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MCRTOF- A MONTE-CARLO PROGRAM FOR MULTIPLE SCATTERING OF NEUTRONS IN RESONANCE ENERGY REGION

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MCRTOF - A Monte-Carlo Program for Multiple Scattering of Neutrons in Resonance Energy Region

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To study the capture and scattering probabilities of neutrons in the resonance energy region, a Monte-Carlo program is coded. Path of a neutron which impinges onto a inclined disk sample is simulated using neutron cross sections calculated from the resonance parameters. Capture, front and rear face scattering, transmission etc.probabilities are obtained from the average destinations of the incident neutrons.

Incident neutron energy is changed step by step in order to reproduce these probabilities over resonances.

In this report are described of the basic multiple scattering loop, coordinate transformations, cross section formulae, motion of the target nucleus, etc.,also with flow chart, input card format, output example, and FORTRAN list in the appendix.
Calculations were made with FACOM-230/75 computer at JAERI.

Keywords: Neutron Resonance, Multiple Scattering, Neutron Capture, Monte-Carlo Program, FORTRAN list, Manual.

MCRTOF－共鳴領域における中性子多重散乱のためのモンテカルロ・プログラム

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共鳴領域中性子の，捕獲，散乱などの確率をしらべるために，モンテカルロプログラムを作成した。傾けた円板に入射する個々の中性子の動きを，共鳴パラメータにより求めた断面積を用いて，完全にシミレートする。多くの入射中性子の平均の命運から，捕獲，前面散乱，後面散乱，横面散乱，透過などの確率を求める。入射中性子のエネルギは共鳴付近で細かく変化させて，上記の各確率の変化をもとめる。②多重散乱基本ループ，座標変換，断面積公式，ターゲット核熱運動を述べ，③フロー・チャート，④入力カードの作り方，またAPPENDIXにFORTRAN LISTを付けた。計算はFACOM－230／75によった。計算出力の例も付けた。

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MCRTOF - A Monte-Carlo Program for Multiple Scattering of Neutrons in Resonance Energy Region

Makio OHKUBO

1. Introduction

In nuclear reactor engineering, the neutron transport or the multiple scattering in the materials are essentially important. Also multiple scattering considerations are inevitably needed for the precise knowledge of capture and scattering probabilities for neutrons impinging onto a material. Many works have been done on the multiple scattering of neutrons in the continuous energy region. However, there are few systematic works on the thick materials having resonances, though some Monte-Carlo programs are available to obtain resonance parameters for the neutron capture and scattering cross section measurements.[1,2,3)]
It is important to study the multiple scattering of neutrons in resonance region, where analytical calculations are too complicated to obtain the reliable results; the Monte-Carlo method is the most suitable.
For this purpose, a Monte-Carlo program MCRTOF was coded to obtain capture and scattering probabilities for neutrons incident on a material disk, with neutron cross section having resonances. With the program, these probabilities were systematically calculated, and the results are compared with the experimental ones with a time-of-flight spectrometer in the JAERI linear accelerator.[4,5,6)]

In this report, details of the Monte-Carlo program are described. The program consists of several blocks;

1) input parameter read-in,
2) cross section file production from given resonance parameters,
3) multiple scattering loop,
4) statistics and print out of the results.

In the program, paths of a neutron which impinges onto a disk inclined with an arbitrary angle to the incident direction are simulated by the Monte-Carlo method, using capture and scattering cross sections which are produced from a given set of resonance parameters. For each incident energy, the probabilities of capture, front and rear face scattering, transmission are obtained by averaging over many incident neutrons. All these probabilities are listed in a format convenient for the comparison with the experimental ones, and these probabilities are illustrated with sheet plots as functions of incident energies. At some energy points, the spacial distributions of neutron capture reactions are also illustrated in a projection on the plane normal to the disk surface.

The methods of calculations are given in § 2, a flow chart in § 3, usage of the program and example outputs in § 4; FORTRAN list in the appendix. Calculations are made with FACOM 230/75 computer at JAERI.

§ 2. Methods of calculations

Following are the assumptions in calculations, basic formulations, and important and essential constituents of the program.

2-1 Geometries

The MCRTOF program treats scattering and capture probabilities of neutrons impinging onto a sample disk of diameter D, thickness T_1, and with reflector layer thickness T_2. The normal of the disk is inclined with an angle α to the incident beam, and the geometry is shown in fig.1. On the disk an orthogonal coordinate system(x,y,z) is defined; the origin at the center of the incident surface, z-axis normal to the surface in a direction forward sample interior, and x-axis is so chosen for the incident neutron passing the origin to be in xz plane.

2-2 Assumptions

In the elementary process of reaction between neutron and nucleus, microscopic cross sections are taken into consideration. The assumptions in Monte-Carlo calculations are as follows.

1) Incident neutrons impinge onto a homogeneous, mono-isotopic material disk inclined with an arbitrary angle to the incident beam at an arbitrary point on the surface. The disk has a reflector layer on rear side. The geometry is shown in fig.1.
2) Neutron cross sections are calculated with the Breit-Wigner single level formula for given resonance parameters(E_0, Γ, Γ_n, g), and mass number, isotopic abundance; the Doppler broadening is considered.
3) Reactions other than elastic scattering and capture are neglected.
4) The angular distribution of scattering is homogeneous in the center of

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3) Reactions other than elastic scattering and capture are neglected.
4) The angular distribution of scattering is homogeneous in the center of

mass system.

5) Chemical binding effect of target nuclei is neglected.

6) Thermal motion of the target nuclei is considered.

2-3 Mean free path

As shown in fig.2 a neutron of energy E_0 impinges onto the disk surface at point Q_0 with an angle α to the normal of the surface, and collides with target nuclei at points Q_1, Q_2,... and captured at Q_i. The mean free path of the neutrons of energy E_0 in the disk is defined as

$$\lambda(E_0) = 1/\Sigma_t(E_0) = 1/(\Sigma_s(E_0) + \Sigma_c(E_0)) \quad \cdots\cdots\cdots (1)$$

where $\Sigma_s(E_0)$, $\Sigma_c(E_0)$ are macroscopic scattering and capture cross sections respectively, which are constructed in the computer core area from the Doppler broadened cross sections based on the Breit-Wigner single level formula. The resonance parameters (E_0, Γ, Γ_n, g), nuclear mass , and isotopic abundance are input. In the energy region of interest, these cross sections are produced as the sum up to five resonances, with energy mesh sufficient for reproduction of the resonances. For a neutron of energy E_0 incident at Q_0 on the surface of the sample, the path length L_1 from Q_0 to the first collision point Q_1 is determined from

$$L_1 = \lambda(E_0) \log_e(1/YR) \quad \cdots\cdots\cdots\cdots\cdots \quad (2)$$

where YR is a uniform random variable of amplitude $0 < YR < 1$ produced sequentially in the program. In the orthogonal coordinate system of fig.1, the coordinates of Q_1 are

$$\left.\begin{aligned} x_1 &= x_0 + L_1 \sin\alpha \\ y_1 &= y_0 \\ z_1 &= L_1 \cos\alpha \end{aligned}\right\} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (3)$$

The region in which Q_1 lies is determined by the boundary conditions. When Q_1 is out of the disk, one count is added in the escape counter, and the program returns to the next neutron impingement.

2-4 Capture reactions

At the point Q_1 either scattering or capture occurs, and the type of reaction is determined from the value of subsequent random variable YR; if the value of YR is less than $\Sigma_s(E_0)/\Sigma_t(E_0)$, the collision is regarded as scattering, and otherwise it is capture. In the case of capture, one count is added in the capture counter, and the program returns to the next neutron impingement.

2-5 Scattering reaction

In the case of elastic collision with a target nucleus of mass A moving at velocity U, the kinetics in both center of mass and laboratory system are discussed below. A coordinate system is taken on which the incident neutron velocity is on x-axis, direction in each stage of multiple scattering, called "microscopic coordinate" system. A neutron moving with velocity $\mathbf{V}$ on x-axis in the laboratory system collides with a nucleus of mass A moving with velocity $\mathbf{U}$ with angle β to the x-axis. The coordinate system is so chosen for the velocity vectors $\mathbf{V}$ and $\mathbf{U}$ to be on xz plane, as shown in fig.3. The vectors $\mathbf{V}$, $\mathbf{U}$ are represented as

$$\mathbf{V} = |V|\begin{pmatrix}1\\0\\0\end{pmatrix} \quad \text{.....(4a)} \qquad \mathbf{U} = |U|\begin{pmatrix}\cos\beta\\0\\-\sin\beta\end{pmatrix} \text{.....} \quad \text{(4b)}$$

The center of mass velocity $\mathbf{V}_0$ is

$$\mathbf{V}_0 = \frac{\mathbf{V}+A\mathbf{U}}{A+1} = \frac{1}{A+1}\begin{pmatrix}V + A\,U\cos\beta\\0\\-AU\sin\beta\end{pmatrix} \quad \text{.........} \quad (5)$$

The neutron velocity in the center of mass system $\mathbf{V}_c$ before collision is

$$\mathbf{V}_c = \mathbf{V} - \mathbf{V}_0 = \frac{A}{A+1}\begin{pmatrix}V - U\cos\beta\\0\\U\sin\beta\end{pmatrix} \text{....................} \quad (6)$$

and

$$|\mathbf{V}_c|^2 = \left(\frac{A}{A+1}\right)^2(V^2 - 2VU\cos\beta + U^2) \quad \text{...........} \quad (7)$$

In elastic collision, the neutron velocity changes to $\mathbf{V}_c'$ and the following relation holds

$$|\mathbf{V}_c'|^2 = |\mathbf{V}_c|^2 \quad \text{......................} \quad (8)$$

where $\mathbf{V}_c'$ is the neutron velocity after collision in the center of mass system. In eq.(7), the thermal motion of a target nucleus makes cos β uniform distribution between -1 and 1, and $|\mathbf{U}|$ Maxwellian distribution.

The neutron velocity after collision, $\mathbf{V}_c'$, is written with scattering angle ϑ and poler angle φ as

$$\mathbf{V}_c' = V_c \begin{pmatrix} \cos\vartheta \\ \sin\vartheta \cos\varphi \\ \sin\vartheta \sin\varphi \end{pmatrix} \qquad \cdots\cdots\cdots\cdots \quad (9)$$

where cos ϑ, due to assumption 4), distribution between -1 and 1, and φ between 0 and 2π uniformly. The neutron velocity after collision in the laboratory system $\mathbf{V}'$ is

$$\mathbf{V}' = \mathbf{V}_c' + \mathbf{V}_0 = \begin{pmatrix} V_c \cos\vartheta + \dfrac{V + AU\cos\beta}{A+1} \\ V_c \sin\vartheta \cos\varphi \\ V_c \sin\vartheta \sin\varphi - \dfrac{AU\sin\beta}{A+1} \end{pmatrix} \qquad \cdots\cdots \quad (10)$$

If the angle γ between $\mathbf{V}$ and $\mathbf{V}_0$ is introduced as shown in fig.3, $\mathbf{V}_0$ is rewritten as

$$\mathbf{V}_0 = V_0 \begin{pmatrix} \cos\gamma \\ 0 \\ -\sin\gamma \end{pmatrix} \qquad \cdots\cdots\cdots\cdots \quad (11)$$

and eq.(10) becomes

$$\mathbf{V}' = \mathbf{V}_c' + \mathbf{V}_0 = \begin{pmatrix} V_c \cos\vartheta + V_0 \cos\gamma \\ V_c \sin\vartheta \cos\varphi \\ V_c \sin\vartheta \sin\varphi - V_0 \sin\gamma \end{pmatrix} \cdots\cdots\cdots \quad (12)$$

The neutron energy after collision in the laboratory system is

$$E_n = \frac{m}{2} |\mathbf{V}'|^2 \qquad \cdots\cdots\cdots\cdots\cdots\cdots \quad (13)$$

where m is the neutron mass, and $|\mathbf{V}'|^2$ is

$$|\mathbf{V}'|^2 = |V_c'|^2 + |V_0|^2 + 2|V_c||V_0| (\cos\vartheta \cos\gamma - \sin\vartheta \sin\gamma \sin\varphi) \cdots\cdots (14)$$

The maximum value of $|V'|^2$ is attained for an angle β under the condition

$$\cos\beta = -\frac{(A-1)}{2} \frac{|U|}{|V|} \qquad \cdots\cdots\cdots\cdots \quad (15)$$

When the condition of eq.(15) is met, $|V'|^2$ is

$$|\mathbf{V}'|^2 = |\mathbf{V}|^2 + A\,|\mathbf{U}|^2 \qquad \cdots\cdots\cdots \qquad (16)$$

and the maximum scattered neutron energy is

$$E_n = \frac{m}{2}\left(V^2 + A\,U^2 \right) \qquad \cdots\cdots\cdots \qquad (17)$$

which means the scattered neutron carries off all the kinetic energy of the system. The equation (14) can be rewritten as

$$V'^2 = V^2 \left\{ \left(1 - \frac{2A}{(1+A)^2}\right) + \left(\frac{2A(A-1)}{(1+A)^2}\cdot\cos\beta\right)\left(\frac{U}{V}\right) + \frac{2A^2}{(1+A)^2}\left(\frac{U}{V}\right)^2 \right\}$$

$$+ \frac{2AV^2}{(1+A)^2}\left(\cos\vartheta \cos\gamma - \sin\vartheta \sin\gamma \sin\varphi \right) * \sqrt{F} \qquad \cdots\cdots\cdots \qquad (18)$$

where F is

$$F = \left(1 - 2\left(\frac{U}{V}\right)\cos\beta + \left(\frac{U}{V}\right)^2 \right)\left(1 + 2A\left(\frac{U}{V}\right)\cos\beta + A^2\left(\frac{U}{V}\right)^2 \right) \qquad \cdots\cdots\cdots (19)$$

For $U/V \rightarrow 0$, $\cos\gamma \rightarrow 1$, and $F \rightarrow 1$ imply, and the eq.(18) takes a simple and familiar form;

$$V'^2 = V^2 \left(1 - \frac{2A}{(1+A)^2}(1 - \cos\vartheta) \right) \qquad \cdots\cdots\cdots \qquad (20)$$

where ϑ is the scattering angle in the center of mass system.

