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PROGRAM POD-P ; A COMPUTER CODE TO CALCULATE CROSS SECTIONS FOR NEUTRON-INDUCED PREEQUILIBRIUM NUCLEAR REACTIONS

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Program POD-P ; A Computer Code to Calculate Cross Sections for Neutron-induced Preequilibrium Nuclear Reactions

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The computer code, POD-P, was developed to calculate energy spectra and angular distributions of emitted particles for the neutron-induced preequiliblium nuclear reactions. The energy-differential cross sections are computed with the classical one-component exciton model for the nucleon and composite-particle emissions. Along with this, the semi-empirical exciton models are also used for the composite-particle emissions. The double-differential cross sections are derived from those model calculations plus the angular-distribution systematics. The computational method and explanation of input parameters are given with some output examples.

Keywords: Nuclear Data, Neutron, Computer Code, Cross Section, Energy Spectrum, Angular Distribution, Preequilibrium Reaction, Exciton Model

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プログラム POD-P；中性子により誘起される前平衡核反応の断面積計算コード

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中性子誘起による前平衡核反応で放出される粒子の、エネルギー及び角度分布断面積を計算するためのコードPOD-Pを開発した。エネルギー微分断面積は古典的な一成分型の励起子模型により計算される。複合粒子放出に対しては半経験的な励起子模型も用いる。また二重微分断面積は励起子模型と角度分布経験式を併用して導出される。計算方法及び入力データの説明を行い、入出力例を示した。

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Contents

1 Introduction 1
2 Computational Methods 1
2.1 The One-component Exciton Model 1
2.2 Semi-empirical Formulas for Pickup and Knockout Processes 4
2.3 Systematics of Angular Distributions 5
3 Explanations of Computer Code 7
3.1 Structure of the Code 7
3.2 Subroutines 10
3.3 Functions 13
3.4 Common Arrays 14
4 Explanations of Input Data 16
5 Comments for Numerical Calculation 18
6 Sample Calculations 18
References 33

目　次

1 序文 1
2 計算方法 1
2.1 励起子模型 1
2.2 ピックアップ及びノックアウト効果の半経験的模型 4
2.3 角度分布経験式 5
3 計算コードの説明 7
3.1 プログラムの構造 7
3.2 サブルーチンの説明 10
3.3 ファンクションの説明 13
3.4 コモンブロック 14
4 入力データの説明 16
5 数値計算に関するコメント 18
6 計算例 18
参考文献 33

1 Introduction

A computer code was developed to calculate energy spectra and angular distributions of emitted particles for the neutron-induced preequilibrium nuclear reactions. Energy-differential and angle-differential cross sections are computed for light ejectiles such as neutron(n), proton(p), deuteron(d), triton(t), ^{3}He and ^{4}He(α).

The code was developed basing on the works of Kalbach[1, 2, 3]. The cross sections are calculated with the classical one-component exciton model. For the emissions of composite particles, the semi-empirical exciton model[1] for pickup- and knockout- reactions are also adopted. Double-differential cross sections are derived from those model calculations plus the angular-distributions systematics[3].

In the preequilibrium calculation, total-reaction cross sections are required as input data for incident- and emitted-partciles. The cross sections are computed with the optical model. In order to obtain reasonable values for them, the local- and global- optical model potential (OMP) parameters developed by Koning and Delaroche[4] were built for neutron and proton. The OMP of Lohr and Haeberli was employed for deuteron, that of Becchetti and Greenlees for triton and ^{3}He, and that of Lemos for ^{4}He [5, 6]. Total-reaction cross sections are evaluated with those OMPs within the maximal orbital angular momentum quantum number of 40. Therefore, the code may be applicable to the particle energies up to about 50 MeV.

The units employed in this code for energy, length, and cross section are MeV, fm (femtometer), and mb (milli-barn), respectively. The units for energy-differential and double-differential cross sections are mb/MeV and mb/sr/MeV (sr: steradian), respectively. It should be noted that this code was developed by referring to the subprogram PRECO-B in the GNASH code[7].

In the next section, the computational methods and formulas utilized in the code are presented. The structure and subroutines of the code are explained in Sec.3. The input parameters are specified in Sec.4, and we remark about the notabilias of numerical calculations in Sec.5. The input and output examples are presented in Sec.6.

2 Computational Methods

2.1 The One-component Exciton Model

In the exciton model, it is assumed that the excited system is formed by the interaction between the projectile and the target nucleus, and particles are emitted from the composite nucleus before the system reaches equilibrium state. The composite states are classified by

the numbers of excited particles and holes (p, h). The initial composite state is specified by (p_0, h_0)=(2, 1) for the nucleon-induced reactions.

The p particles and the h holes are formed at the stage $n(= p + h)$ of the exciton state. The state density ω of the n-stage with the excitation energy E is given by

$$\omega(p, h, E) = \frac{g^n (E - A_{p,h})^{n-1}}{p!h!(n-1)!}, \tag{1}$$

$$A_{p,h} = E_{pauli}(p, h) - \frac{p^2 + h^2 + n}{4g}, \tag{2}$$

$$E_{pauli}(p, h) = \frac{\max(p, h)^2}{g}, \tag{3}$$

where g is the single-particle state density parameter. The symbol $A_{p,h}$ means the Pauli blocking factor to restrict the number of allowed states.

The transitions between the exciton states are brought about by the particle-hole pair-creation and -annihilation. The transition rates from the (p, h) state are expressed with following formulas[1],

$$\lambda_+(p, h, E) = \frac{2\pi}{\hbar} M^2 \frac{g^3 [E - E_{pauli}(p+1, h+1)]^2}{2(n+1)}, \tag{4}$$

$$\lambda_-(p, h, E) = \frac{2\pi}{\hbar} M^2 \frac{gph(n-2)}{2} \left[1 - \frac{(n-1)}{(n-2)} \frac{(p-1)(p-2) + (h-1)(h-2)}{8g(E - A_{p,h})} \right], \tag{5}$$

where $\hbar$ stands for the Planck's constant devided by 2π. The value of M^2 is the matrix element for two-body interaction for initial- and final-states, and it is parameterized with the composite mass number A_c, the constant parameter $k(= 100)$, and the variable $e = E/n$ as follows[2].

$$M^2 = \frac{k}{A_c^3 e} \left(\frac{e}{7}\right)^{1/2} \left(\frac{e}{2}\right)^{1/2} \qquad e < 2 \text{ MeV}$$

$$M^2 = \frac{k}{A_c^3 e} \left(\frac{e}{7}\right)^{1/2} \qquad 2 \le e < 7 \text{ MeV}$$

$$M^2 = \frac{k}{A_c^3 e} \qquad 7 \le e < 15 \text{ MeV}$$

$$M^2 = \frac{k}{A_c^3 e} \left(\frac{15}{e}\right)^{1/2} \qquad e \ge 15 \text{ MeV} \tag{6}$$

In the exciton model, particles are emitted from the composite nucleus. The emission rate of the particle b with the emission energy ϵ in the center-of-mass system is given by[1]

$$W_b(p, h, \epsilon) d\epsilon = \frac{(2s_b + 1)}{\pi^2 \hbar^3} \frac{p_b \epsilon \sigma_b(\epsilon) d\epsilon}{\omega_{TOT}} \times \left[Q_b(p) \sum_{j=0}^{2} \omega(p - p_b, h - j, U) + \sum_{j=1}^{2} Q_b(p - j) \omega(p - p_b - j, h, U) \right], \tag{7}$$

where,

$$\omega_{TOT} = \sum_{j=0}^{2} \omega(p, h-j, E) + \sum_{j=1}^{2} \omega(p-j, h, E). \tag{8}$$

The symbols s_b, p_b and σ_b are the spin, mass number and the inverse total-reaction cross section of the emitted particle b, respectively. The variables U and E correspond to the excitation energies of the residual- and composite-nuclei, respectively. The correction factor $Q_b(p)$ is introduced in order to consider the distinguishability of protons and neutrons in the system, and it is given by[1, 8]

$$Q_b(p) = \left(\frac{A}{Z}\right)^{\pi_b} \left(\frac{A}{N}\right)^{\nu_b} \frac{\pi_b!\nu_b!}{p_b!} R_b(p), \tag{9}$$

and,

$$\begin{aligned} R_b(p) &= \left[\frac{p!}{p_b!(p-p_b)!}\right]^{-1} \\ &\times \sum_{i=0}^{p-p_a} \left[\frac{(p-p_a)!}{i!(p-p_a-i)!} \left(\frac{Z}{A}\right)^{i} \left(\frac{N}{A}\right)^{p-p_a-i}\right] \\ &\times \left[\frac{(\pi_a+i)!}{\pi_b!(\pi_a+i-\pi_b)!}\right] \left[\frac{(p-\pi_a-i)!}{\nu_b!(p-\pi_a-i-\nu_b)!}\right], \end{aligned} \tag{10}$$

where Z, N and A are the charge, neutron and mass numbers of the target nucleus, respectively. The symbols $\pi_{a(b)}, \nu_{a(b)}$ and $p_{a(b)}$ denote the proton, neutron and mass numbers of the projectile (ejectile), respectively. From Eq. (7) the total particle emission rate W at the n-stage is obtained by

$$W(n) = \sum_b \int W_b(p, h, \epsilon) d\epsilon. \tag{11}$$

It should be noted that the state density ω in Eq. (7) is calculated with the single-particle state density parameter g of the residual nucleus, while ω in Eq. (8) is calculated with that of the composite nucleus. The values of U and E in Eqs. (7) and (8) are determined by subtracting the pairing energies [9] from the excitation energies of the residual and composite nuclei.

The probability $P(n, t)$ that the excited composite state exists in the n-stage at time t can be obtained by solving the master equation:

$$\frac{dP}{dt}(n,t) = \lambda^+(n-2)P(n-2,t) + \lambda^-(n+2)P(n+2,t) - [\lambda^+(n) + \lambda^-(n) + W(n)]P(n,t), \tag{12}$$

with the initial condition,

$$P(n, 0) = \delta(p, p_0)\delta(h, h_0), \qquad (p_0 = 2, h_0 = 1). \tag{13}$$

The energy-differential cross section in the center-of-mass system is calculated with the following relation,

$$\frac{d\sigma}{d\epsilon}(a,b) = \sigma_a \sum_n W_b(n,\epsilon)\tau(n), \tag{14}$$

where σ_a is the total-reaction cross section for the projectile a, and $\tau(n)$ stands for the mean lifetime of the n-stage,

$$\tau(n) = \int P(n,t)dt. \tag{15}$$

In the closed form approximation, $\tau(n)$ is calculated by using following equation,

$$\tau(n) = \frac{1}{W(n) + \lambda^+(n)}. \tag{16}$$

The time-integrated occupation probability $P(n)$ for the stage ($n \geq p_0 + h_0 = 3$) is given by

$$P(n) = P'(n)\tau(n), \tag{17}$$

$$P'(n) = P'(n-2)[1 - W(n-2)\tau(n-2)], \tag{18}$$

where,

$$P'(p_0 + h_0 - 2) = 1, \qquad W(p_0 + h_0 - 2) = 0. \tag{19}$$

The energy-differential cross section with the closed form approximation is computed as follows,

$$\frac{d\sigma}{d\epsilon}(a,b) = \sigma_a \sum_n W_b(n,\epsilon)P(n). \tag{20}$$

2.2 Semi-empirical Formulas for Pickup and Knockout Processes

In order to calculate preequilibrium cross sections for composite-particle emissions plausibly, the semi-empirical formulas were supplemented to the code. With the formulas, the contribution of particle pickup can be obtained for the $(n, \alpha(=^4\mathrm{He}))$, (n,d), (n,t) and $(n,^3\mathrm{He})$ reactions, and the knockout effect can be calculated for the (n,α) reaction.

The energy-differential cross section of pickup for the (a,b) reaction is expressed by

$$\frac{d\sigma^p}{d\epsilon}(a,b) = (2s_b+1)p_b\epsilon\sigma_b(\epsilon)\omega_F^p(U)(20)^{\delta_\alpha}\left(\frac{E_a}{p_a}\right)^{-2\Delta}\left(\frac{780}{A}\right)^{\Delta} 1.4\times10^{-4}\, f, \tag{21}$$

where,

$$\omega_F^p(U) = \frac{\Delta!}{\Delta_\pi!\Delta_\nu!}\sum_{i=1}^{\Delta}\omega(0,i,U), \tag{22}$$

$$f(N,Z,\Delta_\nu,\Delta_\pi) = (2Z/A)^{6\Delta_\pi}(2N/A)^{(1-\Delta_\pi)\Delta_\nu(\Delta_\nu+1)/2}. \tag{23}$$

In Eq. (21), δ_α is +1 if an α particle is formed, and zero otherwise in the neutron-induced reactions. The quantities E_a and p_a are the laboratory energy and mass number of the projectile, respectively. The symbols Δ_ν, Δ_π, and $\Delta(=\Delta_\nu+\Delta_\pi)$ are the numbers of transferred neutrons, protons, and nucleons from the target nucleus, respectively. In Eq. (22), $\omega(0,i,U)$ is calculated with the single-particle state density of the residual nucleus.

