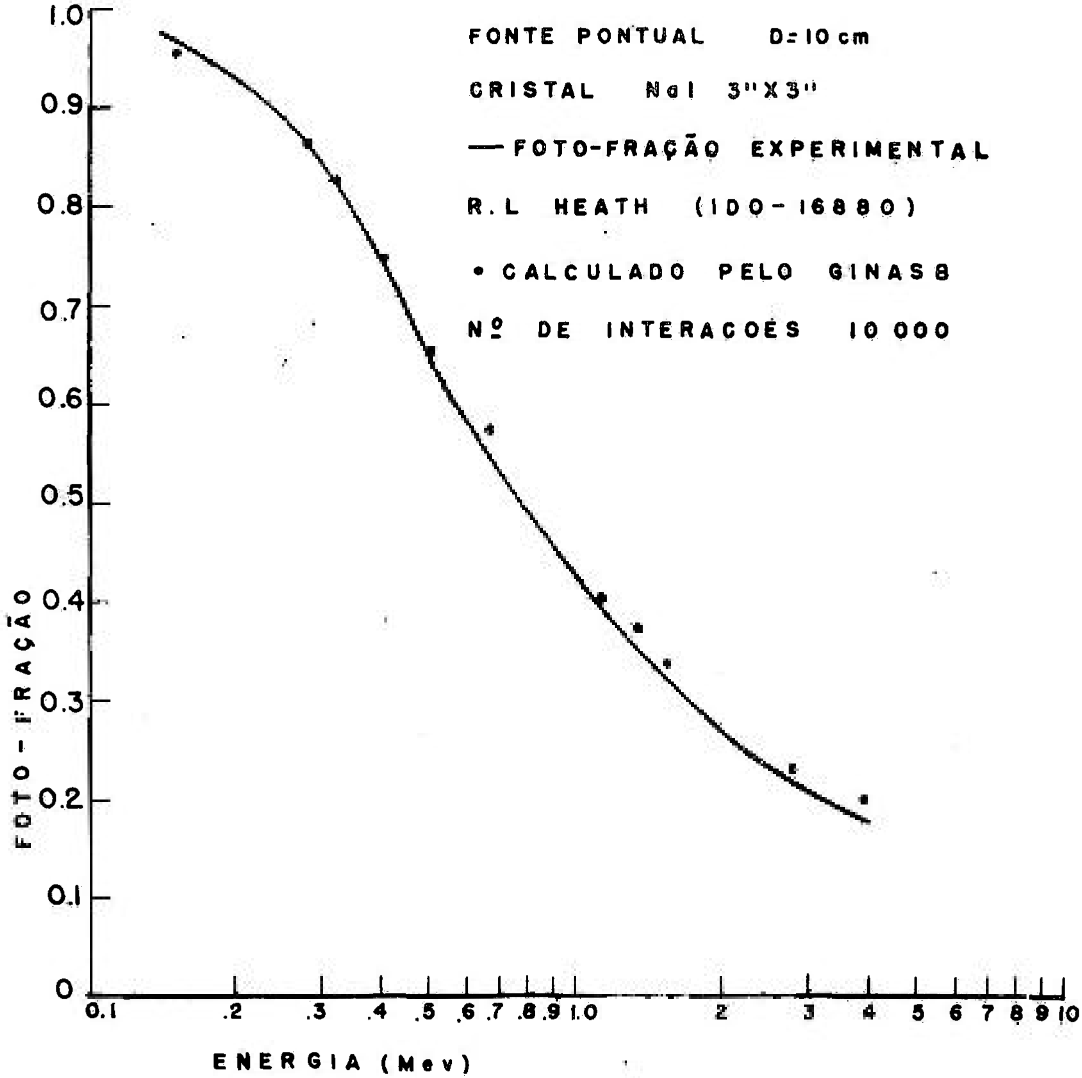
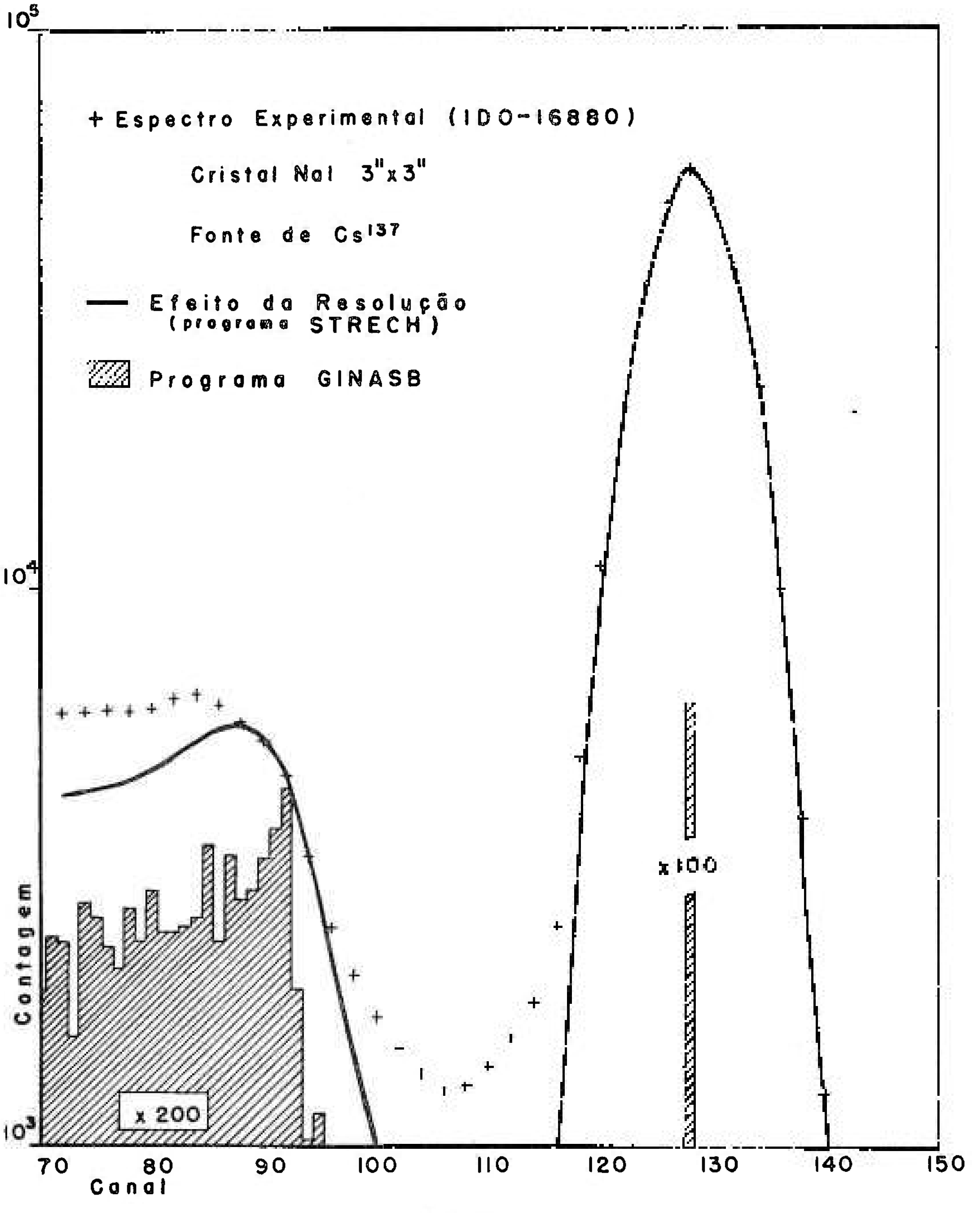

FONTE PONTUAL D=10 cm
CRISTAL NaI 3"X3"
— FOTO-FRAÇÃO EXPERIMENTAL
R.L HEATH (IDO-16880)
• CALCULADO PELO GINAS 8
Nº DE INTERACOÉS 10 000
FOTO-FRAÇÃO
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
2
3
4
5
6
7
8
9
10
ENERGIA (Mev)

Fig. 5



+ Espectro Experimental (IDO-16880)
Cristal NaI 3"x3"
Fonte de Cs137
Efeito da Resolução (programa STRECH)
Programa GINASB
x 200
x 100
Contagem
Canal
10⁵
10⁴
10³
70
80
90
100
110
120
130
140
150

Fig. 6

```
C          GINASB-IBM 1620
C*****************************************************
         ******************
C
C******************NO BREMSSTRAHLUNG
C
C*****************************************************
         ******************
C*****************IDENTIFICACTION*****************
C  KK=2   COMPTON EFFECT
C  KK=4   PAIR PRODUCTION
C  KK=6   ANNIHILATION GAMMAS
C  KK=8   PHOTOELECTRIC EFFECT
C  KK=9   RAYLEIGH SCATTERING
C  KK=10    X RAY
C
C******************COMMENTS*****************
C  INTERV   INTERVAL TO PRINT PARCIAL RESULTS
C  IMP   EQUAL ZERO
C  XIN,YIN,ZIN   POINT COORDENATES
C  FOTOFR   PHOTOFRACTION
C  EINC   INCIDENT ENERGY (MEV )
C  KANAL(KL)   CHANNEL COUNTS
C  NH   NUMBER OF HISTORIES
C  NC   NUMBER OF COMPTON INTERACTIONS
C  NI   PRIMARY INTERACTIONS NUMBER
C  NF   NUMBER PHOTOELETRIC INTERACTIONS
C  NR   NUMBER RAYLEIGH INTERACTIONS
C  NP   NUMBER OF PAIRS INTERACTIONS
C  ALFAD,BETAD,GAMAD - DIRECTION COSINES OF INCIDENT
