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by

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PHONEX, A COMPUTER PROGRAM TO CALCULATE
PHOTONEUTRON SPECTRA

by

M. G. Stamatelatos

ABSTRACT

PHONEX is a FORTRAN-IV computer program to calculate photoneutron spectra for arbitrary energy distributions of gamma rays incident upon specific elements or materials. The photon spectrum and the photoneutron cross section as a function of the photon energy are required as input. Knowledge of the functional dependence of the double-differential photoneutron cross section on the neutron angle in the center-of-mass system is also useful. All kinematic calculations are relativistic. The spectra of both gamma rays and photoneutrons are printed and plotted as desired.

I. INTRODUCTION

PHONEX is a FORTRAN-IV CDC-7600 computer program to calculate photoneutron spectra for arbitrary gamma-ray energy distributions. Although initially written for calculating photoneutron spectra resulting from fission-product decay gamma rays incident upon materials of reactor importance (e.g., ^9Be or ^2H), the program is general enough to calculate photoneutron spectra for any photon distribution incident upon any material for which the double-differential cross sections are known. All kinematic calculations are performed entirely relativistically and their results are, therefore, of general use. PHONEX has been used to calculate ^9Be and ^2H photoneutron spectra resulting from fission product gamma spectra calculated by an extended version of the CINDER code; the input format of PHONEX is designed to read CINDER output directly. These calculations will be reported separately.

II. PROGRAM DESCRIPTION

PHONEX is composed of a main program, PHONEX, and 12 subroutines, SPOUT, MAXMIN, SORTN, CSEN, PROB, PRO, ANCCM, KIN, MOM, AVRG, TEST, and INTERP.

PHONEX reads input data, defines a neutron energy grid, calls computational and output subrou-

tines, and prints and plots normalized as well as non-normalized time-dependent gamma-ray and photoneutron intensities. The last feature is of importance for cases when the input photon distribution is markedly time-dependent as, for example, fission product gamma-ray spectra. The spectrum normalization is with respect to a particular time step for which the gamma-ray and photoneutron intensities are arbitrarily set equal to unity.

SPOUT prints and plots normalized and non-normalized photon and photoneutron spectra* at each time step. The spectrum normalization in this case means that the energy-integrated gamma-ray and photoneutron intensities at the particular time step are respectively set equal to unity. The LASL film plotting subroutine used requires the definition of title, abscissa, and ordinate names. These are introduced through the alphanumeric variables TI, ABSIS, and ORDIN, respectively. These variables should be re-defined as appropriate to the specific problem solved. The variables included in the present version of the program are for use with fission product photon and photoneutron spectra.

*The photoneutron spectra are in units of microscopic cross section (e.g., barns).

MAXMIN calculates the maximum and the minimum photoneutron energies on the basis of kinematic considerations.

SORTN distributes the maximum and the minimum neutron energies into the existing neutron energy grid defined in PHONEX.

CSEN calculates the sine and cosine of the neutron laboratory angle as a function of the gamma-ray and of the photoneutron energies.

PROB calculates the photoneutron energy distribution as a function of the neutron center-of-mass angle.

PRO provides the center-of-mass angular distribution of photoneutrons for given photon energy.

ANGCM calculates the sine and cosine of the neutron center-of-mass angle as a function of its laboratory angle, i.e., performs the laboratory to center-of-mass angular transformation.

KIN calculates the necessary relativistic kinematics parameters for the photoneutron reaction.

MOM calculates the momentum and energy of the photoneutron as well as the photoneutron cross section as a function of the neutron laboratory angle.

AVFG computes gamma-ray and photoneutron energies averaged over corresponding energy distributions.

TEST supplies arbitrary unit line photon distributions for testing the calculations if desirable.

INTERF linearly interpolates input photoneutron cross sections at required gamma-ray energy values.

Further details on the main program and on the subroutines are given in Table I, which describes the input to the program, and in the appendices.

III. GENERAL COMMENTS ON INPUT VARIABLES

In principle, the larger the value of INTEGR, the more accurate the photoneutron spectrum calculation is. In practice, however, values of INTEGR in the range 10 to 20 are sufficient and use of larger values results in unnecessary consumption of computer time.

The values of NEMAX and DELE determine the range of the neutron energy grid and the size of this energy mesh. The product of NEMAX and DELE determines the maximum value of neutron energy for which a spectrum is calculated. This value can be easily obtained from the kinematics of the photoneutron reaction induced by the most energetic photon

in the input gamma-ray spectrum. Let us call this photon energy $E_{\gamma\text{max}}$. Let us call the maximum photoneutron energy $E_{n\text{max}}$. The width of the input photon energy grid is, say, ΔE_{γ} . Then, as a rule of thumb, the value of DELE should be of the order of

$$\Delta E_{\gamma} \times \frac{E_{n\text{max}}}{E_{\gamma\text{max}}}.$$

Once this has been determined, NEMAX can be calculated as the integer ratio of $E_{n\text{max}}$ and DELE.

Hollerith variables HL and ANAME(3) are used as part of the title of the various plots called by the main program, PHONEX, and by subroutine SPOUT. Change of these variables should be accompanied by suitable change of alphanumeric variable T1 in PHONEX and SPOUT.

Subroutine TEST supplies monoenergetic photons of unit intensity which result in photoneutron spectra of energy-integrated intensity equal to the corresponding photoneutron cross sections interpolated from input cross-section data. Any discrepancies between these integrated intensities and the corresponding cross sections are due to approximations in the photoneutron spectrum calculations. These discrepancies can be reduced by increasing the value of INTGR until satisfactory agreement is obtained. Beyond this point, subroutine TEST need not be called during routine runs. This is achieved by setting NTEST $\neq$ 1 as described in the input instructions.

