International Atomic Energy Agency

INDC(PAK)-011
Distrib.: L

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE



# A Computer Code based on Hauser-Feshbach and Moldauer Theory for Nuclear Cross Section Caculations

K. Gul
Scientific Information Division
Pakistan Institute of Nuclear Science and Technology
P.O. Nilore, Islamabad, Pakistan



July 1995

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

INDC(PAK)-011
Distrib.: L

SID-3

# A Computer Code based on Hauser-Feshbach and Moldauer Theory for Nuclear Cross Section Caculations

K. Gul
Scientific Information Division
Pakistan Institute of Nuclear Science and Technology
P.O. Nilore, Islamabad, Pakistan

July 1995

Reproduced by the IAEA in Austria
July 1995

## Abstract

The report describes a computer code which is based on Hauser-Feshbach and Moldauer theory. It considers the calculation of compound elastic, inelastic, (n,p) and (n,$\alpha$) cross sections as one-step process and (n,2n), (n,np) and (n,pn) cross sections as a two-step process. The competition of photons with particles for emission is included in the second step of the reaction only. The available calculations of the elastic and inelastic scattering cross sections with similar codes are compared with the calculations based on the present code.

# Contents

# 1. Introduction

The calculations of nuclear reactions are in general very difficult to carry out partly due to the lack of exact knowledge of nuclear potential and partly due to the involvement of a large number of nucleons in such reactions. The most popular potential used in nuclear reaction calculations is the optical model complex potential [1,2]. The real part of this complex potential gives shape elastic or potential scattering cross section and the imaginary part gives compound elastic and non-elastic cross sections. The nuclear reaction models that represent gradually an increasing degree of complexity of involvement of nucleons in a reaction are direct reaction, pre-equilibrium reaction and fully equilibrated compound nucleus reaction [3-7]. The equilibrium processes taking place through door way states are treated statistically using multistep statistical compound nucleus theories [8-9]. Similarly more complicated direct processes are calculated using multistep statistical direct reaction theories [10]. However, the contribution of pre-equilibrium and multistep statistical processes is small compared with fully equilibrated compound nucleus process in the neutron energy range of 0-14 MeV relevant to fission and fusion technology. The expertise in nuclear reaction calculations using the compound nucleus reaction model is highly desirable. The present code describes a computer code developed by the author for nuclear reaction calculations. It uses Hauser-Feshbach and Moldauer theory [11-12] which is based on the concept of fully equilibrated compound nucleus model. According to this model the incident particle is captured by the target nucleus. It shares its energy with all other nucleons of the nucleus and a thermodynamical equilibrium is attained A fraction of particles possessing energies in excess of their binding energies have a probability of escape and compete with each other including photons for emission from the nucleus. Hauser and Feshbach showed that if the process of formation and decay of the compound nucleus are assumed independent then the use of reciprocity theorem allows the cross sections in all allowed exit channels to be calculated. The calculation requires the transmission coefficients for the incident channels and all allowed exit channels which are computed using appropriate optical model parameters. The present code can be used for the computation of compound elastic, inelastic, (n,p) and (n,$\alpha$) cross sections as a one-step process and (n,pn), (n,np) and (n,2n) cross sections as a two-step process. The code has a provision for computation of elastic and inelastic scattering cross sections with width fluctuation correction using Moldauer theory. The competition of photons with particle emission has only been considered in the second step of the reaction for the emission of second particle. The reported calculations of elastic and inelastic nuclear scattering cross sections by similar codes have been compared with calculations carried out using the present code. The theoretical details of the code are presented in the following sections.

## 2.0 Theoretical Formulation

### 2.1 Hauser-Feshbach Theory

The expression for differential nuclear cross sections on the basis of Hauser-Feshbach is written as follows:

$$\sigma(\theta, n, m) = \frac{\pi\lambda^{2}}{(2i_n + 1)(2I_n + 1)} \sum_{JP} \left[ \frac{\sum_{\ell' j'} \left( \sum_{\ell j} (2\ell + 1)\, A_J(\ell j \ell' j' \theta) T_\ell^n T_{\ell'}^m \right)}{\sum_{\ell'' j'' q} T_{\ell''}^q} \right] \tag{1}$$

where q labels all the allowed outgoing channels, n refers to the incident channel and m refers to the exit channel for which calculation is desired. The spins of the channels are restricted as follows.