The knockout component is derived from following formula,

$$\frac{d\sigma^k}{d\epsilon}(a,b) = \frac{\sigma_a}{p_a\epsilon_a^3}(2s_b+1)p_b\epsilon\sigma_b(\epsilon)\frac{\omega_F^k(U)}{A^2}F_a \times 0.12, \tag{24}$$

where ϵ_a denotes the center-of-mass collision energy. For the (n,α) reaction, ω_F^k and $F_{a(=n)}$ are obtained with

$$\omega_F^k(U) = g_n g_\alpha \left(U - \frac{1}{2g_n} - \frac{1}{2g_\alpha}\right), \tag{25}$$

$$F_n = 0.075 \times \frac{Z}{2A}. \tag{26}$$

g_n and g_α in Eq. (25) are defined as $g_n = (N/A)g$ and $g_\alpha = g/4$, with the single-particle state density g of the residual nucleus.

2.3 Systematics of Angular Distributions

The angular distributions of emitted particles in the preequilibrium reactions can be calculated by using the systematics of Kalbach[3]. The angular distributions in the center-of-mass system for the (a,b) reaction are obtained by

$$\frac{d^2\sigma(a,b)}{d\Omega d\epsilon_b} = \frac{1}{4\pi}\frac{d\sigma(a,b)}{d\epsilon_b}\frac{2a}{e^\xi - e^{-\xi}}\exp(\xi\cos\theta), \tag{27}$$

where ξ stands for the slope parameter, and it is expressed by,

$$\xi(e'_b, e'_a) = 0.04X_1 + 1.8\times10^{-6}X_1^3 + 6.7\times10^{-7}M_a m_b X_3^4, \tag{28}$$

$$X_1 = (E_1 e'_b/e'_a), \tag{29}$$

$$X_3 = (E_3 e'_b/e'_a), \tag{30}$$

$$E_1 = \min(e'_a, 130), \tag{31}$$

$$E_3 = \min(e'_a, 41), \tag{32}$$

$$e'_{b(a)} = \epsilon_{b(a)} + S_{b(a)}. \tag{33}$$

In Eq. (28), M_a is set equal to 1 for the neutron-induced reaction. The value of m_b is equal to 1/2 for the neutron emission, $m_b = 2$ for the α-particle emission, and $m_b = 1$

otherwise. In Eq.(33), ϵ_a and ϵ_b are the center-of-mass energies of incident and emitted particle, respectively. The values of S_a and S_b correspond to the separation energies for the incident and emitted particles, respectively. They can be calculated as follows,

$$\begin{aligned} S_a &= 15.68(A_C - A_A) - 28.07\left[\frac{(N_C - Z_C)^2}{A_C} - \frac{(N_A - Z_A)^2}{A_A}\right] - 18.56(A_C^{2/3} - A_A^{2/3}) \\ &+ 33.22\left[\frac{(N_C - Z_C)^2}{A_C^{4/3}} - \frac{(N_A - Z_A)^2}{A_A^{4/3}}\right] - 0.717\left[\frac{Z_C^2}{A_C^{1/3}} - \frac{Z_A^2}{A_A^{1/3}}\right] + 1.211\left[\frac{Z_C^2}{A_C} - \frac{Z_A^2}{A_A}\right] \\ &- I_a. \end{aligned} \tag{34}$$

where the subscripts C and A refer to the composite and target nuclei, respectively, The symbols N, Z and A express the neutron, proton and mass numbers. The value of I_a is the energy required to break up the particle a into its constituent nucleons. The quantities S_b and I_b are defined similarly, by replacing a, A with b, B. Where, the subscript B refers to the residual nucleus.

The double-differential cross section is obtained by using Eqs. (27)-(34) along with the evaluated energy-differential cross section. The angle-differential cross section is obtained by integrating the double-differential cross section by energy.

3 Explanations of Computer Code

3.1 Structure of the Code

Figure 1 shows the structure of the code. In the subprogram block L001, physical constants, nuclear masses, and other basic quantities are determined. The input parameters are also read and stored. In the block L101, total-reaction cross sections for the collision of the neutron with the target nucleus are calculated and stored. The cross sections and analyzing powers for the shape-elastic scattering are also calculated, and printed out in L101. These subprograms L001 and L101 were taken from the program POD[10].

The energy spectra and angular distributions in the preequilibrium reactions are calculated in the block L301. Pairing energies are stored in the subroutine PAIRIN and the Q-values of the reactions are calculated in PREQ. The inverse cross sections for emitted particles are computed in PREREA, and obtained cross sections are stored in PRESIG. The computational manners in PREREA are similar to L101. With quantities obtained in above subroutines, the preequilibrium model calculations are performed in the block PRECMP. Energy spectra are calculated with the subroutines PRECOM, PRERAT, PREW and PREEQ. The contributions of the particle pickup and knockout are computed in the subroutine PREDIR. Angular distributions are calculated in PREANG. The final results are printed out in the subroutine PRECRO.

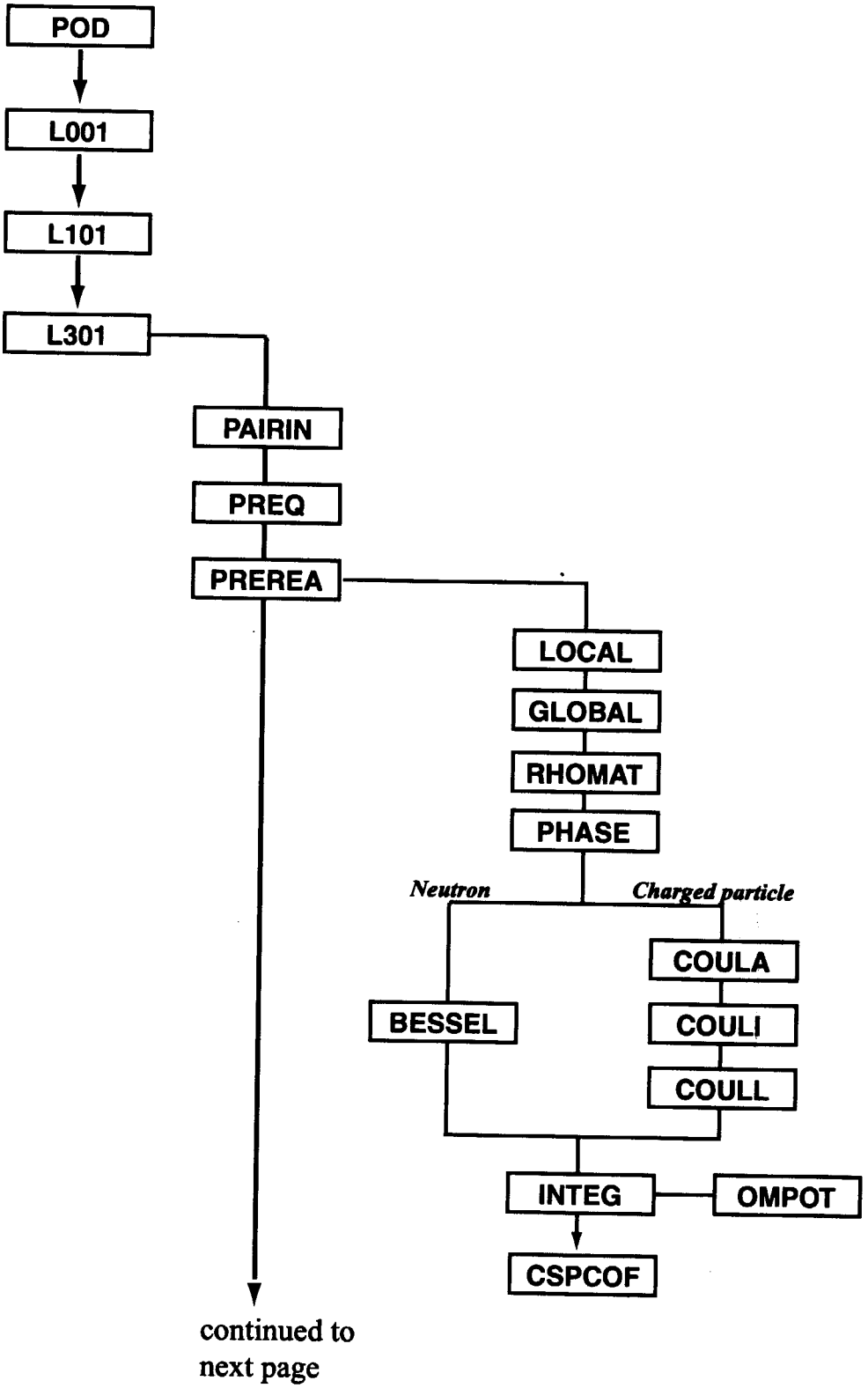

Fig. 1: Flow Chart of Code (1/2)

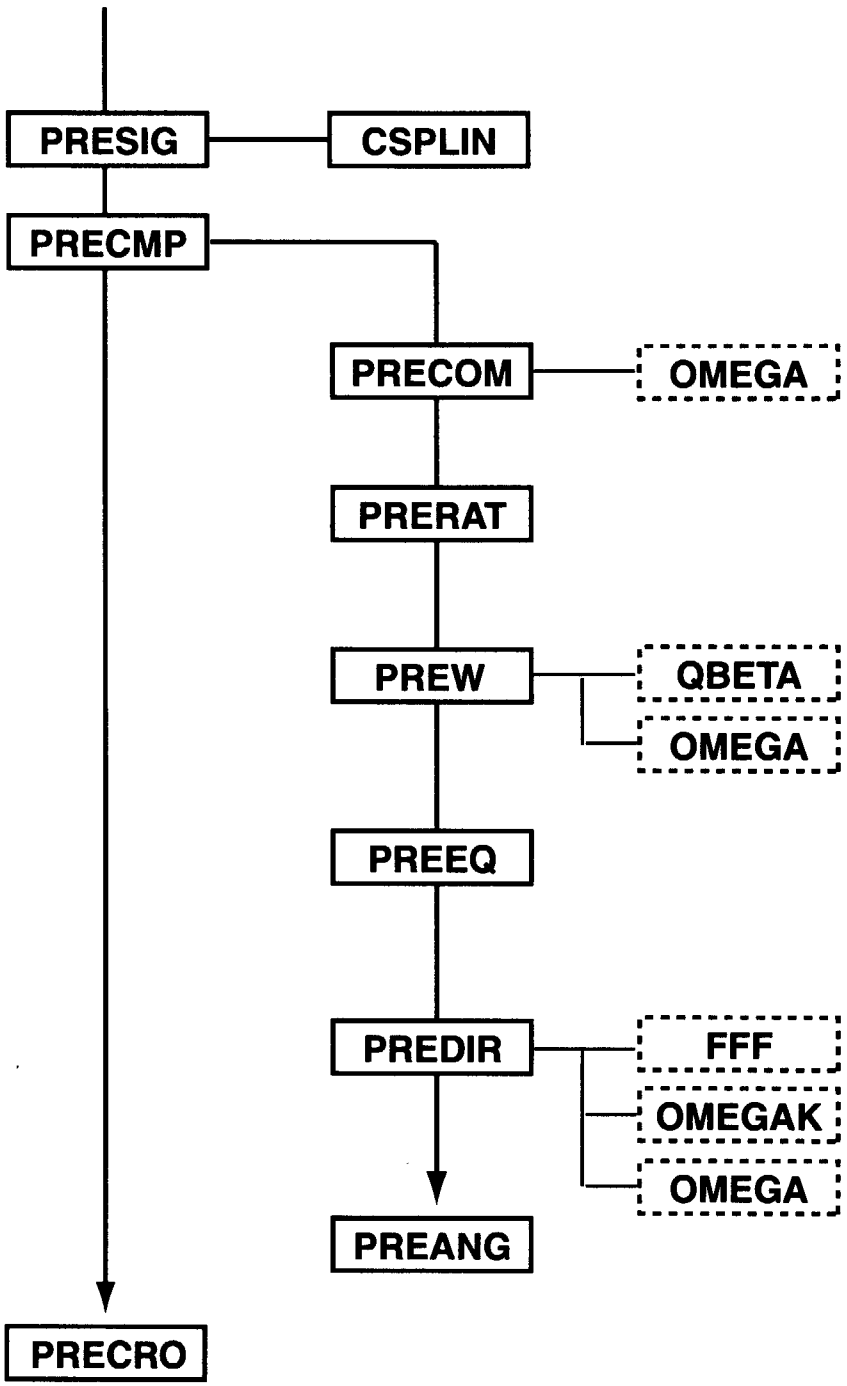

Fig. 1: Flow Chart of Code (2/2)

3.2 Subroutines

L001

CONST Basic constants are defined, and they are stored in COMMON /CNST/,

$$\text{EUNT} = \mu_0 c^2 = 931.494013 \quad \text{MeV}, \tag{35}$$

$$\text{CEK} = \frac{\hbar^2}{2\mu_0} = 20.900794 \quad \text{MeV} \cdot \text{fm}^2, \tag{36}$$

$$\text{COUL} = \frac{2\mu_0 e^2}{\hbar^2} = 0.068895200 \quad \text{fm}^{-1}, \tag{37}$$

$$\text{CSPO} = 2.0 \quad \text{fm}^2, \tag{38}$$

where $\mu_0, c, \hbar$, and e are the atomic mass unit, the speed of light, the Planck's constant divided by 2π, and the elementary charge, respectively.