ACKNOWLEDGMENTS

Many thanks are due to T. R. England for numerous illuminating discussions on the CINDER code and related topics and to T. R. England, D. R. Harris, and R. J. LaBauve for encouraging me to do this work.

TABLE I

INPUT DESCRIPTION

<u>Variable Name</u>	<u>Format</u>	<u>Comment</u>
(1) GNMAT, WATT	A10,1PE12.4	Material for which the photoneutron spectrum is calculated. Irradiation power, in watts, at reactor shutdown time.
(2) NSETS, IMAX, ITYM, TIRAD, NPLOT, NTEST, NITST, INTGR	314,E12.4,414	Number of photon spectrum sets for each fissioning isotope. Number of energy and cross-section points in the input photoneutron cross-section data. Number of time steps at which spectral output is required. Irradiation time, in hours, prior to reactor shutdown. Flag designating whether plotting should be done (=1) or not (=0). Flag designating whether test photon spectra should be supplied (=1) or not (=0). Photon energy group above the (Y,n) threshold where first test Y line should be supplied by TEST (Y lines are subsequently supplied at equal energy group intervals, NITST). Number of sub-intervals into which each neutron energy group should be divided for integration purposes.
(3) TYM(I), I=1, ITYM	4E12.4	Time steps at which SPOUT is called for printing and plotting spectra.
(4) ETHR, EZN, EYZ, EZK, NGMAX, NEMAX, DELE	4E12.4,214, E12.4	Photon laboratory threshold energy in MeV. Neutron rest mass in amu. Recoil nucleus rest mass in amu. Target nucleus rest mass in amu. Number of gamma-ray group boundaries. Number of neutron lower boundaries. Width of neutron energy group in MeV.
(5) ENGM(I), I=1, IMAX	6E12.4	Photon energy points at which photoneutron cross sections are supplied, in MeV.
(6) SIGE(I), I=1, IMAX	6E12.4	Photoelectric (Y,n) cross sections in units of 10^{-28} cm^2 .
(7) SIGM(I), I=1, IMAX	6E12.4	Photomagnetic (Y,n) cross sections in units of 10^{-28} cm^2 .
(8) HL(I), I=1,2	2A10	Hollerith field naming the fissioning isotope.
(9) EGAM(I), I=1, NGMAX	1X,5E12.4	Gamma-ray spectrum group energy boundaries in MeV.
(10) HOL(I), I=1,8	A8,A9,A10,5A9	Hollerith field describing the time step of the photon spectrum.
(11) ANAME(I), I=1,8	A8,A9,A10,5A9	Hollerith field describing the time step shutdown time in hours. ANAME(3) contains the shutdown time in hours (e.g., 1000 hours). ANAME(3) is used in the spectrum title when plotted.
(12) NTS, DFLT, SUMT, FISR, GAMF	1X,I3,4E12.4	Time step number. Length of time step in hours. Accumulated time in hours. Fission rate immediately prior to shutdown. Total gamma rays per fission.
(13) PHIG(N), N=1, NGMX1	1X,5E12.4	Groupwise gamma-ray spectrum.

NOTE: Variable sets 1-7 are to be supplied once. Variable sets 8-9 must be supplied for each fission set. Variables 10-13 must be supplied for each time step of each fission set.

APPENDIX A

CALCULATION OF KINEMATICS PARAMETERS (SUBROUTINE KIN)

The kinematics of relativistic reactions is thoroughly discussed in the literature (Refs. 1-7). The kinematics parameters necessary for cross-section calculations are

1. VE, the velocity of the CM-system relative to the L-system:

$$V = E_Y / (E_Y + E_0^X)$$

where E_Y = photon energy

E_0^X = target nucleus rest energy.

2. ETC, the total photon-target-nucleus energy in the CM-system:

$$E_T^C = \sqrt{E_0^X(2E_Y + E_0^X)}$$

3. AN:

$$A_n = (E_0^X)^2 + 2 E_0^X E_Y + (E_0^n)^2 - (E_0^Y)^2$$

where E_0^n = neutron rest energy

E_0^Y = recoil nucleus rest energy.

4. GM:

$$\gamma = (E_Y + E_0^X) / E_T^C$$

5. RHON:

$$\rho_n = VA_n / \sqrt{A_n^2 - 4(E_T^C)^2(E_0^n)^2}$$

or alternately

$$\rho_n = V / \left\{ E_Y / E_0^n + 1/2 \left[(E_0^n / E_0^X) + (E_0^X / E_0^n) - (E_0^Y / E_0^X)(E_0^Y / E_0^n) \right] \right\}$$

6. PKC:

$$P_K^C = A_n \left\{ E_Y / E_0^n + 1/2 \left[(E_0^n / E_0^X) + (E_0^X / E_0^n) - (E_0^Y / E_0^X)(E_0^Y / E_0^n) \right] \right\} / 2E_T^C$$

APPENDIX B

MAXIMUM AND MINIMUM NEUTRON ENERGIES (SUBROUTINE MAXMIN)

The maximum and the minimum neutron momenta for a given incident photon energy, E_Y , are:

$$p_n^{\min} = \gamma(1 - \rho_n)P_K^C \quad \text{and}$$

$$p_n^{\max} = \gamma(1 + \rho_n)P_K^C$$

The corresponding kinetic energies are $E_n^{\min}$ and $E_n^{\max}$:

$$E_n^{\min} = \sqrt{(p_n^{\min})^2 + (E_0^n)^2} - E_0^n$$

$$E_n^{\max} = \sqrt{(p_n^{\max})^2 + (E_0^n)^2} - E_0^n$$

Where γ , ρ_n , and P_K^C are as defined in Appendix A.

