International Atomic Energy Agency

INDC(CPR)-012/G+CJ

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COMPARISON BETWEEN CHINESE UNIFIED PROGRAM (MUP2) AND INTERNATIONAL NUCLEAR MODEL PROGRAMS

Su Zong Di and P.E. Hodgson
Nuclear Physics Laboratory, Oxford, UK

June 1988

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

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Reproduced by the IAEA in Austria
June 1988

88-02719

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Su Zong Di* and P.E.Hodgson
Nuclear Physics Laboratory, Oxford, U.K.

1. Introduction

MUP2[1] is the second edition of a unified program for the calculation of fast neutron data for medium-heavy nuclei written at the Chinese Nuclear Data Centre (CNDC). It is constructed within the framework of optical model and Hauser-Feshbach theory (HF) for the discrete states and pre-equilibrium statistical theory based on the exciton model and evaporation model for the continuum states. This code can calculate the cross sections of all reaction channels, the elastic and inelastic scattering angular distributions for the discrete states and the secondary neutron spectra. It is a code that is often used at CNDC for analysing and predicting neutron cross sections.

The comparison of results between MUP2 and some international nuclear model codes-SMOG[2], JIB[3] and WILMORE6[4](or WIL6) are presented in this report. SMOG and JIB are the optical model codes that were tested in 1985 by P.E.Hodgson and E.Sartori[5]. A series of nuclear model codes for the spherical optical model for charged particles have been carefully compared and studied in this paper[5]. WIL6 can calculate all cross sections of compound nucleus reaction processes according to the Hauser-Feshbach theory (HF) and the Hauser-Feshbach theory with width fluctuation correction (WHF). Recently, E.Sartori and P.E.Hodgson[6] have completed the preliminary analysis of the Hauser-Feshbach code intercomparison and the calculated results of WIL6 have been examined and have been considered reliable.

We have completed the preliminary comparison between MUP2 and SMOG, JIB, WIL6. In Section 2 we summarize the intercomparison and tabulate the results of calculations of these codes. The results from different codes are good agreement though there are some differences in the mathematical method for solving the Schrodinger radial equation and calculating Coulomb wavefunctions[1], the formulae for calculating angular distributions[7] and the width fluctuation correction[8].

2. Chosen parameters and calculated results

The test calculation refers to neutrons interacting with the synthetic nucleus ^{60}Co (Z=27, N=33) from 0.1 to 15 MeV. Only the elastic and inelastic channels are included, and the others, (n,γ), (n, x) (x is any charged particle) and (n, 2n), are all closed. The assumed states were for ^{60}Co:

U (MeV)	I^{π}
0.0	0^+
0.1	2^+
0.3	4^+
1.0	0^+

* Permanent address: Institute of Atomic Energy, Beijing, People's Republic of China

Table 1 **The comparision of total cross sections in all reaction channels**

Unit: b

E_n (MeV)	0.1	0.2	0.5	1.0	2.0	5.0	8.0	10.0	15.0
σ_t, MUP2	7.5537	5.9825	4.5666	4.0169	3.7379	3.3966	3.1300	3.0039	2.6961
σ_t, SMOG	7.5524	5.9820	4.5667	4.0169	3.7375	3.3962	3.1297	3.0039	2.6958
σ_{se}, MUP2	3.2378	2.7401	2.0423	1.6453	1.5521	1.6265	1.5061	1.4005	1.1999
σ_{se}, SMOG	3.2393	2.7417	2.0437	1.6464	1.5525	1.6264	1.5060	1.4004	1.1999
σ_a, MUP2	4.3159	3.2425	2.5243	2.3716	2.1857	1.7702	1.6239	1.6035	1.4962
σ_a, SMOG	4.3131	3.2403	2.5223	2.3705	2.1850	1.7699	1.6236	1.6033	1.4959
σ_a, WIL6	4.3357	3.2495	2.5164	2.3616	2.1926	1.7696	1.6203	1.5935	1.5019
σ_{el}^{HF}, MUP2	7.5537	5.4916	3.5385	2.5548					
σ_{el}^{WHF}, MUP2	7.5537	5.6752	3.9060	3.0497					
σ_{in}^{HF}, MUP2	0.0000	0.4909	1.0281	1.4621					
σ_{in}^{HF}, WIL6	0.0000	0.4770	1.0120	1.4485					
σ_{in}^{WHF}, MUP2	0.0000	0.3073	0.6606	0.9672					
σ_{in}^{WHF}, WIL6	0.0000	0.2954	0.6516	0.9580					

The following optical model parameters were used:

V_R=50 MeV	Real Saxon-Woods potential depth
W_S=0 MeV	Derivative Saxon-Woods imaginary potential depth
W_V=10 MeV	Imaginary Saxon-Woods potential depth
V_{SO}=0 MeV	Spin-orbit potential depth
r=1.2 fm	Radius parameter of real and imaginary potentials
a=0.6 fm	Diffuseness parameter of real and imaginary potentials

The results of MUP2 were obtained on the IBM computer and the results of SMOG, JIB and WIL6 were obtained on the VAX computer. The comparisons of the cross sections for all reaction channels and the comparisons of the angular distributions of shape elastic scattering are given in tables 1 and 2 respectively. σ_{el}^{HF}, σ_{in}^{HF}, σ_{el}^{WHF} and σ_{in}^{WHF} in Table 1 are the elastic and inelastic scattering cross sections obtained by HF and WHF theory respectively. The cross sections and angular distributions of the compound elastic scattering and inelastic scattering for the discrete states are given in tables 3 to 5. There we do not give the results of statistical model codes for $E_n \geq 2$ MeV, because when the open channels include the continuum states, the pre-equilibrium contribution have been included in the MUP2 calculations.

