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STATISTICAL PROGRAM GAMAJ

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by

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PROGRAM GAMAJ

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DESCRIPTION OF PROGRAM GAMAJ

The program calculates the cross section of formation and the spin distribution of the compound nucleus formed in a nuclear reaction $A+a \longrightarrow C^* \longrightarrow B+b$ and the total width Γ and partial widths Γ^b for the decay by alpha particles, protons, neutrons and deuterons.

1. Formulation

A. Cross Section of Formation and the Spin Distribution of the Compound Nucleus

The cross section for the formation of the compound nucleus with spin J at an excitation energy U_C , from the reaction $A+a \longrightarrow C^*$, is given by

$$\sigma(U_C, J) = \frac{\pi \lambda_a^2 (2J+1)}{(2i_a+1)(2I_A+1)} \sum_{S_a=|I_A-i_a|}^{I_A+i_a} \sum_{\ell_a=|J-S_a|}^{J+S_a} T_a^{\ell_a}(\epsilon_a) \quad (1)$$

where λ_a = de Broglie wave length of the entrance channel,

I_A = spin of the target nucleus,

i_a = spin of projectile,

S_a = spin of the entrance channel;

$$\vec{S}_a = \vec{I}_A + \vec{i}_a$$

$T_a^{\ell_a}(\epsilon_a)$ = optical model transmission coefficient of particle a with orbital angular momentum ℓ_a and channel energy ϵ_a ,

ϵ_a = center of mass energy of the entrance channel, sometimes referred to as the entrance channel energy;

$$\epsilon_a = E_a M_A / (M_a + M_A),$$

M_x = mass of particle x ,

E_a = energy of projectile in the laboratory system.

The channel wavelength λ_a is related to the channel energy by

$$\frac{1}{\lambda_a} = \frac{(2M_o \epsilon_a)^{1/2}}{h} \quad (2)$$

where M_o is the reduced mass of the system.

$$\frac{1}{\lambda_a^2} = 4.784 E_a (\text{MeV}) \frac{M_a M_A^2}{(M_a + M_A)^2} \quad (3)$$

(λ_a^2 in eq. (3) is in barns).

The total cross section for formation of compound nucleus C^* is given by

$$\sigma(U_C) = \sum_J \sigma(U_C, J) \quad (4)$$

and the probability P_J for the formation of the compound nucleus with spin J by

$$P_J = \frac{\sigma(U_C, J)}{\sigma(U_C)} \quad (5)$$

B. Energy Level Widths

a) The Fermi Gas Calculation

The energy width $\Gamma_J^b(U_C)$ of the compound nucleus with spin J at an excitation energy U_C for the decay by emission of particles b leading to a residual nucleus B is given by

$$\Gamma_J^b(U_C) = \frac{D(U_C, J)}{2\pi} \int_0^{U_{B\max}} dU_B \sum_{\ell_b} T_b^{\ell_b}(\epsilon_b) \cdot \frac{\sqrt{J+\ell_b}}{S_b=|J-\ell_b|} \frac{S_b+i\ell_b}{I_B=|S_b-i\ell_b|} \rho_B(U_B, I_B) \quad (6)$$

where

I_B = spin of the residual nucleus B,

i_b = spin of emitted particle b,

S_b = exit channel spin,

$T_b^{i_b}(\epsilon_b)$ = optical model transmission coefficient of particle b with orbital angular momentum l_b and channel energy ϵ_b ,

$D(U_c, J)$ = the spacing of levels with spin J of the compound nucleus at an excitation energy U_c , and

$\rho_B(U_B, I_B)$ = level density of the residual nucleus B

The relation between the exit channel energy ϵ_b and the maximum excitation energy of the residual nucleus is

$$\epsilon_b = U_{B_{\max}} - U_B \quad (7)$$

and

$$U_{B_{\max}} = \epsilon_a + Q_{ab} \quad (8)$$

where Q_{ab} is the ground state Q-value for the reaction.

If Fermig gas form of level density is used, one can write*

$$r_J^b(U_c) = G_J^b / \rho(U_c, J \neq 0), \quad (9a)$$

$$G_J^b = \frac{\exp[J(J+1)/2\sigma_c^2]}{2\pi(2J+1)} \cdot D_J^b \quad (9b)$$

*The symbols r_J^b , G_J^b and D_J^b correspond to the symbols of the computer output GAMA(J), G(J) and DENOM(J), respectively.

$$D_J^b = \int_0^{U_{B_{\max}}} dU_B \sum_{\ell_b} T_b^{\ell_b}(\epsilon_b) \sum_{S_b=|J-\ell_b|}^{J+\ell_b} \sum_{I_B=|S_b-\ell_b|}^{J_b+I_b} \rho_B(U_B, I_B) \quad (9c)$$

$$\rho(U, I) = \frac{a^{1/2} (2I+1)}{24\sqrt{2} C^{3/2} (U-\Delta+t)^2} \exp \left[2a^{1/2} (U-\Delta)^{1/2} - \frac{I(I+1)}{2 ct} \right] \quad (9d)$$

where

a = Fermi gas level density parameter

Δ = energy shift

t = thermodynamic temperature.