         GAMMA
C  ENA   TOTAL ENERGY ABSORBED
C  YF   PHOTOELETRIC TO TOTAL CROSS SECTION RATIO
C  YC   COMPTON TO TOTAL CROSS SECTION RATIO
C  YP   PAIR PRODUCTION TO TOTAL CROSS SECTION RATIO
C  YR   RAYLEIGH TO TOTAL CROSS SECTION RATIO
C
C
C******SWITCH 2 ON-TO INTERRUPT THE PROGRAM
C
C
C******SWITCH 3 ON-TO STUDY POINT SOURCE
C
      DIMENSION KANAL(128)
      COMMON IX,SHIFT,KK,XIN,YIN,ZIN,RCRIST,HCRIST,KS
         ,K,U,COSFI,SENFI,
     1ALFAD,BETAD,GAMAD,UL,COSFIE,SENFIE,EINIC,EF,ENA
         S,XS,YS,ZS,ADS,BDS,
```

```
     2GDS,ECPP,MARX,JU,IRAY,XKR
C
C
C
      SHIFT=10.**(-10.)
      IX=100003
      IRAY=0
      XKR=SQRT(3.)/(4.**(2./3.))
C
C
C
C*********START*********
 1222 READ 10,RCRIST,HCRIST,RFEIXE,EINC,DP
 10   FORMAT(5F7.3)
      READ 9,NI,NF,NR,NC,NP,NH,INTERV,IMP,IU
 9    FORMAT(8I6,I10)
      PRINT 998,RCRIST,HCRIST,RFEIXE,EINC,DP
 998  FORMAT(1H ,15HCRYSTAL RADIUS=F7.3,2HCM,5X,15HCR
         YSTAL HEIGHT=F7.3,2
     1HCM,5X,12HBEAM RADIUS=F7.3,2HCM,5X,7HENERGY=F7.
        .3,3HMEV//,1H ,13HDI
     2ST. SOURCE=F7.3//)
      READ 8900,(KANAL(KL),KL=1,128)
 8900 FORMAT(10I8)
C
      IMP=IMP+INTERV
C
C
 101  EINIC=EINC
      MAPPP=0
      ENA=0
C
C
C     NUMBER OF HISTORIES
      NH=NH+1
      ZIN=0
C
C
      IF(SENSE SWITCH 3)2034,2035
C     POINT SOURCE
 2034  AX=SQRT(RCRIST*RCRIST+DP*DP)
      COSMAX=-DP/AX
      COSG=ACC(IU)*(1.+COSMAX)-1.
      RI=ABS(DP*SQRT(1.-COSG**2)/COSG)
      TETA=3.1416*(2.*ACC(IU)-1.)