APPENDIX C

SINE AND COSINE OF THE NEUTRON LABORATORY ANGLE (SUBROUTINE CSEN)

The sine and cosine of the neutron laboratory angle in terms of the neutron and photon energies, E_n and E_γ , are given by the following expressions:

$$\cos \theta = \left[\left(\frac{E_n}{E_0^n} \right) (2 + \frac{E_n}{E_0^n}) \right]^{-1/2} \left\{ \left(1 + \frac{E_n}{E_0^n} \right) \left(1 + \frac{E_\gamma}{E_0^X} \right) / \left(\frac{E_\gamma}{E_0^X} \right) - \left(\frac{E_0^X}{E_0^n} \right) + \left[1 + \left(\frac{E_0^n}{E_0^X} \right)^2 - \left(\frac{E_0^Y}{E_0^X} \right)^2 \right] / 2 \left(\frac{E_\gamma}{E_0^X} \right) \left(\frac{E_0^n}{E_0^X} \right) \right\} .$$

$$\sin \theta = \sqrt{1 - \cos^2 \theta}$$

APPENDIX D

THE PHOTONEUTRON ENERGY DISTRIBUTION (SUBROUTINE PROB)

The photoneutron energy distribution is readily obtained from the energy-momentum CM- to L-system transformation.¹ The neutron differential energy cross section (i.e., spectrum) is given by

where v and p_k^C are as defined in Appendix A, and $\sigma(\theta_c)$ is the neutron angular distribution in the CM-system.

$$\sigma(E_n) = 2\pi\sigma(\theta_c) \sqrt{1 - v^2/v_{p_k^C}^2} ,$$

APPENDIX E

THE NEUTRON CM ANGULAR DISTRIBUTION (SUBROUTINE PRO)

For low-to-medium energy photons and for materials like deuterium or beryllium, the photoneutron angular distribution is well described by the following expression:⁸⁻¹⁰

where σ_e and σ_m are the photoelectric and photomagnetic disintegration cross sections, respectively. It should be noted that the total photoneutron cross section is

$$\sigma(\theta_c) = \sigma_m/4\pi + (3\sigma_e/8\pi) \sin^2 \theta_c ,$$

$$\sigma_T = \int_{-\pi}^{\pi} 2\pi \sin \theta_c \sigma(\theta_c) d\theta_c = \sigma_e + \sigma_m .$$

If this angular distribution becomes inappropriate, it must be replaced by the adequate distribution.

APPENDIX F

THE SINE AND COSINE OF THE NEUTRON CM ANGLE (SUBROUTINE ANGCM)

The L- to CM-system photoneutron angle transformation is given by the following expressions:

$$\sin \theta_c = \gamma \left[\rho_n \cos \theta + \sqrt{\gamma^2 (1 - \rho_n^2) \sin^2 \theta + \cos^2 \theta} \right] / (\gamma^2 \sin^2 \theta + \cos^2 \theta)$$

and

$$\cos \theta_c = \left(1 - \sin^2 \theta_c \right)^{1/2} ,$$

where the γ and ρ_n are as defined in Appendix A and the unsubscripted θ angle is in the laboratory system.

APPENDIX G

PHOTON AND PHOTONEUTRON AVERAGE ENERGIES (SUBROUTINE AVRQ)

The gamma-ray and photoneutron energies are averaged over their corresponding distribution according to the following expression:

$$\langle E \rangle = \frac{\int_{E_m}^{E_M} E N(E) dE}{\int_{E_m}^{E_M} N(E) dE}$$

where E_m and E_M are the minimum and maximum energies, respectively.

APPENDIX H

PROGRAM LISTING

LASL Identification:

LP-0499

```

PROGRAM PHONEX (IMP,OUT,FSETS,PUN,FILM)
COMMON FGAM(200),COSTH(200),EN(8000),PHIG(200),SPEC(200),HOL(20),
IEND(400),EGMM(200),TI(10),AHSIS(10),ORDIN(10),NUMSP(400),
PSUMC(50),SUMN(50),TOT(50),SIGF(60),SIGM(60),ENGM(60),TYM(10)
COMMON SIGSM(A0)
COMMON AV1(30),AV2(30),AV3(30)
COMMON TEMP(8000)
COMMON PHN(8000)
COMMON HL(5),ANAME(10)
C-----*****
C
C-----PHONEX CALCULATES PHOTONEUTRON SPECTRA FOR ARBITRARY PHOTON
C-----DISTRIBUTIONS INCIDENT ON SPECIFIC MATERIALS FOR WHICH THE
C-----ELECTRIC AND MAGNETIC (GAMMA,N) CROSS SECTIONS MUST BE SPECIFIED
C-----AS A FUNCTION OF ENERGY.
C-----THE KINEMATIC CALCULATIONS ARE ENTIRELY RELATIVISTIC.
C
C-----DEFINITION OF SOME IMPORTANT VARIABLES
C
C-----FGAM = INPUT PHOTON ENERGIES IN MEV
C-----EN = NEUTRON ENERGY MESH IN MEV
C-----PHIG = INPUT GAMMA ENERGY SPECTRUM
C-----SPEC = PHOTONEUTRON SPECTRUM
C-----EGMM = MID-GROUP PHOTON ENERGIES
C-----ENGM = ENERGIES OF INPUT (GAMMA,N) CROSS SECTIONS
C-----SIGF = INPUT ELECTRIC PHOTONEUTRON CROSS SECTION IN 1.0E-24 CM**2
C-----SIGM = INPUT MAGNETIC PHOTONEUTRON CROSS SECTION IN 1.0E-24 CM**2
C-----SIGSM = TOTAL (GAMMA,N) CROSS SECTIONS, SIGF+SIGM
C-----ETHU = THRESHOLD (GAMMA,N) LABORATORY PHOTON ENERGY
C-----FYN = NEUTRON REST MASS IN AMU
C-----FZX = TARGET NUCLEUS REST MASS IN AMU
C-----FZY = RECOIL NUCLEUS REST MASS IN AMU
C
C-----*****
      READ(5,4)GNMAT,EWATT
      4 FORMAT(A10,1P12,4)
      READ(5,5)NSETS,IMAX,ITYM,THAD,NPIOT,NTFST,NITST,INTGR
      5 FORMAT(3I4,4E12,4,4I4)
      IJUMP=0
      NSETS=NSETS-1
      READ(5,16)(TYM(I),I=1,ITYM)
      16 FORMAT(4E12,4)
      READ(5,10)ETHU,FYN,FZY,FZX,IGMAX,IFMAX,DFLE
      10 FORMAT(4E12,4,2I4,4F12,4)
      READ(5,15)(ENGM(I),I=1,IMAX)
      15 FORMAT(6E12,4)
      READ(5,15)(SIGF(I),I=1,IMAX)
      READ(5,15)(SIGM(I),I=1,IMAX)
      DO 261 I=1,IMAX
      IF(SIGF(I).LE.0.) SIGF(I)=1.0E-15
      IF(SIGM(I).LE.0.) SIGM(I)=1.0E-15
      261 CONTINUE
      PRINT 260,GNMAT