$$\begin{aligned} &|J - \ell| \le j \le J + \ell \quad \text{where} \quad |I_n - i_n| \le j \le I_n + i_n \\ &|J - \ell'| \le j' \le J + \ell' \quad \text{where} \quad |I_m - i_m| \le j' \le I_m + i_m \\ &|J - \ell''| \le j'' \le J + \ell'' \quad \text{where} \quad |I_q - i_q| \le j'' \le I_q + i_q \end{aligned} \tag{2}$$

Where $I_n$ and $i_n$ are the spins of the target and the incident particle. $I_m$ and $i_m$ are the spins of the residual and outgoing particles of interest for calculations. $I_q$ and $i_q$ are spins of the residual nuclei and outgoing particles in all the allowed channels for a given compound nucleus state having spin J and parity P. The lower summation depends only on J and P. It is calculated only once for each set of these parameters and it is done in a subroutine of the main programme.

The angle integrated cross section from channel n to m is given by

$$\sigma = \frac{\pi\lambda^{2}}{(2i_n + 1)\, 2I_n + 1)} \left[ \frac{(2J + 1) \sum_{\ell \ell' j j'} T_\ell^n T_{\ell'}^m}{\sum_{\ell'' j'' q} T_{\ell''}^q} \right] \tag{3}$$

The coefficient $A_J(\ell j | \ell' j' | \theta)$ is given by

$$A_J(\ell j | \ell' j' | \theta) = \frac{(2\ell' + 1)(2J + 1)^2}{4\pi} \left| \sum_L C(\ell \ell L; 000)\, W(JJ\ell\ell; Lj)\, C(\ell' \ell' L; 000)\, W(JJ\ell'\ell'; Lj') P_L(\cos\theta) \right| \tag{4}$$

where C and W denote Clebsch-Gordan coefficient and Racah coefficient respectively. The L is defined by $0 \le L \le \min(2\ell, 2\ell', 2J)$ such that it is even. Both C and W are calculated using the recurrence relationships [13].

$$C(\ell\ell L+2;000) = \left(\frac{L+1}{L+2}\right)\left[\frac{(2L+5)(2\ell+L+2)(2\ell-L)}{(2L+1)(2\ell+L+3)(2\ell-L-1)}\right]^{\frac{1}{2}} C(\ell\ell L;000) \quad (5)$$

with

$$C(\ell\ell 0;000) = (-1)^{\ell}\left(\frac{1}{2\ell+1}\right)^{\frac{1}{2}} \quad (6)$$

$$W(JJ\ell\ell; L+2, j) = F(\ell LJ)\frac{K_{L+2}(Jj\ell)}{K_L(Jj\ell)} W(JJ\ell\ell; Lj) \quad (7)$$

where

$$F(\ell LJ) = \left[\frac{(2J+L+3)(2J+L+2)(2\ell+L+3)(2\ell+L+2)}{(2J-L)(2J-L-1)(2\ell-L)(2\ell-L-1)}\right]^{-\frac{1}{2}}$$

and $$W(JJ\ell\ell;0j) = (-1)^{\ell+J-j}\left[\frac{1}{(2J+1)(2\ell+1)}\right]^{\frac{1}{2}} \quad (8)$$

$K_L(Jj\ell)$ is defined by

$$K_{L+1} = \left(\frac{2L+1}{L+1}\right) K_1 K_L - L(2L+1)K_L - \frac{L}{L+1}\left[(2J+1)^2 - L^2\right]\left[(2\ell+1)^2 - L^2\right] K_{L-1} \quad (9)$$

with $K_0 = 1$ and $K_1 = -2\left[j(j+1) - J(J+1) - \ell(\ell+1)\right]$ (10)