2-6 Transformation of coordinate system

For simple understanding of the multiple scattering, two coordinate systems will be defined; geometrical and microscopic. The geometrical coordinate system is disk-fixed; the origin at the center of the incident surface of the disk, and z-axis normal to the surface in a direction to the sample as shown in fig.1. The microscopic coordinate system is fixed to the velocity vector of a neutron, and in each scattering reaction it rides on a new velocity vector with its x-axis on the new velocity vector. An arbitrary velocity vector $\mathbf{V}_G$ in the geometrical coordinate system is transformed by a matrix T to a vector $\mathbf{V}_M$ in the microscopic coordinate system.

$$\mathbf{V}_G = \begin{pmatrix} a \\ b \\ c \end{pmatrix} \qquad \cdots\cdots\cdots \qquad (21)$$

$$T = \frac{1}{\sqrt{a^2+b^2+c^2}} \begin{pmatrix} a & b & c \\ \frac{-b\sqrt{a^2+b^2+c^2}}{a^2+b^2} & \frac{a\sqrt{a^2+b^2+c^2}}{a^2+b^2} & 0 \\ \frac{-ac}{\sqrt{a^2+b^2}} & \frac{-bc}{\sqrt{a^2+b^2}} & \sqrt{a^2+b^2} \end{pmatrix} \quad \ldots (22)$$

$$\mathbf{V}_M = T\,\mathbf{V}_G = \sqrt{a^2+b^2+c^2} \cdot \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \quad \ldots\ldots\ldots\ldots \quad (23)$$

$\mathbf{V}_M$ in eq.(23) is now an input to the scattering reaction of eq.(4). After scattering, $\mathbf{V}_M'$ in the microscopic coordinate system is transformed by T^{-1} into a vector in the geometrical coordinate system, $\mathbf{V}_G'$. T^{-1} is

$$T^{-1} = T^* = \frac{1}{\sqrt{a^2+b^2+c^2}} \begin{pmatrix} a & \frac{-b\sqrt{a^2+b^2+c^2}}{\sqrt{a^2+b^2}} & \frac{-ac}{\sqrt{a^2+b^2}} \\ b & \frac{a\sqrt{a^2+b^2+c^2}}{\sqrt{a^2+b^2}} & \frac{-bc}{\sqrt{a^2+b^2}} \\ c & 0 & \sqrt{a^2+b^2} \end{pmatrix} \quad \ldots\ldots (24)$$

Obviously T and T^{-1}, T^* are unitary matrix, and $|T| = 1$.
That is, the initial velocity vector in the gepmetrical coordinate system, $\mathbf{V}_G$, is transformed into $\mathbf{V}_M$ in the microscopic coordinate system.

$$\mathbf{V}_M = T\,\mathbf{V}_G \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (25)$$

The $\mathbf{V}_M$ changes to $\mathbf{V}_M'$ by elastic collision, and $\mathbf{V}_M'$ is written by scattering matrix S_1 and S_2, as shown in eq.(10).

$$\mathbf{V}_M' = S_1\,\mathbf{V}_M + S_2\,\mathbf{U} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (26)$$

where S_1, S_2 are not unitary matrix. $\mathbf{V}_M'$ is transformed into $\mathbf{V}_G'$ in the geometrical coordinate system through inverse transformation T^{-1}.

$$\mathbf{V}_G' = T^{-1}\,\mathbf{V}_M' \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (27)$$

That is,

$$\mathbf{V}_G' = T^{-1}(S_1 T \mathbf{V}_G + S_2 \mathbf{U}) \qquad \ldots\ldots\ldots\ldots\ldots\ldots \qquad (28)$$

For the multiple scattering, $\mathbf{V}_G'$ is iteratively inserted as a new velocity vector $\mathbf{V}_G$ with additional changes in energy, cross sections and position. When the thermal motion of a target nucleus is neglected, the equation(28) becomes simple:

$$\mathbf{V}_G' = T^{-1} S_1 T \mathbf{V}_G \qquad \ldots\ldots\ldots\ldots\ldots\ldots \qquad (29)$$

The formulations of eqs.(28) and (29) make the elementary scattering process very clear and aid the computer coding for the multiple scattering process. In the energy region of interest, $\mathbf{U}$ is much smaller than $\mathbf{V}_G$, and hence the detailed information is neglected of U, spectrum of lattice vibration, molecular binding effects, etc.

2-7 Boundary conditions

The region in which there exist reaction points Q_i (i=1,2,3,...) is determined by the boundary conditions in fig.1 With the random variable YR ($0 < YR < 1$) the range for the first collision point, $L_1 = \overline{Q_1 - Q_0}$, is determined as

$$L_1 = \ln(1/YR)/\Sigma_T \quad \text{for } YR < \exp(-T_1\Sigma_T/\cos\alpha) \qquad \ldots\ldots \qquad (30)$$

$$L_1 = (\ln(1/YR) - (\Sigma_T - \Sigma_R)T_1/\cos\alpha)/\Sigma_R \qquad \ldots\ldots\ldots \qquad (31)$$
$$\text{for } YR > \exp(-T_1\Sigma_T/\cos\alpha)$$

The reaction region is determined by the following conditions;

1. $z > T_1 + T_2$; transmission or rear region scattering;
2. $z < 0$; front region scattering,
3. $U > D^2/4$; side region scattering.
4. $T_1 + T_2 > z > T_1$, $U < D^2/4$; reaction in the reflector,
5. $T_1 > z > 0$, $U < D^2/4$; scattering or capture in the sample.

The category 1,2,and 3 is escape of the neutrons from the disk and the program returns to the next neutron impingement. In the category 4 and 5, the reaction point is in the disk; scattering in the reflector, or scattering/ capture in the sample. After scattering in the reflector, the range to the next reaction point $L_2 = \overline{Q_2 - Q_1}$ is determined with an equation similar to eq.(31), depending on the cos θ which is the direction of the velocity vector in the laboratory system, as shown in fig.4.

For $\cos\theta > 0$ $\quad L_2 = \ln(1/YR)/\Sigma_R$ .... (32)

For $\cos\theta < 0$

$$\begin{cases} L_2 = ((\Sigma_T - \Sigma_R)(T_1 - z)/\cos\theta + \ln(1/YR))/\Sigma_T \\ \qquad \text{for } 0 < YR < \exp(-\Sigma_R(T_1 - z)/\cos\theta) \quad \ldots\ldots (33) \\ L_2 = \ln(1/YR)/\Sigma_R \quad \text{for } YR > \exp(-\Sigma_R(T_1 - z)/\cos\theta) \quad \ldots\ldots (34) \end{cases}$$

For the scattering in the sample, the range to the next reaction point is determined similarly.

$$L_2 = \ln(1/YR)/\Sigma_T \quad \text{for } \cos\theta \leq 0 \quad \ldots\ldots (35)$$

For $\cos\theta \geq 0$

$$\begin{cases} L_2 = ((\Sigma_R - \Sigma_T)(T_1 - z)/\cos\theta + \ln(1/YR))/\Sigma_R \\ \qquad \text{for } 0 < YR < \exp(-\Sigma_R(T_1 - z)/\cos\theta) \quad \ldots\ldots (36) \\ L_2 = \ln(1/YR)/\Sigma_T \quad \text{for } YR > \exp(-\Sigma_T(T_1 - z)/\cos\theta) \quad \ldots\ldots (37) \end{cases}$$

The path length in the disk until capture RL is obtained as the sum of L_i.

$$RL = L_1 + L_2 + L_3 + \ldots \quad \ldots\ldots (38)$$

2-8 Neutron cross section production

Neutron cross sections are produced from the given resonance parameters, assuming single level Breit-Wigner formula for all resonances.

$$\sigma_t = \sum_i f_i \left[\sigma_0 \left(\frac{\Gamma_\gamma}{\Gamma}\sqrt{\frac{E_0}{E}} + \frac{\Gamma_n}{\Gamma}\right)_i (\psi \cos 2k_i R + \chi \sin 2k_i R\right]_i + \sigma_p \ldots (39a)$$

$$\sigma_c = \sum_i f_i \left(\sigma_0 \left(\frac{\Gamma_\gamma}{\Gamma}\sqrt{\frac{E_0}{E}}\right)\psi\right)_i \quad \ldots\ldots (39b)$$

$$\sigma_s = \sigma_t - \sigma_c \quad \ldots\ldots (39c)$$

$$\sigma_p = 4\pi \lambda\!\!\!^{-2} \cdot \sin kR \simeq 4\pi R^2 \quad \ldots\ldots (39d)$$

f_i is the isotopic abundance for i-th resonance.

In the region of interest, the approximations hold well;
$\sin 2kR \simeq 2kR$, $\cos 2kR \simeq 1$. The cross sections thus are,

$$\sigma_t = \sum_i f_i\, \sigma_0 (\psi + 2kR\,\chi)_i + \sigma_p \qquad \cdots\cdots\cdots \qquad (40a)$$

$$\sigma_c = \sum_i f_i (\sigma_0 \frac{\Gamma_\gamma}{\Gamma} \psi)_i \qquad \cdots\cdots\cdots \qquad (40b)$$

$$\sigma_s = \sum_i f_i (\sigma_0 (\psi \frac{\Gamma_n}{\Gamma} + 2kR\,\chi))_i + \sigma_p \qquad \cdots\cdots\cdots \qquad (40c)$$

where $\sigma_0 = 4\pi \lambda\!\!\!^{-2} g \frac{\Gamma_n}{\Gamma}$ $\quad$ ($4\pi \lambda\!\!\!^{-2} = 2.60 \times 10^6 / E$ (barn/eV)).....(41)

The Doppler integrals ψ, χ are

$$\text{PSI} = \psi(\beta, X) = \frac{1}{\beta\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{1}{1+y^2} \exp(-(X-y)^2/\beta^2)\, dy \qquad \cdots\cdots\cdots \qquad (42)$$

$$\text{CHI} = \chi(\beta, X) = \frac{1}{\beta\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{y}{1+y^2} \exp(-(X-y)^2/\beta^2)\, dy \qquad \cdots\cdots\cdots \qquad (43)$$

where $X = (E-E_0)/(\Gamma/2)$, and $\beta = 2\Delta/\Gamma$ $\quad\cdots\cdots\cdots\cdots\quad$ (44)
Δ is the apparent energy broadening, due to thermal motion of the target nucleus;

$$\Delta = 2\sqrt{\frac{kT\,E}{A}} \qquad \cdots\cdots\cdots\cdots\cdots \qquad (45)$$

where k is the Boltzmann constant, T the temperature of the target nucleus in K, E the neutron energy and A the target mass number. kT=0.0258 eV for T = 300 K. The Doppler integrals are obtained from the subroutine program PFCN.

2-9 The motion of a target nucleus

The thermal motion of a target nucleus leads to disturbance of scattering reaction. The velocity of the target nucleus, U, is a Maxwellian distribution and the incident neutrons interact with these in Doppler broadened cross section. In fact, the neutron velocity after scattering, V_G', is influenced by the motion of target nucleus before collision, as shown in eqs.(26) and (27), and hence V_G' and the cross sections corresponding to the relative velocity $|\mathbf{V} - \mathbf{U}|$ are not separable. However, the approximation is made of the separation between these using Doppler broadening cross sections and independent definitions of $\mathbf{U}$. For the velocity of the target nucleus, $\mathbf{U}$, the following expression is taken;

$$|U| = f * 2200 * \sqrt{\frac{T_{eff}}{A*293}} \quad (m/sec) \quad \ldots\ldots\ldots\ldots \quad (46)$$

where T_{eff} is the effective temperature(K), A the target mass number. f is obtained from the distribution function;

$$F = \frac{2}{\sqrt{\pi}} t^2 \exp(-t^2) \quad \ldots\ldots\ldots\ldots \quad (47)$$

where

$$\int_0^{\infty} F \; dt = 1 \quad \ldots\ldots\ldots\ldots \quad (48)$$

and t is propotional to the velocity of the nucleus. From the homogeneous random variable YR ($0 < YR < 1$), randomly sampled velocity f is obtained with the equation;

$$YR = \int_0^{f} F \; dt = \frac{1}{\sqrt{\pi}} (Erf(f) - f \exp(-f^2)) \; \ldots. \; (49)$$

In the program however, to obtain f from YR, eq.(49) is approximated to a step function of 10 steps considering the computer time.

§ 3 Flow chart

The procedure of the Monte-Carlo simulation of incident neutrons, or a flow chart of the program, is described briefly below.

A flow chart of the program is shown in fig.5; numbers in [ ] are statement numbers in the FORTRAN list in the appendix.

*) The program begins with reading the input parameters; sample geometries, cross section parameters, nuclear mass, energy region and mesh for cross section table, incident neutron energy region and mesh, initial random number, and time-of-flight instrumental parameters for comparison with experiment. Details of the input parameters are given in § 4.

*) In the next stage, a Doppler broadened cross section table is produced in the computer core area from the given resonance parameters and the effective temperature, in the energy region of interest.

$$|U| = f * 2200 * \sqrt{\frac{T_{eff}}{A*293}} \quad \text{(m/sec)} \quad \ldots\ldots\ldots\ldots \quad (46)$$

where T_{eff} is the effective temperature(K), A the target mass number. f is obtained from the distribution function;

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where $$\int_0^\infty F \, dt = 1 \quad \ldots\ldots\ldots\ldots \quad (48)$$

and t is propotional to the velocity of the nucleus. From the homogeneous random variable YR ($0 < YR < 1$), randomly sampled velocity f is obtained with the equation;

$$YR = \int_0^f F \, dt = \frac{1}{\sqrt{\pi}} (\mathrm{Erf}(f) - f \exp(-f^2)) \quad \ldots. \quad (49)$$

In the program however, to obtain f from YR, eq.(49) is approximated to a step function of 10 steps considering the computer time.

§ 3 Flow chart

The procedure of the Monte-Carlo simulation of incident neutrons, or a flow chart of the program, is described briefly below.
A flow chart of the program is shown in fig.5; numbers in [ ] are statement numbers in the FORTRAN list in the appendix.

*) The program begins with reading the input parameters; sample geometries, cross section parameters, nuclear mass, energy region and mesh for cross section table, incident neutron energy region and mesh, initial random number, and time-of-flight instrumental parameters for comparison with experiment. Details of the input parameters are given in § 4.

*) In the next stage, a Doppler broadened cross section table is produced in the computer core area from the given resonance parameters and the effective temperature, in the energy region of interest.

*) For an incident neutron of energy E_0 impinging onto the disk at Q_0 on the surface, the first collision point Q_1 in the disk is obtained from the mean free path, using homogeneous randomized variable YR.

*) The region in which there exists Q_1 is determined by the boundary conditions;in sample,reflector,and escape from the disk(front, rear, and scattering, and transmission).

*) In the reflector[16], only scattering is considered. In the sample, scattering and capture are considered, and the reaction type at Q_1 is identified with the value of random variable YR. If YR is less than $\Sigma_s/(\Sigma_s + \Sigma_c)$, the reaction is regarded as scattering[15], and otherwise it is capture[12].

*) In the case of capture one count is added in one of the capture counters which are categorized according to the number of collisions before the capture(0,1,2,3, and ≥ 4).

*) In the case of scattering[15], the velocity vector in the center of mass system is transformed to a new velocity vector with randomized scattering angle and poler angle. The new velocity vector is transformed into the laboratory system[30], and the neutron energy becomes $E' = E_0 - E_r$, where E_r is the recoil energy. The next collision point Q_2 is sought as before, and the program returns to the identification of region[10].

*) When the thermal motion of a target nucleus is taken into consideration, subroutine program MOVEA1 and VATOM operate, and the velocity vector after scattering has much freedom for neutrons of energy below 1 eV.

*) The incident neutrons disappear in two ways; escape from the disk, and capture in the sample.