AUDI This subroutine reads atomic masses from the table of Audi *et al.*[11] (File 13). The atomic mass for charge Z and mass number A are memorized in AMASS(Z*1000+A) of COMMON /MASS/. Nuclear masses are treated as corresponding atomic masses in this code.

FACTRL Factorials (FC) and their square roots (SFC) are calculated, and they are stored in COMMON /FCTL/.

INPUT Input parameters are read from File 5, and they are stored in the COMMON arrays /ENGY/, /OMP0/ and /PR00/. The input parameters are defined in Sec.4.

L101 L101 calls the subroutines which calculate cross sections and analyzing powers for the shape-elastic scattering. Detailed explanations of these subroutines are given in Ref.[10]. The neutron total-reaction cross sections are required for the preequilibrium model calculation. They are computed, and stored here.

ANGLE Angle-differential cross sections and analyzing powers for the shape-elastic scattering are calculated with the scattering phase shifts (CYETA) obtained in the subroutine INTEG. (See Ref.[10])

BESSEL The spherical Neumann and the spherical Bessel functions (G,F) are evaluated at the matching radius (RHOM) where the scattering phase shifts are calculated. Obtained values and their derivatives (GP,FP) are stored in COMMON/WF01/. (See Ref.[10])

COULA The Coulomb wave functions for the angular momentum quantum number $l = 0$ are evaluated at the asymptotic radius (RHOA). (See Ref.[10])

COULI The Coulomb wave functions in the subroutine COULA are extrapolated from the asymptotic radius (RHOA) to the matching radius (RHOM) where the scattering phase shifts are calculated. (See Ref.[10])

COULL The Coulomb wave functions and their derivatives for the angular momentum quantum number $l \geq 1$ are evaluated at the matching radius (RHOM). Obtained values are stored in COMMON /WF01/. (See Ref.[10])

CSPCOF Coefficients of the cubic spline fits[12] are calculated.

GLOBAL The parameters of optical model potential (OMP) are evaluated, and stored in the COMMON arrays /OMP1/ and /OMP2/. The global OMP parameters of Koning and Delaroche[4] are used for neutron and proton if the local OMP parameters are unavailable. The parameters of Lohr and Haeberli are employed for deuteron, that of Becchetti and Greenlees for triton and ^{3}He, and that of Lemos for ^{4}He. These parameters were taken from Ref.[5] and [6] (See Ref.[10]). The user may change this subroutine in order to utilize other OMP parameters.

INTEG The scattering phase shifts (CYETA) are computed, and stored in COMMON /WF03/. With these values, the transmission coefficients(TRS), the total-reaction (inverse) cross section (SIGRI), and the shape-elastic scattering cross section (SIGEL) are calculated. The results are stored in COMMON /WF03/. (See Ref.[10])

LOCAL The local OMP parameters are stored with the tables of Koning and Delaroche [4]. If the local OMP parameters are unavailable, the global OMP parameters are adopted automatically. These parameters are stored in COMMON /OMP1/ and /OMP2/. (See Ref.[10])

OMPOT The OMP values are computed, and stored in COMMON /OMP3/. (See Ref.[10])

PHASE The phase shifts of the Coulomb scattering (DELL) are calculated, and stored in COMMON /WF02/. (See Ref.[10])

RHOMAT The matching radius (RHOM) at which the scattering phase shifts (CYETA) are calculated is determined, and stored in COMMON /WF00/. (See Ref.[10])

L301 L301 calls the subroutines for the calculation of preequilibrium cross sections. The mass number of composite nucleus (ACOMP), the projectile charge number (NZPRJ=0 for neutron), the projectile neutron number (NNPRJ=1 for neutron), and the particle and hole numbers of the initial composite state (NPART=2, NHOLE=1) are stored in COMMON /PR01/.

PAIRIN The pairing energies are stored in COMMON /PAIR/ with the table of Gilbert and Cameron[9].

PREQ The Q-values (QVALP) of the reactions, and the pairing energies (PAIRE) of composite and residual nuclei are stored in COMMON/PR02/.

PREREA, PRESIG The inverse reaction cross sections are calculated with the optical

model, and they are stored in COMMON /PR03/ and /PR04/. The mesh number of the particle emission energy (NDELT) is determined in PRESIG, and stored in COMMON /PR04/.

PRECMP PRECMP calls the subroutines for the preequilibrium model computations.

PRECOM The state densities of composite nucleus, ω (RTOT) in Eq. (1) and ω_{TOT} (OMGT) in Eq. (8) are computed, and they are stored in COMMON /PR05/. The maximum particle number (NPARTX) considered in the system is initially set as

$$\text{NPARTX} = \min(40, \sqrt{2gE}), \tag{39}$$

where g and E stand for the single-particle state density and excitation energy of the composite nucleus, respectively. The stages which satisfy the following condition are treated as the equilibrium states.

$$\omega_{TOT}(p) > \omega_{TOT}(p+1). \tag{40}$$

On the condition, the minimal particle number (MXPART) indicates the end of preequilibrium stages. Obtained values NPARTX and MXPART are stored in COMMON /PR01/ and /PR05/, respectively.

PRERAT The rates of the particle-hole pair creation λ_+ (RATEP) and annihilation λ_- (RATEM) are calculated with Eqs. (4)-(6), and stored in COMMON /PR05/. The time mesh (DTIME) to solve the master equation Eq. (12) is also determined and stored in COMMON /PR05/.

PREW The particle emission rates W_b (W) and the total particle emission rates W (WT) are computed with Eqs. (7)-(11). The results are stored in COMMON/PR06/.

PREEQ The preequilibrium cross sections of the exciton model are obtained by solving the master equation Eq. (12). If the input value JPRECO is set equal to 0, the cross sections are calculated with Eqs. (13)-(15). The time integration is carried out until the probability (P) of Eq. (12) for the particle number MXPART satisfies the following condition,

$$\frac{P(p = \text{MXPART})}{P(p = \text{MXPART}+1)} \leq \frac{\omega(p = \text{MXPART})}{\omega(p = \text{MXPART}+1)}. \tag{41}$$

Obtained energy-differential cross sections (SPECTP) are stored in COMMON /PR07/.

If JPRECO=1, the cross sections are calculated by using the closed form approximation which are expressed in Eqs. (16)-(20). Obtained energy-differential cross sections (CLOSE) are stored in COMMON /PR08/.

PREDIR The cross sections of the pickup (SPECP) and the knockout (SPECK) processes are calculated with Eqs. (21)-(26) for composite-particle emissions. Obtained results are stored in COMMON/PR09/.

PREANG The angle-differential cross sections (SPECTA) for the preequilibrium reaction are computed with Eqs. (27)-(34), and they are stored in COMMON/PR10/.

PRECRO The preequilibrium energy-differential cross sections (SPECTE), which are the sum of the exciton model and the pickup/knockout semi-empirical model calculations, are stored in COMMON/PR10/. The cross sections are printed out in this subroutine.

3.3 Functions

CSPLIN(N,X,F,S,R) The cubic spline fit is carried out with the coefficients S obtained in the subroutine CSPCOF [12]. N is the number of data points, X is the argument array of the function F to be fitted, and R is the argument value on which the function value F(R) is calculated.

FFF(DELN,DELP) The function f of Eq.(23) is evaluated with the numbers of neutrons and protons which are transferred from the target (DELN and DELP).

OMEGA(NP,NH,G,E) The state density ω for (p,h)=(NP,NH) is computed with the excitation energy E and the single-particle state density G. The manner is followed Eqs. (1)-(3).

OMEGAK(IN,IOUT,E) The function ω_F^k of Eq. (25) is evaluated on the excitation energy E. IN is fixed to 1 for the neutron-induced reactions, and IOUT is 3 for the ^{4}He particle emission.

PLM(L,MXX,X) The Legendre function $P_l^m(x)$ is evaluated for l(L), m(MXX) ≥ 0 and $x = \cos\theta$ (X) [13].

QBETA(NP,IP) The correction factor Q_b for p=NP is calculated with Eqs. (9) and (10). The emitted particle is specified with IP as, IP=1:neutron, 2:proton, 3:^{4}He, 4:deuteron, 5:triton, and 6:^{3}He.

3.4 Common Arrays

Labeled common arrays are utilized in the code. They are defined as follows. (Detailed explanations are given in Ref.[10] for the common arrays OMP0 to OMP3, and WF00 to WF03.)

CNST The basic constants are defined in the subroutine CONST.

ENGY Input data for collision energies (ENL) are stored in the subroutine INPUT.

FCTL Factorials and their square roots are stored in the subroutine FACTRL.

MASS Atomic masses are stored in the subroutine AUDI.

OMP0 Basic parameters are stored in the subroutine INPUT.

OMP1 The OMP parameters are stored in the subroutines LOCAL or GLOBAL.

OMP2 The potential depth and raidus parameters are calculated and stored in the subroutine LOCAL or GLOBAL.

OMP3 The OMP values are computed, and they are stored in the subroutine OMPOT.

OMP4 The reaction cross sections (SIGRIN) are stored in the subroutine L101.

PAIR The pairing energies (PZ, PN) of Ref.[9] are stored in the subroutine PAIRIN.

PR00 The input data for the preequilibrium model calculation are stored in the subroutine INPUT. Definitions of these values are given in Sec.4.

PR01 The basic parameters for the preequilibrium model calculation are stored. The mass number of composite nucleus (ACOMP), the charge and neutron numbers of the projectile (NZPRJ, NNPRJ), the initial particle and hole numbers of the composite nucleus (NPART, NHOLE) are stored in the subroutine L301. The maximum particle number considered (NPARTX) is determined in the subroutine PRECOM.

PR02 The Q-values (QVALP) of the reactions and the pairing energies (PAIRE) are stored in the subroutine PREQ.

PR03 The coefficients for the cubic spline functions to interpolate inverse cross sections are calculated, and stored in the subroutine PREREA.

PR04 The mesh number of the particle emission energy (NDELT) is determined in the subroutine PRESIG. The inverse cross sections (SIGR) on the each mesh are obtained with the cubic spline interpolation.

PR05 The state densities of the composite nucleus (RTOT, OMGT) and the minimal particle number to reach the equilibrium state (MXPART) are calculated, and stored in the subroutine PRECOM. The rates of the particle-hole pair-creation and -annihilation (RATEP, RATEM) are calculated in the subroutine PRERAT. The time mesh (DTIME) to solve the master equation is determined in PRERAT.

PR06 The particle emission rates (W) and the total particle emission rates (WT) are calculated in the subroutine PREW.

PR07 The energy-differential cross sections (SPECTP) are obtained by solving the master equation in the subroutine PREEQ.

PR08 The maximum number of the time steps (MTMAX) to solve the master equation is determined in the subroutine PREEQ. The energy-differential cross sections with the closed form approximation (CLOSE) are stored in PREEQ.

PR09 The energy-differential cross sections for the particle-pickup and alpha-knockout processes (SPECP, SPECK) are computed in the subroutine PREDIR.

PR10 The preequilibrium angular-distributions (SPECTA) are calculated in the subroutine PREANG. The final results of energy-differential cross sections (SPECTE) are obtained in the subroutine PRECRO.

WF00 The wave number (WN) is stored in the subroutines L101 and PREREA. The matching radius (RHOM) where the scattering phase shifts are calculated is determined in the subroutines RHOMAT and COULI. The radius (RHOA) where the asymptotic Coulomb functions are evaluated is determined in the subroutine COULA.

WF01 The spherical Neumann and Bessel functions (G, F) and their derivatives (GP, FP) are evaluated in the subroutine BESSEL in order to obtain the neutron reaction cross section. For charged particles, the Coulomb functions and their derivatives (G, F, GP, FP) are evaluated in the subroutines COULA, COULI and COULL. The maximum value of the orbital angular momentum quantum number (LMAX) is determined in the subroutine BESSEL for neutrons, and COULL for charged particles.

WF02 The Coulomb parameter (YETA) and the phase shifts of the Coulomb scattering (DELL) are computed in the subroutine PHASE.

WF03 The scattering phase shifts (CYETA), the transmission coefficients (TRS), the total-reaction (inverse) cross sections (SIGRI) and the shape-elastic scattering cross sections (SIGEL) are calculated in the subroutine INTEG.

4 Explanations of Input Data

This code reads input data from two files (FILE 5 and 13).

FILE 5 Job control options and fundamental parameters.