## 2.2 Moldauer Theory

For low incident energies the compound nucleus is characterized by low density of levels and a small number of exit channels. The correlations of partial widths necessitates computation of width fluctuation correction to the cross sections calculated using Hauser-Feshbach theory. Moldauer gave the following formula for nuclear cross sections on the basis of compound nucleus cross section model [14]

$$\sigma(\theta, n, m) = \frac{\pi\lambda^2}{(2I_n + 1)(2i_n + 1)} \sum_{JP} \left[ \frac{\sum_{\ell' j'} \left( \sum_{\ell j} (2\ell + 1)\ A_J\ (\ell j | \ell' j' | \theta)\ T_\ell^n\ T_{\ell'}^m \right) C_{nm}\ G_{nm}}{\sum_{\ell'' j'' q} T_{\ell''}^q} \right] \quad (11)$$

where

$$G_{nm} = \int_0^\infty dx\ \Pi_q \left( 1 + \frac{2}{\nu_q} x \frac{< \Gamma_{uq} >}{< \Gamma_u >} \right)^{-\left(\frac{1}{2}\ \nu_q + \delta_{nq} + \delta_{mq}\right)} \quad (12)$$

and
$$C_{nm} = 1 + \frac{2\ \delta_{nm\ell\ell' jj'}}{\nu_q} \qquad \begin{matrix} \delta_{nm\ell\ell' jj'} = 1 \\ \text{for } n = m, \ell = \ell', j = j' \\ \text{otherwise it is zero} \end{matrix} \quad (13)$$

The expression for $G_{nm}$ in terms of transmission coefficients becomes

$$G_{nm} = \int_0^\infty dx\ \Pi_q \left( 1 + \frac{2}{\nu_q}\ x\ \frac{T_{\ell''}^q}{T} \right)^{-\left(\frac{1}{2}\nu_q + \delta_{nq} + \delta_{mq}\right)} \quad (14)$$

where $T = \sum_{\ell''} T_{\ell''}^q$

$\nu_q$ is the degree of freedom that characterizes the distribution of partial widths. The value of $\nu_q$ is given by [15]

$$\nu_q = 1.78 + \left( T_\ell^{1.212} - 0.78 \right) \exp(-0.228T) \quad (15)$$

where $T_\ell$ is the transmission coefficient in the incident channel $\ell$ through which compound nucleus is formed in the state having spin and parity $J^\pi$.

The $G_{nm}$ is written as

$$G_{nm} = \int_{o}^{\infty} \frac{dx}{\left(1+\frac{2x}{\nu_q}\frac{T_\ell^n}{T}\right)\left(1+\frac{2x}{\nu_q}\frac{T_\ell^m}{T}\right)\Pi_q\left(1+\frac{2x}{\nu_q}\frac{T_\ell^q}{T}\right)^{\nu_q/2}} \qquad (16)$$

The integral is evaluated [16] by putting

$$y = \frac{1}{1+\frac{2x}{\nu_q}\frac{T_{max}}{T}} \quad \text{or} \quad x = \frac{\nu_q T}{2T_{max}}\left(\frac{1}{y}-1\right) \qquad (17)$$

where $T_{max}$ is the maximum transmission coefficient in the reaction.

The transformed integral becomes

$$G_{nm} = \frac{\nu_q T}{2T_{max}} \int_{o}^{1} \frac{dy}{y^2\left[1+\frac{T_\ell^n}{T_{max}}\left(\frac{1}{y}-1\right)\right]\left[1+\frac{T_{\ell'}^m}{T_{max}}\left(\frac{1}{y}-1\right)\right]\Pi_q\left[1+\frac{T_\ell^q}{T_{max}}\left(\frac{1}{y}-1\right)^{\nu_q/2}\right]} \qquad (18)$$

This integral is evaluated numerically by Simpson's Rule.

## 2.3 Particle Transmission Coefficients

The transmission coefficients of neutrons, protons, and alpha-particles required for Hauser-Feshbach calculations can be read as a part of input data or calculated internally with the help of a subroutine based on the optical model code [17] by feeding appropriate optical model parameters. If opted the code uses global optical model parameters recommended by Becchetti and Greenless [18] for the calculations of transmission coefficients.

## 2.4 Photons Transmission Coefficients

The gamma-ray transmission coefficient $T_{XL}^{\gamma}(E)$ of multipole-type XL and transition energy E is related to gamma-ray strength function $f_{XL}^{\gamma}(E)$ in the following way [19].