*) For impingement of NTOTAL neutrons with energy E_0, the statistics of capture, front and rear face scattering, and transmission are obtained as averages of the destinations of each incident neutron. These values are printed out with FORMAT-1. In the next stage[9], the incident neutron energy is changed stepwise to reproduce line shape of resonances in the energy region considered. In the MCRTOF program, the energy step corresponds to time-of-flight channels to facilitate the comparison with experiment.

*) For each incident energy, capture and scattering probabilities are obtained and printed out in compact format FORMAT-2, also with graphical representation of these values(RPLT). Spacial distribution of capture points in the sample is obtained as option(ZRPLOT). Also energy-angle distributions for front face scattering are obtained in two-dimensional representation(EPPLOT).

§ 4. Usage of the program

4-1 Instructions on the useage

Format of the input data cards are given in the following, and notes in inputting are described card by card. Also some comments on cards are briefed.

Card No.1

(I6)
NCASE

NCASE: Number of cases to be computed with parameter set of the input card No.2 through No.8.

Card No.2

(20A4)
TITLE

TITLE: Title and arbitrary comments for the case.

Card No.3

(F6.4)	(F6.4)	(F6.4)	(F6.4)	(F6.4)	(F6.4)	(F6.3)	(F6.4)	(F6.0)
D	T1	T2	X0	Y0	DTETA	DENS	RADN	TEFF

D : Disk diameter(cm),

T1 ; Disk sample thickness (cm),

T2 : Disk reflector thickness (cm),

X0 : x of the incident position (cm),

Y0 : y of the incident position (cm),

DTETA: Angle(degree) between incidence and normal of the disk surface,

DENS : Mass density of the disk (g/cm^3),

RADN : Nuclear radius in 10^{-12}cm,

TEFF : Effective temperature of the target nucleus(K).

Card No.4

(I6)
NRESON

NRESON : Number of resonances of which parameters are to be input in the following resonance cards. NRESON must be $\lesssim$ 5.

Card No.5

(F12.6)	(F12.6)	(F12.6)	(F12.6)	(F12.6)	(F12.6)
ER(I)	GN(I)	GT(I)	GJ(I)	A(I)	F(I)

ER(I) : Resonance energy of i-th resonance (eV),

GN(I) : Neutron width of the resonance (eV),

GT(I) : Total width of the resonance (eV),

GJ(I) : Spin statistical factor of the resonance,

A(I) : Mass number of the nucleus,

F(I) : Isotopic abundance of the resonance.

Card No.6

(F12.6)	(F12.6)	(F12.6)	(F12.6)	(F12.6)	(F12.6)
EMIN	EMAX	DE	DE2	FLOSS	SIGMR

EMIN : Minimum energy region where the cross section table is constructed,

EMAX : Maximum energy region where the cross section table is constructed,

DE : Energy mesh of the cross section table. (EMAX-EMIN)/DE must be $\leq$ 1000.

DE2 : not used,

FLOSS : Additional energy loss factor in scattering. Energy loss is in form

(Recoil energy)*(1.0 + FLOSS).

SIGMR : Total cross section of the reflector nucleus.

Card No.7

(F12.10)	(F12.4)	(I6)	(I6)	(I6)	(I6)
RANDOM	XMESH	NTOTAL	MOVE	IPD	ISKIP

RANDOM : The initial value of homogeneous random number series YR ($0<YR<1$), sequentially produced from the previous value with FORTRAN statement;

YR = YR * 243. - INT(YR * 243.)

XMESH : Mesh (cm) in the distribution of path length, and z-distribution.

NTOTAL : Maximum number of trial neutrons for an incident energy.

MOVE : If MOVE = 0, motion of the target nucleus is neglected, if MOVE $\neq$ 0 thermal motion of the target nucleus is considered.

IPD : IPD = 1 : x and z distributions of capture points are printed out.

IPD = 2 : path length distributions until capture is printed out.

IPD = 3 : projection of capture points in sample on xy plane, and energy-angle distribution for front face scattering are illustrated.

For another value of IPD, only probabilities are printed out.

ISKIP : Calculations are made for TOF channels of N,N+ISKIP, N+2*ISKIP,....

Card No.8

(F12.6)	(F12.6)	(F12.6)	(F12.6)
PL	DT	ECMIN	ECMAX

PL : Flight path length (m),

DT : Channel width of the time of flight analyzer (μsec),

ECMIN : Lowest energy of the incident neutron (eV),

ECMAX : Highest energy of the incident neutron (eV). The region ECMIN,ECMAX must be included in the region EMIN, EMAX.

4-2 Example calculations

As an example, the output print-out for the 132 eV resonance in cobalt of 3 mm thickness is shown in fig.7; cross sections, calculated results of capture, front and rear face scattering, and transmission etc. are printed out for each incident energy. For several energy points, spacial distributions of capture points, energy-angle distributions for front face scattering are printed out. Capture (C), front face scattering(S), rear face scattering(F), transmission (T) are illustrated as functions of incident energy. Calculations are compared with experimental data; capture and front-face scattering for tungsten of three thicknesses are shown in fig.6.

The program is fairly speedy due to high speed production of random number sequence at the sacrifice of eventual occurence of short period in it. The production of a good random number sequence with short computer time is desirable.

The author would like to thank Dr. A.Asami for careful reading the manuscript.

References

1) F.H. Fröhner; GA-6909 (1966)

2) J.G.Sullivan, G.G.Warner, R.C. Block, R.W.Hockenbury; RPI-325-155

3) J.E.Lynn and M.C.Moxon; unpublished.

4) M.Ohkubo; Nucl.Sci.Eng. 66(1978)217

5) M.Ohkubo; JAERI-M 6034(1975)

6) M.Ohkubo; JAERI-M 6918(1977)

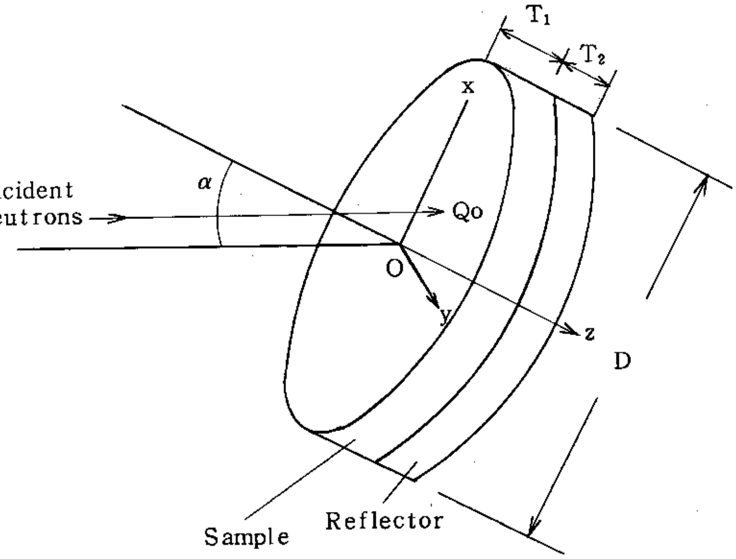


Fig.1 Geometry for Calculations

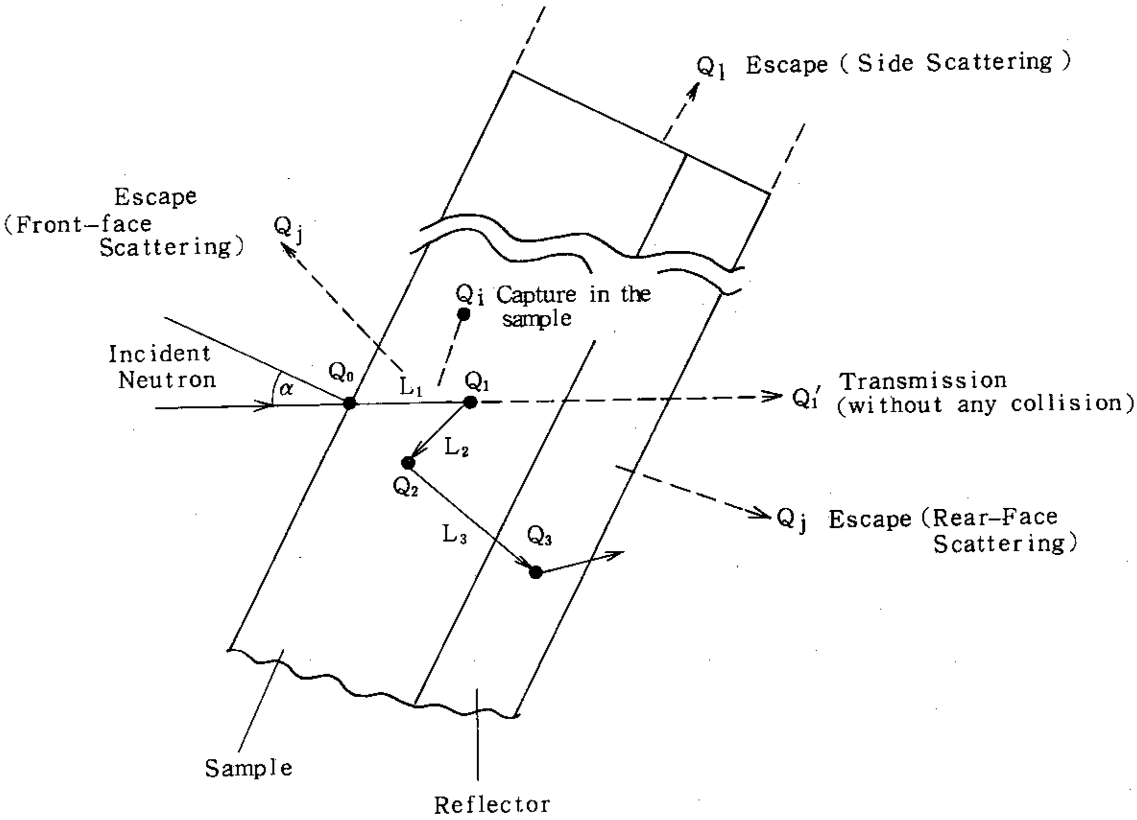


Fig.2 Destinations of the incident neutrons.

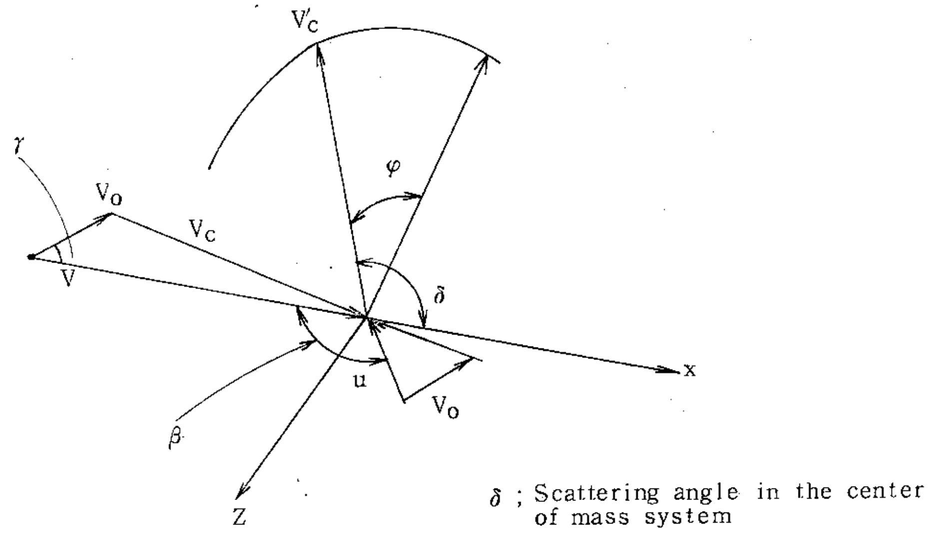


Fig.3 Velocity vectors for scattering of a neutron with a moving nucleus.

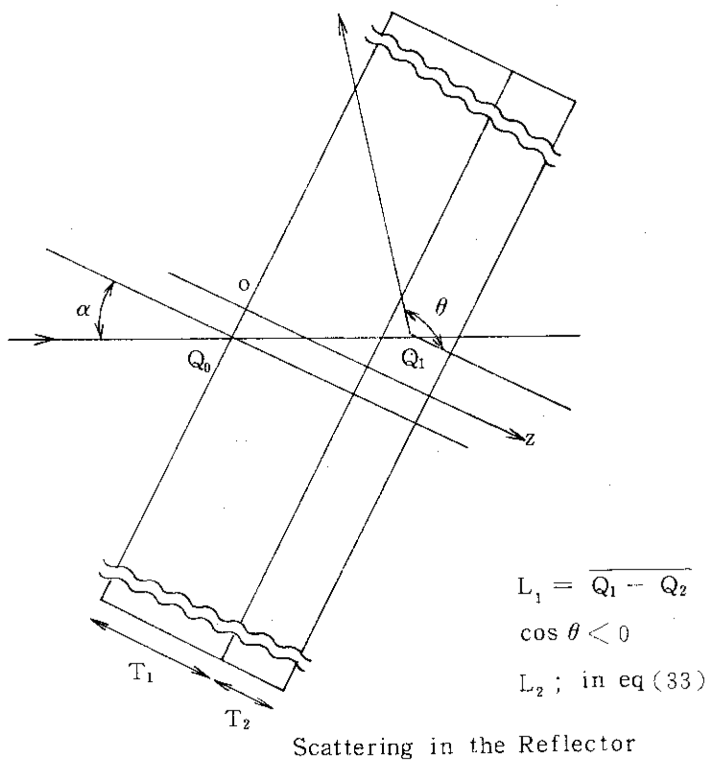


Fig.4 Definitions of the boundary condition. In the case of scattering in the reflector