FILE 13 The mass table of Audi *et al.*[11]. The data were downloaded from following address.

http://csnwww.in2p3.fr/amdc/

FILE 5 are read with following format(the first 8 parameters must be integers).

```
      READ(5,*)IPRJ, ISPIN, ITAG, NTE, NEN, IP1, NR, NTH
      READ(5,1000)(ENL(IE),IE=1,NEN)
 1000 FORMAT(8E10.0)
      READ(5,*)NDWBA,IDWBA
```

IPRJ Set IPRJ=1 to specify the neutron-induced reaction.

ISPIN Twice the projectile spin quantum number (SPIN). Set ISPIN=1.

ITAG ZT × 1000 + AT, where ZT is the target charge, and AT is the target mass number.

NTE 0 : Collision energies are given in the center-of-mass system.
1 : Collision energeis are given in the laboratory system.

NEN Number of collision energies to be calculated. (The maximum is 30)

IP1 Set IP1=0 to use the built-in OMP parameters.

NR Number of the radial mesh for wave functions. (The maximum is 1000)

NTH Number of the angular mesh for angle-differential cross sections. (The maximum is 100)

ENL Collision energies in MeV.

NDWBA Set NDWBA=0 by integer.

IDWBA Set IDWBA=0 by integer.

Subsequently, the parameters for the preequilibrium model calculation are read, where the first two parameters IPRECO and JPRECO must be integers.

```
      READ(5,*)IPRECO, JPRECO
      READ(5,1000)PRECO1, PRECO2, PRECO3, DELPRE
```

READ(5,1000)(GPRE(I-1), I=1,IPRECO+1)

IPRECO 1 : The n emission is considered in the preequilibrium reaction.

2 : The n and p emissions are considered.

3 : The n, p, and ^{4}He emissions are considered.

4 : The n, p, ^{4}He and d emissions are considered.

5 : The n, p, ^{4}He, d and t emissions are considered.

6 : The n, p, ^{4}He, d, t, and ^{3}He emissions are considered.

JPRECO 0 : The master equation is solved numerically.

1 : The closed form approximation is used.

PRECO1 The normalization factor used in the exciton model calculation (divided by 100). Default is 1.0. PRECO1 corresponds to the parameter F2 of the GNASH code[7].

PRECO2 The normalization factor for the pickup spectra of the composite particles. Default value is 0.5.

PRECO3 The normalization factor for the alpha-knockout spectrum. Default value is 1.0.

DELPRE Width of energy bins in MeV for the preequilibrium energy spectra.

GPRE The single-particle state density in MeV^{-1}. GPRE(0) is the state density of the composite nucleus. GPRE(1) is that of the target nucleus. GPRE(2) is the density of the residual nucleus after the proton emission. Similarly, GPRE(3) to GPRE(6) correspond to the densities of the residual nuclei after the ^{4}He, d, t and ^{3}He emissions, respectively. If zero or negative values are inputed, they are set equal to A/13, where A is the mass number of corresponding composite, target or residual nucleus.

5 Comments for Numerical Calculation

It should be pointed out that the calculated cross sections for the preequilibrium are affected by the selection of IPRECO, even though other input parameters are fixed. This is because the total particle emission rate of Eq. (11) depends on how many kind of particle emissions are included in the calculation. The change of the total particle emission rate affects the lifetimes in Eqs. (15) and (16), and that causes the variance of cross sections. Such dependence on IPRECO may appear in the second digit numbers of calculated cross sections.

6 Sample Calculations

Following four calculations were carried out, and the input and output data are given in Figs.2-9. The program was compiled with fortran g77 on the Cygwin (a Linux-like environment for Windows). Note that computed cross sections below about 10^{-10} (mb) might be different from our values explicitly, because accuracies of extremely small values are sensitive to the difference of computational environments.

i)The preequilibrium cross sections for n+^{93}Nb collision at the neutron energy E_{LAB}=25.7 MeV. The cross sections are calculated with the options IPRECO=6 and JPRECO=0. The value of PRECO1 is set equal to 1.75. The input data are given in Fig.2. The calculated energy-differential cross sections for neutron emission are presented in Fig.3 with experimental data[14].

ii)The preequilibrium cross sections for n+^{65}Cu collision at E_{LAB}=15 and 20 MeV. The cross sections are calculated with the options IPRECO=6 and JPRECO=0. The input and output data are given in Figs.4 and 5, respectively.

iii)The preequilibrium cross sections for n+^{209}Bi collision at E_{LAB}=20 MeV. The cross sections are calculated with the options IPRECO=5 and JPRECO=0. The input and output data are given in Figs.6 and 7, respectively.

iv)The preequilibrium cross sections for n+^{209}Bi collision at E_{LAB}=20 MeV. The cross sections are calculated with the options IPRECO=5 and JPRECO=1. The input and output data are given in Figs.8 and 9, respectively.

```
  1    1     41093   1     1    0    153   37
 25.7
  0    0
  6   0
1.75      0.5       1.0       0.5
     0.        0.        0.        0.        0.        0.        0.
---------1---------2---------3---------4---------5---------6---------7
```

Fig.2 Input data to calculate preequilibrium cross sections for n+^{93}Nb collision at E_{LAB} =25.7 MeV with the options IPRECO=6, JPRECO=0, and PRECO1=1.75

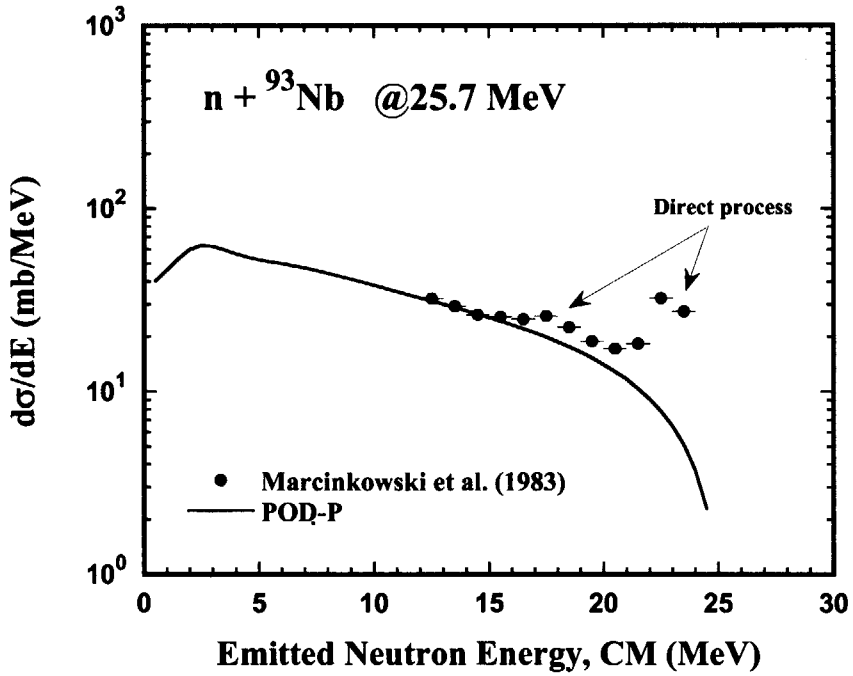

Fig.3 Calculated neutron-emission preequilibrium cross sections for n+^{93}Nb collision at E_{LAB} =25.7 MeV with the options IPRECO=6, JPRECO=0, and PRECO1=1.75 compared with experimental data.

```
   1    1      29065    1      2     0     153    37
  15.0       20.0
   0    0
   6    0
   1.0        0.5        1.0        0.4
6.504819  6.383234  6.261649  6.991161  5.957685  5.714514  7.295124
---------1---------2---------3---------4---------5---------6---------7
```

Fig.4 Input data to calculate preequilibrium cross sections for n+^{65}Cu collision at E_{LAB} =15 and 20 MeV with the options IPRECO=6 and JPRECO=0

```
PROJECTILE CHARGE =   0.00   MASS NUMBER =   1.00   SPIN =   0.50
TARGET     CHARGE =  29.00   MASS NUMBER =  65.00
IP1 =  0 NR =  153
IPRECO =   6      JPRECO =   0
PRECO1 =   1.000  PRECO2 =   0.500  PRECO3 =   1.000
DELPRE =   0.400

 +++ ENTER L101 +++

ELAB =  15.000 MEV     ECM  =  14.771 MEV     WAVE NUMBER =   0.83780
RHOM =   9.813         LMAX =  17       COULOMB PARAMETER =   0.000

  ANGLE DIFFERENTIAL CROSS SECTION FOR ELASTIC SCATTERING
-------------------------------------------------------------
 CM ANGLE    CROSS SECTION                      ANALYZING
  DEG          MB/SR                              POWER
-------------------------------------------------------------
   0.00       3.749E+03                          0.000E+00
   5.00       3.510E+03                          1.314E-02
  10.00       2.871E+03                          2.832E-02
  15.00       2.036E+03                          4.830E-02
  20.00       1.232E+03                          7.757E-02
  25.00       6.204E+02                          1.237E-01
  30.00       2.526E+02                          1.938E-01
  35.00       8.602E+01                          2.318E-01
  40.00       3.690E+01                         -1.016E-01
  45.00       3.078E+01                         -5.824E-01
  50.00       2.716E+01                         -7.895E-01
  55.00       1.735E+01                         -9.420E-01
  60.00       8.302E+00                         -8.661E-01
  65.00       7.298E+00                          8.095E-02
  70.00       1.484E+01                          2.075E-01
  75.00       2.558E+01                         -1.328E-02
  80.00       3.294E+01                         -2.089E-01
  85.00       3.319E+01                         -3.688E-01
  90.00       2.688E+01                         -4.951E-01
  95.00       1.771E+01                         -5.625E-01
 100.00       1.009E+01                         -4.730E-01
 105.00       6.728E+00                         -1.276E-01
 110.00       7.656E+00                          3.937E-02
 115.00       1.074E+01                         -3.789E-02
 120.00       1.329E+01                         -7.276E-02
 125.00       1.360E+01                         -1.661E-02
 130.00       1.166E+01                          9.301E-02
```

135.00	8.778E+00	1.346E-01
140.00	6.514E+00	-1.245E-01
145.00	5.821E+00	-6.111E-01
150.00	6.783E+00	-6.121E-01
155.00	8.918E+00	-4.852E-02
160.00	1.162E+01	5.887E-01
165.00	1.440E+01	9.593E-01
170.00	1.684E+01	9.381E-01
175.00	1.854E+01	5.678E-01
180.00	1.915E+01	0.000E+00

SHAPE ELASTIC CROSS SECTION = 1.4032E+03 MB
REACTION CROSS SECTION = 1.4775E+03 MB

ELAB = 20.000 MEV ECM = 19.694 MEV WAVE NUMBER = 0.96741
RHOM = 11.122 LMAX = 19 COULOMB PARAMETER = 0.000

ANGLE DIFFERENTIAL CROSS SECTION FOR ELASTIC SCATTERING

CM ANGLE DEG	CROSS SECTION MB/SR	ANALYZING POWER
0.00	3.853E+03	0.000E+00
5.00	3.502E+03	2.689E-03
10.00	2.609E+03	8.945E-03
15.00	1.547E+03	2.562E-02
20.00	6.818E+02	7.263E-02
25.00	1.926E+02	2.312E-01
30.00	3.639E+01	6.554E-01
35.00	5.256E+01	-7.585E-02
40.00	9.317E+01	-2.873E-01
45.00	9.309E+01	-3.897E-01
50.00	6.083E+01	-5.309E-01
55.00	3.017E+01	-6.925E-01
60.00	2.079E+01	-4.530E-01
65.00	2.896E+01	-8.411E-02
70.00	3.977E+01	-1.689E-02
75.00	4.229E+01	-5.569E-02
80.00	3.547E+01	-1.414E-01
85.00	2.477E+01	-2.651E-01
90.00	1.590E+01	-3.647E-01
95.00	1.126E+01	-2.410E-01
100.00	1.012E+01	1.342E-01
105.00	1.059E+01	4.077E-01
110.00	1.116E+01	4.119E-01
115.00	1.102E+01	2.134E-01
120.00	9.850E+00	-5.586E-02
125.00	7.781E+00	-2.437E-01
130.00	5.428E+00	-1.581E-01
135.00	3.693E+00	3.883E-01
140.00	3.232E+00	9.272E-01
145.00	3.998E+00	7.055E-01
150.00	5.324E+00	3.325E-01
155.00	6.466E+00	2.611E-01
160.00	7.129E+00	4.933E-01
165.00	7.502E+00	8.200E-01
170.00	7.867E+00	9.124E-01
175.00	8.241E+00	5.962E-01
180.00	8.410E+00	0.000E+00