$$T_{XL}^{\gamma}(E) = 2\pi E^{2L+1} f_{XL}^{\gamma}(E) \qquad (19)$$

where

$$f_{XL}^{\gamma} = \frac{\overline{\Gamma}_{\lambda\gamma f}^{XL}}{\overline{D}_{\gamma} E^{2L+1}} \tag{20}$$

where $\lambda$ refers to the initial state and f to the final state of the transition. The average gamma-ray width $\overline{\Gamma}_{\lambda\gamma f}^{XL}$ and the average level spacing $\overline{D}_{\lambda}$ are given in eV and the gamma-ray energy, E, is given in MeV. Brink [20] and Axel [21] have assumed that E1 giant dipole resonance is described by a classical Lorentzian line shape and thus partial with, $\overline{\Gamma}_{\lambda\gamma o}$ of the state $\lambda$ for transition to the ground state is given by

$$\overline{\Gamma}_{\lambda\gamma o} = \frac{8.67\text{x}10^{-8}\ \overline{D}_{\lambda}\sigma_o E^4\ \Gamma_g^2}{\left[E^2 - E_g^2\right]^2 + E^2\Gamma_g^2} \tag{21}$$

where $\sigma_o$ is the peak resonance cross section and equals $13A/\Gamma_g$ mb. The transition energy E, the giant dipole resonance energy $E_g$ and the resonance width $\Gamma_g$ are in MeV. The average level spacing $\overline{D}_{\lambda}$ and width $\overline{\Gamma}_{\lambda\gamma o}$ are in eV. The above expression holds for a unit spin of the state $\lambda$ and a zero spin of the ground state. In order to generalize the above expression to arbitrary spin-values, we rewrite the above expression in the fellowing form:

$$\overline{\Gamma}_{\lambda\gamma o} = 8.67\text{x}10^{-8}\text{x}3\left(\frac{2J_f+1}{2J_i+1}\right)\frac{\overline{D}_{\lambda}\ E^4\sigma_o\Gamma_g^2}{\left(E - E_g\right)^2 + E^2\Gamma_g^2} \tag{22}$$

The gamm-ray transmission coefficient becomes

$$T_{EI}^{\gamma}(E) = 2\pi\frac{\overline{\Gamma}_{\lambda\gamma_o}}{\overline{D}_{\lambda}} = 2.125\text{x}10^{-5}\left(\frac{2J_f+1}{2J_i+1}\right)\frac{A\,\Gamma_g E^4}{\left(E - E_g\right)^2 + E^2\Gamma_g^2} \tag{23}$$

The calculated values of the transmission coefficients for E1 transilens are normalized using a measured value of the gamma-ray width. The measured E1 transition width is also used to normalize the widths calculated on the basis of single particle model [22-23]. The following expressions have been used for calculation of wid0.ths on the basis of the single particle model [22].

$$\Gamma_{\lambda\gamma f}\,(E1) = 6.8\times10^{-8}E^{3}A^{2/3}\frac{D_\lambda}{D_o}$$

$$\Gamma_{\lambda\gamma f}\,(M1) = 2.1\times10^{-8}E^{3}\frac{D_\lambda}{D_o} \qquad (24)$$

$$\Gamma_{\lambda\gamma f}\,(E2) = 4.9\times10^{-14}E^{5}A^{4/3}\frac{D_\lambda}{D_o}$$

where $\Gamma_{\lambda\gamma f}$ and $D_\lambda$ are in eV and the gamma-ray energy E and $D_o$ in MeV. A value of 15 MeV for $D_o$ has been used.

## 2.5 Energy Level Densities

The knowledge of energy level densities is needed in nuclear cross section calculations involving energy regions where the number of levels is high and the information on their spins and parties is poor. The energy level densities play a very crucial role in these calculations. There are two types of energy level density formulas currently being used in the nuclear cross section calculations. Both of these have been included in the present code. The details of these formulas are given in the following sections.

### 2.5.1 Gilbert-Cameron Composite Formula

The density of levels per MeV of energy E, spin J at high energies is given by [24]

$$\rho_2(E,J) = \frac{1}{24\sqrt{2}}\,\frac{\exp\left(2\sqrt{aU}\right)}{\sigma^{3}a^{1/4}U^{5/4}}\,(2J+1)\exp\left(-\frac{(J+1/2)^{2}}{2\sigma^{2}}\right) \qquad (25)$$

where

$$U = E - U_o = E - P(z) - P(N)$$
$$\sigma^{2} = 0.0888\,(aU)^{1/2}\,A^{2/3}$$

Here P(z) and P(N) are pairing energies listed by Gilbert and Cameron [24]. The value of the level density parameter a ($MeV^{-1}$) is calculated from the following expression for the undeformed nuclei.