      XIN=RI*COS(TETA)
      YIN=RI*SIN(TETA)
```

```
      ALFAD=XIN/SQRT(XIN*XIN+YIN*YIN+DP*DP)
      BETAD=YIN/SQRT(XIN*XIN+YIN*YIN+DP*DP)
      GAMAD=COSG
      GO TO 4080
C
C
C     DISTANCY FROM CRYSTAL CENTER
 2035 R=RFEIXE*SQRT(ACC(IU))
C
C*****ENTANCE COORDENATES OF INCIDENT GAMMA RAY
 462  TETA=3.1416*(2.*ACC(IU)-1.)
      XIN=R*COS(TETA)
      YIN=R*SIN(TETA)
C
C     DIRECTION COSINES OF INCIDENT GAMMA RAY
 3034 ALFAD=0
      BETAD=0
      GAMAD=-1
C
C
 4080 ELECOL=-1./POLSC(EINIC)*LOG(ACC(IU))
C
      IF(SENSE SWITCH 3)2397,2396
 2397 XIN=XIN+ALFAD*ELECOL
      YIN=YIN+BETAD*ELECOL
 2396 ZIN=ZIN+ELECOL*GAMAD
 2398 KK=1
      CALL GERAL
      ENA=ENA+ENAS
      GO TO (1,102),KS
 102  NI=NI+1
C
C*********TYPE OF INTERACTIONS
 105  CALL REPOL(EINIC,YR,YF,YC,YP)
 4566 Y=ACC(IU)
      IF(Y-YF)18,18,107
 107  IF(Y-(YF+YC))108,108,109
 108  NC=NC+1
      GO TO 8
 109  IF(Y-(YF+YC+YP))280,280,9111
C
C
C*********COMPTON EFFECT
 8    ALFA=EINIC/.511
 23   R1=ACC(IU)
      IF(R1-(2.*ALFA+1.)/(2.*ALFA+9.))21,21,22
 21   R2=ACC(IU)
```

```
      Y=1.+2.*ALFA*R2
      R3=ACC(IU)
      IF(R3-4.*(1./Y-1./Y**2))24,24,23
 24   U=1.-2.*R2
      GO TO 26
 22   R2=ACC(IU)
      Y=(2.*ALFA+1.)/(1.+2.*ALFA*R2)
      U=1.-1./ALFA*(Y-1.)
      R3=ACC(IU)
      IF(R3-.5*(U**2+1./Y))26,26,23
 26   ALFAL=ALFA/Y
      EF=.511*ALFAL
      CALL NEUMAM(IU,COSFI,SENFI)
      CAA=(1.+EINIC/.511)**2*(1.-U)
      UL=SQRT (CAA/(CAA+1.+U))
      COSFIE=-COSFI
      SENFIE=-SENFI
      KK=2
      K=2
      CALL GERAL
      ENA=ENA+ENAS
      GO TO (1,104),KS
 104  XIN=XS
      YIN=YS
      ZIN=ZS
C
C
C     FINAL DIRECTION COSINES
      ALFAD=ADS
      BETAD=BDS
      GAMAD=GDS
      EINIC=EF
      GO TO 105
C
C
C*********PAIR PRODUCTION
 280  IF(EINIC-1.50)4566,5280,5280
 5280 ECPP=.5*(EINIC-1.022)
      NP=NP+1
      U=COS(.511/ECPP)
      CALL NEUMAM(IU,COSFI,SENFI)
      UL=U
      IF(KK-1)33,34,33
 33   ALFAD=ADS
      BETAD=BDS
      GAMAD=GDS
 34   COSFIE=-COSFI
```

```
      SENFIE=-SENFI
      KK=4
      K=2
      CALL GERAL
      ENA=ENA+ENAS
      GO TO (1,1  ,1010),KS
C
C
C     FIRST ANNIHILATION GAMMA RAY
 1010 XIN=XS
      YIN=YS
      ZIN=ZS
      XINN=XS
      YINN=YS
      ZINN=ZS
      ELE=-1./POLSC(.511)*LOG(ACC(IU))
      KK=6
C
C
C     DIRECTION COSINES OF ANNIHILATION GAMMA RAY
 3999 XAN=XKR*(2 .*ACC(IU)-1.)
      YAN=XKR*(2 .*ACC(IU)-1 .)
      VAN=ACC(IU)
      DD=XAN*XAN+YAN*YAN+VAN*VAN
      IF(DD*DD-VAN)4476,4476,3999
 4476  ALFAD=2.*XAN*VAN/DD
      BETAD=2.*YAN*VAN/DD
      GAMAD=(VAN*VAN-XAN*XAN-YAN*YAN)/DD
 2731 XIN=XIN+ALFAD*ELE
      YIN=YIN+BETAD*ELE
 5441 ZIN=ZIN+ELE*GAMAD
 1002 CALL GERAL
      ENA=ENA+ENAS
      MAPPP=MARX
      GO TO (1011,1,1105),KS
 1105 EINIC=.511
      GO TO 105
C
C     SECOND ANNIHILATION GAMMA RAY
 1011 KK=7
      EINIC=.511
      GAMAD=-GAMAD
      ALFAD=-ALFAD
      BETAD=-BETAD
      XIN=XINN
      YIN=YINN
      ZIN=ZINN
```

```
      ELE=-1./POLSC(EINIC)*LOG(ACC(IU))
      GO TO 2731
C
C
C******PHOTOELETRIC EFFECT
 18   IF(EINIC-2.00)5218,5218,4566
 5218 NF=NF+1
      IF(EINIC-.033164)5220,5220,5219
 5220  ELIG=.005187
      GO TO 6588
 5219 ELIG=.033164
 6588 ECIN=EINIC-ELIG
      CCC=(EINIC/.511)**2
      DDD=1.+1.022/ECIN
      BC=SQRT(CCC*DDD/(1.+CCC*DDD))
 587  TETA=3.1416*(1.-ACC(IU))
      AK=2.*BC*(1.+ELIG/ECIN)
      DNDOM=SIN(TETA)**2*(1.+AK*COS(TETA))
      IF(DNDOM)587,586,586
 586  COSMAX=SQRT((1.+AK)**2+AK**2)/AK-(1.+AK)/AK
      DNDTET=SIN(TETA)**2*(1.+AK*COS(TETA))/((1.-COSM
         AX**2)*(1.+AK*COSMA
     1X))
      IF(ACC(IU)-DNDTET)1586,1586,587
 1586 UL=COS(TETA)
      CALL NEUMAM(IU,COSFIE,SENFIE)