SHAPE ELASTIC CROSS SECTION = 1.1156E+03 MB
REACTION CROSS SECTION = 1.4228E+03 MB

+++ ENTER L301 +++

PREEQUILIBRIUM ENERGY SPECTRA
ENL = 15.000 NPARTX = 11 MXPART = 7 MTMAX = 8972

ENERGY MEV	NEUTRON	PROTON	ALPHA MB/MEV	DEUTERON	TRITON	HE-3
0.400	1.33E+01	8.97E-09	1.06E-17	2.08E-12	1.10E-14	4.80E-15
0.800	2.30E+01	9.11E-07	3.53E-16	9.81E-10	1.34E-11	3.61E-14
1.200	2.86E+01	6.76E-05	8.82E-15	3.35E-07	1.16E-08	0.00E+00
1.600	3.14E+01	2.14E-03	1.96E-13	3.62E-05	2.59E-06	0.00E+00
2.000	3.28E+01	1.69E-02	4.11E-12	5.84E-04	5.92E-05	0.00E+00
2.400	3.39E+01	7.44E-02	8.28E-11	4.31E-03	5.29E-04	0.00E+00
2.800	3.48E+01	2.18E-01	1.62E-09	1.91E-02	2.60E-03	0.00E+00
3.200	3.55E+01	4.66E-01	3.11E-08	5.70E-02	7.94E-03	0.00E+00
3.600	3.60E+01	7.98E-01	5.28E-07	1.30E-01	1.67E-02	0.00E+00
4.000	3.60E+01	1.17E+00	6.50E-06	2.40E-01	2.49E-02	0.00E+00
4.400	3.55E+01	1.54E+00	5.02E-05	3.79E-01	2.63E-02	0.00E+00
4.800	3.46E+01	1.89E+00	2.66E-04	5.38E-01	2.13E-02	0.00E+00
5.200	3.35E+01	2.19E+00	1.11E-03	7.08E-01	0.00E+00	0.00E+00
5.600	3.22E+01	2.43E+00	3.97E-03	8.84E-01	0.00E+00	0.00E+00
6.000	3.08E+01	2.61E+00	1.22E-02	1.06E+00	0.00E+00	0.00E+00
6.400	2.93E+01	2.74E+00	3.23E-02	1.25E+00	0.00E+00	0.00E+00
6.800	2.79E+01	2.82E+00	7.49E-02	1.44E+00	0.00E+00	0.00E+00
7.200	2.64E+01	2.86E+00	1.54E-01	0.00E+00	0.00E+00	0.00E+00
7.600	2.50E+01	2.86E+00	2.84E-01	0.00E+00	0.00E+00	0.00E+00
8.000	2.36E+01	2.83E+00	4.67E-01	0.00E+00	0.00E+00	0.00E+00
8.400	2.21E+01	2.77E+00	6.87E-01	0.00E+00	0.00E+00	0.00E+00
8.800	2.07E+01	2.66E+00	9.14E-01	0.00E+00	0.00E+00	0.00E+00
9.200	1.93E+01	2.52E+00	1.12E+00	0.00E+00	0.00E+00	0.00E+00
9.600	1.78E+01	2.35E+00	1.27E+00	0.00E+00	0.00E+00	0.00E+00
10.000	1.63E+01	2.14E+00	1.35E+00	0.00E+00	0.00E+00	0.00E+00
10.400	1.48E+01	1.89E+00	1.37E+00	0.00E+00	0.00E+00	0.00E+00
10.800	1.33E+01	1.61E+00	1.33E+00	0.00E+00	0.00E+00	0.00E+00
11.200	1.17E+01	1.30E+00	1.23E+00	0.00E+00	0.00E+00	0.00E+00
11.600	1.01E+01	9.64E-01	1.09E+00	0.00E+00	0.00E+00	0.00E+00
12.000	8.44E+00	5.93E-01	9.29E-01	0.00E+00	0.00E+00	0.00E+00
12.400	6.72E+00	1.89E-01	7.49E-01	0.00E+00	0.00E+00	0.00E+00
12.800	4.93E+00	0.00E+00	5.68E-01	0.00E+00	0.00E+00	0.00E+00
13.200	3.09E+00	0.00E+00	3.99E-01	0.00E+00	0.00E+00	0.00E+00
13.600	0.00E+00	0.00E+00	2.56E-01	0.00E+00	0.00E+00	0.00E+00
14.000	0.00E+00	0.00E+00	1.53E-01	0.00E+00	0.00E+00	0.00E+00
14.400	0.00E+00	0.00E+00	5.93E-02	0.00E+00	0.00E+00	0.00E+00
14.800	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
TOTAL	3.09E+02	1.86E+01	5.80E+00	2.68E+00	4.01E-02	1.64E-14

PREEQUILIBRIUM ANGULAR DISTRIBUTION

ENERGY MEV	NEUTRON	PROTON	ALPHA MB/SR	DEUTERON	TRITON	HE-3
0.000	4.23E+01	2.88E+00	9.63E-01	4.94E-01	7.65E-03	2.92E-15
5.000	4.22E+01	2.87E+00	9.60E-01	4.93E-01	7.62E-03	2.91E-15
10.000	4.19E+01	2.84E+00	9.50E-01	4.87E-01	7.53E-03	2.87E-15
15.000	4.15E+01	2.80E+00	9.35E-01	4.78E-01	7.38E-03	2.82E-15
20.000	4.08E+01	2.75E+00	9.14E-01	4.65E-01	7.18E-03	2.75E-15
25.000	4.00E+01	2.68E+00	8.88E-01	4.50E-01	6.93E-03	2.67E-15
30.000	3.90E+01	2.59E+00	8.58E-01	4.32E-01	6.64E-03	2.57E-15
35.000	3.79E+01	2.50E+00	8.24E-01	4.12E-01	6.33E-03	2.45E-15
40.000	3.67E+01	2.40E+00	7.87E-01	3.91E-01	5.98E-03	2.33E-15
45.000	3.54E+01	2.30E+00	7.49E-01	3.69E-01	5.62E-03	2.21E-15
50.000	3.40E+01	2.19E+00	7.08E-01	3.46E-01	5.25E-03	2.07E-15
55.000	3.26E+01	2.08E+00	6.68E-01	3.22E-01	4.89E-03	1.94E-15
60.000	3.12E+01	1.96E+00	6.27E-01	3.00E-01	4.52E-03	1.81E-15
65.000	2.98E+01	1.85E+00	5.87E-01	2.77E-01	4.17E-03	1.68E-15
70.000	2.84E+01	1.74E+00	5.48E-01	2.56E-01	3.83E-03	1.56E-15
75.000	2.70E+01	1.64E+00	5.10E-01	2.35E-01	3.51E-03	1.44E-15
80.000	2.57E+01	1.53E+00	4.75E-01	2.16E-01	3.21E-03	1.33E-15
85.000	2.44E+01	1.44E+00	4.41E-01	1.98E-01	2.93E-03	1.22E-15
90.000	2.31E+01	1.35E+00	4.10E-01	1.82E-01	2.67E-03	1.12E-15
95.000	2.20E+01	1.26E+00	3.80E-01	1.66E-01	2.44E-03	1.03E-15
100.000	2.09E+01	1.18E+00	3.53E-01	1.53E-01	2.23E-03	9.52E-16
105.000	1.99E+01	1.11E+00	3.29E-01	1.40E-01	2.04E-03	8.78E-16

110.000	1.89E+01	1.04E+00	3.07E-01	1.29E-01	1.87E-03	8.11E-16
115.000	1.80E+01	9.81E-01	2.86E-01	1.19E-01	1.72E-03	7.51E-16
120.000	1.72E+01	9.26E-01	2.68E-01	1.10E-01	1.58E-03	6.98E-16
125.000	1.65E+01	8.76E-01	2.52E-01	1.02E-01	1.46E-03	6.50E-16
130.000	1.59E+01	8.32E-01	2.38E-01	9.56E-02	1.36E-03	6.09E-16
135.000	1.53E+01	7.94E-01	2.25E-01	8.96E-02	1.27E-03	5.73E-16
140.000	1.48E+01	7.60E-01	2.15E-01	8.45E-02	1.20E-03	5.41E-16
145.000	1.43E+01	7.30E-01	2.05E-01	8.02E-02	1.13E-03	5.15E-16
150.000	1.39E+01	7.05E-01	1.97E-01	7.65E-02	1.08E-03	4.92E-16
155.000	1.36E+01	6.85E-01	1.91E-01	7.35E-02	1.03E-03	4.74E-16
160.000	1.34E+01	6.68E-01	1.85E-01	7.11E-02	9.97E-04	4.59E-16
165.000	1.32E+01	6.55E-01	1.81E-01	6.93E-02	9.70E-04	4.47E-16
170.000	1.30E+01	6.46E-01	1.79E-01	6.80E-02	9.51E-04	4.40E-16
175.000	1.29E+01	6.41E-01	1.77E-01	6.72E-02	9.40E-04	4.35E-16
180.000	1.29E+01	6.39E-01	1.76E-01	6.70E-02	9.36E-04	4.33E-16
TOTAL	3.09E+02	1.86E+01	5.80E+00	2.68E+00	4.01E-02	1.64E-14

PREEQUILIBRIUM ENERGY SPECTRA

ENL = 20.000 NPARTX = 13 MXPART = 8 MTMAX = 7674

ENERGY MEV	NEUTRON	PROTON	ALPHA MB/MEV	DEUTERON	TRITON	HE-3
0.400	1.25E+01	9.22E-09	7.47E-18	2.13E-12	8.61E-15	1.43E-14
0.800	2.18E+01	9.52E-07	2.39E-16	9.85E-10	1.08E-11	2.06E-13
1.200	2.75E+01	7.18E-05	5.76E-15	3.29E-07	9.65E-09	2.24E-12
1.600	3.06E+01	2.30E-03	1.24E-13	3.48E-05	2.24E-06	2.16E-11
2.000	3.24E+01	1.85E-02	2.50E-12	5.47E-04	5.44E-05	1.94E-10
2.400	3.37E+01	8.25E-02	4.88E-11	3.93E-03	5.24E-04	1.67E-09
2.800	3.50E+01	2.46E-01	9.29E-10	1.69E-02	2.82E-03	1.38E-08
3.200	3.61E+01	5.31E-01	1.73E-08	4.90E-02	9.78E-03	1.11E-07
3.600	3.69E+01	9.20E-01	2.88E-07	1.08E-01	2.44E-02	7.83E-07
4.000	3.73E+01	1.36E+00	3.48E-06	1.94E-01	4.63E-02	4.12E-06
4.400	3.72E+01	1.82E+00	2.65E-05	2.97E-01	7.22E-02	1.42E-05
4.800	3.66E+01	2.27E+00	1.39E-04	4.08E-01	9.83E-02	3.46E-05
5.200	3.58E+01	2.66E+00	5.80E-04	5.20E-01	1.22E-01	6.61E-05
5.600	3.48E+01	3.01E+00	2.08E-03	6.28E-01	1.41E-01	9.19E-05
6.000	3.36E+01	3.29E+00	6.43E-03	7.32E-01	1.55E-01	1.36E-04
6.400	3.25E+01	3.52E+00	1.73E-02	8.31E-01	1.64E-01	0.00E+00
6.800	3.13E+01	3.69E+00	4.09E-02	9.24E-01	1.67E-01	0.00E+00
7.200	3.02E+01	3.84E+00	8.64E-02	1.01E+00	1.64E-01	0.00E+00
7.600	2.91E+01	3.95E+00	1.64E-01	1.10E+00	1.56E-01	0.00E+00
8.000	2.80E+01	4.03E+00	2.80E-01	1.18E+00	1.43E-01	0.00E+00
8.400	2.69E+01	4.08E+00	4.31E-01	1.26E+00	1.25E-01	0.00E+00
8.800	2.59E+01	4.10E+00	6.05E-01	1.34E+00	1.01E-01	0.00E+00
9.200	2.49E+01	4.09E+00	7.85E-01	1.42E+00	7.25E-02	0.00E+00
9.600	2.39E+01	4.05E+00	9.54E-01	1.50E+00	3.85E-02	0.00E+00
10.000	2.29E+01	3.98E+00	1.10E+00	1.58E+00	3.81E-02	0.00E+00
10.400	2.19E+01	3.89E+00	1.23E+00	1.66E+00	0.00E+00	0.00E+00
10.800	2.09E+01	3.77E+00	1.32E+00	1.75E+00	0.00E+00	0.00E+00
11.200	1.99E+01	3.63E+00	1.39E+00	1.83E+00	0.00E+00	0.00E+00
11.600	1.90E+01	3.48E+00	1.43E+00	1.92E+00	0.00E+00	0.00E+00
12.000	1.80E+01	3.32E+00	1.44E+00	0.00E+00	0.00E+00	0.00E+00
12.400	1.70E+01	3.15E+00	1.43E+00	0.00E+00	0.00E+00	0.00E+00
12.800	1.60E+01	2.96E+00	1.40E+00	0.00E+00	0.00E+00	0.00E+00
13.200	1.51E+01	2.77E+00	1.35E+00	0.00E+00	0.00E+00	0.00E+00
13.600	1.41E+01	2.57E+00	1.28E+00	0.00E+00	0.00E+00	0.00E+00
14.000	1.31E+01	2.35E+00	1.20E+00	0.00E+00	0.00E+00	0.00E+00
14.400	1.21E+01	2.13E+00	1.11E+00	0.00E+00	0.00E+00	0.00E+00
14.800	1.12E+01	1.90E+00	1.01E+00	0.00E+00	0.00E+00	0.00E+00
15.200	1.01E+01	1.65E+00	9.05E-01	0.00E+00	0.00E+00	0.00E+00
15.600	9.11E+00	1.40E+00	7.95E-01	0.00E+00	0.00E+00	0.00E+00
16.000	8.06E+00	1.13E+00	6.84E-01	0.00E+00	0.00E+00	0.00E+00
16.400	6.99E+00	8.47E-01	5.74E-01	0.00E+00	0.00E+00	0.00E+00
16.800	5.88E+00	5.52E-01	4.68E-01	0.00E+00	0.00E+00	0.00E+00
17.200	4.75E+00	2.43E-01	3.67E-01	0.00E+00	0.00E+00	0.00E+00
17.600	3.58E+00	0.00E+00	2.75E-01	0.00E+00	0.00E+00	0.00E+00
18.000	2.37E+00	0.00E+00	1.94E-01	0.00E+00	0.00E+00	0.00E+00
18.400	0.00E+00	0.00E+00	1.26E-01	0.00E+00	0.00E+00	0.00E+00
18.800	0.00E+00	0.00E+00	7.39E-02	0.00E+00	0.00E+00	0.00E+00