$$a/A = 0.00917S + 0.142 \qquad (26)$$

and for deformed nuclei it is given by

$$a/A = 0.00917S + 0.120 \qquad (27)$$

where S is given by

$$S = S(z) + S(N)$$

S(z) and S(N) are shell corrections in MeV tabulated by Gilbert and Cameron. The level density per MeV, of all J's is given by

$$\rho_2 = \frac{1}{12\sqrt{2}} \frac{\exp\left(2\sqrt{au}\right)}{\sigma\, a^{1/4}\, U^{5/4}} \tag{28}$$

The nuclear temperature $\tau$ in MeV is given by

$$\frac{1}{\tau} = \frac{dp_2}{dU} = \sqrt{\frac{a}{U}} - \frac{5}{4}\frac{1}{U} \tag{29}$$

The above formulas for level density are used for energies greater than $E_x$ (MeV) where

$$E_x = U_x + P(z) + P(N)$$

and $$U_x = 2.5 + 150/A \tag{30}$$

Below $E_x$ the following simple formula for level density is used.

$$\rho_1(E) = \frac{1}{T} \exp\left(\frac{E - E_o}{T}\right) \tag{31}$$

The temperature T and $E_o$ are determined by fitting $\rho_2$ and $\rho_1$ at $E = E_x$ (32)

$$T = \tau(U_x)$$

and

$$E_o = E_x - T \log_e (T\, \rho_2(U_x)) \tag{33}$$

2.5.2 Back-shifted Fermi-gas Model Formula

The back-shifted Fermi-gas model formula is based on two empirically fitted parameters a and $\Delta$. The level density formula is given by [25].

$$\rho(U, J) = \frac{1}{24\sqrt{2}} \frac{\exp\left[2(a(U - \Delta))^{1/2}\right]}{\sigma^3 a^{1/4} (U - \Delta + t)^{5/4}} (2J + 1) \exp\left(\frac{-J(J+1)}{\sigma^2}\right) \tag{34}$$

and the total density $\rho$ per MeV is given by

$$\rho(U) = \frac{1}{12\sqrt{2}} \frac{1}{\sigma a^{1/4}} \frac{\exp\left[2(a(U-\Delta))^{1/2}\right]}{(U-\Delta+t)^{5/4}} \qquad (35)$$

The thermodynamic temperature t in MeV is given by

$$U - \Delta = at^2 - t$$

$\sigma$ is the spin cut-off parameter and it is given by

$$\sigma^2 = g < m_j^2 > t$$

Here $< m_j^2 >$ is the average squared projection of spins and g is the density of single particle states near the Fermi level. From theoretical arguments $\sigma^2$ is expected to approach at high excitations the value

$$\sigma^2_{rigid} = I_{rigid} \frac{t}{\hbar^2} = 0.0150\, A^{5/3} t \qquad (38)$$

where $I_{rigid}$ = 2/5 $MR^2$ is the rigid body moment of inertia and a nucleus radius 1.25 $A^{1/3}$ fm is assumed.

## 3.0 Comparison with other Codes

The differential elastic and inelastic scattering cross sections of 3.3 MeV neutrons scattered from $^{58}$Ni calculated using the present code are compared with the available calculations of ABAREX code [26] in table 1. The ABAREX code calculations given in the laboratory system have been converted to the centre-of-mass system. As the calculated cross sections are symmetric about 90 degree in the centre-of-mass system, cross sections for comparison have been included only upto 90 degree. The Hauser-Feshbach calculations are given under the columns headed by H.F. The cross sections corrected for width fluctuation are given in the columns under Moldauer. The integrated elastic and inelastic scattering cross sections of different levels are listed in table 2. The following optical model parameters with derivative Woods-Saxon form factor for imaginary potential and Thomas form factor for the spin orbit potential have been used.

| | | |
|---|---|---|
| Real potential well depth | = | 45.1 MeV |
| Real potential well radius | = | 1.2975 $A^{1/3}$ fm |
| Real potential well diffuseness | = | 0.6380 fm |

| | | |
|---|---|---|
| Imaginary potential well depth | = | 11.7 MeV |
| Imaginary well radius | = | 1.302 $A^{1/3}$ fm |
| Imaginary potential well diffuseness | = | 0.3344 fm |
| Real spin-orbit potential well depth | = | 5.5 MeV |
| Real spin-orbit potential well radius | = | 1.005 $A^{1/3}$ MeV |
| Real spin-orbit potential well diffuseness | = | 0.65 fm |

The calculations for differential elastic, inelastic and integrated cross sections of 0.072 MeV neutrons scattered from $^{238}U$ carried out using the present code are compared with the calculations of Wilmore code [16] in table 3. The transmission coefficients of neutrons used are also listed in table 3. There is a very good agreement between the calculations carried out using the present code and the available calculations of the ABAREX code and Wilmore code.