      IF(KK-1)914,913,914
 914  ALFAD=ADS
      BETAD=BDS
      GAMAD=GDS
 913  KK=8
      K=-1
      CALL GERAL
      ENA=ENA+ENAS
 1    IF(MAPPP)911,911,1012
 1012  MAPPP=0
      GO TO 1011
C
C
C*****RAYLEIGH SCATTERING
 9111 IF(EINIC-1.500)8886,4566,4566
 8886 NR=NR+1
      IRAY=1
      SENC=.026*53.**(1./3.)*.511/EINIC
      COSC=1.-2.*SENC*SENC
 7466  COSTQ=2.*ACC(IU)-1.
      IF(ABS(COSC)-1.)7411,7411,1273
```

```
 7411 IF(COSTQ-COSC)7466,1273,1273
 1273 DN=EXP(-.100*COSTQ)
 8101 Y=ACC(IU)
      IF(DN-Y)7466,1808,1808
 1808 UL=COSTQ
 2605 IF(KK-1)2607,2608,2607
 2607 ALFAD=ADS
      BETAD=BDS
      GAMAD=GDS
 2608 KK=9
      CALL NEUMAM(IU,COSFIE,SENFIE)
      EINIC=EINIC-.001
 2712 K=-1
      CALL GERAL
      IRAY=0
      ENA=ENA+.001
      GO TO(1,9105),KS
 9105 XIN=XS
      YIN=YS
      ZIN=ZS
      ALFAD=ADS
      BETAD=BDS
      GAMAD=GDS
      GO TO 105
C**********TOTAL ENERGY DISTRIBUTION
C
C
 911  IF(ENA)912,2010,912
 912  II=ENA/EINC*128.
      IF(II-128)4914,915,8316
 915  KANAL(II)=KANAL(II)+1
      GO TO 2010
 8316  PRINT 9,NH
 919  STOP 1
 4914  KANAL(II+1)=KANAL(II+1)+1
C
C
C**********PRINTING RESULTS
 2010 IF(SENSE SWITCH 2)996,601
 601  IF(NI-IMP)101,1180,1180
 1180 IMP=IMP+INTERV
      IF(IMP-10000-INTERV)996, 996,919
 996  PRINT 997,NH,NI,NC,NR,NF,NP,IU,IMP
      PRINT 849,(KL,KANAL(KL),KL=1,128)
      LI=0
      DO 6666 KL=1,128
 6666  LI=LI+KANAL(KL)
```

```
      ALI=LI
      SSS=KANAL(128)
      FOTOFR=SSS/ALI
      ANI=NI
      ANH=NH
      EFIC=ANI/ANH
      ERRO=SQRT(FOTOFR*(1.-FOTOFR)/ANI)
      PRINT 4896,LI,FOTOFR,ERRO,EFIC
 4896 FORMAT(/1H ,10HTOTAL SUM=I10,6X,14HPHOTOFRACTIO
     . N=F7.4,3X,6HERROR=F,
    38.4,6X,10HEFICIENCY=F6.3//)
      IMP1=IMP-INTERV
      PUNCH 10,RCRIST,HCRIST,RFEIXE,EINC,DP
      PUNCH 9,NI,NF,NR,NC,NP,NH,INTERV,IMP1,IU
      PUNCH 8900,(KANAL(KL),KL=1,128)
       IF(NI-10000) 101,1222,1222
 849  FORMAT(10(1H ,I3,I5,4X))
 997  FORMAT(1H ,3HNH=I7,4X,3HNI=I7,4X,3HNC=I7,4X,3HN
        R=I7,4X,3HNF=I7,4X,
    13HNP=I7,4X,3HIU=I10,4X,4HIMP=I5//)
      END
```

*****

```
*LDISKNEUMAM
*FANDK1010
      SUBROUTINE NEUMAM(IU,COSFIS,SENFIS)
      COMMON,IXX,SHIFTT,
 25   XIS=2 .*ACC(IU)-1.
      YIS=ACC(IU)
      D=XIS**2+YIS**2
      IF(D-1.)27,27,25
 27   COSFIS=(XIS**2-YIS**2)/D
      SENFIS=2.*XIS*YIS/D
 1    RETURN
      END
```

****

```
*LDISKPOLSC
*FANDK1010
      FUNCTION POLSC(X)
      COMMON IXX,SHIFTT
      A=.43429448*LOG(X)
      Y=((((((((.1630869*A+.079652989)*A-.66729676)*A-
         .11527865)*A+.90459
     1708)*A-.2132722)*A+.24577625)*A-.58069245)*A-.6
         7765706
      POLSC=10.**Y
      RETURN
      END
```

****

```
*LDISKREPOL
*FANDK1010
      SUBROUTINE REPOL(X,YR,YF,YC,YP)
      COMMON IXX,SHIFTT
C     YR=RAYLEIGH/TOTAL
C     YF=PHOTOELETRIC/TOTAL
C     YC=COMPTON/TOTAL
C     YP=PAIRS/TOTAL
      IF(X-.033)402,401,401
 401  A=.43429448*LOG(X)
      YC=((((((((-.17024671*A-.084704039)*A+.68939041)
         *A+.12726459)*A-.90
     1236746)*A+.25930447)*A-.36749336)*A+.053181121)
         *A-.025698404
      YC=10.**YC
      IF(X-2.00)256,256,257
 256  YF=((((((((-.17447168*A-.089253265)*A+.70086592)
         *A+.12898819)*A-1.0
     1959355)*A+.21999997)*A+.50032088)*A-1.4761774)*
         A-1.2033302
      YF=10.**YF
      GO TO 258
 257  YF=0
 258  IF(X-1.5)10,11,11
   10 YP=0.
      GO TO 60
```

```
   11 YP=((((((((((-5.2057247*A+11.729524)*A-2.1291118
          )*A-6.8502781)*A-1.