The relation between a , Δ , t and U is given by the equation of state,

$$U-\Delta = at^2 - t, \quad (10)$$

and the quantity c is related to the moment of inertia by

$$c = \mathcal{J}/\hbar^2 = 0.0137 A^{5/3} \text{ MeV}^{-1}, \quad (11)$$

and the spin cutoff factor σ is given by

$$\sigma^2 = ct \quad (12)$$

The summations in (9c) are performed up to $\ell_{b_{\max}} = 17$ and $S_{b_{\max}} = 14$, and the integral is approximated by sums according to Simpson's rule, with 0.5 MeV steps. The partial widths Γ_J^b are calculated for alpha particles, protons, neutrons and deuterons, for $J=0-17$.

b) The "Constant Temperature" Calculation

The partial width $\Gamma_J^b(U_c)$ of eq. (6) is calculated using the constant temperature form of the level density,

$$\rho_B(U_B, I_B) = \rho_n(U_c - B_n) \exp \left[\frac{U_B - (U_c - B_n) + (\Delta_n - \Delta_b)}{T} \right] \cdot \frac{2I_B + 1}{2\sigma_B^2} \exp \left[- \frac{I_B(I_B + 1)}{2\sigma_B^2} \right], \quad (13)$$

in which the level densities $\rho_B(U_B, I_B)$ of each residual nucleus B is calculated relative to the level density $\rho_n(U_c - B_n)$ of the residual nucleus reached by emission of neutrons with zero energy. The quantity B_n is the neutron binding energy, T the nuclear temperature, and $\Delta_n - \Delta_b$ a correction for the energy shift difference for the fictive ground state energies in the residual nucleus reached by emission of a neutron and a particle b . One can then write

$$r_J^b(U_c) = G_J^b \frac{\rho_n(U_c - B_n, I_B=0)}{\rho_c(U_c, J=0)} \quad (14a)$$

$$G_J^b = \frac{\exp[J(J+1)/2\sigma_c^2]}{2\pi(2J+1)} \cdot D_J^b \quad (14b)$$

$$D_J^b = 2\sigma_n^2 \int_0^{U_{B_{\max}}} dU_{B_{\max}} \int_{I_b}^{I_b^{\ell}} T_b^{\ell, b}(\epsilon_b) \frac{\sum_{I_B=|S_b - I_b|}^{S_b + I_b}}{S_b = |J - I_b|} \frac{(2I_B + 1)}{2\sigma_B^2} \exp \left[\frac{U_B - (U_c - B_n) + \Delta_n - \Delta_b}{T_B} - \frac{I_B(I_B + 1)}{2\sigma_B^2} \right] \quad (14c)$$

When the ratio $\rho_n(U_c - B_n, I_B=0)/\rho_c(U_c, J=0)$ is calculated using the constant temperature form of level density (eq. (13)), it is independent of the excitation energy U_c of the compound nucleus,

$$\frac{1}{R} = \frac{\rho_n(U_c - B_n, I_B=0)}{\rho_c(U_c, J=0)} = \frac{\mathcal{I}_c}{\mathcal{I}_n \exp\left[\frac{B_n + \Delta_n - \Delta_c}{T_c}\right]} \quad (15)$$

where $\mathcal{I}_c$ and $\mathcal{I}_n$ are the moments of inertia of the compound nucleus and the nucleus reached by neutron emission, respectively. If one assumes a constant temperature level density to hold for all the excitation energies covering the excitation energy regions of the residual nuclei and the compound nucleus, the integral given by eq. (14c) varies very little with U_c . Γ_J is then essentially independent of the excitation energy.

c) The "Modified Constant Temperature" Calculation

One expects the temperature to be approximately constant over small energy intervals but probably not to be constant for the excitation energies of the residual nuclei all the way to the excitation energy of the compound nucleus. For this reason, the ratio in eq. (14a) is calculated with the Fermi gas form of level density (eq. (9d)); the constant temperature form is used only for the residual nuclei. In this way, only $\frac{1}{R}$ is affected, its value in the modified temperature calculation is given by

$$\begin{aligned} \frac{1}{R} &= \frac{\rho_n(U_c - B_n, I_B=0)}{\rho_c(U_c, J=0)} \\ &= \left(\frac{a_n \mathcal{I}_c^3}{a_c \mathcal{I}_n^3} \right)^{1/2} \left(\frac{U_c + t_c - \Delta_c}{U_c - B_n + t_n - \Delta_n} \right)^2 \cdot \\ &\quad \exp \left[2 a_n^{1/2} (U_c - B_n - \Delta_n)^{1/2} - 2 a_c^{1/2} (U_c - \Delta_c)^{1/2} \right] \end{aligned} \quad (16)$$

III. Total Energy Widths

The total decay width of the compound nucleus with spin J , Γ_J , is calculated by summing the partial widths for all outgoing particles

$$\Gamma_J = \sum_b \Gamma_J^b \quad (17)$$

The average lifetime τ of the compound nucleus is found from a weighted sum of the lifetimes of the nuclei with different angular momentum J . Since $\tau = h/\Gamma$, one obtains

$$\frac{1}{\Gamma} = \frac{\sum_J \sigma_J / \Gamma_J}{\sum_J \sigma_J} \quad (18)$$

where σ_J is the cross section for formation of the compound nucleus with spin J and is given by eq. 1.

2. Program Description

The program consists of the main program, called GAMAJ, two subroutine programs called TLREAD and DENOMR, and two subroutine functions, called DEN and SIG. The subprogram TLREAD is used for reading the transmission coefficients and checking the right order of the input cards. The subprogram DENOMR computes the quantity D_J^b of eq. (9c) and (14c) for alpha particles, protons, neutrons and deuterons, and for J values 0-17. The level density is given by the product of the function DEN times the function SIG, which compute the energy and spin dependent parts of the level density, respectively.

3. Data Card Formats

Constants (transmission coefficients and level density parameters) referring to emission of different kinds of particles and the corresponding residual nuclei reached by the emission of these particles, are labeled by an index NU with the following meaning:

NU	PARTICLE
1	compound nucleus
2	alpha particles
3	protons
4	neutrons
5	deuterons

Card 1 Format (I2, 78H)

- col 2 The number 1 must always appear in this column.
- cols 3-80 Descriptive title; this title is printed as a heading for the output.

Card 2 Format (6E12.5)

- cols 1-12 AM--Mass of the projectile.
- cols 13-24 TM--Mass of the target.
- cols 25-36 SIGMA-- σ_c^2 , square of the spin cutoff factor of the compound nucleus.
- cols 37-48 CROS--not used in present calculations.
- cols 49-60 DL--The quantity R of Eq. (15) or (16) for the "constant temperature" or the "modified constant temperature" calculations, respectively. It must be left blank for the "Fermi gas" calculation.

cols 61-72 CGAMA, not used in the present calculations.