19.200	0.00E+00	0.00E+00	3.08E-02	0.00E+00	0.00E+00	0.00E+00
19.600	0.00E+00	0.00E+00	1.74E-02	0.00E+00	0.00E+00	0.00E+00
TOTAL	4.03E+02	3.89E+01	9.83E+00	8.91E+00	7.37E-01	1.39E-04

PREEQUILIBRIUM ANGULAR DISTRIBUTION

ENERGY MEV	NEUTRON	PROTON	ALPHA MB/SR	DEUTERON	TRITON	HE-3
0.000	5.89E+01	6.63E+00	1.85E+00	1.92E+00	1.61E-01	3.14E-05
5.000	5.88E+01	6.61E+00	1.85E+00	1.91E+00	1.60E-01	3.12E-05
10.000	5.83E+01	6.54E+00	1.82E+00	1.88E+00	1.58E-01	3.07E-05
15.000	5.75E+01	6.43E+00	1.79E+00	1.84E+00	1.54E-01	3.00E-05
20.000	5.64E+01	6.28E+00	1.74E+00	1.78E+00	1.49E-01	2.90E-05
25.000	5.51E+01	6.09E+00	1.68E+00	1.71E+00	1.43E-01	2.77E-05
30.000	5.36E+01	5.87E+00	1.61E+00	1.62E+00	1.36E-01	2.63E-05
35.000	5.18E+01	5.63E+00	1.53E+00	1.53E+00	1.28E-01	2.47E-05
40.000	4.99E+01	5.36E+00	1.45E+00	1.43E+00	1.20E-01	2.31E-05
45.000	4.79E+01	5.08E+00	1.36E+00	1.33E+00	1.11E-01	2.13E-05
50.000	4.58E+01	4.80E+00	1.27E+00	1.23E+00	1.02E-01	1.96E-05
55.000	4.37E+01	4.51E+00	1.18E+00	1.13E+00	9.38E-02	1.79E-05
60.000	4.15E+01	4.22E+00	1.10E+00	1.03E+00	8.54E-02	1.63E-05
65.000	3.93E+01	3.94E+00	1.01E+00	9.35E-01	7.75E-02	1.47E-05
70.000	3.72E+01	3.67E+00	9.32E-01	8.46E-01	7.00E-02	1.32E-05
75.000	3.52E+01	3.41E+00	8.56E-01	7.64E-01	6.30E-02	1.18E-05
80.000	3.32E+01	3.16E+00	7.84E-01	6.88E-01	5.66E-02	1.06E-05
85.000	3.13E+01	2.93E+00	7.18E-01	6.18E-01	5.07E-02	9.45E-06
90.000	2.96E+01	2.71E+00	6.57E-01	5.55E-01	4.55E-02	8.43E-06
95.000	2.79E+01	2.52E+00	6.02E-01	4.99E-01	4.08E-02	7.52E-06
100.000	2.63E+01	2.33E+00	5.51E-01	4.49E-01	3.66E-02	6.71E-06
105.000	2.49E+01	2.17E+00	5.06E-01	4.05E-01	3.29E-02	6.00E-06
110.000	2.36E+01	2.02E+00	4.66E-01	3.66E-01	2.96E-02	5.38E-06
115.000	2.24E+01	1.88E+00	4.30E-01	3.31E-01	2.68E-02	4.84E-06
120.000	2.13E+01	1.76E+00	3.98E-01	3.02E-01	2.43E-02	4.37E-06
125.000	2.03E+01	1.66E+00	3.70E-01	2.76E-01	2.22E-02	3.97E-06
130.000	1.94E+01	1.56E+00	3.46E-01	2.54E-01	2.03E-02	3.63E-06
135.000	1.86E+01	1.48E+00	3.24E-01	2.35E-01	1.88E-02	3.33E-06
140.000	1.79E+01	1.41E+00	3.06E-01	2.19E-01	1.75E-02	3.09E-06
145.000	1.73E+01	1.35E+00	2.91E-01	2.05E-01	1.63E-02	2.88E-06
150.000	1.68E+01	1.29E+00	2.78E-01	1.94E-01	1.54E-02	2.71E-06
155.000	1.64E+01	1.25E+00	2.67E-01	1.85E-01	1.47E-02	2.57E-06
160.000	1.61E+01	1.22E+00	2.58E-01	1.77E-01	1.41E-02	2.46E-06
165.000	1.58E+01	1.19E+00	2.52E-01	1.72E-01	1.36E-02	2.37E-06
170.000	1.56E+01	1.17E+00	2.47E-01	1.68E-01	1.33E-02	2.32E-06
175.000	1.55E+01	1.16E+00	2.44E-01	1.66E-01	1.31E-02	2.28E-06
180.000	1.55E+01	1.16E+00	2.44E-01	1.65E-01	1.30E-02	2.27E-06
TOTAL	4.02E+02	3.89E+01	9.82E+00	8.91E+00	7.36E-01	1.39E-04

Fig.5 Preequilibrium cross sections for n+^{65}Cu collision at E_{LAB} =15 and 20 MeV calculated with the options IPRECO=6 and JPRECO=0

```
  1    1     83209   1     1    0    153   37
 20.0
  1    0
  5  .  0
  1.0       0.5       1.0       0.4
12.07197  10.55079  10.84556  10.27912  9.336981  9.875993
---------1---------2---------3---------4---------5---------6
```

Fig.6 Input data to calculate preequilibrium cross sections for n+^{209}Bi collision at E_{LAB} =20 MeV with the options IPRECO=5 and JPRECO=0

```
PROJECTILE CHARGE =   0.00   MASS NUMBER =   1.00   SPIN =   0.50
TARGET     CHARGE =  83.00   MASS NUMBER = 209.00
IP1 =  0 NR =  153
IPRECO =   5      JPRECO =   0
PRECO1 =   1.000  PRECO2 =   0.500  PRECO3 =   1.000
DELPRE =   0.400

 +++ ENTER L101 +++

ELAB =  20.000 MEV     ECM  =  19.904 MEV     WAVE NUMBER =   0.97772
RHOM =  13.485         LMAX =  22       COULOMB PARAMETER =   0.000

  ANGLE DIFFERENTIAL CROSS SECTION FOR ELASTIC SCATTERING
-------------------------------------------------------------
 CM ANGLE   CROSS SECTION                      ANALYZING
  DEG          MB/SR                            POWER
-------------------------------------------------------------
   0.00       2.098E+04                        0.000E+00
   5.00       1.802E+04                       -2.118E-03
  10.00       1.119E+04                       -6.906E-03
  15.00       4.639E+03                       -2.046E-02
  20.00       1.027E+03                       -6.066E-02
  25.00       1.094E+02                        1.420E-01
  30.00       2.596E+02                        3.414E-01
  35.00       3.562E+02                        2.937E-01
  40.00       2.318E+02                        2.625E-01
  45.00       8.785E+01                        7.598E-02
  50.00       2.339E+01                       -4.537E-01
  55.00       1.456E+01                        4.772E-01
  60.00       2.683E+01                        8.008E-01
  65.00       4.123E+01                        2.577E-01
  70.00       4.203E+01                       -2.560E-01
  75.00       2.732E+01                       -6.724E-01
  80.00       1.382E+01                       -6.952E-01
  85.00       1.418E+01                        2.446E-02
  90.00       2.105E+01                        5.102E-02
  95.00       2.175E+01                       -2.197E-01
 100.00       1.610E+01                       -5.844E-01
 105.00       1.125E+01                       -7.331E-01
 110.00       9.206E+00                       -3.051E-01
 115.00       8.321E+00                        1.262E-01
 120.00       9.061E+00                       -7.027E-02
 125.00       1.063E+01                       -4.632E-01
 130.00       9.130E+00                       -6.609E-01
```

135.00	4.791E+00	-6.653E-01
140.00	3.437E+00	-8.574E-02
145.00	6.177E+00	7.115E-02
150.00	6.859E+00	-2.380E-02
155.00	4.102E+00	-3.755E-01
160.00	4.896E+00	-6.620E-01
165.00	1.082E+01	-3.067E-01
170.00	1.273E+01	-8.588E-02
175.00	6.523E+00	1.005E-01
180.00	1.910E+00	0.000E+00

SHAPE ELASTIC CROSS SECTION = 3.3589E+03 MB
REACTION CROSS SECTION = 2.5218E+03 MB

+++ ENTER L301 +++

PREEQUILIBRIUM ENERGY SPECTRA
ENL = 20.000 NPARTX = 17 MXPART = 10 MTMAX = 12478

ENERGY MEV	NEUTRON	PROTON	ALPHA MB/MEV	DEUTERON	TRITON	HE-3
0.400	2.45E+01	9.55E-16	8.15E-27	4.06E-18	2.24E-22	
0.800	4.55E+01	2.39E-14	8.02E-26	1.55E-16	1.44E-20	
1.200	6.83E+01	4.53E-13	5.91E-25	4.44E-15	6.94E-19	
1.600	9.79E+01	7.65E-12	3.86E-24	1.14E-13	2.99E-17	
2.000	1.26E+02	1.22E-10	2.35E-23	2.76E-12	1.22E-15	
2.400	1.43E+02	1.88E-09	1.38E-22	6.45E-11	4.77E-14	
2.800	1.49E+02	2.84E-08	7.81E-22	1.47E-09	1.83E-12	
3.200	1.51E+02	4.17E-07	4.33E-21	3.27E-08	6.83E-11	
3.600	1.52E+02	4.81E-06	2.35E-20	5.33E-07	1.77E-09	
4.000	1.54E+02	3.49E-05	1.26E-19	4.84E-06	2.27E-08	
4.400	1.53E+02	1.87E-04	6.68E-19	3.04E-05	1.90E-07	
4.800	1.51E+02	7.95E-04	3.50E-18	1.43E-04	1.13E-06	
5.200	1.48E+02	2.78E-03	1.81E-17	5.32E-04	5.10E-06	
5.600	1.44E+02	8.24E-03	9.32E-17	1.64E-03	1.86E-05	
6.000	1.40E+02	2.13E-02	4.75E-16	4.33E-03	5.72E-05	
6.400	1.37E+02	4.90E-02	2.41E-15	1.04E-02	1.51E-04	
6.800	1.35E+02	1.02E-01	1.21E-14	2.27E-02	3.58E-04	
7.200	1.34E+02	1.94E-01	6.06E-14	4.57E-02	7.95E-04	
7.600	1.33E+02	3.41E-01	3.02E-13	8.46E-02	1.68E-03	
8.000	1.31E+02	5.57E-01	1.49E-12	1.45E-01	3.29E-03	
8.400	1.30E+02	8.56E-01	7.35E-12	2.30E-01	5.90E-03	
8.800	1.27E+02	1.24E+00	3.61E-11	3.43E-01	9.68E-03	
9.200	1.25E+02	1.72E+00	1.76E-10	4.81E-01	1.48E-02	
9.600	1.22E+02	2.28E+00	8.12E-10	6.41E-01	2.10E-02	
10.000	1.18E+02	2.91E+00	3.24E-09	8.15E-01	2.80E-02	
10.400	1.15E+02	3.60E+00	1.07E-08	9.98E-01	3.51E-02	
10.800	1.11E+02	4.33E+00	3.38E-08	1.18E+00	4.17E-02	
11.200	1.07E+02	5.07E+00	1.23E-07	1.37E+00	4.75E-02	
11.600	1.04E+02	5.79E+00	4.94E-07	1.55E+00	5.22E-02	
12.000	1.00E+02	6.48E+00	1.64E-06	1.73E+00	5.56E-02	
12.400	9.63E+01	7.11E+00	3.70E-06	1.90E+00	5.77E-02	
12.800	9.26E+01	7.65E+00	6.44E-06	2.08E+00	5.84E-02	
13.200	8.88E+01	8.09E+00	1.09E-05	2.24E+00	5.78E-02	
13.600	8.49E+01	8.41E+00	1.94E-05	2.40E+00	5.58E-02	
14.000	8.08E+01	8.62E+00	3.47E-05	2.56E+00	5.24E-02	
14.400	7.65E+01	8.69E+00	6.02E-05	2.72E+00	4.78E-02	
14.800	7.20E+01	8.65E+00	1.01E-04	2.88E+00	4.20E-02	
15.200	6.73E+01	8.48E+00	1.69E-04	3.04E+00	3.48E-02	
15.600	6.25E+01	8.20E+00	2.82E-04	3.21E+00	2.64E-02	
16.000	5.76E+01	7.82E+00	4.70E-04	3.37E+00	1.66E-02	
16.400	5.24E+01	7.33E+00	7.84E-04	3.54E+00	7.44E-03	
16.800	4.72E+01	6.74E+00	1.30E-03	3.72E+00	0.00E+00	
17.200	4.18E+01	6.05E+00	2.11E-03	3.90E+00	0.00E+00	
17.600	3.62E+01	5.25E+00	3.36E-03	0.00E+00	0.00E+00	
18.000	3.05E+01	4.35E+00	5.23E-03	0.00E+00	0.00E+00	
18.400	2.46E+01	3.35E+00	7.97E-03	0.00E+00	0.00E+00	