     1552049)*A+.93532872)*A+4.2913581)*A+6.5603012)*
          A-15.539123)*A+10.8
     117165)*A-3.273708
      YP=10.**YP
   60 IF(X-1.5)20,20,21
   21 YR=0.
      GO TO 30
   20 YR=((((-1.3547494*A-3.0837056)*A-1.506932)*A-.5
          7961172)*A-1.182879
     19)*A-1.749261
      YR=10.**YR
   30 RETURN
  402 YR=0
      YC=0
      YP=0
      YF=1
      RETURN
      END
```

****

```
*LDISKACC
*FANDK1010
      FUNCTION ACC(IU)
      COMMON IXX,SHIFTT
      IX=IXX
      SHIFT=SHIFTT
      IU=IX*IU
       RU=IU
      ACC=RU*SHIFT
      RETURN
      END
```

****

```
*LDISKGERAL
*FANDK1010
      SUBROUTINE GERAL
C
C
      COMMON IXX,SHIFTT,KKK,X,Y,Z,RCRIST,HCRIST,KKKS,
         KENT,UE,COSE,SENE,
     1ALFE,BETE,GAME,UEE,COSFE,SENFE,EINIC1,EF1,ENAS,
         XTAUX,YTAUX,ZTAUX,
     2ALFAUX,BETAUX,GAMAUX,ECPP1,MARX,IU,IRAYS,XKRR
      KF=0
      MF=0
      MARX=0
      ENAS=0
      IKKK=KKK
      MARP=-1
      KONT=0
      XT=X
      YT=Y
      ZT=Z
      GO TO (301,302,1,302,1,301,301,302,302),IKKK
 1    STOP
 302  A=UEE
      B=COSFE
      C=SENFE
      D=GAME
      E=ALFE
      F=BETE
      KE=KENT
 6    IF(ABS(D)-1.)21,2,21
 21   CA=SQRT(1.-A*A)
      GA=SQRT(1.-D*D)
      AA=A*E+CA/GA*(E*D*B-F*C)
      BB=A*F+CA/GA*(F*D*B+E*C)
      GG=A*D-CA*GA*B
      GO TO 3
 2    CA=SQRT(1.-A*A)
      AA=CA*B
      BB=CA*C
      GG=D*A/ABS(D)
 3    IF(KE)1400,5,4
 1400 IF(IRAYS)8775,1311,8775
 1311 KF=1
 4    ALFASS=AA
      BETSS=BB
      GAMSS=GG
      IF(KF)328,328,918
```

```
328   A=UE
      B=COSE
      C=SENE
      KE=KE-2
      GO TO 6
5     ALFAS=AA
      BETAS=BB
      GAMAS=GG
      IF(IKKK-2)701,701,702
702   EELETR=ECPP1
      GO TO 506
701   EELETR=EINIC1-EF1
506   DISTAN=.693*LOG(EELETR/10.7415+1.)*2.86
203   XE=X+DISTAN*ALFASS
      YE=Y+DISTAN*BETSS
      ZE=Z+DISTAN*GAMSS
1009  XT=XE
      YT=YE
      ZT=ZE
 301   IF(ZT)1301,8,9
1301  IF(ABS(ZT)-HCRIST)8,8,9
8     D=SQRT(XT*XT+YT*YT)
      IF(D-RCRIST)11,11,9
11    GO TO (403,401,405,408,404,418,419,420,4031,303
         3),IKKK
9     GO TO (303,304,303,306,306,303,403,800,303,712)
         ,IKKK
800   MF=1
      GO TO 304
408   ENAS=EELETR
      IKKK=IKKK+1
      MARP=MARP+1
      GO TO 600
507   ALFASS=ALFAS
      BETSS=BETAS
      GAMSS=GAMAS
      GO TO 203
306   MARP=MARP+1
304   AK1=XT*ALFASS+YT*BETSS
      R1Q=XT*XT+YT*YT
      DISTA1=AK1-SQRT(AK1*AK1+(RCRIST*RCRIST-R1Q)*(1.
         -GAMSS**2))
      DISTA1=DISTA1/(1.-GAMSS*GAMSS)
      IF(DISTA1)1477,6765,6765
6765  DIF=DISTAN-DISTA1
      IF(ABS(Z+DIF*ALFASS)-HCRIST)4476,1477,1477
1477  IF(ZT)2477,1479,1479
```

```
1479  DISTA1=ZT/GAMSS
      GO TO 4476
2477  DISTA1=(HCRIST+ZT)/GAMSS
4476  IF(DISTAN-DISTA1)4611,1476,1476
4611  DISTA1=DISTAN
1476  E1=(EXP(DISTA1/(.693*2.86))-1.)*10.7415
      IF(MF)501,501,421
501   ENAS=ENAS+EELETR-E1
      IKKK=IKKK+1
600   IF(MARP   )201,507,303
404   ENAS=ENAS+EELETR
      KONT=KONT+1
405   XTAUX=XE
      YTAUX=YE
      ZTAUX=ZE
      ALFAUX=ALFASS
      BETAUX=BETSS
      GAMAUX=GAMSS
      IF(KONT)418,403,418
403   KKKS=2
      RETURN
201   IF(EF1-.033) 13,14,14
14    ELECG=-1./POLSC(EF1)*LOG(ACC(IU))
8813  DISTAN=ELECG
      GO TO 507
13    IF(EF1-.010)813,814,814
814   COEFAB=EXP(-7.1827)*EF1**(-2.8871)
      ELECG=-1./COEFAB*LOG(ACC(IU))
      GO TO 8813
813   ENAS=ENAS+EF1
      GO TO 303
401   E1=0
      GO TO 501
303   KKKS=1
      RETURN
418   MARX=1
419   KKKS=3
      RETURN
918   EELETR=EINIC1-.033164
      IF(EELE TR) 9271,420,506
9271  EELETR=EINIC1-.005187
      GO TO 506
421   ENAS=EELETR-E1
      GO TO 1006
420   ENAS=EELETR
      GO TO 1006
8775  ALFAUX=AA
```

```
      BETAUX=BB
      GAMAUX=GG
      ELER=-1./POLSC(EINIC1)*LOG(ACC(IU))
      XE=X+ELER*ALFAUX
      YE=Y+ELER*BETAUX
      ZE=Z+ELER*GAMAUX
      GO TO 1009
4031  XTAUX=XE
      YTAUX=YE
      ZTAUX=ZE
      KKKS=2
      RETURN
1006  IF(EINIC1-.033164)  6011,5211,5211
5211   COEFX=23.165056
5212   EL=-1./COEFX*LOG(ACC(IU))
3999  XAN=XKRR*(2.*ACC(IU)-1.)
      YAN=XKRR*(2.*ACC(IU)-1.)