Card 3 Format (5F6.1)

cols 1-6 SIP--Projectile spin.

cols 7-12 SIT--Target spin.

cols 13-18 SIR

cols 19-24 SIELAT } not used in the present calculations.

cols 25-30 SIMEG }

Card 4 Format (13I3) All numbers on this card must be integers (without a decimal point).

col 3 IPAR--IPAR = 1 for odd parity of the target and IPAR = 2 for even parity.
Note: IPAR is not used in the calculation but must appear on the card.

col 6 I2PAR=N--I2PAR=0 if the transmission coefficients are given after the 10th card; I2PAR=1 if no transmission coefficients are given, and the coefficients of the previous case are used. I2PAR=2 read only the incoming transmission coefficients.

col 9 NUOUT -- not used in the present calculations.

col 12 IC

col 15 IP--IC = IP = 1 for the "Fermi-gas" calculations, and IC = IP = 2 for the constant temperature calculations.

col 16-18 JEM(1)--leave blank

cols 20-21 JEM(2)--Number of energies for which transmission coefficients are given for

emission of alpha particles.

cols 23-24 JEM(3)--The same for protons.

cols 25-27 JEM(4)--The same for neutrons.

cols 29-30 JEM(5)--The same for deuterons.

Note: Transmission coefficients for each kind of particles must be given at least for one energy and up to 40;
 $1 \leq [JEM(NU), NU=2,5] \leq 40$.

cols 31-33	JEL	} not used in the present calculations.
cols 34-36	JEH	
cols 37-39	JEI	

Card 5 Format (E12.3, 10F6.2)

cols 1-12 EB--Projectile energy in the laboratory system.

cols 13-18 ETL--Excitation energy of the compound nucleus.

Card 6 Format (5F8.5)

cols 1-8 ESTARM(1)--leave blank

cols 9-16 ESTARM(2)--Maximum excitation energy (MeV) of the residual nucleus reached by emission of alpha particles.

$$ESTARM(2) = \epsilon_a + Q$$

Q = Q value of the reaction for α -emission
 (e.g. for $^{59}\text{Co}(p,\alpha)^{56}\text{Fe}$, $E_p=11$ MeV, $Q=3.23$ MeV)

$$ESTARM(2) = 11 \frac{59}{60} + 3.23 = 14.05$$

cols 17-24 ESTARM(3)--The same for the emission of protons.

cols 25-32 ESTARM(4)--The same for the emission of neutrons.

cols 33-40 ESTARM(5)--The same for the emission of deuterons.

Cards 7-10 give the level density parameters. The meaning of the symbols A, B, C, and D depends on the functional form of the level density.

For constant temperature-constant spin cutoff factor type

$$A = T$$

$$B = (U_C - B_n) - (\Delta_n - \Delta_B)$$

$$C = 2\sigma_n^2$$

$$D = \sigma_B^2$$

For Fermi gas model

$$A = a$$

$$B = \Delta$$

$$C = 24\sqrt{2} = 33.941$$

$$D = \mathcal{J}/h^2$$

Indices 2, 3, 4 and 5 refer to the residual nuclei reached by α -particle, proton, neutron and deuteron emission, respectively. Index 1 is referring to the compound nucleus and the quantities A(1), B(1), C(1) and D(1) are only required for the Fermi gas calculation.

Card 7 Format (5E12.5)

cols 1-12 A(1)

cols 13-24 A(2)

cols 25-36 A(3)

cols 37-48 A(4)

cols 49-60 A(5)

Card 8 Format (5E12.5)

cols 1-12 B(1)
cols 13-24 B(2)
cols 25-36 B(3)
cols 37-48 B(4)
cols 49-60 B(5)

Card 9 Format (5E12.5)

cols 1-12 C(1)
cols 13-24 C(2)
cols 25-36 C(3)
cols 37-48 C(4)
cols 49-60 C(5)

Card 10 Format (5E12.5)

cols 1-12 D(1)
cols 13-24 D(2)
cols 25-36 D(3)
cols 37-48 D(4)
cols 49-60 D(5)

The following cards have the optical model transmission coefficients, 6 on each card, 3 cards for each energy (starting with $T_a^{k_a}=0$ up to $T_a^{k_a}=17$, zeros or blanks should be used if necessary so that 3 cards will be present for each energy). The first card of each set of three must have the number 0 in column 74, the second the number 6, and the third the number 12 in columns 73-74. In all cards column 78 must have the number 1 for the incoming channel transmission coefficients, and number 2, 3, 4 or 5 for the outgoing channel for α -particles, protons, neutrons or deuterons, respectively. The mass number

of the compound nucleus must be in columns 79-80 in all cards for identification. An error will be indicated if any one of columns 73-80 has a wrong number.

Cards 11-13 have the transmission coefficients for the incoming channel. Then follow JEM(2) sets of 18 coefficients for α -particles, with 0.5 MeV steps starting with the highest α -energy (lowest excitation energy of the residual nucleus) until the energy of the particles becomes less than 0.5 MeV or the transmission coefficients become negligible. Then JEM(3) sets for protons, JEM(4) sets for neutrons and JEM(5) sets for deuterons.

Cards 11- Format (6E12.6, I2, 2X, 2I2)

Transmission coefficients (TL) in fields of I2 (as described above).