```



```

      NTS=NTS-1
      READ(S,40) (PHIG(N),N=1,NGMX1)
40  FORMAT(1X,5E12.4)
      PHIG(N)=PHIG(N)*((EGAM(N1+1)-ETHR)/(EGAM(N1+1)-EGAM(N1)))
41  IF(NTS.EQ.0) GO TO 24
      DO 50 K=1,NEMAX
50  SPEC(K)=0.
      FINTGR=INTGR
      DELF=DELE/FINTGR
      NEMAX=NEMAX*INTGR
      DO 61 N=1,NEMAX
61  TEMP(N)=0.
      DO 60 J=1,NEMAX
60  EN(J)=(J-1)*DELE
      NGDIF=NGMAX-N1
      DO 1000 NG=N1,NGMX1
      GAMMA=EGMM(NG)
      CALL INTERP(SE,SM,GAMMA,IMAX,IJUMP,NGDIF,GNMAT)
      CALL KIN(GAMMA,FZX,EZN,EZY,VE,ETC,AN,RHON,GM,PKC)
      CALL MAXMIN(EZN,RHON,GM,PKC,PNMIN,PNMAX,ENMIN,FNMAX)
      CALL SORTN(ENMIN,FNMAX,NEMAX,NMN,NMX)
      DO 70 L=NMN,NMX
      ENEUT=(EN(L)+FN(L+1))*0.5
      IF(FNEUT.LT.ENMIN) ENEUT=ENMIN
      IF(FNEUT.GT.ENMAX) ENEUT=ENMAX
      IF(NMN.EQ.NMX) ENEUT=0.5*(ENMIN+FNMAX)
      CALL CSEN(GAMMA,FNEUT,EZX,ETHP,EZN,CSTH,STH,EZY)
      CALL ANGCM(RHON,GM,STHC,CTHC,CSTH,STH)
      CALL PRO(STHC,CTHC,PTHC,GAMMA,IMAX,SE,SM)
      CALL PROB(VE,GM,PKC,PTHC,PH)
      PBN(L)=PR
70  TEMP(L)=TEMP(L)+PHIG(NG)*PBN(L)*DELE
1000 CONTINUE
      DELF=DELE*FINTGR
      NEMAX=NEMAX/INTGR
      DO 71 M=1,NEMAX
71  EN(M)=(M-1)*DELE
      DO 72 K=1,NEMAX
      KP1=(K-1)*INTGR+1
      KP2=KP1+INTGR-1
      DO 72 L=KP1,KP2
72  SPEC(K)=SPEC(K)+TEMP(L)
      IF(NTS.LT.0) GO TO 79
      SUMN(NTS)=0.
      SUMG(NTS)=0.
      DO 73 K=N1,NGMX1
73  SUMG(NTS)=SUMG(NTS)+PHIG(K)
      DO 75 L=1,NEMAX
75  SUMN(NTS)=SUMN(NTS)+SPEC(L)*1.E-04
      CALL AVRG(EAVG,EAVN,DELE,NEMAX,NGMX1,EAVGT,N1)
      AV1(NTS)=EAVG
      AV2(NTS)=EAVGT
      AV3(NTS)=EAVN
      TOT(NTS)=SUMT-TIRAD
      NSKIP=0
      QT=TOT(NTS)
      DO 77 K=1,IITYM
      IF(QT.EQ.IYMK) NSKIP=1
77  CONTINUE
      IF(NSKIP.NE.1) GO TO 74
79  CALL SPOUT(NTS,DELT,SUMT,FISR,GAMF,N1,NGMAX,NGMX1,NEMAX,NPLOT,EAVG
1,EAVN,EAVGT)
76  CONTINUE
      IF(NPHIG.LT.NGMX1) GO TO 29
      IF(NTS.EQ.NSETS) GO TO 80
      GO TO 24
80  CONTINUE
      NPRNT=0
81  NPRNT=NPRNT+1
      PRINT 999
999  FORMAT(1H1)
      IF(NPRNT.NE.1) PRINT 90
      IF(NPRNT.EQ.1) PRINT 91