      VAN=ACC(IU)
      DD=XAN*XAN+YAN*YAN+VAN*VAN
      IF(DD*DD-VAN)5476,5476,3999
5476  FAD=2.*XAN*VAN/DD
      TAD=2.*YAN*VAN/DD
      AMAD=(VAN*VAN-XAN*XAN-YAN*YAN)/DD
2731  XXIN=X+FAD*EL
      YYIN=Y+TAD*EL
      ZZIN=Z+EL*AMAD
879   XT=XXIN
      YT=YYIN
      ZT=ZZIN
      IKKK=10
      GO TO 301
3033   IF(EINIC1-.033164)6011,6033,6033
6011  ENAS=ENAS+.005187
      GO TO 303
6033  ENAS=ENAS+.033164
      GO TO 303
712   IF(EINIC1-.033164)332,333,333
333   ENAS=ENAS+.005187
      GO TO 303
332   ENAS=ENAS
      GO TO 303
      END
```

****

```
C***************GINASB  IBM / 360**************
C
C
C*****************************************************
         *******************
C
C
C*******************NO BREMSSTRAHLUNG
C
C*****************************************************
         *******************
C******************IDENTIFICACTION******************
C  KK=2    COMPTON EFFECT
C  KK=4    PAIR PRODUCTION
C  KK=6    ANNIHILATION GAMMAS
C  KK=8    PHOTOELECTRIC EFFECT
C  KK=9    RAYLEIGH SCATTERING
C  KK=10    X RAY
C
C*******************COMMENTS******************
C  INTERV   INTERVAL TO PRINT PARCIAL RESULTS
C  IMP   EQUAL ZERO
C  XIN,YIN,ZIN   POINT COORDENATES
C  FOTOFR   PHOTOFRACTION
C  EINC   INCIDENT ENERGY (MEV )
C  KANAL(KL)   CHANNEL COUNTS
C  NH   NUMBER OF HISTORIES
C  NC   NUMBER OF COMPTON INTERACTIONS
 C  NI   PRIMARY INTERACTIONS NUMBER
C  NF   NUMBER PHOTOELETRIC INTERACTIONS
C  NR   NUMBER RAYLEIGH INTERACTIONS
C  NP   NUMBER OF PAIRS INTERACTIONS
C  ALFAD,BETAD,GAMAD - DIRECTION COSINES OF INCIDENT
         GAMMA
C  ENA   TOTAL ENERGY ABSORBED
C  YF   PHOTOELETRIC TO TOTAL CROSS SECTION    RATIO
C  YC   COMPTON TO TOTAL CROSS SECTION RATIO
C  YP   PAIR PRODUCTION TO TOTAL CROSS SECTION RATIO
C  YR   RAYLEIGH TO TOTAL CROSS SECTION RATIO
C
C
C
C
C*****IDENT EQUAL ZERO- BROAD OR NARROW BEAM
C*****IDENT EQUAL ONE- POINT SOURCE
C
      DIMENSION KANAL(128)
```

```
      COMMON IX,SHIFT,KK,XIN,YIN,ZIN,RCRIST,HCRIST,KS
         ,K,U,COSFI,SENFI,
     1ALFAD,BETAD,GAMAD,UL,COSFIE,SENFIE,EINIC,EF,ENA
         S,XS,YS,ZS,ADS,BDS,
     2GDS,ECPP,MARX,IU,IRAY,XKR
C
C
C
      SHIFT=10.**(-10.)
      IX=100003
      IRAY=0
      XKR=SQRT(3.)/(4.**(2./3.))
C
C
C
C*********START*********
 1222 READ 10,RCRIST,HCRIST,RFEIXE,EINC,DP
 10   FORMAT(5F7.3)
      READ 9,NI,NF,NR,NC,NP,NH,INTERV,IMP,IU,IDENT
 9    FORMAT(8I6,I9,I2)
      PRINT 998,RCRIST,HCRIST,RFEIXE,EINC,DP
 998  FORMAT(1H ,15HCRYSTAL RADIUS=F7.3,2HCM,5X,15HCR
         YSTAL HEIGHT=F7.3,2
     1HCM,5X,12HBEAM RADIUS=F7.3,2HCM,5X,7HENERGY=F7.
        3,3HMEV//,1H ,13HDI
     2ST. SOURCE=F7.3//)
      READ 8900,(KANAL(KL),KL=1,128)
 8900 FORMAT(10I8)
C
      IMP=IMP+INTERV
C
C
 101  EINIC=EINC
      MAPPP=0
      ENA=0
C
C
C     NUMBER OF HISTORIES
      NH=NH+1
      ZIN=0
C
C
C     POINT SOURCE
      IF(IDENT)2034,2035,2034
 2034 AX=SQRT(RCRIST*RCRIST+DP*DP)
      COSMAX=-DP/AX
      COSG=ACC(IU)*(1.+COSMAX)-1.
```

```
      RI=ABS(DP*SQRT(1.-COSG**2)/COSG)
      TETA=3.1416*(2.*ACC(IU)-1.)
      XIN=RI*COS(TETA)
      YIN=RI*SIN(TETA)
      ALFAD=XIN/SQRT(XIN*XIN+YIN*YIN+DP*DP)
      BETAD=YIN/SQRT(XIN*XIN+YIN*YIN+DP*DP)
      GAMAD=COSG
      GO TO 4080
C
C
C     DISTANCY FROM CRYSTAL CENTER
 2035 R=RFEIXE*SQRT(ACC(IU))
C
C*****ENTANCE COORDENATES OF INCIDENT GAMMA RAY
 462  TETA=3.1416*(2.*ACC(IU)-1.)
      XIN=R*COS(TETA)
      YIN=R*SIN(TETA)
C
C     DIRECTION COSINES OF INCIDENT GAMMA RAY
 3034 ALFAD=0
      BETAD=0
      GAMAD=-1
C
C
 4080 ELECOL=-1./POLSC(EINIC)*ALOG(ACC(IU))
C
      IF(IDENT)2397,2396,2397
 2397 XIN=XIN+ALFAD*ELECOL
      YIN=YIN+BETAD*ELECOL
 2396 ZIN=ZIN+ELECOL*GAMAD
 2398 KK=1
      CALL GERAL
      ENA=ENA+ENAS
      GO TO (1,102),KS
 102  NI=NI+1
C
C*********TYPE OF INTERACTIONS
 105  CALL REPOL(EINIC,YR,YF,YC,YP)
 4566 Y=ACC(IU)
      IF(Y-YF)18,18,107
 107  IF(Y-(YF+YC))108,108,109
 108  NC=NC+1
      GO TO 8
 109  IF(Y-(YF+YC+YP))280,280,9111
C
C
C*********COMPTON EFFECT
```

```
 8      ALFA=EINIC/.511
 23     R1=ACC(IU)
        IF(R1-(2.*ALFA+1.)/(2.*ALFA+9.))21,21,22
 21     R2=ACC(IU)
        Y=1.+2.*ALFA*R2
        R3=ACC(IU)
        IF(R3-4.*(1./Y-1./Y**2))24,24,23
 24     U=1.-2.*R2
        GO TO 26
 22     R2=ACC(IU)
        Y=(2.*ALFA+1.)/(1.+2.*ALFA*R2)
        U=1.-1./ALFA*(Y-1.)