4. Output of Program GAMAJ

- 1) All input parameters except the transmission coefficients.
- 2) Level density of compound nucleus $\rho(U_c, J=0)$
- 3) Γ , the total width in MeV
- 4) Γ^b , the partial width for each of the open channels.
- 5) Γ_J^b , partial width for each open channel and for values of $J=0-17$
- 6) $\sigma_J(U_c)$ of eq. 1
- 7) P_J given by eq. 5
- 8) DENOM(J) and G(J)

II. PROGRAM LISTING

-14-

```

C      PROGRAM GAMAJ
      COMMON/8,C,D,IC,IP,DN ,GAMA,CGAMA,CLO,SIGMA,TL,JEM,MT,NPROBL,
      INUOUT,N,ESTARM,SPIN,FO,I2PAR
      DIMENSIONA(5),B(5),C(5),D(5),DN(18,5) ,GAMA(18),TL(5,18,40),JEM(5)
      1,ESTARM(5),SPIN(5),Z(18,18,15),PB(10) ,PA(5,40,10),PAU(5,40,10),
      2Q(18),PBO(5,10),ETL(10),AGTOT(18)
      3,GAG(5),GTOT(18),OTOT(18),GAM(18,5),PJ(18),P(18),AGAM(18,5),GAG(5)
10 READ (5,12,END=800) NPROBL
      GO TO 810
800 CALL EXIT
810 CONTINUE
12 FORMAT(12,78H
1
      READ 13,AM,TM,SIGMA,CROS,DL,CGAMA,
      1SIP,SIT,SIR,SIELAT,SIMEG,
      21PAR,I2PAR,NUOUT,IC,IP,(JEM(J),J=1,5),JEL,JEM,JEL,
      3EB,(ETL(J),J=1,10)
13 FORMAT(6E12.5/5F6.1/13I3/E12.3,10F6.2)
17 READ 21,(ESTARM(I),I=1,5),(A(I),I=1,5),(B(I),I=1,5),(C(I),I=1,5),
      1(D(I),I=1,5)
21 FORMAT(5F8.5/5E12.5/5E12.5/5E12.5/5E12.5)
      NUOUT=1
      NU=NUOUT
      FO=0.
      MAM=AM+.5
      MT=TM+.5
      MT=MT+MAM
      SIMIN=ABS(SIP-SIT)
      SIMAX=SIP+SIT
      I111=SIMAX
      S111=I111
      IF(SIMAX-S111)400,400,410
400 N=5
      GO TO 420
410 N=9
420 PRINT 401
      PRINT 12,NPROBL
401 FORMAT(1H1)
      IF(1PAR-1)800,50,51
50 PRINT 70,SIT,TM,NU
      GO TO 52
51 PRINT 71,SIT,TM,NU
52 PRINT 72,SIP,AM,JEL
53 PRINT 73, N,EB,JEM,IC,IP,JEL,(JEM(J),J=1,5),(ESTARM(J),J=1,5)
      PRINT 74,(A(J),J=1,5),(B(J),J=1,5),(C(J),J=1,5),(D(J),J=1,5)
70 FORMAT(1H ,120X,11HGAMAJ //14H+TARGET SPIN =F5.1,3H1-),
      18X,12HTARGET MASS=F10.5,8X,4HNU =13)
71 FORMAT(1H ,120X,11HGAMAJ //14H+TARGET SPIN =F5.1,3H1+),
      18X,12HTARGET MASS=F10.5,8X,4HNU =13)
72 FORMAT(14H PROJ. SPIN =F5.1,3H1+),8X,12HPROJ. MASS=F10.5,
      18X,4HJEL=13)
73 FORMAT( //14H TAPE12-COEF)=13,13X,12HPROJ.EN.(1)=,
      1F10.5,8X,4HLEH=13/14H IC =13,13X,12HIP =13,15X,
      24HJEL=13/16X,3H1=1,12X,3H1=2,12X,3H1=3,12X,3H1=4,12X,3H1=5/
      38H JEM(1)=,113,4115 /11H ESTARM(1)=,1X,5E15.5)
74 FORMAT(6H A(1)=6X,5E15.5/6H B(1)=,6X,5E15.5/6H C(1)=,6X,5E15.5/
      16H D(1)=,6X,5E15.5/)
      IF (I2PAR-1) 60,61,60
60 CALL TLREAD

```

```

61 CONTINUE
  SPIN(1)=1.
  SPIN(2)=0.
  SPIN(3)=.5
  SPIN(4)=.5
  SPIN(5)=1.
  SUMPJ=0.
  FACTOR=1./((2.*S(P+1.)*(2.*SIT+1.)*0.001523*EB*((TM/(AM+TM))**2)*A
  IM)
  JS1=SIMIN+1
  JS2=SIMAX+1
  DO 69 J=1,18
    PJ(J)=0.
  DO 68 JS=JS1,JS2
    JL1=IABS(J-JS)+1
    IF(N-6)62,62,63
62 JL2=J+JS-1
    FJ=J-1
    GO TO 64
63 JL2=J+JS
    FJ=J
    FJ=FJ-0.5
64 DO 67 JL=JL1,JL2
    IF(JL-18)67,67,68
67 PJ(J)=PJ(J)+TL(1,JL,1)
68 CONTINUE
    PJ(J)=PJ(J)*((2.*FJ+1.)*FACTOR
69 SUMPJ=SUMPJ+PJ(J)
    DO 65 J=1,18
65 P(J)=PJ(J)/SUMPJ
    PRINT 199,SIGMA,ETL(1)
    GO TO (83,84,84),IC
83 E=ETL(1)*2.
    DL=DEN(E,1)*SIG(0.,0.,E,1)
    PRINT 206,DL
    GO TO 1500
84 PRINT 207,DL
1500 CALL DENDMR
    DC 80 J=1,5
80 GA(J)=0.
    SPB=0.
    GAV=0.
    DO 100 J=1,18
      GTOT(J)=0.
      DTOT(J)=0.
      F=J-1
      IF(N-6)81,81,82
82 F=F+.5
81 SP = (2.*F+1.)*EXP ((-F)*(F+1.)/(2.*SIGMA))*2.*3.14159
      SP = 1./SP
      DO 90 NJ=2,5
        GAM(J,NJ)=SP *DN(J,NJ)
        AGAM(J,NJ)=GAM(J,NJ)/DL
        DTOT(J)=DTOT(J)+DN(J,NJ)
90 GTOT(J)=GTOT(J)+GAM(J,NJ)
      AGTOT(J)=GTOT(J)/DL
      IF(AGTOT(J).EQ.0.0) GO TO 91
      PB(J)=P(J)/AGTOT(J)
      GO TO 92