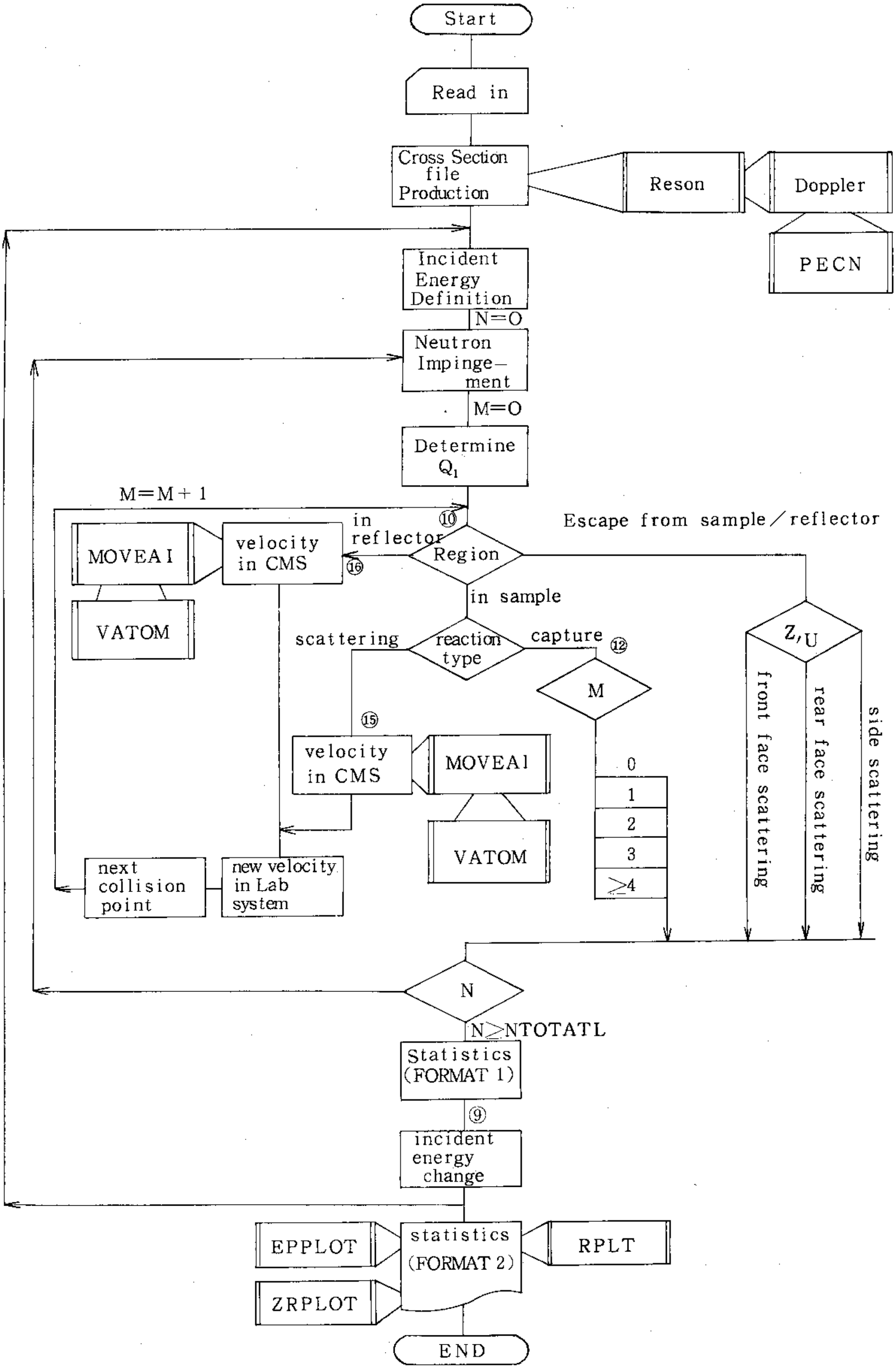


Fig.5 Flow chart

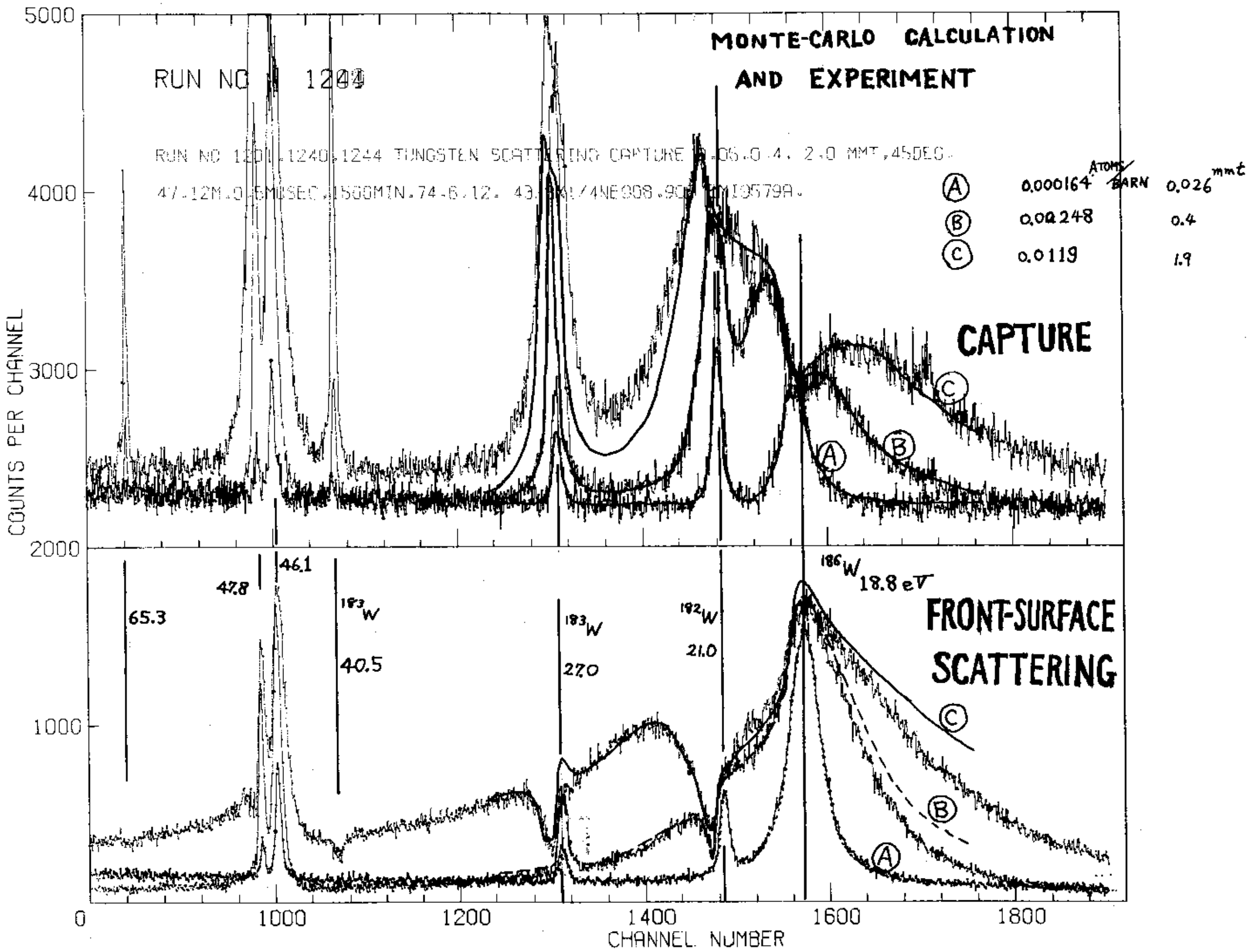


Fig.6 Comparison of the Monte-Carlo calculations with experiments for tungsten in the energy region from 15 to 30 eV.
Upper part; Neutron capture gamma ray counts versus time-of-flight channel for tungsten samples of three thicknesses.
Lower part; Scattered neutron counts corresponding to the upper figure.

Fig. 7

```
TITLE(20) COBALT-59  132 EV RESONANCE   WITH LEVELS 4322, 5015 EV,    MCRTOF
D= 30.00   T1=  0.3000   T2=0.0        X0=0.0        Y0=0.0        DTETA=  0.0    DENS= 8.800    NUCLRAD=0.7200    TEFFECTIVE= 300.0

  132.000000        5.128000        5.609000         0.562500       59.000000        1.000000

 4322.000000      110.200001      110.700001         0.562500       59.000000        1.000000

 5015.000000      651.000000      652.000000         0.437500       59.000000        1.000000

EMIN=   40.000000     EMAX=  200.000000     DE=        0.2000     DF2=    0.200000     TARGET MOVE      0
RANDOM=0.2577373758      XMESH= 0.010      NTOTAL=  1000   PATH LENGTH= 47.380     CHANNEL WIDTH=  2.000       FCMIN= 100.000
ECMAX= 170.000      LOSS FACTOR= 0.0        SIGMR=  0.0


*******************************************************************************************************************************
    RESON ENERG       GN          GT        G-FACTOR  MASS NO   ABOUNDANCE

      132.00    5.128000    5.609000       0.5625      59.0000       1.0000

     4322.00  110.200001  110.700001       0.5625      59.0000       1.0000

     5015.00  651.000000  652.000000       0.4375      59.0000       1.0000

*******************************************************************************************************************************
                    DOPPLER BROADENED CROSS SECTION
```

	ENERGY(EV)		CAPTURE CS	40.80	SCA2T86S	93.16	TOTAL026(BARN)				
42.80	2.85	88.43	91.28*	43.80	2.84	86.26	89.10*	41.80	2.85	90.73	93.5*
45.80	2.83	82.25	85.09*	46.80	2.83	80.40	83.24*	44.80	2.84	84.20	87.0*
48.80	2.84	77.00	79.84*	49.80	2.85	75.42	78.27*	47.80	2.84	78.65	81.4*
51.80	2.87	72.52	75.39*	52.80	2.88	71.18	74.07*	50.80	2.86	73.93	76.7*
54.80	2.91	68.72	71.63*	55.80	2.93	67.58	70.52*	53.80	2.90	69.92	72.8*
57.80	2.96	65.50	68.46*	58.80	3.00	64.55	67.55*	56.80	2.96	66.51	69.4*
60.80	3.06	62.81	65.88*	61.80	3.10	62.03	65.12*	59.80	3.03	63.65	66.6*
63.80	3.17	60.61	63.78*	64.80	3.21	59.96	63.19*	62.80	3.13	61.29	64.4*
66.80	3.30	58.88	62.18*	67.80	3.33	58.40	61.75*	65.80	3.25	59.40	62.6*
69.80	3.46	57.59	61.05*	70.80	3.52	57.27	60.78*	68.80	3.40	57.97	61.3*
72.80	3.65	56.77	60.42*	73.80	3.72	56.60	60.32*	71.80	3.58	56.99	60.5*
75.80	3.87	56.43	60.30*	76.80	3.96	56.43	60.39*	74.80	3.79	56.49	60.2*
78.80	4.14	56.62	60.76*	79.80	4.24	56.80	61.05*	77.80	4.05	56.49	60.5*
81.80	4.47	57.39	61.86*	82.80	4.59	57.80	62.39*	80.80	4.35	57.06	61.4*
84.80	4.86	58.86	63.72*	85.80	5.01	59.53	64.53*	83.80	4.72	58.29	63.0*
87.80	5.34	61.16	66.50*	88.80	5.52	62.15	67.66*	86.80	5.17	60.29	65.4*
90.80	5.92	64.50	70.42*	91.80	6.15	65.90	72.04*	89.80	5.71	63.26	68.9*
93.80	6.65	69.16	75.83*	94.80	6.93	71.11	78.04*	92.80	6.39	67.45	73.8*
96.80	7.56	75.64	83.20*	97.80	7.92	78.29	86.21*	95.80	7.23	73.25	80.4*
99.80	8.74	84.52	93.26*	100.80	9.21	88.19	97.39*	98.80	8.31	81.24	89.5*
102.80	10.28	96.85	107.14*	103.80	10.91	101.99	112.90*	101.80	9.72	92.28	102.0*
105.80	12.36	114.27	126.63*	106.80	13.22	121.63	134.85*	104.80	11.60	107.76	119.3*
108.80	15.27	139.51	154.77*	109.80	16.49	150.41	166.90*	107.80	14.18	129.98	144.1*
111.80	19.49	177.47	196.96*	112.80	21.33	194.36	215.69*	110.80	17.89	162.96	180.8*
114.80	25.97	237.53	263.50*	115.80	28.92	265.37	294.29*	113.80	23.47	214.16	237.6*
117.80	36.67	339.45	376.12*	118.80	41.83	389.39	431.22*	116.80	32.43	298.82	331.2*
120.80	56.20	530.32	586.52*	121.80	66.41	631.62	698.03*	119.80	48.20	451.61	499.8*
123.80	97.42	943.35	1040.77*	124.80	121.65	1189.72	1311.36*	122.80	79.71	764.65	844.3*
126.80	205.18	2051.00	2256.18*	127.80	278.87	2820.72	3099.58*	125.80	155.74	1539.36	1695.1*
129.80	549.30	5698.06	6247.36*	130.80	737.46	7751.91	8489.37*	128.80	389.77	3991.61	4381.3*
132.80	791.07	8546.88	9337.95*	133.80	607.65	6663.04	7270.89*	131.80	853.88	9097.98	9951.8*
135.80	300.29	3393.65	3693.97*	136.80	215.00	2468.75	2683.75*	134.80	429.13	4775.26	5204.3*
138.80	120.80	1433.23	1554.03*	139.80	94.38	1138.70	1233.08*	137.80	158.77	1852.82	2011.5*
141.80	61.47	767.50	828.96*	142.80	50.93	647.07	698.00*	140.80	75.43	925.73	1001.1*
								143.80	42.80	553.46	596.2*

```
MONTE CARLO ANALYSES OF NEUTRONS IN MATERIALS

   COBALT-59  132 EV RESONANCE    WITH LEVELS 4322, 5015 EV.     MCRTOF
 DIAMETER= 30.00 (CM)      SAMPLE THICKNESS= 0.30000(CM)      REFLECTOR THICKNESS= 0.0      (CM)      ATOM/BARN= 0.02695
 INCIDENT POSITION X0 =  0.0       Y0=  0.0        INCIDENT ANGLE =  0.0  DEGREE        SAMPLE DENSITY= 8.800
 NUMBER OF INCIDENT NEUTRONS=   1000                         FLIGHT PATH(M)=47.380      CHANNEL WIDTH(MUSEC)= 2.000

ENERGY(EV)  SIGMA    SIGMS       M0       M1       M2       M3       M4     MTOTAL        MTRANS  BKSCAT  FDSCAT  ENERGY(EV)    RANDOM
                                 P0       P1       P2       P3       P4     FTOTAL        PTRANS  PBACK   PFDS

NUMBER OF SCATT  5278      SCATT IN REFLECTOR=      0     ENERGY INT PCAPTURE=  1.056     CHANNEL INT BKSCATT+TRANS+      INT TRANS  0.36*
 1  170.00    0.33    6.98     0.0240  0.0450  0.0470  0.0250  0.2670  0.4080           0.0560  0.3600  0.1760         170.00    0.599418*

               5278                         0                                 1.056                                                0.360    *
 2  167.44    0.39    7.77     0.0450  0.0360  0.0260  0.0280  0.3060  0.4410          0.0870  0.3080  0.1640         167.44    0.597171*

               5743                         0                                 2.172                                                0.668    *
 3  164.94    0.46    8.75     0.0470  0.0400  0.0320  0.0420  0.3090  0.4700          0.0570  0.3160  0.1570         164.94    0.478416*

               6144                         0                                 3.334                                                0.984    *
 4  162.49    0.54    9.86     0.0420  0.0420  0.0330  0.0530  0.3370  0.5070          0.0400  0.3310  0.1220         162.49    0.734413*

               6455                         0                                 4.561                                                1.315    *
 5  160.10    0.64   11.25     0.0600  0.0270  0.0680  0.0370  0.3350  0.5270          0.0260  0.3660  0.0810         160.10    0.045387*

               5694                         0                                 5.807                                                1.681    *
 6  157.76    0.78   13.02     0.0490  0.0510  0.0400  0.0440  0.3740  0.5580          0.0080  0.3410  0.0930         157.76    0.413108*

               6694                         0                                 7.098                                                2.022    *
 7  155.47    0.94   15.12     0.0470  0.0380  0.0570  0.0530  0.3620  0.5570          0.0090  0.3570  0.0770         155.47    0.190650*

               6853                         0                                 8.359                                                2.379    *
 8  153.23    1.16   17.86     0.0700  0.0890  0.0660  0.0720  0.2930  0.5960          0.0010  0.3540  0.0490         153.23    0.046791*

               5586                         0                                 9.679                                                2.733    *
 9  151.04    1.46   21.55     0.0780  0.0640  0.0620  0.0600  0.3180  0.5820          0.0     0.3580  0.0600         151.04    0.169837*

               6286                         0                                10.941                                                3.091    *
10  148.90    1.86   26.68     0.0720  0.1130  0.0810  0.0640  0.2980  0.6280          0.0     0.3220  0.0500         148.90    0.060783*

               5332                         0                                12.273                                                3.413    *
```