## References


1. H. Feshbach, C.E. Porter and V.F. Weisskopf, Phys. Rev. 96 (1954) 448
2. P.E. Hodgson, 'The Optical Model of Elastic Scattering', Clarendon Press Oxford , 1963
3. D.F. Jackson, 'Nuclear Reactions', Methuen Co. Ltd., London, 1965
4. N. Austern, 'Direct Nuclear Reactions', Wiley Interscience, New York, 1970.
5. G.R. Satchler, 'Introduction to Nuclear Reactions', The Macmillan Press Ltd., London, 1980.
6. M. Blann, Ann. Rev. Nucl. Sci. 25 (1975) 123
7. H. Gruppelaar, P. Angel and P.E. Hodgson, Il Nuovo Cimento 9 (1986) 1
8. H. Feshbach, A.K. Kerman and S. Koonin, Ann. Phys. (N.Y.) 125 (1980) 425
9. M. Avrigeanu and P.E. Hodgson, International Centre for Theoretical Physics Report No. IC/92/31, 1992, Trieste, Italy.
10. H. Feshbach, Phys. Rev. 48 (1993) R2553
11. W. Hauser and H. Feshbach, Phys. Rev. 87 (1952) 366
12. P.A. Moldauer, Phys. Rev. 135 (1964) B642
13. M.E. Rose, 'Elementary Theory of Angular Momentum', Wiley, New York, 1957
14. P.A. Moldauer, Phys. Rev. C13 (1975) 2093
15. P.A. Moldauer, Nucl. Phys. A344 (1980) 185
16. D. Wilmore, Atomic Energy Research Establishment Harwell report AERE-R5053 (1966)
17. K. Gul, Pakistan of Nuclear Science and Technology Division, Report No. SID-2 (1994)
18. F.D. Becchetti and G.W. Greenless, Phys. Rev. 182 (1969) 1190
19. M. Aslam Lone in 'Neutron Capture Gamma-ray Spectroscopy' Ed. R.E. Chrien and W.R. Kane, Plenum Press New York, 1978
20. D.M. Brink, Thesis, Oxford University, 1966 unpublished
21. P. Axel, Phys. Rev. 126 (1962)

22. J.M. Blatt and V.F. Weisskopf, 'Theoretical Nuclear Physics', Princeton University Press, 1958.

23. D.H. Wilkinson in 'Nuclear Spectroscopy, Part B', ed. Fay Ajzenberg-Selov, Academic Press New York 1960 P 644

24. A. Gilbert and A.G.W. Cameron, Cand. J. Phys. 43 (1965) 1446

25. W. Dilg, W. Schantl, H. Vonach and M. Uhl, Nucl. Phys. A217 (1973) 269

26. R.D. Lawson, 'Workshop on Computation and Analysis of Nuclear Data Relevant to Nuclear Energy and Safety', H4.SMR614/6 10 Feb. - 13 March, 1992.

Table 1. Comparison of the calculations of differential elastic and inelastic scattering cross sections of 3.3 MeV neutrons from $^{58}Ni$ carried out using the present code and ABAREX code. The differential cross sections are in c.m. system and given in mb/steradian.