```

```

90 FORMAT(1H0,20X,*TIME IN HOURS*,15X,*TOTAL PHOTONEUTRONS PER FISSION*//)
91 FORMAT(1H0,20X,*TIME IN HOURS*, 7X,*TOTAL PHOTONEUTRONS PER FISSION*//)
IN (X1.0F-24 CM 2)*//)
DO 110 K=1,NSFTS
PRINT 100,K,TOT(K),SUMN(K)
170 FORMAT(3X,13,15X,1PE12.4,25X,1PE12.4)
110 CONTINUE
PRINT 999
PRINT 120
120 FORMAT(1H0,20X,*TIME IN HOURS*,15X,*TOTAL GAMMAS PER FISSION*//)
DO 140 L=1,NSFTS
PRINT 130,L,TOT(L),SUM(L)
130 FORMAT(3X,13,15X,1PE12.4,20X,1PE12.4)
140 CONTINUE
ABSYS(1)=10HSHUTDOWN T
ABSYS(2)=10HIME (HOURS)
ABSYS(3)=10H)
ORDIN(1)=10HNORMALIZED
ORDIN(2)=10H PHOTONEUT
ORDIN(3)=10HNRONS / FIS
ORDIN(4)=10H5JON / WAT
ORDIN(5)=2HT
TI(1)=10HIME-DEFFN
TI(2)=10HMENT DISTR
TI(3)=10HIBUTION
TI(4)=HL(1)
TI(5)=HL(2)
DO 145 I=1,NSFTS
IF (SUMN(I).LE.1.E-15) SUMN(I)=1.E-15
145 CONTINUE
IF (NPLOT.NE.1) GO TO 141
IF (NPRINT.EQ.1) GO TO 141
CALL PLOTM(TOT,SUMN,-NSFTS,-1.0,0.0,0.1,0.1,0.0,TI,50,
1ABSYS,21,ORDIN,42)
141 CONTINUE
ORDIN(1)=10HPOWER 17FII
ORDIN(2)=10H GAMMA-RAY
ORDIN(3)=10HS / FISSION
ORDIN(4)=AHN / WAT
DO 150 I=1,NSFTS
IF (SUMG(I).LE.1.E-15) SUMG(I)=1.E-15
150 CONTINUE
IF (NPLOT.NE.1) GO TO 142
IF (NPRINT.EQ.1) GO TO 142
CALL PLOTM (TOT,SUMG,-NSFTS,-1.0,0.0,0.1,0.1,0.0,TI,50,
1ABSYS,21,ORDIN,34)
142 CONTINUE
IF (NPRINT.NE.1,OR,NPLOT.NE.1) GO TO 300
PRINT 310
310 FORMAT(1H1,20X,*TIME IN HOURS*,15X,*AV. GAMMA F*,15X,*AV. GAMMA F*//)
IF (G.F. THRESHOLD).E-12X,*AV. NEUTRON E*//)
DO 330 I=1,NSFTS
PRINT 320,I,TOT(I),AV1(I),AV2(I),AV3(I)
320 FORMAT(3X,13,15X,1PE12.4,15X,1PE12.4,22X,1PE12.4,22X,1PE12.4)
330 CONTINUE
ORDIN(1)=10HAVERAGE FN
ORDIN(2)=10HENERGY (MEV)
TI(1)=10HAVERAGE GA
TI(2)=10HMAA ENERGY
TI(3)=HL(1)
TI(4)=HL(2)
CALL PLOTM(TOT,AV1,-NSFTS,-1.0,0.0,0.1,0.1,0.0,TI,40,ABSYS,21,ORDIN,
120)
CALL PLOTM(TOT,AV1,-NSFTS,-1.0,0.0,0.1,0.1,0.0,TI,40,ABSYS,21,ORDIN,
120)
TI(3)=10H (E G.T. T
TI(4)=10HRESHOLD)
TI(5)=HL(1)
TI(6)=HL(2)
CALL PLOTM(TOT,AV2,-NSFTS,-1.0,0.0,0.1,0.1,0.0,TI,60,ABSYS,21,ORDIN,
120)