```

```

91 PB(J)=0.0
92 SPB=SPB+PB(J)
   DO 99 NJ=2,5
99 GA(NJ)=GA(NJ)+PB(J)*AGAM(J,NJ)
100 CONTINUE
   DO 110 J=2,5
   GA(J)=GA(J)/SPB
110 GAV=GAV+GA(J)
   PRINT 200,GAV,(GA(J),J=2,5)
   PRINT 204
   PRINT 202
   DO 130 J=1,18
   F=J-1
   IF(N-6)130,130,112
112 F=F+.5
130 PRINT 203,F,(AGAM(J,NJ),NJ=2,5),AGTOT(J),P(J),PJ(J)
   PRINT 205,SUMPJ
   PRINT 201
   PRINT 202
   DO 120 J=1,18
   F=J-1
   IF(N-6)120,120,113
113 F=F+.5
120 PRINT 203,F,(DN(J,NJ),NJ=2,5),DTOT(J)
   PRINT 208
   PRINT 202
   DO 140 J=1,18
   F=J-1
   IF(N-6)140,140,139
139 F=F+.5
140 PRINT 203,F,(GAM(J,NJ),NJ=2,5),GTOT(J)
199 FORMAT(28H SPIN CUT-OFF (COMP. NUCL.)=6.2/28M EXCITATION ENERGY
1   =E10.3/)
200 FORMAT(34H GAMA          TOTAL          =,E12.5,4H MEV/
1   34H GAMA          FOR ALPHA      EMISSION =,E12.5,4H MEV/
2   34H GAMA          FOR PROTON     EMISSION =,E12.5,4H MEV/
3   34H GAMA          FOR NEUTRON    EMISSION =,E12.5,4H MEV/
4   34H GAMA          FOR DEUTERON   EMISSION =,E12.5,4H MEV/)
201 FORMAT(1H1,39X,8HDENCM(J)/)
202 FORMAT(3X,1HJ9X,12HHE4-EMISSION5X,10HP-EMISSION5X,10HN-EMISSION5X,
110HD-EMISSION7X,5HTOTAL/)
203 FORMAT(F5.1,5X,5E15.5,13X,2E15.5)
204 FORMAT(40X,7HGAMA(J),68X,15HC. N. FORMATION/100X,29HSIGMA/SIGMATOT
X CROSS-SECTION/116X,12H(MILLIBARNS))
205 FORMAT(/112X,6HTOTAL=,E12.5)
206 FORMAT(28H LEVEL DENSITY (UC, J=0) = E10.3)
207 FORMAT(28H P(UC, J=0)/P(UC-8N, J=0) = E10.3)
208 FORMAT(///40X,4HG(J)/)
   GC TO 10
   END
SUBROUTINE TREAD
C ROUTINE TO READ IN TL CARDS PRODUCED BY OPT MOD.
C THE NU=1 CHANNEL IS GIVEN FOR ONLY ONE ENERGY SINCE
C IT IS THE N14 AND WILL NOT BE CONSIDERED AS AN EXIT CHANNEL.
COMMON A,B,C,D,IC,IP,DN ,GAMA,CGAMA,CLO,SIGMA,T ,JEM,MT,NPROBL,
INOUT,N,ESTARM,SPIN,FO,12PAR
DIMENSION A(5),B(5),C(5),D(5),DN(18,5) ,GAMA(18),T (5,18,40),JEM(5)
1,ESTARM(5),SPIN(5)
C FIRST READ NU=1, JE=1 CARDS.

```

```

      DO 52 L INDEX=1,13,6
      LINMAX=LINDEX+5
      L=LINDEX-1
      READ          103,(T(1,LIND,1),LIND=LINDEX,LINMAX),
1 ILCARD,NUCARD,MTCARD
C   CHECK CARDS FOR PROPER INDICES AND ORDER.
      IF(1-NUCARD) 53,54,53
54  IF(L-LCARD)53,56,53
56  IF(MT-MTCARD) 53,52,53
52  CONTINUE
      IF (12PAR-2) 202,203,203
203 CONTINUE
      RETURN
C   NOW READ IN FOR THE REST OF THE CHANNELS, AND CHECK ORDER.
202 GO TO(200,201,201,201), NPROBL
201 NU1=NUOUT
      NU2=NUOUT
      GO TO 57
200 NL1=2
      NU2=5
57  DO 2  NU=NU1,NU2
      GO TO(70,70,80,80),NPROBL
70  JEMAX=JEM(NU)
      GO TO 90
80  JEMAX=1
90  CONTINUE
      DO 2  JE=1,JEMAX
      DO 2  LINDEX=1,13,6
      LINMAX=LINDEX+5
      L=LINDEX-1
      READ          103,(T(NU,LIND,JE),LIND=LINDEX,
1 LINMAX),LCARD,NUCARD,MTCARD
      IF(NU-NUCARD) 3,4,3
4  IF(L-LCARD)3,6,3
6  IF(MT-MTCARD) 3,2,3
2  CONTINUE
      RETURN
53  NU=1
      JE=1
3  PRINT 104,NU,JE,L,MT
103 FORMAT(6F12.6,12,2X,2I2)
104 FORMAT(23H0THE TSUBL-CARD FOR NU=I2,5H, JE=I2,7H, L   =I2,9H, AND
1 MT=I2,35H IS OUT OF PLACE IN THE INPUT DECK.)
      CALL EXIT
      END
      SUBROUTINE DENOMR
      COMMON/NA,B,C,D,IC,IP,DN ,GAMA,CGAMA,CLD,SIGMA,TL,JEM,MT,NPROBL,
1 NUOUT,N,ESTARM,SPIN,FO
      DIMENSIONA(5),B(5),C(5),D(5),DN(18,5) ,GAMA(18),TL(5,18,40),JEM(5)
1,ESTARM(5),SPIN(5),SUM(5,40),DENOM(18)
10  DO 500J=1,18
      DENOM(J)=0.
      RJ=J-1
      IF(N=6)20,20,15
15  RJ=RJ+0.5
20  DO 501 NU=2,5
      DO 25 NZERO=1,40
25  SUM(NU,NZERO)=0.
C   IF N=5(J-INT) J=J-1   IF N=9(J-1/2INT) J=J-.5