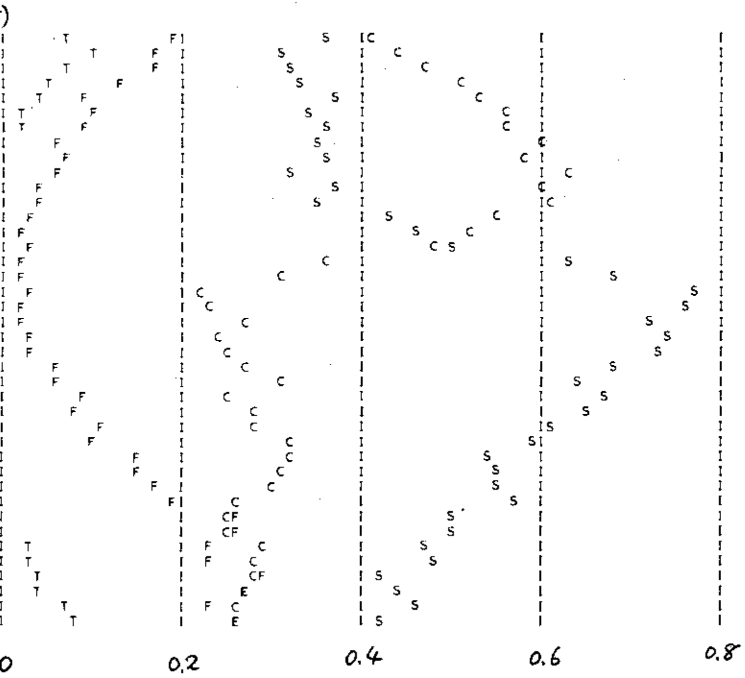
```
MONTE CARLO ANALYSES OF NEUTRONS IN MATERIALS

  COBALT-59  132 EV RESONANCE   WITH LEVELS 4322, 5015 EV,    MCRTOF
DIAMETER= 30.00 (CM)      SAMPLE THICKNESS= 0.30000(CM)      REFLECTOR THICKNESS= 0.0     (CM)      ATOM/BARN= 0.02695
INCIDENT POSITION X0 =  0.0       Y0=  0.0        INCIDENT ANGLE =  0.0  DEGREE       SAMPLE DENSITY= 8.800
NUMBER OF INCIDENT NEUTRONS=    1000                          FLIGHT PATH(M)=47.380      CHANNEL WIDTH(MUSEC)= 2.000

ENERGY(EV)  SIGMA     SIGMS        M0       M1       M2       M3       M4     MTOTAL          MTRANS  BKSCAT  FDSCAT  ENERGY(EV)    RANDOM
                                   P0       P1       P2       P3       P4     PTOTAL          PTRANS  PBACK   PFDS

NUMBER OF SCATT  5786     SCATT IN REFLECTOR=      0      ENERGY INT PCAPTURE= 13.521      CHANNEL INT BKSCATT+TRANS,     INT TRANS  3.77*
11  146.80     2.51    34.14    0.0630  0.0550  0.1050  0.0620  0.3160  0.6010            0.0      0.3650  0.0340        146.80      0.077796*
                                                                                 13.521                                            3.778    *
                5786                               0
12  144.74     3.38    44.28    0.0770  0.0610  0.1140  0.0600  0.3030  0.6150            0.0      0.3530  0.0320        144.74      0.501747*
                                                                                 14.772                                            4.131    *
                5430                               0
13  142.73     4.74    60.07    0.0610  0.0720  0.1160  0.0550  0.2410  0.5450            0.0      0.4310  0.0240        142.73      0.040519*
                                                                                 15.857                                            4.562    *
                5072                               0
14  140.76     7.08    86.53    0.0710  0.0710  0.1130  0.0430  0.2260  0.5240            0.0      0.4620  0.0140        140.76      0.781715*
                                                                                 16.879                                            5.024    *
                4729                               0
15  138.83    10.85   128.75    0.0660  0.0730  0.0920  0.0520  0.1940  0.4770            0.0      0.5020  0.0210        138.83      0.015434*
                                                                                 17.790                                            5.526    *
                4680                               0
16  136.94    19.31   221.78    0.0530  0.0440  0.0780  0.0260  0.1580  0.3590            0.0      0.6280  0.0130        136.94      0.533546*
                                                                                 18.462                                            6.154    *
                4212                               0
17  135.09    35.86   400.31    0.0690  0.0670  0.0480  0.0290  0.0990  0.3120            0.0      0.6780  0.0100        135.09      0.026710*
                                                                                 19.034                                            6.832    *
                3525                               0
18  133.27    65.05   706.84    0.0550  0.0230  0.0420  0.0160  0.0840  0.2200            0.0      0.7650  0.0150        133.27      0.844352*
                                                                                 19.429                                            7.597    *
                3062                               0
19  131.50    74.13   785.59    0.0760  0.0340  0.0360  0.0080  0.0770  0.2310            0.0      0.7640  0.0050        131.50      0.260231*
                                                                                 19.836                                            8.361    *
                2775                               0
20  129.75    46.14   477.34    0.0790  0.0380  0.0370  0.0150  0.0980  0.2670            0.0      0.7240  0.0090        129.75      0.081352*
                                                                                 20.297                                            9.085    *
                2903                               0
```

```
  COBALT-59  132 EV RESONANCE   WITH LEVELS 4322, 5015 EV,    MCRTOF
DIAMETER= 30.00 (CM)      SAMPLE THICKNESS= 0.30000(CM)      REFLECTOR THICKNESS= 0.0      (CM)      ATOM/BARN= 0.02695
INCIDENT POSITION X0 =  0.0       Y0=  0.0        INCIDENT ANGLE =  0.0  DEGREE
NUMBER OF INCIDENT NEUTRONS=    1000      FLIGHT PATH(M)=47.380      CHANNEL WIDTH(MUSEC)= 2.000      TEFFECTIVE=  300.00
```

OBSERVED YIELD FOR 1000/E**0.8 NEUTRON FLUX

	ENERGY	PCAPTURE	PBKSCAT	PFDSCAT	OPEN BEAM	TRANS BEAM	EFFICIENCY	YCAPTUR	SCATBK	SCATFD	
2	167.441	0.441	0.308	0.164	216.355	18.823	0.109	95.412	7.233	3.851	2
3	164.939	0.470	0.316	0.157	213.837	12.189	0.109	100.503	7.387	3.670	3
4	162.493	0.507	0.331	0.122	211.365	8.455	0.110	107.162	7.702	2.839	4
5	160.102	0.527	0.366	0.081	208.938	5.432	0.111	110.111	8.478	1.876	5
6	157.762	0.558	0.341	0.093	206.555	1.652	0.112	115.258	7.863	2.144	6
7	155.473	0.557	0.357	0.077	204.214	1.838	0.112	113.747	8.195	1.768	7
8	153.234	0.596	0.354	0.049	201.915	0.202	0.113	120.341	8.090	1.120	8
9	151.043	0.582	0.358	0.060	199.656	0.0	0.114	116.200	8.144	1.365	9
10	148.899	0.628	0.322	0.050	197.437	0.0	0.115	123.991	7.293	1.132	10
11	146.799	0.601	0.365	0.034	195.257	0.0	0.115	117.349	8.230	0.767	11
12	144.744	0.615	0.353	0.032	193.114	0.0	0.116	118.765	7.925	0.718	12
13	142.732	0.545	0.431	0.024	191.007	0.0	0.117	104.099	9.633	0.536	13
14	140.762	0.524	0.462	0.014	188.937	0.0	0.118	99.003	10.281	0.312	14
15	138.832	0.477	0.502	0.021	186.901	0.0	0.119	89.152	11.123	0.465	15
16	136.941	0.359	0.628	0.013	184.900	0.0	0.119	66.379	13.854	0.287	16
17	135.089	0.312	0.678	0.010	182.932	0.0	0.120	57.075	14.893	0.220	17
18	133.274	0.220	0.765	0.015	180.997	0.0	0.121	39.819	16.732	0.328	18
19	131.495	0.231	0.764	0.005	179.093	0.0	0.122	41.371	16.639	0.109	19
20	129.752	0.267	0.724	0.009	177.221	0.0	0.122	47.318	15.701	0.195	20
21	128.043	0.242	0.743	0.015	175.379	0.0	0.123	42.442	16.044	0.324	21
22	126.368	0.252	0.727	0.021	173.567	0.0	0.124	43.739	15.633	0.452	22
23	124.726	0.268	0.683	0.049	171.784	0.0	0.125	46.038	14.625	1.049	23
24	123.115	0.314	0.635	0.051	170.029	0.0	0.125	53.389	13.540	1.087	24
25	121.535	0.254	0.667	0.079	168.302	0.0	0.126	42.749	14.163	1.677	25
26	119.986	0.278	0.654	0.068	166.603	0.0	0.127	46.316	13.830	1.438	26
27	118.465	0.284	0.612	0.104	164.930	0.0	0.128	46.840	12.888	2.190	27
28	116.974	0.316	0.594	0.090	163.283	0.0	0.128	51.597	12.457	1.887	28
29	115.511	0.323	0.541	0.136	161.661	0.0	0.129	52.217	11.299	2.840	29
30	114.075	0.310	0.548	0.142	160.065	0.0	0.130	49.620	11.399	2.954	30
31	112.665	0.298	0.545	0.157	158.493	0.0	0.131	47.231	11.290	3.252	31
32	111.282	0.255	0.567	0.178	156.944	0.0	0.131	40.021	11.698	3.672	32
33	109.923	0.253	0.502	0.245	155.419	0.0	0.132	39.321	10.315	5.034	33
34	108.590	0.252	0.497	0.251	153.917	0.0	0.133	38.787	10.172	5.137	34
35	107.280	0.294	0.466	0.216	152.438	3.659	0.134	44.817	9.499	4.403	35
36	105.995	0.277	0.483	0.221	150.980	2.869	0.134	41.821	9.806	4.487	36
37	104.732	0.283	0.415	0.276	149.544	3.888	0.135	42.321	8.392	5.581	37
38	103.491	0.268	0.442	0.261	148.129	4.296	0.136	39.699	8.903	5.257	38
39	102.273	0.256	0.460	0.223	146.734	8.951	0.137	37.564	9.228	4.474	39
40	101.076	0.260	0.419	0.252	145.360	10.030	0.137	37.794	8.373	5.036	40

COBALT-59 132 EV RESONANCE WITH LEVELS 4322, 5015 EV, MCRTOF



	E_n (eV)	PROBABILITY CAPTURE (C)	PROBABILITY SCATTERING (S)
1	170,00	0,408	0,360
2	167,44	0,441	0,308
3	164,94	0,470	0,316
4	162,49	0,507	0,331
5	160,10	0,527	0,366
6	157,76	0,558	0,341
7	155,47	0,557	0,357
8	153,23	0,596	0,354
9	151,04	0,582	0,358
10	148,90	0,628	0,322
11	146,80	0,601	0,365
12	144,74	0,615	0,353
13	142,73	0,545	0,431
14	140,76	0,524	0,462
15	138,83	0,477	0,502
16	136,94	0,359	0,628
17	135,09	0,312	0,678
18	133,27	0,220	0,765
19	131,50	0,231	0,764
20	129,75	0,267	0,724
21	128,04	0,242	0,743
22	126,37	0,252	0,727
23	124,73	0,268	0,683
24	123,11	0,314	0,635
25	121,54	0,254	0,667
26	119,99	0,278	0,654
27	118,47	0,284	0,612
28	116,97	0,316	0,594
29	115,51	0,323	0,541
30	114,07	0,310	0,548
31	112,67	0,298	0,545
32	111,28	0,255	0,567
33	109,92	0,253	0,502
34	108,59	0,252	0,497
35	107,28	0,294	0,466
36	105,99	0,277	0,483
37	104,73	0,283	0,415
38	103,49	0,268	0,442
39	102,27	0,256	0,460
40	101,08	0,260	0,419

T : transmission
C : capture
S : Front face scattering
F : Rear face scattering

DISTRIBUTION OF CAPTURE POINTS Z-X (ZRPLOT)
ENERGY= 144,74 MESH LENGTH(CM) 0,010

	0									10										20										30
1	0	0	1	0	0	0	0	0	0	5	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
2	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	5	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	1	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	5	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	5	5	2	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	1	0	6	3	0	4	0	0	5	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	1	1	5	8	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
14	6	14	4	12	1	6	6	1	1	0	0	0	0	1	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0
→ 15	103	68	68	31	19	15	3	3	2	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	13	18	6	8	4	3	1	4	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	11	3	4	1	2	2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
19	5	1	0	1	3	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	5	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	5	2	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	4	5	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

incident point

FRONT SURFACE SCATTERING,ENERGY, ANGLE DISTRIBUTION **(EPPLOT)**

INCIDENT ENERGY= 144.7(EV) AVRAGE RECOIL ENERGY= 4.74 INCIDENT ANGLE= 0.0

		-90	-80	-70	-60	-50	-40	-30	-20	-10	00	10	20	30	40	50	60	70	80	90	
1	144.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	144.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	143.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	143.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	142.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	142.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	141.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	141.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	140.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	140.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	140.0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
12	139.5	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2
13	139.1	6	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	4	17
14	138.6	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
15	138.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	137.6	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	3
17	137.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	2
18	136.7	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3
19	136.2	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
20	135.7	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	4
21	135.3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	6
22	134.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	134.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	133.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	133.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	132.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	132.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	131.9	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
29	131.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	131.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	130.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	130.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	129.6	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	4	0	0	0	9
34	129.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	128.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	2
36	128.1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	6
37	127.7	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
38	127.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	5
39	126.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
40	126.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	125.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
42	125.3	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2
43	124.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	124.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	123.9	0	0	0	6	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	8
46	123.4	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	3
47	122.9	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
48	122.4	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	5	0	0	10
49	122.0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	5	0	0	10
50	121.5	13	26	8	45	10	1	7	2	1	0	0	5	1	8	14	17	28	48	10	244
		25	35	10	53	21	12	7	2	1	0	0	5	5	9	15	32	43	63	15	0

13 142,73 4,74 60,07 0,0610 0,0720 0.1160 0.0550 0.2410 0,5450 0.0 0,4310 0,0240 142,73 0.040519*