```



```

60 FORMAT(3X,I3,25X,1PE12.4,25X,1PE12.4)
50 CONTINUE
  IF(NIS.LT.0) GO TO 111
  ARSIS(1)=10HGAMMA ENER
  ARSIS(2)=9HGY (MEV)
  ORDIN(1)=10HNORMALIZED
  ORDIN(2)=10H GAMMA-RAY
  ORDIN(3)=10HS / FISSIO
  ORDIN(4)=10HN / WATT
  TI(1)=10HFISSION PR
  TI(2)=10HODUCT GAMM
  TI(3)=10HA-RAY SPFC
  TI(4)=10HTRUM AT
  TI(5)=ANAME(3)
  TI(6)=HL(1)
  TI(7)=HL(2)
  END(1)=EGAM(1)
  DUMSP(1)=PHIG(1)
  NGSUM=NGMAX
  NGS=2*NGSUM-1
  DO 70 N=3,NGS,2
    N2=N/2
    END(N-1)=EGAM(N2+1)
    END(N)=EGAM(N2+1)+0.00001
    DUMSP(N-1)=PHIG(N2)
70  DUMSP(N)=PHIG(N2+1)
    DO 75 I=1,NGS
      IF(DUMSP(I).LT.1.E-15)DUMSP(I)=1.E-15
75  CONTINUE
85  FORMAT(3X,I3,14X,1PE12.4,20X,1PE12.4)
    IF(NPLOT.NE.1. OR.NPRNT.EQ.1) GO TO 300
    CALL PLOTM(END,DUMSP,NGS,-1,0,0,0.0,1.0,1.0,TI,70,
      IARSIS,19,ORDIN,40)
300 CONTINUE
    DO 100 J=1,NGS
      END(J)=0.
100  DUMSP(J)=0.
      ARSIS(1)=10HPHOTONEUTR
      ARSIS(2)=10HON ENFRGY
      ARSIS(3)=6H(MEV)
      ORDIN(1)=10HNORMALIZED
      ORDIN(2)=10H PHOTONEUT
      ORDIN(3)=10HRONS X HAR
      ORDIN(4)=10HNS / FISSI
      ORDIN(5)=10HON / WATT
      TI(2)=10HODUCT PHOT
      TI(3)=10HONNEUTRON S
      TI(4)=10HPECTRUM AT
      TI(5)=ANAME(3)
      TI(6)=HL(1)
      TI(7)=HL(2)
      END(1)=EN(1)
      DUMSP(1)=SPEC(1)
      NNS=2*NEMAX-1
      DO 110 N=3,NNS,2
        N2=N/2
        END(N-1)= EN(N2+1)
        END(N)= EN(N2+1)+1.0E-5
        DUMSP(N-1)=SPEC(N2)
110  DUMSP(N)=SPEC(N2+1)
111  PRINT 5
      IF(NPRNT.EQ.1) PRINT 120
      IF(NPRNT.NE.1) PRINT 121
120  FORMAT(1H0,13X,*NEUTRON ENERGY(BOUNDARY)*, 7X,*PHOTONEUTRONS/FISSI
      10N (X1.E-28 CM 2)/)
121  FORMAT(1H0,16X,*NEUTRON ENERGY(BOUNDARY)*,12X,*PHOTONEUTRONS/FISSI
      10N*/ )
      DO 130 I=1,NEMAX
        PRINT 140,I,EN(I),SPEC(I)
140  FORMAT(3X,I3,15X,1PE12.4,23X,1PE12.4)

```

```

130 CONTINUE
  IF (NTS.LT.0) GO TO 401
  IF (NPRNT.NE.1) GO TO 500
  PRINT 350,EAVG
350 FORMAT(1H0,///,30X,*AVERAGE GAMMA ENERGY = *,1PE12.4,* MEV*)
  PRINT 351,EAVGT
351 FORMAT(1H0,///,30X,*AVERAGE GAMMA ENERGY FOR GAMMAS WITH F G.T. (G
  1,N) THRESHOLD = *,1PE12.4,* MEV*)
  PRINT 450,EAVN
450 FORMAT(1H0,///,30X,*AVERAGE PHOTONEUTRON ENERGY = *,1PE12.4,* MEV
  1*)
500 CONTINUE
  DO 135 I=1,NNS
  IF (DUMSP(I).LE.1.E-15) DUMSP(I)=1.E-15
135 CONTINUE
  IF (NPLOT.NE.1. OR.NPRNT.EQ.1) GO TO 400
  CALL PLOTM(END,DUMSP,NNS,-1.0,0.0,0.0,1.0,1.0,T1,70,
  1,ABSYS,26,ORDIN,50)
400 CONTINUE
401 IF (NPRNT.NE.1) GO TO 190
  QSUM=0.
  DO 145 K=1,NEMAX
145 QSUM=QSUM+SPEC(K)
  DO 150 K=1,NEMAX
150 SPEC(K)=SPEC(K)/QSUM
  QGAMF=0.
  DO 155 L=1,NGMX1
155 QGAMF=QGAMF+PHIG(L)
  DO 160 J=1,NGMAX
160 PHIG(J)=PHIG(J)/QGAMF
  PRINT 204
204 FORMAT(1H0,///)
  IF (NTS.GE.0) PRINT 205,GAMF
  PRINT 210,QGAMF
205 FORMAT(1H,30X,*TOTAL GAMMAS PER FISSION = *,1PE12.4//)
210 FORMAT(1H,30X,*TOTAL GAMMAS/FISSION WITH F G.T. (G,N) THRESHOLD =
  1 *,1PE12.4//)
  QSUM=QSUM*1.E-04
  PRINT 200,QSUM
200 FORMAT(1H0,///,30X,*TOTAL PHOTONEUTRONS PER FISSION = *,1PE12.4,2X
  1,*X 1.0E-24 CM**2//)
  PRINT 170
170 FORMAT(1H0,30X,*FOLLOWING ARE NORMALIZED SPECTRA*//)
  GO TO 35
190 CONTINUE
  RETURN
  END

```

```

      SURROUTINE MAXMIN(FZN,PHON,GM,PKC,PNMIN,PNMAX,ENMIN,ENMAX)
C-----*****
C
C-----MAXMIN CALCULATES THE MAXIMUM AND THE MINIMUM PHOTONEUTRON
C-----ENERGIES FOR A GIVEN GAMMA-RAY ENERGY
C
C-----*****
      PNMIN=GM*PKC*(1.-PHON)
      PNMAX=GM*PKC*(1.+PHON)
      ENMIN=(PNMIN**2.+FZN**2.)**.5-E7N
      ENMAX=(PNMAX**2.+FZN**2.)**.5-FZN
      RETURN
      END