```

```

      JEMAX=JEM(NU)
30 DO 301 JE=1,JEMAX
   E=JE-1
C    U=E/2
      DENT=DEN(E,NU)
40 DO 302 L=1,18
      RL=L-1
      TLFAC=TL(NU,L,JE)
      IF(TLFAC-1.0E-10)301,41,41
41 DENS=DENT*TLFAC
42 NSMIN=ABS(RJ-RL)+1.
      NSMAX=J+L-1
      IF(NSMIN-15)43,43,302
43 IF(NSMAX-15)46,46,44
44 NSMAX=15
46 DO 303 NS=NSMIN,NSMAX
      S=NS-1
C    IF N=5  S=S, IF N=9  S=S+.5          SMAX=14
      IF(N-6)60,60,50
50 S=S+.5
60 IMIN=ABS(S-SPIN(NU))+1.
      IMAX=S+SPIN(NU)+1.
      DO 303 I=IMIN,IMAX
      RI=I-1
      IF(N-6)70,70,72
70 GO TO (80,80,85,85,80),NU
72 GO TO (80,85,80,80,85),NU
85 RI=RI+.5
80 SUM(NU,JE)=SUM(NU,JE)+DENS*S IG(RI,FO,E,NU)
303 CONTINUE
302 CCNTINJE
301 CONTINUE
      DN(J,NU)=0.
      TES=JEM(NU)
      TEST=ESTARM(NU)*2.-TES
      NEST=TEST
      IF(NEST)410,400,410
400 NT2=JEM(NU)/2
      NT2=NT2*2
      IF(JEM(NU)-NT2)401,401,402
401 DN(J,NU)=(SUM(NU,JEMAX)+SUM(NU,JEMAX-1))/2.
402 DN(J,NU)=DN(J,NU)+SUM(NU,JEMAX)*(ESTARM(NU)*2.-JEM(NU)+1)/2.
      JEMS=(JEM(NU)+1)/2
      JEMS=JEMS*2-3
      GO TO 420
410 JEMS=JEM(NU)/2
      JEMS=JEMS*2-1
420 DO 430 JE=1,JEMS,2
430 DN(J,NU)=DN(J,NU)+((SUM(NU,JE)+4.0*SUM(NU,JE+1)+SUM(NU,JE+2))/3.
      DN(J,NU)=DN(J,NU)*.5
501 DENOM(J)=DENOM(J)+DN(J,NU)
500 DENOM(J)=SQRT(DENOM(J))
      RETURN
      END
      FUNCTION DEN(E,NU)
      DIMENSION A(5),B(5),C(5),D(5)
      COMMON A,B,C,D,IC
      U=E/2.
1 GO TO (5,9),IC

```

```

5 CHEK=A(NU)*C(NU)*(U-B(NU))*D(NU)
  IF(CHEK)6,6,7
6 DEN=0.
  RETURN
7 T=(1.+SQRT(1.+4.*(U-B(NU))*A(NU)))/(2.*A(NU))
  DEN=A(NU)**.5*EXP(2.*SQRT(A(NU)*(U-B(NU))))/((U-T-B(NU))**2
  1*C(NU))
  RETURN
9 IF(A(NU))6,6,10
10 DEN=C(NU)*EXP((U-B(NU))/A(NU))
  RETURN
  END
  FUNCTION SIG(FI,FO,E,NU)
  DIMENSION A(5),B(5),C(5),D(5)
  COMMON A,B,C,D,IC,IP
  U=E/2.
2 GO TO (1,19,19,19),IP
1 IF(A(NU)*D(NU)*(U-B(NU)))5,5,15
5 SIG=0.
  RETURN
15 T=(1.+SQRT(1.+4.*(U-B(NU))*A(NU)))/(2.*A(NU))
  SIG=(2.*FI+1.)*EXP((FI+.5)**2/(-2.*D(NU)*T))/(D(NU)**1.5)
  RETURN
19 IF(D(NU))5,5,20
20 SIG=(2.*FI+1.)*EXP(-FI*(FI+1.)/(2.*D(NU)))/(2*D(NU))
  RETURN
  END