18.800	1.85E+01	2.23E+00	1.18E-02	0.00E+00	0.00E+00
19.200	1.22E+01	1.01E+00	1.69E-02	0.00E+00	0.00E+00
19.600	5.69E+00	0.00E+00	2.34E-02	0.00E+00	0.00E+00
20.000	0.00E+00	0.00E+00	3.12E-02	0.00E+00	0.00E+00
20.400	0.00E+00	0.00E+00	3.98E-02	0.00E+00	0.00E+00
20.800	0.00E+00	0.00E+00	4.90E-02	0.00E+00	0.00E+00
21.200	0.00E+00	0.00E+00	5.81E-02	0.00E+00	0.00E+00
21.600	0.00E+00	0.00E+00	6.68E-02	0.00E+00	0.00E+00
22.000	0.00E+00	0.00E+00	7.47E-02	0.00E+00	0.00E+00
22.400	0.00E+00	0.00E+00	8.15E-02	0.00E+00	0.00E+00
22.800	0.00E+00	0.00E+00	8.69E-02	0.00E+00	0.00E+00
23.200	0.00E+00	0.00E+00	9.08E-02	0.00E+00	0.00E+00
23.600	0.00E+00	0.00E+00	9.32E-02	0.00E+00	0.00E+00
24.000	0.00E+00	0.00E+00	9.42E-02	0.00E+00	0.00E+00
24.400	0.00E+00	0.00E+00	9.38E-02	0.00E+00	0.00E+00
24.800	0.00E+00	0.00E+00	9.21E-02	0.00E+00	0.00E+00
25.200	0.00E+00	0.00E+00	8.92E-02	0.00E+00	0.00E+00
25.600	0.00E+00	0.00E+00	8.50E-02	0.00E+00	0.00E+00
26.000	0.00E+00	0.00E+00	7.98E-02	0.00E+00	0.00E+00
26.400	0.00E+00	0.00E+00	7.35E-02	0.00E+00	0.00E+00
26.800	0.00E+00	0.00E+00	6.63E-02	0.00E+00	0.00E+00
27.200	0.00E+00	0.00E+00	5.82E-02	0.00E+00	0.00E+00
27.600	0.00E+00	0.00E+00	4.94E-02	0.00E+00	0.00E+00
28.000	0.00E+00	0.00E+00	3.98E-02	0.00E+00	0.00E+00
28.400	0.00E+00	0.00E+00	2.97E-02	0.00E+00	0.00E+00
28.800	0.00E+00	0.00E+00	1.91E-02	0.00E+00	0.00E+00
29.200	0.00E+00	0.00E+00	8.09E-03	0.00E+00	0.00E+00
29.600	0.00E+00	0.00E+00	2.57E-04	0.00E+00	0.00E+00
TOTAL	1.89E+03	6.14E+01	6.50E-01	1.89E+01	3.10E-01

PREEQUILIBRIUM ANGULAR DISTRIBUTION

ENERGY MEV	NEUTRON	PROTON	ALPHA MB/SR	DEUTERON	TRITON	HE-3
0.000	2.63E+02	1.10E+01	1.28E-01	4.08E+00	6.15E-02	
5.000	2.62E+02	1.10E+01	1.27E-01	4.06E+00	6.12E-02	
10.000	2.60E+02	1.08E+01	1.25E-01	4.01E+00	6.04E-02	
15.000	2.57E+02	1.07E+01	1.23E-01	3.91E+00	5.92E-02	
20.000	2.53E+02	1.04E+01	1.19E-01	3.78E+00	5.75E-02	
25.000	2.47E+02	1.01E+01	1.15E-01	3.63E+00	5.53E-02	
30.000	2.41E+02	9.66E+00	1.10E-01	3.45E+00	5.29E-02	
35.000	2.34E+02	9.23E+00	1.04E-01	3.25E+00	5.02E-02	
40.000	2.26E+02	8.77E+00	9.83E-02	3.04E+00	4.73E-02	
45.000	2.18E+02	8.28E+00	9.21E-02	2.83E+00	4.43E-02	
50.000	2.09E+02	7.78E+00	8.57E-02	2.61E+00	4.12E-02	
55.000	2.00E+02	7.28E+00	7.94E-02	2.39E+00	3.82E-02	
60.000	1.91E+02	6.78E+00	7.33E-02	2.18E+00	3.52E-02	
65.000	1.82E+02	6.29E+00	6.73E-02	1.98E+00	3.23E-02	
70.000	1.73E+02	5.83E+00	6.16E-02	1.79E+00	2.95E-02	
75.000	1.65E+02	5.38E+00	5.63E-02	1.62E+00	2.69E-02	
80.000	1.56E+02	4.96E+00	5.13E-02	1.46E+00	2.45E-02	
85.000	1.48E+02	4.57E+00	4.68E-02	1.31E+00	2.23E-02	
90.000	1.41E+02	4.20E+00	4.26E-02	1.17E+00	2.02E-02	
95.000	1.33E+02	3.87E+00	3.88E-02	1.06E+00	1.84E-02	
100.000	1.27E+02	3.57E+00	3.54E-02	9.49E-01	1.67E-02	
105.000	1.20E+02	3.29E+00	3.23E-02	8.56E-01	1.52E-02	
110.000	1.15E+02	3.04E+00	2.96E-02	7.73E-01	1.39E-02	
115.000	1.09E+02	2.82E+00	2.72E-02	7.01E-01	1.27E-02	
120.000	1.05E+02	2.62E+00	2.50E-02	6.38E-01	1.17E-02	
125.000	1.00E+02	2.45E+00	2.32E-02	5.83E-01	1.08E-02	
130.000	9.63E+01	2.30E+00	2.16E-02	5.37E-01	1.00E-02	
135.000	9.28E+01	2.16E+00	2.02E-02	4.96E-01	9.32E-03	
140.000	8.97E+01	2.05E+00	1.90E-02	4.62E-01	8.75E-03	
145.000	8.70E+01	1.95E+00	1.79E-02	4.34E-01	8.25E-03	
150.000	8.48E+01	1.87E+00	1.71E-02	4.10E-01	7.85E-03	
155.000	8.29E+01	1.80E+00	1.64E-02	3.91E-01	7.51E-03	
160.000	8.13E+01	1.74E+00	1.58E-02	3.75E-01	7.24E-03	
165.000	8.01E+01	1.70E+00	1.54E-02	3.64E-01	7.04E-03	
170.000	7.93E+01	1.67E+00	1.51E-02	3.56E-01	6.90E-03	

175.000	7.88E+01	1.65E+00	1.49E-02	3.51E-01	6.81E-03
180.000	7.86E+01	1.65E+00	1.49E-02	3.49E-01	6.78E-03
TOTAL	1.89E+03	6.14E+01	6.49E-01	1.89E+01	3.10E-01

Fig.7 Preequilibrium cross sections for $n+^{209}$Bi collision at E_{LAB} =20 MeV calculated with the options IPRECO=5 and JPRECO=0

```
   1    1     83209   1     1    0    153   37
  20.0
   1    0
   5    1
   1.0       0.5       1.0       0.4
12.07197  10.55079  10.84556  10.27912  9.336981  9.875993
---------1---------2---------3---------4---------5---------6
```

Fig.8 Input data to calculate preequilibrium cross sections for n+^{209}Bi collision at E_{LAB} =20 MeV with the options IPRECO=5 and JPRECO=1

```
PROJECTILE CHARGE =   0.00   MASS NUMBER =   1.00   SPIN =   0.50
TARGET     CHARGE =  83.00   MASS NUMBER = 209.00
IP1 =  0 NR =  153
IPRECO =   5      JPRECO =   1
PRECO1 =   1.000  PRECO2 =   0.500  PRECO3 =   1.000
DELPRE =   0.400

 +++ ENTER L101 +++

ELAB =  20.000 MEV     ECM  =  19.904 MEV     WAVE NUMBER =   0.97772
RHOM =  13.485         LMAX =  22       COULOMB PARAMETER =   0.000

  ANGLE DIFFERENTIAL CROSS SECTION FOR ELASTIC SCATTERING
-------------------------------------------------------------
 CM ANGLE    CROSS SECTION                      ANALYZING
  DEG          MB/SR                              POWER
-------------------------------------------------------------
   0.00       2.098E+04                          0.000E+00
   5.00       1.802E+04                         -2.118E-03
  10.00       1.119E+04                         -6.906E-03
  15.00       4.639E+03                         -2.046E-02
  20.00       1.027E+03                         -6.066E-02
  25.00       1.094E+02                          1.420E-01
  30.00       2.596E+02                          3.414E-01
  35.00       3.562E+02                          2.937E-01
  40.00       2.318E+02                          2.625E-01
  45.00       8.785E+01                          7.598E-02
  50.00       2.339E+01                         -4.537E-01
  55.00       1.456E+01                          4.772E-01
  60.00       2.683E+01                          8.008E-01
  65.00       4.123E+01                          2.577E-01
  70.00       4.203E+01                         -2.560E-01
  75.00       2.732E+01                         -6.724E-01
  80.00       1.382E+01                         -6.952E-01
  85.00       1.418E+01                          2.446E-02
  90.00       2.105E+01                          5.102E-02
  95.00       2.175E+01                         -2.197E-01
 100.00       1.610E+01                         -5.844E-01
 105.00       1.125E+01                         -7.331E-01
 110.00       9.206E+00                         -3.051E-01
 115.00       8.321E+00                          1.262E-01
 120.00       9.061E+00                         -7.027E-02
 125.00       1.063E+01                         -4.632E-01
 130.00       9.130E+00                         -6.609E-01
```

135.00	4.791E+00	-6.653E-01
140.00	3.437E+00	-8.574E-02
145.00	6.177E+00	7.115E-02
150.00	6.859E+00	-2.380E-02
155.00	4.102E+00	-3.755E-01
160.00	4.896E+00	-6.620E-01
165.00	1.082E+01	-3.067E-01
170.00	1.273E+01	-8.588E-02
175.00	6.523E+00	1.005E-01
180.00	1.910E+00	0.000E+00