5072 0 15,857 4,562 *

CAPTURE THICKNESS MESH= 0.010

Z= 147 180 55 47 26 22 1 8 8 7 14 0 7 0 8 0 0 0 7 0 0 0 0 0 0 0 8 0 0 0

RADIAL DISTRIBUTION OF CAPTURE POINT

R= 8 1 0 0 0 24 0 7 0 0 0 0 16 62 329 45 15 14 8 0 0 0 0 16 0 0 0 0 0 0

14 140,76 7,08 86,53 0,0710 0,0710 0,1130 0,0430 0,2260 0,5240 0.0 0,4620 0,0140 140,76 0,781715*

Appendix

FACOM 230-75 (M7) FORTRAN-D -760820- V06-L08 78.10.30 PAGE 1

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CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C     SHEET PLOT      1977.2.       MCRTOF8                  M.OHKUBO.
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C    RESONANCE SAMPLE    ,DIA.D(CM),THICK,T1(CM) ,REFLECTOR THICK T2(CM)
C      Z DISTRIBUTION, RADIAL DISTRIBUTION PRINT  1978 2 23         M.O.
C      IPD =0 NOT PRINT,  =1 PATH LENGTH DIST PRINT,, NOT 0,1,  Z DIST PRINT
C
C      MAIN PROGRAM   ************************************************
       COMMON/SIGM/SGA(1000),SGS(1000),SGT(1000) ,RADN
      1/RESDA/NRESON,ER(5),GN(5),GT(5),GJ(5),A(5),F(5),EMIN,DE,EMAX
      2/TMOV/EREF,EAFT,D1(3),D2(3)/BOLTZM/AN,IXXX,U,YR/TEMP/TEFF
       COMMON/PROB/CAPTUR (200),SCATBK(200),SCATFD(200),PTRANS(200)
      1,TITLE(20),ACON,TMIN,DT,ECMIN,ECMAX/ZDIST/MZR(50,50)/SKP/ISKIP
       COMMON /EPSI/MEPSI(50,50)
       DIMENSION MRL(50), ANGL(3,3), TV(3),CM(3),MCZ(50),MU(50)
C
       CALL DATAON
C  ***********  PARAMETER READ IN  ****************                ************
C
       READ(5,99) NCASE
    99 FORMAT(I6)
       DO 7 IJ=1,NCASE
       READ(5,100)(TITLE(I),I=1,20)
   100 FORMAT(20A4)
       READ(5,102) D,T1,T2 ,X0, Y0,DTETA,DENS,RADN ,TEFF
   102 FORMAT(6F6.4,F6.3,2F6.4)
       READ(5,530) NRESON
   530 FORMAT(I6)
       READ(5,531) (ER(I),GN(I),GT(I),GJ(I),A(I),F(I),I=1,NRESON)
   531 FORMAT(6F12.6)
       READ(5,532)  EMIN,EMAX,DE ,DE2,      FLOSS ,SIGMR
   532 FORMAT(6F12.6)
       READ(5,106) RANDOM,XMESH,NTOTAL,MOVE,IPD,ISKIP
   106 FORMAT(F12.10,F12.4,4I6)
       READ(5,110) PL,DT,ECMIN,ECMAX
   110 FORMAT(4F12.3)
C       ******       INPUT END      ************
C
C        PARAMETER LIST UP        ********
       WRITE(6,220)          (TITLE(I),I=1,20),D,T1,T2,X0,Y0,DTETA,DENS,
      1RADN,TEFF
   220 FORMAT(1H1/                  5X,'TITLE(20)',20A4/5X,'D=',F6.2,3X,'T1=',
      1,F8.4,3X,'T2=',F6.4,3X,'X0=',F6.4,3X,'Y0=',F6.4,3X,'DTETA=',F6.2,
      23X,'DENS=',F6.3,3X,'NUCLRAD=',F6.4,3X,'TEFFECTIVE=',F6.1)
       DO 240 K=1,NRESON
       WRITE(6,222) ER(K),GN(K),GT(K),GJ(K),A(K),F(K)
   222 FORMAT(/5X,6(F12.6,3X))
   240 CONTINUE
       WRITE(6,224) EMIN,EMAX,DE,DE2,MOVE
   224 FORMAT(/5X,'EMIN=',F12.6,5X,'EMAX=',F12.6,5X,'DE=',F12.4,5X,'DE2=',
      1,F12.6,5X,'TARGET MOVE', I6)
       WRITE(6,226) RANDOM,XMESH,NTOTAL,PL,DT,ECMIN,ECMAX,FLOSS,SIGMR
   226 FORMAT(5X,'RANDOM=',F12.10,5X,'XMESH=',F6.3,5X,'NTOTAL=',I6,3X,
      1'PATH LENGTH=',F7.3,5X,'CHANNEL WIDTH=',F7.3,5X,'ECMIN='F8.3/
      2 5X,'ECMAX=',F8.3,5X,'LOSS FACTOR=',F6.3,'     SIGMR=',F6.2)
C
C       *******    CROSS SECTION LIST     ********************
       CALL RESON
```

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* SOURCE STATEMENT (FTMAIN)*

```
C    *******************************************************************
C
C            CAREA = ENERGY INTEGRAL OF CAPTURE PROBABILITY
C        SUMBKS = CHANNEL INTEGRAL  OF FRONT REGION SCATTERING
C         SUMCAP = HANNEL INTEGRAL  OF CAPTURE PROBABILITY
C        SUMDIP =  HANNEL INTEGRAL  OF  TRANSMISSION DIP
       CAREA=0
       SUMBKS=0
       SUMCAP=0
       SUMDIP=0
       PMESH=XMESH
C
       TETA=3.1416*DTETA/180.
       ACON=(72.3*PL)**2
       YR=RANDOM
       IF(YR.LT.0.0001) YR=YR*1000. +0.84376521
C      CONVERSION FROM ENERGY REGION TO FLIGHT TIME REGION
       TMIN=72.3*PL/SQRT(ECMAX)
       TMAX=72.3*PL/SQRT(ECMIN)
C      ****************************************************************
       IF(ECMAX.GT.EMAX) GO TO 9999
       IF(ECMIN.LT.EMIN) GO TO 9999
C
C***** INCIDENT ENERGY DEFINITION  **********************************
C     INCIDENT ENERGY IS DEFINED FROM THE TIME OF FLIGHT CHANNEL
C
       IF(ISKIP.EQ.0)ISKIP=1
       KPRINT=0
C
C
       DO 9 IT=1,200,ISKIP
       TOF=TMIN+DT*(IT-1)
       IF(TOF.GE.TMAX) GO TO 9
       E0=ACON/TOF**2
       E=E0
       IF(E0.GT.ECMAX.OR.E0.LE.ECMIN) GO TO 9
       JE=(E-EMIN)/DE +1
       IF(JE.GT.1000) GO TO 9
       IF(JE.LT.1) JE=1
       REAV=2*A(1)*E/((1+A(1))**2)
       ATDN=0.6023*DENS/A(1)
       AB=ATDN*T1
C
C     ATDN  NUCLEAR DENSITY IN ATOMS/CM3 X10(-24)
C      MACRO CROSS SECTION,    SIGMA0,SIGMS0, SIGMT0
C      ****************************************************************
       SIGMA0=SGA(JE)*ATDN
       SIGMS0=SGS(JE)*ATDN
       SIGMT0=SGT(JE)*ATDN
C
       IF(SIGMR.LT.0.0001) SIGMR=0.0001
       SIGMR0=SIGMR*ATDN
       SIGAA=0.0
C
       AN=A(1)
       MSUF=0
       MFDS=0
       MESC=0
       M0=0
```

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* SOURCE STATEMENT (FTMAIN  )*

      M1=0
      M2=0
      M3=0
      M4=0
      M=0
      NJ=0
      NK=0
C
      DO 3 L=1,50
      MRL(L)=0
      MCZ(L)=0
      MU(L)=0
      DO3 J=1,50
      MZR(L,J)=0
      MEPSI(L,J)=0
    3 CONTINUE
C
C*****BEGINING OF A NEUTRON HISTORY ************************
C
      DO 51 I=1,NTOTAL
      EBEF=E0
      SIGYA=SIGMA0
      SIGMT=SIGMT0
      SIGMS=SIGMS0
      SIGMR=SIGMR0
      ATOM=SIGMT*T1
      ANSIGT=SIGMT*T1
      DIP=1.-EXP(-ANSIGT/COS(TETA))
      DO 170 IK=1,3
      TV(IK)=0
      DO 170 JK=1,3
      IF(IK-JK)171,172,171
  171 ANGL(IK,JK)=0
      GO TO 170
  172 ANGL(IK,JK)=1.
  170 CONTINUE
C
C     DTETA IS ANGLE(DEG) BETWEEN INCIDENT AND AXIS OF DISK SAMPLE
C     NEUTRON INCIDENT IN XZ PLANE ,Z IS PERPENDICULAR TO THE SAMPLE SURFACE
      COST=COS(TETA)
      SINT=SIN(TETA)
      ANGL(1,1)=COST
      ANGL(1,3)=SINT
      ANGL(3,3)=ANGL(1,1)
      ANGL(3,1)=-ANGL(1,3)
C
      SUMRL=0
C     RL  RANGE TO 1ST REACTION
      TZ=T1/ANGL(1,1)
      YR=YR*243.-INT(243.*YR)
      IF(YR.LT.0.0001) YR=YR*1000. +0.7895377
      V1=ALOG(1./YR)
      V2=EXP(-SIGMT*TZ)
      IF(YR-V2) 40,40,41
   41 RL=V1/SIGMT
      GO TO 42
   40 RL=(V1-(SIGMT-SIGMR)*TZ)/SIGMR
   42 CONTINUE
C

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* SOURCE STATEMENT (FTMAIN  )*

      X=X0+RL*ANGL(3,1)
      Y=Y0
      Z= RL*ANGL(1,1)
      SUMRL=RL
      N=0
C
C***** REGION AND REACTION TYPE ****************************************
C
C     RETURN POSITION FOR MORE THAN 1 SCATTERING EVENT
   10 CONTINUE
C     *****************************************************************
      IF(Z.GT.T1+T2) GO TO 62
      IF(Z.LT.0.) GO TO 61
      U=X**2 +Y**2
      IF(U.GT. D**2/4.)GO TO 60
      IF(Z.GT.T1) GO TO 16
      YR=YR*243.-INT(243.*YR)
      IF(YR.LT.SIGMA/SIGMT) GO TO 12
      GO TO 15
C
C***** CAPTURE IN THE SAMPLE **********************************************
   12 M=M+1
  150 IF(N.NE.0) GO TO 152
      M0=M0+1
      GO TO 50
  152 IF(N.NE.1) GO TO 154
      M1=M1+1
      GO TO 50
  154 IF(N.NE.2) GO TO 156
      M2=M2+1
      GO TO 50
  156 IF(N.NE.3) GO TO 158
      M3=M3+1
      GO TO 50
  158 M4=M4+1
      GO TO 50
   50 CONTINUE
C     PATH LENGTH DISTRIBUTION UNTIL CAPTURE
      IRL=SUMRL/XMESH+1
      IF(IRL.GT.50) IRL=50
      MRL(IRL)=MRL(IRL)+1
C     SPACIAL DISTRIBUTION OF CAPTURE POINTS
C     CAPTURE THICKNESS DISTRIBUTION
      ICZ=Z/XMESH +1
      IF(ICZ.GT.50) ICZ=50
      MCZ(ICZ)=MCZ(ICZ)+1
C      DISTRIBUTION OF X                           ****************
      IRJ=(X-X0)/RMESH+15.5
      IF(IRJ.LE.1) IRJ=1
      IF(IRJ.GT.50) IRJ=50
      MU(IRJ)=MU(IRJ)+1
      MZR(ICZ,IRJ)=MZR(ICZ,IRJ)+1
C
      GO TO 51
C
C***** SCATTERING IN THE  SAMPLE    ******************************************
   15 CONTINUE
      YR=YR*243.-INT(243.*YR)
      IF(YR.LT.0.0001) YR=YR*1000. +0.282965731
```

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FACOM 230-75 (M7)  FORTRAN-D   -760820- V06-L08    78.10.30    PAGE   5

* SOURCE STATEMENT (FTMAIN  )*

          IF(MOVE.EQ.0) GO TO 16
C
C         *****   MOVING TARGET        *************************
          CALL MOVEA1
C
          GO TO 20
       16 PCM=2.*YR-1.
          PLAB=(1.+AN*PCM)/SQRT(1.+AN**2+2.*AN*PCM)
          RECOIL=EBEF*2.*AN*(1.-PCM)/((1.+AN)**2)
          EAFT=EBEF-RECOIL*(1.+FLOSS)
       20 JE=(EAFT-EMIN)/DE+1
          IF(JE.LT.1) JE=1
          IF(JE.GT.1000) GO TO 9
          SIGMA=SGA(JE)*ATDN
          SIGMS=SGS(JE)*ATDN
          SIGMT=SIGMA+SIGMS
          YR=YR*243.-INT(243.*YR)
          Q1=SIN(YR*6.2832)
          Q2=COS(YR*6.2832)
          YR=YR*243.-INT(243.*YR)
          IF(YR.LT.0.0001) YR=YR*1000. +0.77899135
          P=COST*PLAB+SINT*Q2*SQRT(1.-PLAB**2)
          IF(P)70,70,72
       70 RL=ALOG(1./YR)/SIGMT
          GO TO 71
       72 IF(YR-EXP(-SIGMT*(T1-Z)/P)) 73,73,74
       73 RL=((SIGMR-SIGMT)*(T1-Z)/P + ALOG(1./YR))/SIGMR
          GO TO 71
       74 RL=ALOG(1./YR)/SIGMT
       71 CONTINUE
          NJ=NJ+1
          SUMRL=SUMRL+RL
          YR=YR*243.-INT(243.*YR)
          IF(YR.LT.0.0001) YR=YR*1000. +0.6534567213
          GO TO 30
C
C*****SCATTERING IN THE REFLECTOR***************************
       16 CONTINUE
          YR=YR*243.-INT(243.*YR)
          IF(YR.LT.0.0001) YR=YR*1000. +0.34562781
          IF(MOVE.EQ.0) GO TO 118
C
C         *****   MOVING TARGET        *************************
          CALL MOVEA1
C
          GO TO 120
      118 PCM=2.*YR-1.
          RECOIL=EBEF*2.*AN*(1.-PCM)/((1.+AN)**2)
          EAFT=EBEF-RECOIL*(1.+FLOSS)
      120 JE=(EAFT-EMIN)/DE+1
          IF(JE.LT.1) JE=1
          IF(JE.GT.1000) GO TO 9
          SIGMA=SGA(JE)*ATDN
          SIGMS=SGS(JE)*ATDN
          SIGMT=SIGMA+SIGMS
          YR=YR*243.-INT(243.*YR)
          Q1=SIN(YR*6.2832)
          Q2=COS(YR*6.2832)
          P=COST*PLAB+SINT*Q2*SQRT(1.-PLAB**2)