```

```

      SURROUTINE SORTN(ENMIN,ENMAX,NEMAX,NMN,NMX)
      COMMON FGAM(200),COSTH(200),EN(2000),PHIG(200),SPEC(200),HOL(20),
      1TEND(400),FGMM(200),TI(10),ABSYS(10),ORDIN(10),DUMSP(400),

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      2SUMG(50),SUMN(50),TOT(50),SIGF(60),SIGM(60),ENGM(60),TYM(10)
      COMMON SIGSM(60)
      COMMON AV1(30),AV2(30),AV3(30)
      COMMON TEMP(8000)
      COMMON PRN(8000)
      COMMON HL(5),ANAME(10)
C-----*****
C
C-----SORTN SORTS THE MAXIMUM AND THE MINIMUM NEUTRON ENERGIES INTO A
C-----PRFDETERMINED NEUTRON ENERGY GRID
C
C-----*****
      DO 10 I=1,NEMAX
      INDEX=I
      IF (ENMIN-EN(I))20,20,10
10  CONTINUE
20  NMN=INDEX-1
      DO 30 I=NMN,NFMAX
      IND=I
      IF (ENMAX-EN(I))40,40,30
30  CONTINUE
40  NMX=IND-1
      RETURN
      END

      SUBROUTINE CSFN(GAMMA,ENEUT,EZX,ETHR,EZN,CSTH,STH,EZY)
C-----*****
C
C-----CSEN CALCULATES THE SINE AND COSINE OF THE NEUTRON LABORATORY
C-----ANGLE AS A FUNCTION OF THE GAMMA-RAY AND THE NEUTRON ENERGIES
C
C-----*****
      R1=ENEUT/EZN
      R2=GAMMA/EZX
      R3=EZN/EZX
      R4=EZY/EZX
      Q1=(R1*(2.+R1))*0.5
      Q1=1./Q1
      Q2=(1.+R1)*(1.+R2)/R2-1./R3-(1.+R3**2.-R4**2.)/(2.*R2*R3)
      CSTH=Q1*Q2
      IF (CSTH.LT.-1.) CSTH=-1.
      IF (CSTH.GT.1.) CSTH=1.
      STH=(1.-CSTH*CSTH)**0.5
      RETURN
      END

      SUBROUTINE PRPB(VF,GM,PKC,PTHC,PB)
C-----*****
C
C-----PRPB CALCULATES THE PHOTONEUTRON ENERGY DISTRIBUTION AS A FUNCTION
C-----OF THE NEUTRON CENTER-OF-MASS ANGLE
C
C-----*****
      PI=3.141592654
      P4=2.*PI*PTHC/(GM*VF*PKC)
      RETURN
      END

```

```

      SUBROUTINE PRO(STHC,CTHC,PTHC,GAMMA,IMAX,SE,SM)
C-----*****
C
C-----PRO CALCULATES THE CENTER-OF-MASS PHOTONEUTRON ANGULAR
C-----DISTRIBUTION
C
C-----*****
      PI=3.141592654
      PTHC=(1./(4.*PI))*(SM+1.5*SE*STHC*STHC)
      RETURN
      END

```

```

      SUBROUTINE ANGCM(RHON,GM,STHC,CTHC,CSTH,STH)
C-----*****
C
C-----ANGCM CALCULATES THE SINE AND COSINE OF THE NEUTRON CENTER-OF-
C-----MASS ANGLE AS A FUNCTION OF ITS LABORATORY ANGLE
C
C-----*****
      CG=CSTH/GM
      STH2=STH*STH
      CG2=CG*CG
      Q1=(1.-RHON)*(1.+RHON)*STH2
      Q2=(Q1+CG2)**0.5
      Q3=(RHON*CG+Q2)/(STH2+CG2)
      STHC=STH*Q3
      CTHC=(1.-STHC*STHC)**0.5
      RETURN
      END

```

```

      SUBROUTINE KIN(GAMMA,EZX,FZN,FZY,VF,ETC,AN,RHON,GM,PKC)
C-----*****
C
C-----KIN CALCULATES RELATIVISTIC KINEMATICS PARAMETERS FOR THE
C-----PHOTONEUTRON REACTION
C
C-----*****
      VE=GAMMA/(GAMMA+FX)
      Q9=(1.+2.*GAMMA/ETC)**0.5
      ETC=FX*Q9
      QU=FZN+EZY-EZX
      AN=2.*(EZX*(FZN+GAMMA)-QU*(FZY-QU*0.5))
      R1=GAMMA/EZN
      R2=ETC/EZX
      R3=FZY/EZX
      R4=FZY/EZN
      DEN=R1*0.5*(R2+1./Q2-R3*R4)
      DEN1=(ETC/EZX)/DEN
      Q10=1.-DEN1
      Q11=1.+DEN1
      D=(Q10*Q11)**0.5
      RHON=VF/D
      GM=GAMMA/ETC*1./Q9
      PKC=D*AN/(2.*ETC)
      RETURN
      END

```



```

      SUBROUTINE MOM(CSTH,PNEUT,ENEUT,EZN,VE,RHON,GM,STH)
C-----*****
C
C-----MOM CALCULATES THE NEUTRON ENERGY AND THE PHOTONEUTRON CROSS
C-----SECTION AS A FUNCTION OF THE NEUTRON LABORATORY ANGLE
C
C-----*****
      RHON2=PHON*RHON
      VE2=VE*VE
      STH2=STH*STH
      GM2=GM*GM
      Q=(1.-(RHON2-VE2)*STH2*GM2)**0.5
      Q1=0+RHON*CSTH
      CSTH2=CSTH*CSTH
      PNEUT=PKC*Q1/(GM*(1.-VE2*CSTH2))
      EZN2=EZN*EZN
      PNT2=PNEUT*PNEUT
      ENEUT=(PNT2+EZN2)**0.5-EZN
      RETURN
      END