SHAPE ELASTIC CROSS SECTION = 3.3589E+03 MB
REACTION CROSS SECTION = 2.5218E+03 MB

+++ ENTER L301 +++

PREEQUILIBRIUM ENERGY SPECTRA
ENL = 20.000 NPARTX = 17 MXPART = 10 MTMAX = 12478

ENERGY MEV	NEUTRON	PROTON	ALPHA MB/MEV	DEUTERON	TRITON	HE-3
0.400	2.33E+01	9.02E-16	1.28E-26	3.80E-18	2.12E-22	
0.800	4.34E+01	2.26E-14	1.25E-25	1.45E-16	1.35E-20	
1.200	6.55E+01	4.29E-13	9.17E-25	4.20E-15	6.47E-19	
1.600	9.41E+01	7.27E-12	5.95E-24	1.08E-13	2.78E-17	
2.000	1.22E+02	1.16E-10	3.61E-23	2.63E-12	1.13E-15	
2.400	1.38E+02	1.80E-09	2.09E-22	6.17E-11	4.42E-14	
2.800	1.45E+02	2.73E-08	1.18E-21	1.42E-09	1.70E-12	
3.200	1.47E+02	4.03E-07	6.48E-21	3.16E-08	6.35E-11	
3.600	1.49E+02	4.66E-06	3.50E-20	5.17E-07	1.65E-09	
4.000	1.51E+02	3.39E-05	1.86E-19	4.71E-06	2.13E-08	
4.400	1.51E+02	1.82E-04	9.76E-19	2.97E-05	1.79E-07	
4.800	1.49E+02	7.79E-04	5.06E-18	1.40E-04	1.07E-06	
5.200	1.47E+02	2.73E-03	2.60E-17	5.23E-04	4.87E-06	
5.600	1.43E+02	8.12E-03	1.32E-16	1.61E-03	1.79E-05	
6.000	1.39E+02	2.10E-02	6.68E-16	4.28E-03	5.51E-05	
6.400	1.37E+02	4.85E-02	3.35E-15	1.03E-02	1.46E-04	
6.800	1.35E+02	1.01E-01	1.66E-14	2.26E-02	3.48E-04	
7.200	1.33E+02	1.93E-01	8.23E-14	4.55E-02	7.78E-04	
7.600	1.32E+02	3.39E-01	4.04E-13	8.42E-02	1.65E-03	
8.000	1.31E+02	5.55E-01	1.97E-12	1.44E-01	3.24E-03	
8.400	1.29E+02	8.53E-01	9.58E-12	2.30E-01	5.82E-03	
8.800	1.27E+02	1.24E+00	4.63E-11	3.42E-01	9.58E-03	
9.200	1.25E+02	1.72E+00	2.22E-10	4.81E-01	1.46E-02	
9.600	1.22E+02	2.28E+00	1.01E-09	6.40E-01	2.08E-02	
10.000	1.18E+02	2.91E+00	3.97E-09	8.15E-01	2.78E-02	
10.400	1.15E+02	3.60E+00	1.29E-08	9.98E-01	3.49E-02	
10.800	1.11E+02	4.33E+00	3.99E-08	1.18E+00	4.16E-02	
11.200	1.08E+02	5.07E+00	1.43E-07	1.37E+00	4.73E-02	
11.600	1.04E+02	5.80E+00	5.62E-07	1.55E+00	5.20E-02	
12.000	1.00E+02	6.49E+00	1.84E-06	1.73E+00	5.55E-02	
12.400	9.65E+01	7.12E+00	4.04E-06	1.91E+00	5.76E-02	
12.800	9.28E+01	7.66E+00	6.92E-06	2.08E+00	5.84E-02	
13.200	8.90E+01	8.10E+00	1.15E-05	2.25E+00	5.77E-02	
13.600	8.51E+01	8.43E+00	2.01E-05	2.41E+00	5.57E-02	
14.000	8.10E+01	8.63E+00	3.54E-05	2.57E+00	5.24E-02	
14.400	7.67E+01	8.71E+00	6.05E-05	2.73E+00	4.78E-02	
14.800	7.22E+01	8.67E+00	1.01E-04	2.89E+00	4.19E-02	
15.200	6.75E+01	8.50E+00	1.67E-04	3.05E+00	3.48E-02	
15.600	6.27E+01	8.23E+00	2.77E-04	3.22E+00	2.64E-02	
16.000	5.77E+01	7.84E+00	4.60E-04	3.38E+00	1.66E-02	
16.400	5.26E+01	7.35E+00	7.65E-04	3.55E+00	7.43E-03	
16.800	4.73E+01	6.76E+00	1.27E-03	3.73E+00	0.00E+00	
17.200	4.19E+01	6.07E+00	2.06E-03	3.92E+00	0.00E+00	
17.600	3.63E+01	5.27E+00	3.29E-03	0.00E+00	0.00E+00	
18.000	3.06E+01	4.37E+00	5.14E-03	0.00E+00	0.00E+00	
18.400	2.47E+01	3.36E+00	7.85E-03	0.00E+00	0.00E+00	

18.800	1.86E+01	2.24E+00	1.17E-02	0.00E+00	0.00E+00
19.200	1.23E+01	1.01E+00	1.68E-02	0.00E+00	0.00E+00
19.600	5.71E+00	0.00E+00	2.32E-02	0.00E+00	0.00E+00
20.000	0.00E+00	0.00E+00	3.10E-02	0.00E+00	0.00E+00
20.400	0.00E+00	0.00E+00	3.96E-02	0.00E+00	0.00E+00
20.800	0.00E+00	0.00E+00	4.88E-02	0.00E+00	0.00E+00
21.200	0.00E+00	0.00E+00	5.79E-02	0.00E+00	0.00E+00
21.600	0.00E+00	0.00E+00	6.67E-02	0.00E+00	0.00E+00
22.000	0.00E+00	0.00E+00	7.46E-02	0.00E+00	0.00E+00
22.400	0.00E+00	0.00E+00	8.14E-02	0.00E+00	0.00E+00
22.800	0.00E+00	0.00E+00	8.68E-02	0.00E+00	0.00E+00
23.200	0.00E+00	0.00E+00	9.08E-02	0.00E+00	0.00E+00
23.600	0.00E+00	0.00E+00	9.32E-02	0.00E+00	0.00E+00
24.000	0.00E+00	0.00E+00	9.41E-02	0.00E+00	0.00E+00
24.400	0.00E+00	0.00E+00	9.38E-02	0.00E+00	0.00E+00
24.800	0.00E+00	0.00E+00	9.21E-02	0.00E+00	0.00E+00
25.200	0.00E+00	0.00E+00	8.92E-02	0.00E+00	0.00E+00
25.600	0.00E+00	0.00E+00	8.50E-02	0.00E+00	0.00E+00
26.000	0.00E+00	0.00E+00	7.98E-02	0.00E+00	0.00E+00
26.400	0.00E+00	0.00E+00	7.35E-02	0.00E+00	0.00E+00
26.800	0.00E+00	0.00E+00	6.63E-02	0.00E+00	0.00E+00
27.200	0.00E+00	0.00E+00	5.82E-02	0.00E+00	0.00E+00
27.600	0.00E+00	0.00E+00	4.94E-02	0.00E+00	0.00E+00
28.000	0.00E+00	0.00E+00	3.98E-02	0.00E+00	0.00E+00
28.400	0.00E+00	0.00E+00	2.97E-02	0.00E+00	0.00E+00
28.800	0.00E+00	0.00E+00	1.91E-02	0.00E+00	0.00E+00
29.200	0.00E+00	0.00E+00	8.09E-03	0.00E+00	0.00E+00
29.600	0.00E+00	0.00E+00	2.57E-04	0.00E+00	0.00E+00
TOTAL	1.87E+03	6.15E+01	6.49E-01	1.89E+01	3.09E-01

PREEQUILIBRIUM ANGULAR DISTRIBUTION

ENERGY MEV	NEUTRON	PROTON	ALPHA MB/SR	DEUTERON	TRITON	HE-3
0.000	2.61E+02	1.10E+01	1.27E-01	4.09E+00	6.13E-02	
5.000	2.61E+02	1.10E+01	1.27E-01	4.07E+00	6.11E-02	
10.000	2.59E+02	1.09E+01	1.25E-01	4.02E+00	6.03E-02	
15.000	2.55E+02	1.07E+01	1.23E-01	3.92E+00	5.90E-02	
20.000	2.51E+02	1.04E+01	1.19E-01	3.79E+00	5.73E-02	
25.000	2.46E+02	1.01E+01	1.15E-01	3.64E+00	5.52E-02	
30.000	2.39E+02	9.68E+00	1.10E-01	3.46E+00	5.28E-02	
35.000	2.32E+02	9.25E+00	1.04E-01	3.26E+00	5.01E-02	
40.000	2.25E+02	8.79E+00	9.82E-02	3.05E+00	4.72E-02	
45.000	2.16E+02	8.30E+00	9.19E-02	2.83E+00	4.42E-02	
50.000	2.08E+02	7.80E+00	8.56E-02	2.61E+00	4.11E-02	
55.000	1.99E+02	7.29E+00	7.93E-02	2.40E+00	3.81E-02	
60.000	1.90E+02	6.79E+00	7.32E-02	2.19E+00	3.51E-02	
65.000	1.81E+02	6.31E+00	6.72E-02	1.99E+00	3.22E-02	
70.000	1.72E+02	5.84E+00	6.16E-02	1.80E+00	2.94E-02	
75.000	1.63E+02	5.39E+00	5.62E-02	1.62E+00	2.69E-02	
80.000	1.55E+02	4.97E+00	5.13E-02	1.46E+00	2.44E-02	
85.000	1.47E+02	4.58E+00	4.67E-02	1.31E+00	2.22E-02	
90.000	1.39E+02	4.21E+00	4.25E-02	1.18E+00	2.02E-02	
95.000	1.32E+02	3.88E+00	3.87E-02	1.06E+00	1.83E-02	
100.000	1.25E+02	3.57E+00	3.53E-02	9.51E-01	1.67E-02	
105.000	1.19E+02	3.30E+00	3.22E-02	8.57E-01	1.52E-02	
110.000	1.14E+02	3.05E+00	2.95E-02	7.74E-01	1.39E-02	
115.000	1.08E+02	2.83E+00	2.71E-02	7.02E-01	1.27E-02	
120.000	1.03E+02	2.63E+00	2.50E-02	6.39E-01	1.17E-02	
125.000	9.92E+01	2.45E+00	2.31E-02	5.85E-01	1.08E-02	
130.000	9.53E+01	2.30E+00	2.15E-02	5.38E-01	9.97E-03	
135.000	9.18E+01	2.17E+00	2.01E-02	4.97E-01	9.30E-03	
140.000	8.87E+01	2.05E+00	1.89E-02	4.63E-01	8.72E-03	
145.000	8.61E+01	1.95E+00	1.79E-02	4.35E-01	8.23E-03	
150.000	8.38E+01	1.87E+00	1.71E-02	4.11E-01	7.82E-03	
155.000	8.19E+01	1.80E+00	1.64E-02	3.91E-01	7.49E-03	
160.000	8.04E+01	1.74E+00	1.58E-02	3.76E-01	7.22E-03	
165.000	7.92E+01	1.70E+00	1.54E-02	3.64E-01	7.02E-03	
170.000	7.84E+01	1.67E+00	1.51E-02	3.56E-01	6.88E-03	

175.000	7.79E+01	1.66E+00	1.49E-02	3.51E-01	6.79E-03
180.000	7.77E+01	1.65E+00	1.49E-02	3.50E-01	6.76E-03
TOTAL	1.87E+03	6.15E+01	6.48E-01	1.89E+01	3.09E-01

Fig.9 Preequilibrium cross sections for $n+^{209}$Bi collision at E_{LAB} =20 MeV calculated with the options IPRECO=5 and JPRECO=1

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国際単位系 (SI) と換算表

表 1　SI 基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表 2　SI と併用される単位

名称	記号
分，時，日	min，h，d
度，分，秒	°，′，″
リットル	l，L
トン	t
電子ボルト	eV
原子質量単位	u

$1\ \mathrm{eV} = 1.60218 \times 10^{-19}\ \mathrm{J}$

$1\ \mathrm{u} = 1.66054 \times 10^{-27}\ \mathrm{kg}$

表 5　SI 接頭語

倍数	接頭語	記号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

表 3　固有の名称をもつ SI 組立単位

量	名称	記号	他の SI 単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m \cdot kg/s^2$
圧力，応力	パスカル	Pa	N/m^2
エネルギー，仕事，熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表 4　SI と共に暫定的に維持される単位

名称	記号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

$1\ \text{Å} = 0.1\ \mathrm{nm} = 10^{-10}\ \mathrm{m}$

$1\ \mathrm{b} = 100\ \mathrm{fm}^2 = 10^{-28}\ \mathrm{m}^2$

$1\ \mathrm{bar} = 0.1\ \mathrm{MPa} = 10^5\ \mathrm{Pa}$

$1\ \mathrm{Gal} = 1\ \mathrm{cm/s}^2 = 10^{-2}\ \mathrm{m/s}^2$

$1\ \mathrm{Ci} = 3.7 \times 10^{10}\ \mathrm{Bq}$

$1\ \mathrm{R} = 2.58 \times 10^{-4}\ \mathrm{C/kg}$

$1\ \mathrm{rad} = 1\ \mathrm{cGy} = 10^{-2}\ \mathrm{Gy}$

$1\ \mathrm{rem} = 1\ \mathrm{cSv} = 10^{-2}\ \mathrm{Sv}$

（注）

1. 表 1－5 は「国際単位系」第 5 版，国際度量衡局 1985 年刊行による。ただし，1 eV および 1 u の値は CODATA の 1986 年推奨値によった。
2. 表 4 には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. bar は，JIS では流体の圧力を表わす場合に限り表 2 のカテゴリーに分類されている。
4. EC 閣僚理事会指令では bar，barn および「血圧の単位」mmHg を表 2 のカテゴリーに入れている。

換　算　表

力	N(=10^5dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　1 Pa·s(N·s/m^2)=10 P(ポアズ)(g/(cm·s))

動粘度　1 m^2/s=10^4St(ストークス)(cm^2/s)

圧力	MPa(=10 bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J(=10^7erg)	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal = 4.18605 J (計量法)
= 4.184 J (熱化学)
= 4.1855 J (15 °C)
= 4.1868 J (国際蒸気表)

仕事率　1 PS (仏馬力)
= 75 kgf·m/s
= 735.499 W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

(86 年 12 月 26 日現在)

Program POD-P ; A Computer Code to Calculate Cross Sections for Neutron-induced Preequilibrium Nuclear Reactions

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