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* SOURCE STATEMENT (FTMAIN  )*

          YR=YR*243.-INT(243.*YR)
          IF(YR.LT.0.0001) YR=YR*1000. +0.56378122
          IF(P)80,82,82
       82 RL=ALOG(1./YR)/SIGMR
          GO TO 81
       80 IF(YR-EXP(-SIGMR*(T1-Z)/P))83,84,84
       83 RL=((SIGMT-SIGMR)*(T1-Z)/P +ALOG(1./YR))/SIGMT
          GO TO 81
       84 RL=ALOG(1./YR)/SIGMR
       81 CONTINUE
          NK=NK+1
          SUMRL=SUMRL+RL
          YR=YR*243.-INT(243.*YR)
          IF(YR.LT.0.0001) YR=YR*1000. +0.74836123564
          GO TO 30
C
C
C***** NEXT REACTION POSITION ******************************
       30 N=N+1
          V=SQRT(1.-PLAB**2)                                        ****
C
          DO 192 I10 =1,3
          TV(I10)=0
          CM(I10)=0
      192 CONTINUE
C
C         CM(3) IS SCATTERING VECTOR WITH RESPECT TO INCIDENT DIRECTION
C         TV(3) IS SCATTERING VECTOR IN X,Y,Z COORDINATE
C         ANGL(3,3) IS TRANSFORMATION MATRIX
C
          IF(MOVE.NE.0) GO TO 194
          CM(1)=V*Q2
          CM(2)=V*Q1
          CM(3)=PLAB                                                ****
          GO TO 196
      194 CM(1)=D2(1)
          CM(2)=D2(2)
          CM(3)=D2(3)
      196 CONTINUE
          DO 190 L3=1,3
          DO 190 L4=1,3
          TV(L3)=TV(L3)+ANGL(L3,L4)*CM(L4)
      190 CONTINUE
          X=X+TV(1)*RL
          Y=Y+TV(2)*RL
          Z=Z+TV(3)*RL
          CMN2=CM(1)**2+CM(2)**2+CM(3)**2
          TVN2=TV(1)**2+TV(2)**2+TV(3)**2
          T=TV(2)/TV(1)
          SEC=SQRT(1.+T**2)
          TV4=SQRT(1.-TV(3)**2)
          TV1=TV(1)
          SINA=ABS(T)*SIGN(1.,TV1)/SEC
          TV2=TV(2)
          COSA=SIGN(1.,TV2)/SEC
C
          ANGL(1,1)=TV(3)*COSA
          ANGL(1,2)=-SINA
          ANGL(1,3)=TV4*COSA
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                    FACOM 230-75 (M7)  FORTRAN-D    -760820- V06-L08    78.10.30    PAGE   7

* SOURCE STATEMENT (FTMAIN  )*

            ANGL(2,1)=TV(3)*SINA
            ANGL(2,2)=COSA
            ANGL(2,3)=TV4*SINA
            ANGL(3,1)=-TV4
            ANGL(3,2)=0
            ANGL(3,3)=TV(3)
      C
            EBEF=EAFT
            GO TO 10
      C     RETURN TO 10 FOR MULTIPLE SCATTERING
      C
      C*****ESCAPE FROM THE REGION ******************************
         61 MSUF=MSUF+1
      C                                  ******* FRONT SURFACE SCATTERING ********
            JREC=(E-EAFT)/REAV*10.
            IF(JREC.GT.50) JREC=50
            IF(JREC.LT.1) JREC=1
            JDEG=ATAN(SQRT(1.-ANGL(1,1)**2)/ANGL(1,1))*18./3.1416 +10.5
            IF(JDEG.GT.50) JDEG=50
            IF(JDEG.LT.1) JREC=1
            MEPSI(JREC,JDEG)=MEPSI(JREC,JDEG) +1
      C
      C      ENERGY,  ANGLE    FOR  FRONT SURFACE SCATTERING   ********************
            GO TO 60
         62 IF(N.NE.0) MFDS=MFDS+1
         60 MESC=MESC+1
            YR=YR*243.-INT(243.*YR)
            IF(YR.LT.0.0001) YR=YR*1000. +0.86523147562
      C     ****************************************************************
      C*****END OF A NEUTRON HISTORY *****************************
      C     RETURN TO NEXT NEUTRON IMPINGEMENT               DO 51 I=1,NTOTAL
         51 CONTINUE
      C      END OF 'NTOTAL' NEUTRONS
      C
      C
      C
            RANDOM=YR
      C
      C****** STATISTICS ***************************************************
      C  ******************************************************************
      C     ****   FORMAT 1   1   1   1   *************
      C
            MTRANS=NTOTAL-M-MSUF-MFDS
            M5=M
            PE=FLOAT(MESC)/FLOAT(NTOTAL)
            P0=FLOAT(M0)/FLOAT(NTOTAL)
            P1=FLOAT(M1)/FLOAT(NTOTAL)
            P2=FLOAT(M2)/FLOAT(NTOTAL)
            P3=FLOAT(M3)/FLOAT(NTOTAL)
            P4=FLOAT(M4)/FLOAT(NTOTAL)
            P5=FLOAT(M5)/FLOAT(NTOTAL)
            PBK=FLOAT(MSUF)/FLOAT(NTOTAL)
            PFDS=FLOAT(MFDS)/FLOAT(NTOTAL)
            CAX=2.*P5*E0*DT/TOF
      C
            SUMBKS=SUMBKS+PBK
            SUMDIP=SUMDIP+DIP
      C                   SUMCAP =CAPTURE PROBABILITY INTEGRAL WITH RESPECT TO ENERGY


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* SOURCE STATEMENT (FTMAIN  )*

            SUMCAP=SUMCAP + CAX
            CAPTUR(IT)=P5
            SCATBK(IT)=PBK
            SCATFD(IT)=PFDS
            PTRANS(IT)=FLOAT(MTRANS)/FLOAT(NTOTAL)
            GNTGT=SIGMS0/SIGMT0
      C
            IF(IT-1-(IT-1)/10*10.EQ.0) GO TO 1001
            GO TO 1002
       1001 WRITE(6,206)
        206 FORMAT(1H1,/5X,'MONTE CARLO ANALYSES OF NEUTRONS IN MATERIALS'/)
            WRITE(6,200) ( TITLE(I),I=1,20),D,T1,T2,AB,X0,Y0,DTETA, DENS,NTOTAL
           1L,PL,DT
        200 FORMAT(1H ,5X,20A4/ 5X,'DIAMETER=',F6.2,' (CM)',5X,'SAMPLE THICKNE
           1SS=',  F8.5,'(CM)',5X,'REFLECTOR THICKNESS=', F8.5,' (CM)' ,5X,'ATOM
           2OM/BARN=', F8.5/
           3 5X,'INCIDENT POSITION X0 =',F6.2, 5X,'Y0=', F6.2, 5X,'INCIDENT AN
           4GLE =', F6.2, ' DEGREE',5X,'SAMPLE DENSITY=',F6.3/
           5                           5X,'NUMBER OF INCIDENT NEUTRONS=',I7
           4,20X,'FLIGHT PATH(M)=',F6.3,5X,'CHANNEL WIDTH(MUSEC)=',F6.3//
           5 2X,'ENERGY(EV)  SIGMA     SIGMS          M0          M1        M2        M3
           6         M4     MTOTAL          MTRANS  BKSCAT  FDSCAT  ENERGY(EV)    RANDOM
           7OOM'/
           7  36X,'P0',7X,'P1',6X,'P2',6X, 'P3',6X,'P4', 4X,'PTOTAL', 8X,
           8'PTRANS',2X,'PBACK',3X,'PFDS',/)
      C
            WRITE(6,230) NJ,NK,SUMCAP,SUMBKS,DIP,SUMDIP
        230 FORMAT(2X,'NUMBER OF SCATT',I6,5X, 'SCATT IN REFLECTOR=',I6,
           15X,'ENERGY INT PCAPTURE=',F7.3, 5X,'CHANNEL INT BKSCATT+TRANS,
           2INT TRANS', F7.3,5X,F6.4,5X,F8.3)
      C
       1002 WRITE(6,202) IT,E0,SIGMA0,SIGMS0, P0,P1,P2,P3,P4,P5, PTRANS(IT),
           1 PBK,PFDS,E0,RANDOM,IT
        202 FORMAT(I4,3F8.2,5X,6(F6.4,2X),7X,3(F6.4,2X),2X,F9.2,4X,F12.10,I4/
           2)
            WRITE(6,232) NJ,NK,SUMCAP,SUMBKS,DIP,SUMDIP
        232 FORMAT(17X,I6,24X,I6,25X,F7.3,40X,F7.3,5X,F6.4,5X,F8.3)
      C
      C              *************                                     **********
            IF(IPD.EQ.0) GO TO 1004
            IF(IPD.EQ.1) GO TO 1006
            IF(IPD.EQ.3) GO TO 1006
      C
            WRITE(6,210) XMESH,GNTGT
        210 FORMAT(10X,'PATH LENGTH DISTRIBUTION  MESH=', F6.4,5X,'SIGMS/SIGMT
           1 =', F6.4)
            WRITE(6,211) (MRL(K),K=1,30)
        211 FORMAT(5X,30I4)
            GO TO 1004
      C
       1006 WRITE(6,234) XMESH
        234 FORMAT(10X,'CAPTURE THICKNESS MESH=',F6.3)
            WRITE(6,235) (MCZ(K),K=1,30)
        235 FORMAT(5X,'Z=', 30I4)
            WRITE(6,237)
        237 FORMAT(10X,'RADIAL DISTRIBUTION OF CAPTURE POINT')
            WRITE(6,238) (MU(I),I=1,30)
        238 FORMAT(5X,'R=',30I4)
            IF(IPD.EQ.3) GO TO 1008
```

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                 FACOM 230-75 (M7)  FORTRAN-D    -760820- V06-L08    78,10,30    PAGE   9

* SOURCE STATEMENT (FTMAIN  )*

        338              GO TO 1004
                  C
                  C      CAPTURE POINTS DISPLAY IN X VERSUS Z  WITH A MESH XMESH(CM)
        339         1008 IF(KPRINT-1,NE,(KPRINT-1)/10*10) GO TO 1004
        340              CALL ZRPLOT(E,XMESH)
        341              CALL EPPLOT(Z, REAV,DTETA)
                  C                      *          ***************************
                  C
        342         1004 CONTINUE
        343              YR=YR*243,-INT(243,*YR)
        344              IF(YR,EQ,0,) YR=0.00001
        345            8 CONTINUE
        346              KPRINT=KPRINT+1
                  C               *************                  *************            **********
                  C      *****    ENERGY  ROOP RETURN POINT    *********************
                  C
                  C      RETURN TO NEXT INCIDENT ENERGY POINT
        347            9 CONTINUE
                  C      ****************************************************************
                  C               *************                  *************            **********
        348              WRITE(6,231)
        349          231 FORMAT(120(1H*)///)
                  C
                  C      ****   FORMAT 2   2   2   2   2************
                  C      *M**************************************************************
        350              JPRINT=0
                  C
        351              HFACT=EXP(2./SQRT((EMIN+EMAX)/2.))
                  C
        352              DO 400 I=1,200,ISKIP
        353              TOF1=TMIN+DT*(I-1)
        354              EL=ACON/TOF1**2
        355              IF(EL.GE.ECMAX.OR.EL.LE.ECMIN) GO TO 400
        356              IF(JPRINT/40*40.EQ.JPRINT) GO TO 777
        357              GO TO 779
        358          777 WRITE(6,401) (TITLE(K),K=1,20),D,T1,T2,AB,X0,Y0,DTETA,NTOTAL,PL,DT
                        1,TEFF
        359          401 FORMAT(1H1/5X,20A4/ 5X,'DIAMETER=',F6.2,' (CM)',5X,'SAMPLE THICKNE
                        1SS=',  F8.5,'(CM)',5X,'REFLECTOR THICKNESS=', F8.5,' (CM)' ,5X,'AT
                        2OM/BARN=', F8.5/
                        3 5X,'INCIDENT POSITION X0 =',F6.2, 5X,'Y0=', F6.2, 5X,'INCIDENT AN
                        4GLE =', F6.2, ' DEGREE'/  5X,'NUMBER OF INCIDENT NEUTRONS=',I7,
                        5 5X,'FLIGHT PATH(M)=',F6.3,5X,'CHANNEL WIDTH(MUSEC)=',F6.3,
                        6 5X,'TEFFECTIVE=',F8.2/)
        360              WRITE(6,402)
        361          402 FORMAT(      /10X,'OBSERVED YIELD FOR 1000/E**0.8 NEUTRON FLUX'//
                        110X,'ENERGY',3X,'PCAPTURE',3X,'PBKSCAT',3X,'PFDSCAT',3X,
                        2 'OPEN BEAM',2X,'TRANS BEAM',2X,'EFFICIENCY',2X,'YCAPTUR',4X,
                        3'SCATBK' ,4X,'SCATFD'/)
        362          779 CONTINUE
        363              FLUX=10000./EL**0.8
        364              TFILT=EXP(-2./SQRT(EL))*HFACT
        365              EFFICY=1.-EXP(-2,36*0.63/SQRT(EL))
        366              FTOF=(EL**1.5)*2./(72,3*PL)
        367              OPBEAM=FLUX*FTOF*TFILT
        368              TY=OPBEAM*PTRANS(I)
        369              CUNTC=OPBEAM*CAPTUR(I)
        370              CUNTSB=OPBEAM*EFFICY*SCATBK(I)
        371              CUNTSF=OPBEAM*EFFICY*SCATFD(I)


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* SOURCE STATEMENT (FTMAIN  )*

        372              WRITE(6,404)I,EL,CAPTUR(I),SCATBK(I),SCATFD(I),OPBEAM,TY,EFFICY,
                        1CUNTC,CUNTSB,CUNTSF,I
        373          404 FORMAT(2X,I4,4F10.3,3X,3F10,3,3X,3F10.3,I6)
        374              JPRINT=JPRINT+1
        375          400 CONTINUE
                  C
                  C      ****    SHEET PLOT *****  **
        376              CALL RPLT
                  C
                  C      ****************************************************************
        377            7 CONTINUE
                  C
        378              GO TO 2
                  C               *************                                           **********
        379         9999 WRITE(6,9998) EMIN,EMAX,ECMIN,ECMAX
        380         9998 FORMAT(//10X,'REGION OVER'/10X,'CROSS SECTION FILE...FROM',
                        1F8.3,'   TO   ',F8.3/10X,'REGION OF CALCULATION...FROM  ',F8.3,
                        2'   TO   ',F8,3)
        381            2 CONTINUE
        382              STOP
        383              END
```