| $E_x$ ($J^\pi$) | $\theta_{c.m}$ | H.F | | Moldauer | |
|---|---|---|---|---|---|
| | | ABAREX Code | PRESENT Code | ABAREX Code | PRESENT Code |
| 0.0 ($0^+$) | 0.0 | 45.5 | 44.25 | 83.60 | 82.05 |
| | 15.0 | | 39.61 | | 72.84 |
| | 15.3 | 40.38 | | 73.60 | |
| | 30.0 | | 29.57 | | 53.28 |
| | 30.5 | 29.55 | | 52.95 | |
| | 45.0 | | 20.92 | | 37.02 |
| | 45.7 | 21.06 | | 37.07 | |
| | 60.0 | | 16.44 | | 28.94 |
| | 60.9 | 16.93 | | 29.66 | |
| | 75.0 | | 14.86 | | 26.14 |
| | 76.0 | 15.02 | | 26.33 | |
| | 90.0 | | 14.56 | | 25.49 |
| | 91.0 | 14.40 | | 25.22 | |
| 1.45 ($2^+$) | 0.0 | 44.79 | 44.8 | 37.0 | 37.26 |
| | 15.0 | | 45.46 | | 37.78 |
| | 15.3 | 45.43 | | 37.57 | |
| | 30.0 | | 46.56 | | 38.79 |
| | 30.7 | 46.65 | | 38.67 | |
| | 45.0 | | 47.11 | | 39.23 |
| | 45.9 | 46.99 | | 39.0 | |
| | 60.0 | | 46.56 | | 38.70 |
| | 61.2 | 46.64 | | 38.39 | |
| | 75.0 | | 45.50 | | 37.74 |
| | 76.3 | 45.22 | | 37.45 | |
| | 90.0 | | 44.98 | | 37.28 |
| | 91.3 | 44.79 | | 37.07 | |
| 2.459 ($4^+$) | 0.0 | 10.96 | 10.92 | 9.67 | 9.81 |
| | 15.0 | | 11.11 | | 9.99 |
| | 15.5 | 11.18 | | 9.85 | |
| | 30.0 | | 11.59 | | 10.44 |
| | 31.0 | 11.70 | | 10.31 | |
| | 45.0 | | 12.18 | | 10.98 |
| | 46.4 | 12.39 | | 10.90 | |
| | 60.0 | | 12.68 | | 11.45 |
| | 61.7 | 12.99 | | 11.43 | |
| | 75.0 | | 12.99 | | 11.75 |
| | 76.9 | 13.41 | | 11.80 | |
| | 90.0 | | 13.10 | | 11.85 |
| | 92.0 | 13.50 | | 11.88 | |
| 2.776 ($2^+$) | 0.0 | 17.57 | 17.66 | 15.20 | 15.39 |
| | 15.0 | | 17.71 | | 15.43 |
| | 15.7 | 17.62 | | 15.24 | |
| | 30.0 | | 17.81 | | 15.51 |
| | 31.3 | 17.67 | | 15.30 | |
| | 45.0 | | 17.84 | | 15.51 |
| | 46.8 | 17.62 | | 15.25 | |
| | 60.0 | | 17.74 | | 15.41 |
| | 62.3 | 17.44 | | 15.08 | |
| | 75.0 | | 17.63 | | 15.27 |
| | 77.5 | 17.23 | | 14.89 | |
| | 90.0 | | 17.56 | | 15.20 |
| | 92.6 | 17.50 | | 14.80 | |

Table 1 continued ...

| | | | | | |
|---|---|---|---|---|---|
| 2.902 ($1^+$) | 0.0 | 11.90 | 11.72 | 10.17 | 10.04 |
| | 15.0 | | 11.61 | | 9.94 |
| | 15.5 | 11.78 | | 10.05 | |
| | 30.0 | | 11.32 | | 9.65 |
| | 31.5 | 11.50 | | 9.77 | |
| | 45.0 | | 10.91 | | 9.26 |
| | 47.2 | 11.13 | | 9.41 | |
| | 60.0 | | 10.50 | | 8.87 |
| | 62.6 | 10.76 | | 8.61 | |
| | 75.0 | | 10.20 | | 8.58 |
| | 77.9 | 10.52 | | 8.82 | |
| | 90.0 | | 10.08 | | 8.47 |
| | 93.0 | 10.54 | | 8.75 | |
| 2.942 ($0^+$) | 0.0 | 5.50 | 5.52 | 4.59 | 4.60 |
| | 15.0 | | 5.38 | | 4.47 |
| | 15.8 | 5.34 | | 4.44 | |
| | 30.0 | | 5.01 | | 4.13 |
| | 31.6 | 4.95 | | 4.08 | |
| | 45.0 | | 4.59 | | 3.75 |
| | 46.3 | 4.54 | | 3.70 | |
| | 60.0 | | 4.27 | | 3.46 |
| | 62..8 | 4.24 | | 3.44 | |
| | 75.0 | | 4.09 | | 3.30 |
| | 78.1 | 4.09 | | 3.31 | |
| | 90.0 | | 4.03 | | 3.26 |
| | 93.1 | 4.05 | | 3.28 | |
| 3.038 ($1^+$) | 0.0 | 11.56 | 11.59 | 10.04 | 10.12 |
| | 15.0 | | 11.60 | | 10.12 |
| | 16.0 | 11.56 | | 10.04 | |
| | 30.0 | | 11.60 | | 10.11 |
| | 32.0 | 11.54 | | 10.03 | |
| | 45.0 | | 11.59 | | 10.10 |
| | 47.8 | 11.49 | | 9.98 | |
| | 60.0 | | 11.56 | | 10.05 |
| | 63.4 | 11.42 | | 9.90 | |
| | 75.0 | | 11.53 | | 10.01 |
| | 78.8 | 11.36 | | 9.84 | |
| | 90.0 | | 11.52 | | 10.0 |
| | 93.9 | 11.32 | | 9.81 | |