```


.0058	.0016	.0004	.0001	.	.	6	264
.	.	.	.	.	.	12	264
.1548	.1259	.0860	.0454	.0200	.0069	0	264
.0021	.0006	.0002	.	.	.	6	264
.	.	.	.	.	.	12	264
.0631	.0503	.0325	.0164	.0069	.0023	0	264
.0007	.0002	.0001	.	.	.	6	264
.	.	.	.	.	.	12	264
.0210	.0166	.0103	.0051	.0020	.0007	0	264
.0002	.0001	.	.	.	.	6	264
.	.	.	.	.	.	12	264
.0057	.0045	.0027	.0013	.0005	.0002	0	264
.0001	.	.	.	.	.	6	264
.	.	.	.	.	.	12	264
.0012	.0010	.0006	.0003	.0001	.	0	264
.	.	.	.	.	.	6	264
.	.	.	.	.	.	12	264
.0002	.0002	.0001	.	.	.	0	264
.	.	.	.	.	.	6	264
.	.	.	.	.	.	12	264
.9078	.7623	.8075	.7805	.2876	.1210	0	364
.0108	.0010	.0001	.	.	.	6	364
.	.	.	.	.	.	12	364
.9102	.7496	.8002	.7308	.2528	.0930	0	364
.0079	.0007	.0001	.	.	.	6	364
.	.	.	.	.	.	12	364
.9125	.7342	.7912	.6723	.2182	.0697	0	364
.0056	.0005	.0001	.	.	.	6	364
.	.	.	.	.	.	12	364
.9142	.7163	.7794	.6062	.1845	.0511	0	364
.0004	.0003	.	.	.	.	6	364
.	.	.	.	.	.	12	364
.9155	.6949	.7646	.5328	.1524	.0366	0	364
.0027	.0002	.	.	.	.	6	364
.	.	.	.	.	.	12	364
.9158	.6698	.7452	.4549	.1225	.0255	0	364
.0018	.0001	.	.	.	.	6	364
.	.	.	.	.	.	12	364
.9151	.6398	.7206	.3751	.0958	.0172	0	364
.0012	.0001	.	.	.	.	6	364
.	.	.	.	.	.	12	364
.9122	.6043	.6885	.2979	.0724	.0113	0	364
.0007	.0001	.	.	.	.	6	364
.	.	.	.	.	.	12	364
.9067	.5618	.6477	.2266	.0527	.0072	0	364
.0005	.	.	.	.	.	6	364
.	.	.	.	.	.	12	364
.8968	.5121	.5957	.1647	.0367	.0043	0	364
.0003	.	.	.	.	.	6	364
.	.	.	.	.	.	12	364
.8808	.4542	.5312	.1137	.0244	.0025	0	364
.0001	.	.	.	.	.	6	364
.	.	.	.	.	.	12	364
.8546	.3888	.4528	.0742	.0154	.0014	0	364
.0001	.	.	.	.	.	6	364
.	.	.	.	.	.	12	364
.8132	.3170	.3631	.0455	.0091	.0007	0	364
.	.	.	.	.	.	6	364
.	.	.	.	.	.	12	364

.6917	.3228	.3594	.0180	.0017	.	12	464
.	.	.	.	.	.	0	464
.	.	.	.	.	.	6	464
.6739	.2375	.2399	.0044	.0004	.	12	464
.	.	.	.	.	.	0	464
.	.	.	.	.	.	6	464
.6114	.1216	.0814	.0004	.	.	12	464
.	.	.	.	.	.	0	464
.	.	.	.	.	.	6	464
.0538	.0316	.0127	.0029	.0004	.	12	464
.	.	.	.	.	.	0	564
.	.	.	.	.	.	6	564
.0089	.0049	.0018	.0037	.0001	.	12	564
.	.	.	.	.	.	0	564
.	.	.	.	.	.	6	564
.0006	.0003	.0001	.	.	.	12	564
.	.	.	.	.	.	0	564
.	.	.	.	.	.	6	564
.	.	.	.	.	.	12	564

IV. SAMPLE OUTPUT

-24-

1 GAMA J CALC. 642M C.N. 80N1+HE4 16.595 MEV F.G. RIG MOM OF CV(24.27)

GAMA J

TARGET SPIN = 0.01+1 TARGET MASS = 59.93079 NU = 1
 PROJ. SPIN = 0.01+1 PROJ. MASS = 4.00260 JEL = 0
 TAPE12-COEFF = 5 PROJ. EN. (1) = 16.59499 LEH = 0
 IC = 1 IP = 1 JEL = 0

	I=1	I=2	I=3	I=4	I=5
JEM(I)=	0	22	21	15	3
ESTAR(I)=	0.0	0.15560E 02	0.11810E 02	0.76600E 01	0.31900E 01
A(I)=	0.69000E 01	0.58000E 01	0.68000E 01	0.70000E 01	0.70000E 01
B(I)=	0.90000E 00	0.50000E 00	-0.50000E 00	-0.15000E 01	-0.15000E 01
C(I)=	0.33940E 02	0.33940E 02	0.33940E 02	0.33940E 02	0.33940E 02
D(I)=	0.14030E 02	0.12600E 02	0.13670E 02	0.13670E 02	0.13310E 02

SPIN CUT-OFF (COMP. MXCL.) = 24.27
 EXCITATION ENERGY = 0.199E 02

LEVEL DENSITY IUC, J=01 = 0.302E 05

GAMA TOTAL = 0.43159E-02 MEV
 GAMA FOR ALPHA EMISSION = 0.42882E-03 MEV
 GAMA FOR PROTON EMISSION = 0.14762E-02 MEV
 GAMA FOR NEUTRON EMISSION = 0.24109E-02 MEV
 GAMA FOR DEUTERON EMISSION = 0.74589E-07 MEV

GAMA(J)

SIGMA/SIGMATOT C. N. FORMATION
 CROSS-SECTION
 (MILLIBARNS)

J	HE4-EMISSION	P-EMISSION	N-EMISSION	O-EMISSION	TOTAL
0.0	0.60910E-03	0.26030E-02	0.42236E-02	0.27246E-06	0.74359E-02
1.0	0.60147E-03	0.25499E-02	0.41401E-02	0.25749E-06	0.72917E-02
2.0	0.58663E-03	0.24472E-02	0.39782E-02	0.23006E-06	0.70122E-02
3.0	0.56533E-03	0.23013E-02	0.37472E-02	0.19447E-06	0.66140E-02
4.0	0.52859E-03	0.21211E-02	0.34402E-02	0.15565E-06	0.61199E-02
5.0	0.50735E-03	0.19167E-02	0.31324E-02	0.11808E-06	0.55566E-02
6.0	0.47279E-03	0.16988E-02	0.27802E-02	0.85005E-07	0.49518E-02
7.0	0.43584E-03	0.14773E-02	0.24195E-02	0.58108E-07	0.43326E-02
8.0	0.39738E-03	0.12610E-02	0.20648E-02	0.37734E-07	0.37232E-02
9.0	0.35819E-03	0.10571E-02	0.17281E-02	0.23272E-07	0.31434E-02
10.0	0.31900E-03	0.87070E-03	0.14186E-02	0.13620E-07	0.26083E-02
11.0	0.28049E-03	0.70492E-03	0.11424E-02	0.75538E-08	0.21278E-02
12.0	0.24325E-03	0.56100E-03	0.90217E-03	0.39613E-08	0.17064E-02
13.0	0.20766E-03	0.43503E-03	0.69202E-03	0.19592E-08	0.13347E-02
14.0	0.17349E-03	0.32150E-03	0.50357E-03	0.90890E-09	0.99877E-03
15.0	0.14030E-03	0.16323E-03	0.27895E-03	0.38510E-09	0.58247E-03
16.0	0.11031E-03	0.79925E-04	0.13442E-03	0.14699E-09	0.32466E-03
17.0	0.83791E-04	0.17171E-04	0.26303E-04	0.45829E-10	0.12727E-03