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* SOURCE STATEMENT *

```
C        SUBROUTINE RPLT
C        SUBROUTINE RPLT
C        SUBROUTINE RPLT
         SUBROUTINE RPLT
         COMMON/SIGM/SGA(1000),SGS(1000),SGT(1000) ,RADN
        1/RESDA/NRESON,ER(5),GN(5),GT(5),GJ(5),A(5),F(5),EMIN,DE,EMAX
         COMMON/PROB/CAPTUR (200),SCATBK(200),SCATFD(200),PTRANS(200)
        1,TITLE(20),ACON,TMIN,DT,ECMIN,ECMAX/ZDIST/MZR(50,50)/SKP/ISKIP
         COMMON /EPSI/MEPSI(50,50)
         DIMENSION C1(100),C2(100),C3(100),C4(100)
         DATA STAR,BLNK/1H*,1H /
         DATA   FIGC,FIGS,FIGF,FIGT,FIGX/1HC,1HS,1HF,1HT,1HX/
C
         WRITE(6,150) (TITLE(I),I=1,20)
     150 FORMAT(1H1,/5X,20A4)
         WRITE(6,152)
     152 FORMAT(115X,'PROBABILITY'/   112X,'CAPTURE',2X,'SCATTERING'  )
C
         DO 30 I=1,200,ISKIP
         TOF=TMIN+DT*(I-1)
         E=ACON/TOF**2
         IF(E.LT.ECMIN) GO TO 30
         J1=100.*CAPTUR (I) +0.5
         J2=100.*SCATBK(I)  +0.5
         J3=100.*SCATFD(I)  +0.5
         J4=100.*PTRANS(I)  +0.5
C
         DO 34 II=1,100
         IF(J1-II) 60,62,60
      60 IF(J2-II)69,68,69
      62 IF(J2-II) 64,66,64
      64 C1(II)=FIGC
         GO TO 34
      66 C1(II)=STAR
         GO TO 34
      69 C1(II)=BLNK
         GO TO 34
      68 C1(II)=FIGS
      34 CONTINUE
C
         WRITE(6,160) I,E, (C1(K),K=1,100), CAPTUR (I), SCATBK(I)
     160 FORMAT( I5,F7.2,1HI,100A1,1HI,F6.3,2X,F6.3)
         WRITE(6,162)
     162 FORMAT(1H+,12X,19X,1HI,19X,1HI,19X,1HI,19X,1HI)
         DO 44 K=1,100
         IF(J3-K) 70,72,70
      70 IF(J4-K)79,78,79
      72 IF(J4-K) 74,76,74
      74 C2(K)=FIGF
         GO TO 44
      76 C2(K)=FIGX
         GO TO 44
      79 C2(K)=BLNK
         GO TO 44
      78 C2(K)=FIGT
      44 CONTINUE
         WRITE(6,166)    (C2(J),J=1,100)
     166 FORMAT(1H+,13X,100A1)
      30 CONTINUE
```

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* SOURCE STATEMENT (RPLT   )*

```
         RETURN
         END
```

```
FACOM 230-75 (M7)  FORTRAN-D    -760820- V06-L08    78,10,18    PAGE  13

* SOURCE STATEMENT *

C        SUBROUTINE RESON
C        SUBROUTINE RESON
C        SUBROUTINE RESON
         SUBROUTINE RESON
C   ***********************************************************************
C        DOPPLER INTEGRAL   FOR RESONANCE                       1974.1.31
         COMMON/DOPPL/XE,TE,PSI,CHI/SIGM/SGA(1000),SGS(1000),SGT(1000),RADN
        1/RESDA/NRESON,ER(5),GN(5),GT(5),GJ(5),A(5),F(5),EMIN,DE,EMAX
        2/TEMP/TEFF
         DIMENSION OBSIGA(1000,5),OBSIGS(1000,5),OBSIGT(1000,5),CS0(5)
         RA=RADN
         DO 542 J=1,1000
         SGA(J)=0
         SGS(J)=0
         SG1(J)=0
         DO 542 K=1,5
         OBSIGA(J,K)=0
         OBSIGS(J,K)=0
         OBSIGT(J,K)=0
     542 CONTINUE
         WRITE(6,901)
     901 FORMAT(///120(1H*))
         WRITE(6,604)
     604 FORMAT(     9X,'RESON ENERG',6X,'GN',9X,'GT',6X,'G-FACTOR  MASS NO
        1  ABOUNDANCE',/)
         DO 10 I=1,NRESON
         WRITE(6,602) ER(I),GN(I),GT(I),GJ(I),A(I),F(I)
     602 FORMAT(/5X,F12.2,2F12.6,3F12.4)
      10 CONTINUE
         DO 550 I=1,1000
         E=EMIN+(I-1)*DE
         IF(E.GT.EMAX) GO TO 550
         DO 540 K=1,NRESON
         T=4.*0.025*TEFF/294.*E/(A(K)*GT(K)*GT(K))
         TE=T
         XE=2.*(E-ER(K))/GT(K)
C
C        ***   DOPPLER INTEGRAL     *****************
         CALL DOPPLA
C   ***********************************************************************
         CS0(K)=(2600000./E)*GJ(K)*GN(K)/GT(K)
         OBSIGA(I,K)=PSI*CS0(K)*(GT(K)-GN(K))/GT(K)
         OBSIGS(I,K)=CS0(K)*(PSI*GN(K)/GT(K)+CHI*0.0044*RA*SQRT(E))
         OBSIGT(I,K)=OBSIGA(I,K)+OBSIGS(I,K)
     540 CONTINUE
     550 CONTINUE
         WRITE(6,605)
     605 FORMAT(//5X,100(1H*))
         WRITE(6,608)
     608 FORMAT(25X, 'DOPPLER BROADENED CROSS SECTION')
         WRITE(6,606)
     606 FORMAT(//25X,'ENERGY(EV)'6X,'CAPTURE CS',10X,'SCATT CS',12X,'TOTAL
        1 CS(BARN)')
C        *****************************************************************
         PS=12.56*RA*RA
          IN=0
         DO 562 J=1,1000
         E=EMIN+(J-1)*DE
         IF(E.GT.EMAX) GO TO 562

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* SOURCE STATEMENT (RESON   )*

         DO 560 K=1,NRESON
         SGA(J)=SGA(J)+OBSIGA(J,K)*F(K)
         SGS(J)=SGS(J)+OBSIGS(J,K)*F(K)
         SGT(J)=SGT(J)+OBSIGT(J,K)*F(K)
     560 CONTINUE
         SGS(J)=SGS(J)+PS
         SGT(J)=SGT(J)+PS
         IF(J/5*5.NE.J) GO TO 562
         IN=IN+1
         JKL=IN-(IN/3*3) +1
         GO TO(620,621,622),JKL
     620 WRITE(6,600) E,SGA(J),SGS(J),SGT(J)
     600 FORMAT(5X, (4F10.2,1H*))
         GO TO 562
     621 WRITE(6,601) E,SGA(J),SGS(J),SGT(J)
     601 FORMAT(1H+,47X,4F10.2,1H*)
         GO TO 562
     622 WRITE(6,603) E,SGA(J),SGS(J),SGT(J)
     603 FORMAT(1H+,95X,4F10.2,1H*)
     562 CONTINUE
     563 CONTINUE
         WRITE(6,607)
     607 FORMAT(5X,120(1H*))
         RETURN
         END
```

```
          FACOM 230-75 (M7)  FORTRAN-D    -760820- V06-L08    78,10,18    PAGE  15
* SOURCE STATEMENT *

          C      SUBROUTINE DOPPLER
          C      SUBROUTINE DOPPLER
          C      SUBROUTINE DOPPLER
      1          SUBROUTINE DOPPLA
          C  ******************************************************************************
          C      CALCULATION OF DOPPLER INTEGRAL      COPY  PFCN  1974,1,28, M,OHKUBO
      2          COMMON /PFCNS/SXI,ETA,U,V/ DOPPL/XE,TE,PSI,CHI
      3          SXI=0,5*XE/SQRT(TE)
      4          ETA=0,5/SQRT(TE)
          C
      5          CALL PFCN
          C      **************************************************************************
      6          PSI=  1,77246*ETA*U
      7          CHI=  1,77246*ETA*V
      8          RETURN
      9          END

          FACOM 230-75 (M7)  FORTRAN-D    -760820- V06-L08    78,10,18    PAGE  16
* SOURCE STATEMENT *

          C      SUBROUTINE MOVEA1
          C      SUBROUTINE MOVEA1
          C      SUBROUTINE MOVEA1
      1          SUBROUTINE MOVEA1
          C      **************************************************************************
          C
          C      MOVING TARGET IN SCATTERING PROCESS
      2          COMMON/BOLTZM/A,IXXX,U,YR/TMOV/E1,E2,D1(3),D2(3)/TEMP/TEFF
          C
      3          DIMENSION  VO(3),VC(3),VCR(3),VB(3),VR(3)
      4          VB(1)=0
      5          VB(2)=0
      6          VB(3)=SQRT(E1)*1,00E06/72,3
      7          VBN2=(VB(1)**2+VB(2)**2+VB(3)**2)
      8          VBL=SQRT(VBN2)
          C
      9          YR=YR*243,-INT(243,*YR)
     10          IF(YR.LT,0.0001) YR=YR*1000. +0,21435677351
          C
     11          CALL VATOM
          C      **********************************************************************
     12          YR=YR*243,-INT(YR*243,)
     13          COSB=2,*YR-1,
     14          YR=YR*243,-INT(YR*243,)
     15          SINB=SIGN(1,,0,5-YR)*SQRT(1,-COSB**2)
     16          VCN2=(A/(A+1,))**2*(VBN2-2,*VBL*U*COSB+U**2)
     17          VCL=SQRT(VCN2)
     18          VO(1)=0
     19          VO(2)=(-A*U*SINB)/(A+1,)
     20          VO(3)=(VBL+A*U*COSB)/(A+1,)
     21          VOL=SQRT(VBN2+2,*A*U*VBL*COSB+(A*U)**2)/(A+1)
          C      **************************************************************************
     22          YR=YR*243,-INT(243,*YR)
          C
     23          COSD=2,*YR-1,
     24          SIND=SQRT(1,-COSD**2)
     25          COSG=(VBL+A*U*COSB)/VOL/(A+1,)
     26          SING=(A/(A+1,))*U*SINB/VOL
     27          YR=YR*243,-INT(243,*YR)
     28          PHY=2,*3,1416*YR
     29          COSP=COS(PHY)
     30          SINP=SQRT(1,-COSP**2)*SIGN(1,,0,5-YR)
     31          YR=YR*243,-INT(243,*YR)
     32          TELTA=2,*3,1416*YR
     33          COST=COS(TELTA)
     34          SINT=SQRT(1,-COST**2)*SIGN(1,,0,5-YR)
          C
          C      VELOCITY AFTER SCATTERING  VR(3)
          C      **************************************************************************
     35          VR(1)=VCL*SIND*(SINP*COST-COSP*SINT)-VOL*SING*SINT
     36          VR(2)=-VCL*SIND*(COSP*COST+SINP*SINT)-VOL*SING*COST
     37          VR(3)=VCL*COSD+VOL*COSG
     38          VRN2=VCN2+VOL**2+2,*VOL*VCL*(COSD*COSG+SIND*SING*COSP)
     39          VRL=SQRT(VRN2)
     40          ERATIO=VRN2/VBN2
     41          E2=ERATIO*E1
     42          D2(1)=VR(1)/VRL
     43          D2(2)=VR(2)/VRL
     44          D2(3)=VR(3)/VRL

          FACOM 230-75 (M7)  FORTRAN-D    -760820- V06-L08    78,10,18    PAGE  17
* SOURCE STATEMENT (MOVEA1  )*

     45          RETURN
     46          END
```

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* SOURCE STATEMENT *

```
C       SUBROUTINR VATOM
C       SUBROUTINR VATOM
C       SUBROUTINR VATOM
        SUBROUTINE VATOM
C       ****************************************  1975,5,24, M,OHKUBO***********
        COMMON /BOLTZM/ A,IXXX,U,YR/ TEMP/TEFF
        DIMENSION B(10)
        DATAB(1)/0,64/,B(2)/0,90/,B(3)/1,10/,B(4)/1,28/,B(5)/1,45/,
       1 B(6)/1,62/,B(7)/1,82/,B(8)/2,02/,B(9)/2,28/,B(10)/2,27/
        YR=YP*243,-INT(243,*YR)
        K=YR*10,+1,
        F=B(K)
C       THERMAL VELOCITY OF A=1  ATOM IS EQAL TO  2200 M/SEC.
        U=F*2200,*SQRT(TEFF/(A*293,5))
        RETURN
        END
```

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* SOURCE STATEMENT *

```
C       SUBROUTINE ZRPLOT(MZR,E,XMESH)
C       SUBROUTINE ZRPLOT(MZR,E,XMESH)
C       SUBROUTINE ZRPLOT(MZR,E,XMESH)
        SUBROUTINE ZRPLOT(    E,XMESH)
        COMMON/ZDIST/MZR(50,50)
        COMMON /EPSI/MEPSI(50,50)
        WRITE(6,200) E,XMESH
    200 FORMAT(1H1,5X,'DISTRIBUTION OF CAPTURE POINTS Z-X'/ 5X,'ENERGY=',
       1 F6,2,10X,'MESH LENGTH(CM)', F6,3,/7X, '0',38X,'10',38X,'20',38X,
       1'30'//)
        DO 10 I=1,30
        WRITE(6,202) I,(MZR(J,I),J=1,30)
    202 FORMAT(1X,I4,30I4/)
     10 CONTINUE
        RETURN
        END
```

FACOM 230-75 (M7) FORTRAN-D -760820- V06-L08 78,10,18 PAGE 20

* SOURCE STATEMENT *

```
C       SUBROUTINE EPPLOT(E,REAV,DTETA)
C       SUBROUTINE EPPLOT(E,REAV,DTETA)
C       SUBROUTINE EPPLOT(E,REAV,DTETA)
C       SUBROUTINE EPPLOT(E,REAV,DTETA)
        SUBROUTINE EPPLOT(E,REAV,DTETA)
        COMMON /EPSI/MEPSI(50,50)
        DIMENSION NS(20)
        DO 30 L=1,20
        NS(L)=0
     30 CONTINUE
        WRITE(6,200)
    200 FORMAT(1H1,5X,'FRONT SURFACE SCATTERING,ENERGY, ANGLE DISTRIBUTION
       1'/)
        WRITE(6,204) E,  REAV  ,DTETA
    204 FORMAT(5X, 'INCIDENT ENERGY=',F6,1,'(EV)', 5X,'AVRAGE RECOIL ENERGY
       1Y=',F6,2,5X,'INCIDENT ANGLE=',F6,1/14X,'-90  -80  -70  -60  -50  -
       240  -30  -20  -10   00   10   20   30   40   50   60   70   80   9
       30'/)
        DO 10 I=1,50
        EAFT=E-REAV*0,1*(I-1)
        N=0
        DO 12 J=1,19
        N=N+MEPSI(I,J)
        NS(J)=NS(J)+MEPSI(I,J)
     12 CONTINUE
        WRITE(6,202) I,EAFT, (MEPSI(I,J),J=1,19),N
    202 FORMAT(2X,I4,F6,1,19I5,5X,I6)
     10 CONTINUE
        WRITE(6,206) (NS(K),K=1,20)
    206 FORMAT(/12X,20I5)
        RETURN
        END
```