        R3=ACC(IU)
        IF(R3-.5*(U**2+1./Y))26,26,23
 26     ALFAL=ALFA/Y
        EF=.511*ALFAL
        CALL NEUMAM(IU,COSFI,SENFI)
        CAA=(1.+EINIC/.511)**2*(1.-U)
        UL=SQRT (CAA/(CAA+1.+U))
        COSFIE=-COSFI
        SENFIE=-SENFI
        KK=2
        K=2
        CALL GERAL
        ENA=ENA+ENAS
        GO TO (1,104),KS
 104    XIN=XS
        YIN=YS
        ZIN=ZS
C
C
C       FINAL DIRECTION COSINES
        ALFAD=ADS
        BETAD=BDS
        GAMAD=GDS
        EINIC=EF
        GO TO 105
C
C
C*********PAIR PRODUCTION
 280    IF(EINIC-1.50)4566,5280,5280
 5280 ECPP=.5*(EINIC-1.022)
        NP=NP+1
        U=COS(.511/ECPP)
        CALL NEUMAM(IU,COSFI,SENFI)
        UL=U
        IF(KK-1)33,34,33
```

```
 33   ALFAD=ADS
      BETAD=BDS
      GAMAD=GDS
 34   COSFIE=-COSFI
      SENFIE=-SENFI
      KK=4
      K=2
      CALL GERAL
      ENA=ENA+ENAS
      GO TO (1,1  ,1010),KS
C
C
C     FIRST ANNIHILATION GAMMA RAY
 1010 XIN=XS
      YIN=YS
      ZIN=ZS
      XINN=XS
      YINN=YS
      ZINN=ZS
      ELE=-1./POLSC(.511)*ALOG(ACC(IU))
      KK=6
C
C
C     DIRECTION COSINES OF ANNIHILATION GAMMA RAY
 3999 XAN=XKR*(2 .*ACC(IU)-1.)
      YAN=XKR*(2 .*ACC(IU)-1 .)
      VAN=ACC(IU)
      DD=XAN*XAN+YAN*YAN+VAN*VAN
      IF(DD*DD-VAN)4476,4476,3999
 4476  ALFAD=2.*XAN*VAN/DD
      BETAD=2.*YAN*VAN/DD
      GAMAD=(VAN*VAN-XAN*XAN-YAN*YAN)/DD
 2731 XIN=XIN+ALFAD*ELE
      YIN=YIN+BETAD*ELE
 5441 ZIN=ZIN+ELE*GAMAD
 1002 CALL GERAL
      ENA=ENA+ENAS
      MAPPP=MARX
      GO TO (1011,1,1105),KS
 1105 EINIC=.511
      GO TO 105
C
C     SECOND ANNIHILATION GAMMA RAY
 1011 KK=7
      EINIC=.511
      GAMAD=-GAMAD
      ALFAD=-ALFAD
```

```
      BETAD=-BETAD
      XIN=XINN
      YIN=YINN
      ZIN=ZINN
      ELE=-1./POLSC(EINIC)*ALOG(ACC(IU))
      GO TO 2731
C
C
C******PHOTOELETRIC EFFECT
 18   IF(EINIC-2.00)5218,5218,4566
 5218 NF=NF+1
      IF(EINIC-.033164)5220,5220,5219
 5220  ELIG=.005187
      GO TO 6588
 5219 ELIG=.033164
 6588 ECIN=EINIC-ELIG
      CCC=(EINIC/.511)**2
      DDD=1.+1.022/ECIN
      BC=SQRT(CCC*DDD/(1.+CCC*DDD))
 587  TETA=3.1416*(1.-ACC(IU))
      AK=2.*BC*(1.+ELIG/ECIN)
      DNDOM=SIN(TETA)**2*(1.+AK*COS(TETA))
      IF(DNDOM)587,586,586
 586  COSMAX=SQRT((1.+AK)**2+AK**2)/AK-(1.+AK)/AK
      DNDTET=SIN(TETA)**2*(1.+AK*COS(TETA))/((1.-COSM
         AX**2)*(1.+AK*COSMA
     1X))
      IF(ACC(IU)-DNDTET)1586,1586,587
 1586 UL=COS(TETA)
      CALL NEUMAM(IU,COSFIE,SENFIE)
      IF(KK-1)914,913,914
 914  ALFAD=ADS
      BETAD=BDS
      GAMAD=GDS
 913  KK=8
      K=-1
      CALL GERAL
      ENA=ENA+ENAS
 1    IF(MAPPP)911,911,1012
 1012  MAPPP=0
      GO TO 1011
C
C
C*****RAYLEIGH SCATTERING
 9111 IF(EINIC-1.500)8886,4566,4566
 8886 NR=NR+1
      IRAY=1
```

```
      SENC=.026*53.**(1./3.)*.511/EINIC
      COSC=1.-2.*SENC*SENC
 7466  COSTQ=2.*ACC(IU)-1.
      IF(ABS(COSC)-1.)7411,7411,1273
 7411 IF(COSTQ-COSC)7466,1273,1273
 1273 DN=EXP(-.100*COSTQ)
 8101 Y=ACC(IU)
      IF(DN-Y)7466,1808,1808
 1808 UL=COSTQ
 2605 IF(KK-1)2607,2608,2607
 2607 ALFAD=ADS
      BETAD=BDS
      GAMAD=GDS
 2608 KK=9
      CALL NEUMAM(IU,COSFIE,SENFIE)