0.10631E-01	0.11217E 02
0.31919E-01	0.33678E 02
0.53113E-01	0.56040E 02
0.74276E-01	0.78369E 02
0.95334E-01	0.10059E 03
0.11526E 00	0.12162E 03
0.13518E 00	0.14263E 03
0.14672E 00	0.15481E 03
0.14792E 00	0.15607E 03
0.11111E 00	0.11724E 03
0.52930E-01	0.55847E 02
0.17926E-01	0.18914E 02
0.50378E-02	0.53154E 01
0.16697E-02	0.17617E 01
0.58748E-03	0.61985E 00
0.23137E-03	0.24412E 00
0.10555E-03	0.11137E 00
0.37317E-04	0.39374E-01

TOTAL = 0.10551E 04

J	HE4-EMISSION	P-EMISSION	N-EMISSION	O-EMISSION	TOTAL
0.0	0.11557E 03	0.49389E 03	0.80138E 03	0.51696E-01	0.14109E 04
1.0	0.32855E 03	0.13929E 04	0.22615E 04	0.14065E 00	0.39830E 04
2.0	0.49182E 03	0.20517E 04	0.33352E 04	0.19288E 00	0.58789E 04
3.0	0.58640E 03	0.23870E 04	0.38868E 04	0.20171E 00	0.68604E 04
4.0	0.60909E 03	0.23989E 04	0.39134E 04	0.17603E 00	0.69215E 04
5.0	0.57074E 03	0.21562E 04	0.35238E 04	0.13284E 00	0.62508E 04
6.0	0.49089E 03	0.17638E 04	0.28866E 04	0.88259E-01	0.51414E 04
7.0	0.39132E 03	0.13264E 04	0.21723E 04	0.52173E-01	0.38901E 04
8.0	0.29081E 03	0.92285E 03	0.15111E 04	0.27615E-01	0.27247E 04
9.0	0.20220E 03	0.59675E 03	0.97551E 03	0.13137E-01	0.17745E 04
10.0	0.13182E 03	0.35980E 03	0.58621E 03	0.56283E-02	0.10778E 04
11.0	0.80681E 02	0.20277E 03	0.32860E 03	0.21728E-02	0.61206E 03
12.0	0.46386E 02	0.10698E 03	0.17204E 03	0.75540E-03	0.32541E 03
13.0	0.25032E 02	0.52440E 02	0.83418E 02	0.23617E-03	0.16089E 03
14.0	0.12631E 02	0.23380E 02	0.36620E 02	0.66095E-04	0.72630E 02
15.0	0.58783E 01	0.68390E 01	0.11688E 02	0.16135E-04	0.24405E 02
16.0	0.25448E 01	0.18439E 01	0.31011E 01	0.33909E-05	0.74898E 01
17.0	0.10176E 01	0.20855E 00	0.31945E 00	0.55659E-06	0.15456E 01

G(J)

J	HE4-EMISSION	P-EMISSION	N-EMISSION	O-EMISSION	TOTAL
0.0	0.18393E 02	0.78605E 02	0.12754E 03	0.82276E-02	0.22455E 03
1.0	0.18163E 02	0.77001E 02	0.12502E 03	0.77757E-02	0.22019E 03
2.0	0.17715E 02	0.73899E 02	0.12013E 03	0.69474E-02	0.21175E 03
3.0	0.17072E 02	0.69494E 02	0.11316E 03	0.58724E-02	0.19973E 03
4.0	0.16263E 02	0.64052E 02	0.10449E 03	0.47002E-02	0.18481E 03
5.0	0.15321E 02	0.57880E 02	0.94591E 02	0.35659E-02	0.16780E 03
6.0	0.14277E 02	0.51299E 02	0.83955E 02	0.25670E-02	0.14953E 03
7.0	0.13161E 02	0.44610E 02	0.73063E 02	0.17547E-02	0.13084E 03
8.0	0.12000E 02	0.38080E 02	0.62351E 02	0.11395E-02	0.11243E 03
9.0	0.10816E 02	0.31923E 02	0.52184E 02	0.70277E-03	0.94924E 02
10.0	0.98330E 01	0.26293E 02	0.42839E 02	0.41131E-03	0.78766E 02
11.0	0.86700E 01	0.21287E 02	0.34498E 02	0.22811E-03	0.64255E 02
12.0	0.73455E 01	0.16941E 02	0.27243E 02	0.11962E-03	0.51530E 02
13.0	0.62710E 01	0.13137E 02	0.20898E 02	0.59165E-04	0.40306E 02
14.0	0.52450E 01	0.97087E 01	0.15207E 02	0.27447E-04	0.30161E 02
15.0	0.42367E 01	0.49291E 01	0.84236E 01	0.11629E-04	0.17589E 02
16.0	0.33311E 01	0.24136E 01	0.40593E 01	0.44386E-05	0.98040E 01
17.0	0.25303E 01	0.51854E 00	0.79429E 00	0.13839E-05	0.38431E 01