Table 2. Comparison of integrated elastic and inelastic scattering cross sections of 3.3 MeV neutrons from $^{58}$Ni. All cross sections are in millibarns and energies of the levels are in MeV.

| Level | $J^{\pi}$ | Hauser - Feshbach | | Moldauer | |
|---|---|---|---|---|---|
| | | ABAREX Code | PRESENT Code | ABAREX Code | PRESENT Code |
| 0.0 | $0^+$ | 257.0 | 252.4 | 455.5 | 449.2 |
| 1.45 | $2^+$ | 577.4 | 579.3 | 478.5 | 481.4 |
| 2.459 | $4^+$ | 159.6 | 156.6 | 140.5 | 141.4 |
| 2.776 | $2^+$ | 219.1 | 222.7 | 189.5 | 193.3 |
| 2.902 | $1^+$ | 137.4 | 133.6 | 115.9 | 113.1 |
| 2.942 | $0^+$ | 55.8 | 55.7 | 45.5 | 45.3 |
| 3.038 | $2^+$ | 143.7 | 145.3 | 124.6 | 126.3 |

Total cross section:
ABAREX code: 1550.0 mb
Present code: 1550.0 mb

Table 3. Comparison of the elastic and inelastic scatteirng cross sections of 0.072 MeV neutrons from $^{238}U$ computed using Wilmore code and present code. The transmission coefficients in the order of $\ell$=0, $\ell$=1, etc. for the ground state are 0.23827, 0.12472, 0.00170, 0.0004 and for the first excited state are 0.15838, 0.03598, 0.00018. The differential cross sections are in millibarn per steradian and energies are in MeV.

| Ex ($J^\pi$) | $\theta_{c.m}$ | Hauser - Feshbach | | Moldauer | | Integrated Cross Sections |
|---|---|---|---|---|---|---|
| | | Wilmore Code | Present Code | Wilmore Code | Present Code | |
| 0.0 ($0^+$) | 0.0 | 457.6 | 453.1 | 522.1 | 516.5 | A. Hauser-Feshbach |
| | 15.0 | 446.4 | 442.1 | 508.0 | 502.6 | Wilmore Code : 4353 mb |
| | 30.0 | 415.9 | 411.8 | 469.6 | 464.7 | Present Code : 4310 mb |
| | 45.0 | 374.2 | 370.5 | 417.4 | 413.0 | |
| | 60.0 | 332.5 | 329.2 | 365.3 | 361.4 | B. Moldauer |
| | 75.0 | 302.0 | 299.0 | 327.3 | 323.7 | Wilmore Code : 4810 mb |
| | 90.0 | 290.8 | 287.8 | 313.4 | 310.0 | Present Code : 4758 mb |
| 0.045 ($2^+$) | 0.0 | 70.9 | 70.2 | 41.8 | 41.0 | A. Hauser-Feshbach |
| | 15.0 | 72.8 | 72.2 | 42.90 | 42.1 | Wilmore Code : 1132 mb |
| | 30.5 | 78.1 | 77.4 | 45.9 | 45.1 | Present Code : 1121 mb |
| | 45.0 | 85.3 | 84.5 | 50.1 | 49.3 | |
| | 60.0 | 92.5 | 91.6 | 54.3 | 53.4 | B. Moldauer |
| | 75.0 | 97.7 | 96.8 | 57.3 | 56.4 | Wilmore Code : 664 mb |
| | 90.0 | 99.7 | 98.7 | 58.4 | 57.5 | Present Code : 654 mb |

95-02633