      EINIC=EINIC-.001
 2712 K=-1
      CALL GERAL
      IRAY=0
      ENA=ENA+.001
      GO TO(1,9105),KS
 9105 XIN=XS
      YIN=YS
      ZIN=ZS
      ALFAD=ADS
      BETAD=BDS
      GAMAD=GDS
      GO TO 105
C**********TOTAL ENERGY DISTRIBUTION
C
C
 911  IF(ENA)912,2010,912
 912  II=ENA/EINC*128.
      IF(II-128)4914,915,8316
 915  KANAL(II)=KANAL(II)+1
      GO TO 2010
 8316  PRINT 9,NH
 919  STOP 1
 4914  KANAL(II+1)=KANAL(II+1)+1
C
C
C**********PRINTING RESULTS
 2010 GO TO 601
 601  IF(NI-IMP)101,1180,1180
 1180 IMP=IMP+INTERV
      IF(IMP-10000-INTERV)996, 996,919
 996  PRINT 997,NH,NI,NC,NR,NF,NP,IU,IMP
```

```
      PRINT 849,(KL,KANAL(KL),KL=1,128)
      LI=0
      DO 6666 KL=1,128
6666   LI=LI+KANAL(KL)
      ALI=LI
      SSS=KANAL(128)
      FOTOFR=SSS/ALI
      ANI=NI
      ANH=NH
      EFIC=ANI/ANH
      ERRO=SQRT(FOTOFR*(1.-FOTOFR)/ANI)
      PRINT 4896,LI,FOTOFR,ERRO,EFIC
4896  FORMAT(/1H ,10HTOTAL SUM=I10,6X,14HPHOTOFRACTIO
       . N=F7.4,3X,6HERROR=F.
     38.4,6X,10HEFICIENCY=F6.3//)
      IMP1=IMP-INTERV
      PUNCH 10,RCRIST,HCRIST,RFEIXE,EINC,DP
      PUNCH 9,NI,NF,NR,NC,NP,NH,INTERV,IMP1,IU,IDENT
      PUNCH 8900,(KANAL(KL),KL=1,128)
      IF(NI-10000)101,1222,1222
849   FORMAT(10(1H ,I3,I5,4X))
997   FORMAT(1H ,3HNH=I7,4X,3HNI=I7,4X,3HNC=I7,4X,3HN
         R=I7,4X,3HNF=I7,4X,
     13HNP=I7,4X,3HIU=I9 ,4X,4HIMP=I5//)
      END
```

*****

```
      FUNCTION ACC(IU)
      IU=IU*65539
      IF(IU)5,6,6
5     IU=IU+2147483647+1
6     YFL=IU
      ACC =YFL*.4656613E-09
      RETURN
      END
```

*****

```
*FANDK1008

C***************STRECH   I B M 1620***************
C********STRECH PROGRAM********
C
C
C      A,B-COEFFICIENTS OF SIGMA = A*E+B*E**.5
C      E128-ENERGY (MEV ) OF CHANNEL NO.128
C      N - NO. OF CHANNELS
C      N - COUNTS / CHANNEL - OUTPUT FROM GINASB PROGR
          AM
C      C(N) - COUNTS AFTER TAKING INTO ACCOUNT THE RES
          OLUTION EFFECT
C****
C      SWITCH 1 - ON - TO INTERRUPT THE PROGRAM
C      SWITCH 2 - ON - TO CHECK THE CHANNEL THAT IS BE
          ING PROCESSED
C      SWITCH 3 - ON - TO CHECK THE LIMITS MAXIMUM AND
           MINIMUM OF THE
C      INTEGRAL
C
C
       DIMENSION C(145),AN(145),CN(145)
 1     READ 10,A,B,E128,N
 10    FORMAT(3E14.8,I4)
       FN=N
       DO 30 I=1,N
 30    CN(I)=0
       READ 9,(C(M),M=1,N)
       PRINT 3000,(C(M),M=1,N)
 3000  FORMAT(10F9.2)
 9     FORMAT(10I8)
       SOMA=0
       DO 191 MM=1,N
 191   SOMA=SOMA+C(MM)
       PRINT 4080,SOMA
 4080  FORMAT(/1H ,10HTOTAL SUM=E14.8//)
       AINT=E128/FN
       I=N
       KONT=0
 90    FI=I
       DO 101 LKK=1,N
 101    AN(LKK)=0
       SIGMA=A*SQRT(FI*AINT)+B*AINT*FI
       SIGMA2=SIGMA**2
       SEXP=0
       DO 5 K=1,N
```

```
      IF(SENSE SWITCH 2)107,108
107   TYPE 9,I,K
108   FK=K
      X=(FI-FK)**2/(2.*SIGMA2)*AINT**2
      IF(ABS(X)-10.)202,202,5
202   SEXP=SEXP+EXP(-X)
      CONST=C(I)/((2.*3.1416)**.5*SIGMA)
      AN(K)=EXP(-X)*CONST
5     CONTINUE
      FATN=(2.*3.1416)**.5*SIGMA/SEXP
      IF(I-N)402,171,402
171   W= .5
402   Y=W*FATN*C(I)/(1.E-03*SIGMA*(2.*3.1416)**.5)
      FI=I
      IF(Y)2089,2090,2089
2089  KMAX=FI+1./AINT*(2.*SIGMA2*LOG(Y))**.5
      KMIN=FI-1./AINT*(2.*SIGMA2*LOG(Y))**.5
      GO TO 9902
2090  KMAX=FI
      KMIN=FI
9902  IF(SENSE SWITCH 3)1902,1901
1902  PRINT 902,KMIN,KMAX
902   FORMAT(2I4)
1901  IF(KMAX-N)700,700,702
702   KMAX=N
700   IF(KMIN-1)698,698,669
698   KMIN=1
669   IF(SENSE SWITCH 3)2902,3901
2902  PRINT 902,KMIN,KMAX
3901  DO 447 JJ=KMIN,KMAX
      CN(JJ)=CN(JJ)+AN(JJ)*W*FATN
447   CONTINUE
701   IF(KONT)31,31,32
31    W=W+.5
      GO TO 555
32    W=1
555   I=I-1
      IF(W-1.) 90,403,403
403   KONT=1
      IF(I-1)406,406,7000
7000  IF(SENSE SWITCH 1)406,90
406   PRINT 100,(KK,CN(KK),KK=1,N)
100    FORMAT(10(1H ,I3,1H),F8.1,1X))
      SOMACN=0
      DO 558 ML=1,N
558   SOMACN=SOMACN+CN(ML)
      PRINT 4080,SOMACN
```

```
      PRINT 2666
 2666 FORMAT(//1H ,24HPHOTOPEAK NORMALIZATION//)
      CC128=CN(128)
      DO 598 ML=1,N
 598  CN(ML)=C(128)/CC128*CN(ML)
      PRINT 100,(KX,CN(KX),KX=1,N)
      GO TO 1
      END
```

****