```

```

      SUBROUTINE AVRG(FAVG,FAVN,DELF,NFMAX,NGMX1,EAVGT,N1)
      COMMON EGAM(200),COSTH(200),EN(8000),PHIG(200),SPEC(200),HOL(20),
      IEND(400),EGMM(200),TI(10),AHSTS(10),ORDIN(10),DUMSP(400),
      PSUMG(50),SUMN(50),TOT(50),SIGE(60),SIGM(60),ENGM(60),TYM(10)
      COMMON SIGSM(60)
      COMMON AVI(30),AV2(30),AV3(30)
      COMMON TEMP(8000)
      COMMON PRN(8000)
      COMMON HL(5),ANAME(10)
C-----*****
C
C-----AVRG AVERAGES GAMMA-RAY AND PHOTONEUTRON ENERGIES OVER
C-----THEIR CORRESPONDING DISTRIBUTIONS
C
C-----*****
      QFAVN=0.
      QEAVN=0.
      DO 700 K=1,NFMAX
      QEAVN=QEAVN+(FN(K)*0.5*DELF)*SPEC(K)
700 QFAVN=QFAVN+SPEC(K)
      FAVN=QFAVN/QFAVN
      QFAVG=0.
      QEAVG=0.
      DO 400 L=1,NGMX1
      QEAVG=QEAVG+EGMM(L)*PHIG(L)
400 QFAVG=QFAVG+PHIG(L)
      FAVG=QFAVG/QFAVG
      QEGT=0.
      QFGT=0.
      DO 600 I=1,NGMX1
      QEGT=QEGT+EGMM(I)*PHIG(I)
600 QFGT=QFGT+PHIG(I)
      FAVG1=QEGT/QFGT
      RETURN
      END

```

```

      SUBROUTINE INTERP(EG,SG,GAMMA,INAC,IJUMP,IGDII,GMMAT)
      COMMON EGAM(200),COSTH(200),EN(8000),PHIG(200),SPEC(200),HOL(20),
      IEND(400),EGMM(200),TI(10),AHSTS(10),ORDIN(10),DUMSP(400),
      PSUMG(50),SUMN(50),TOT(50),SIGE(60),SIGM(60),ENGM(60),TYM(10)
      COMMON SIGSM(60)
      COMMON AVI(30),AV2(30),AV3(30)
      COMMON TEMP(8000)
      COMMON PRN(8000)
      COMMON HL(5),ANAME(10)

```

```

C-----*****
C
C-----INTERP LINEARLY INTERPOLATES INPUT PHOTONEUTRON CROSS SECTIONS
C
C-----*****
      IJUMP=IJUMP+1
      IF (IJUMP.EQ.1) PRINT 999,GNMAT
999  FORMAT(1H1,35X,A10,*INTERPOLATED PHOTONEUTRON CROSS SECTIONS IN 1.
      10E-28 CM 2*/ )
      IF (IJUMP.EQ.1) PRINT 998
998  FORMAT(1H0,21X,*GAMMA ENERGY (MEV)*,10X,*SIGMA ELECTRIC*,10X,*SIGM
      1A MAGNETIC*,11X,*SIGMA TOTAL*/ )
      IF (GAMMA.LT.ENGM(1)) GO TO 25
      IF (GAMMA.GT.ENGM(IMAX)) GO TO 28
      DO 10 I=1,IMAX
      IX=I
      IF (GAMMA-ENGM(I)) 30,20,10
10  CONTINUE
20  SE=SIGF(IX)
      SM=SIGM(IX)
      GO TO 50
25  IX=2
      GO TO 30
28  IX=IMAX
30  QF1=(SIGE(IX)-SIGE(IX-1))/(ENGM(IX)-ENGM(IX-1))
      QF2=(SIGE(IX-1)*ENGM(IX)-SIGE(IX)*ENGM(IX-1))/(ENGM(IX)-ENGM(IX-1))
1)  QM1=(SIGM(IX)-SIGM(IX-1))/(ENGM(IX)-ENGM(IX-1))
      QM2=(SIGM(IX-1)*ENGM(IX)-SIGM(IX)*ENGM(IX-1))/(ENGM(IX)-ENGM(IX-1))
1)  SE=QF1*GAMMA+QF2
      SM=QM1*GAMMA+QM2
50  SEM=SE+SM
      IF (IJUMP.GT.NGDIF) GO TO 60
      PRINT 997,GAMMA,SE,SM,SEM
997  FORMAT(1H,23X,1PE12.4,14X,1PE12.4,12X,1PE12.4,11X,1PE12.4)
60  CONTINUE
      RETURN
      END

```

```

      SUBROUTINE TEST(NPHIG,NTS,NGMX1)
      COMMON FGAM(200),COSTH(200),EN(8000),PHIG(200),SPEC(200),HOL(20),
1END(400),EGMM(200),TI(10),ABSYS(10),ORDIN(10),DUMSP(400),
2SUMG(50),SUMN(50),TOT(50),SIGF(60),SIGM(60),ENGM(60),TYM(10)
      COMMON SIGSM(60)
      COMMON AV1(30),AV2(30),AV3(30)
      COMMON TFMP(8000)
      COMMON PH1(8000)
      COMMON HL(5),ANAME(10)

```

```

C-----*****
C
C-----TEST SUPPLIES UNIT LINE PHOTON SPECTRA FOR TEST PURPOSES
C
C-----*****
      DFLT=1.
      SUMT=1.
      FISS=1.
      GAMF=1.
      NTS=-1
      DO 10 I=1,NGMX1
10  PH1(I)=0.
      PH1(I,PHIG)=1.
      RETURN
      END

```

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