The results of two kinds of statistical model, HF theory and WHF theory, are given in the tables. All results of these codes show quite good agreement. The cross sections agree to better 3%, and the results of MUP2 and SMOG agree to 0.1%. Since the results of MUP2 and JIB are nearly the same, they are not tabulated.

Table 2 **The comparision of the cross sections for shape elastic scattering**

Unit: b/sr

Code	MUP2	SMOG	MUP2	SMOG	MUP2	SMOG	MUP2	SMOG
$\theta_c \backslash E_n$ (MeV)	0.1	0.1	0.5	0.5	1.0	1.0	2.0	2.0
0^0	0.331	0.331	0.417	0.417	0.578	0.578	0.942	0.943
10^0	0.330	0.330	0.410	0.410	0.560	0.560	0.895	0.895
30^0	0.320	0.320	0.359	0.359	0.433	0.433	0.581	0.581
50^0	0.302	0.303	0.277	0.277	0.258	0.258	0.223	0.223
70^0	0.280	0.280	0.193	0.193	0.118	0.118	0.036	0.036
90^0	0.255	0.256	0.126	0.126	0.045	0.045	0.006	0.006
110^0	0.233	0.233	0.084	0.084	0.027	0.027	0.023	0.023
130^0	0.214	0.214	0.065	0.065	0.037	0.036	0.029	0.029
150^0	0.201	0.201	0.059	0.059	0.055	0.055	0.031	0.031
170^0	0.194	0.194	0.060	0.060	0.069	0.069	0.038	0.037
180^0	0.193	0.193	0.060	0.060	0.071	0.071	0.039	0.039
Code	MUP2	SMOG	MUP2	SMOG	MUP2	SMOG	MUP2	SMOG
$\theta_c \backslash E_n$ (MeV)	5.0	5.0	8.0	8.0	10.0	10.0	15.0	15.0
0^0	1.750	1.749	2.318	2.317	2.676	2.676	3.245	3.244
10^0	1.591	1.590	2.026	2.025	2.259	2.259	2.531	2.531
30^0	0.712	0.713	0.638	0.638	0.518	0.518	0.234	0.234
50^0	0.099	0.099	0.024	0.024	0.004	0.004	0.017	0.017
70^0	0.002	0.002	0.013	0.013	0.008	0.008	0.002	0.002
90^0	0.028	0.028	0.013	0.013	0.009	0.008	0.013	0.013
110^0	0.024	0.024	0.004	0.004	0.005	0.005	0.008	0.008
130^0	0.006	0.006	0.001	0.001	0.003	0.003	0.008	0.008
150^0	0.002	0.002	0.003	0.003	0.003	0.003	0.007	0.007
170^0	0.018	0.018	0.030	0.030	0.031	0.030	0.033	0.033
180^0	0.022	0.022	0.039	0.039	0.043	0.043	0.057	0.057

Table 3 **The comparision of the cross sections for compound elastic scattering**

Unit: b/sr

Model	HF	HF	WHF	WHF	HF	HF	WHF	WHF
Code	MUP2	WIL6	MUP2	WIL6	MUP2	WIL6	MUP2	WIL6
$\theta_c \backslash E_n$ (MeV)	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
0^0	0.3893	0.3904	0.3893	0.3898	0.2468	0.2487	0.2736	0.2733
10^0	0.3871	0.3882	0.3871	0.3875	0.2456	0.2474	0.2717	0.2715
20^0	0.3807	0.3819	0.3807	0.3813	0.2419	0.2437	0.2663	0.2663
30^0	0.3712	0.3724	0.3712	0.3718	0.2363	0.2381	0.2581	0.2583
40^0	0.3598	0.3612	0.3598	0.3606	0.2295	0.2313	0.2482	0.2487
50^0	0.3481	0.3496	0.3481	0.3491	0.2223	0.2240	0.2379	0.2386
60^0	0.3375	0.3391	0.3375	0.3386	0.2155	0.2171	0.2284	0.2293
70^0	0.3291	0.3308	0.3291	0.3303	0.2099	0.2115	0.2209	0.2218
80^0	0.3238	0.3255	0.3238	0.3250	0.2063	0.2079	0.2160	0.2169
90^0	0.3219	0.3237	0.3219	0.3232	0.2051	0.2066	0.2143	0.2152
Integral (b)	4.3159	4.3357	4.3159	4.3288	2.7515	2.7725	2.9351	2.9439
$\theta_c \backslash E_n$ (MeV)	0.5	0.5	0.5	0.5	1.0	1.0	1.0	1.0
0^0	0.1433	0.1436	0.1979	0.1975	0.1036	0.1035	0.1793	0.1784
10^0	0.1421	0.1425	0.1952	0.1948	0.1018	0.1016	0.1750	0.1742
20^0	0.1387	0.1391	0.1876	0.1873	0.0965	0.0965	0.1632	0.1625
30^0	0.1336	0.1341	0.1765	0.1764	0.0891	0.0892	0.1467	0.1462
40^0	0.1276	0.1282	0.1639	0.1640	0.0810	0.0812	0.1290	0.1287
50^0	0.1214	0.1221	0.1517	0.1520	0.0736	0.0739	0.1132	0.1132
60^0	0.1159	0.1166	0.1414	0.1417	0.0677	0.0681	0.1014	0.1014
70^0	0.1115	0.1123	0.1337	0.1341	0.0637	0.0641	0.0938	0.0939
80^0	0.1087	0.1095	0.1291	0.1295	0.0615	0.0619	0.0898	0.0899
90^0	0.1078	0.1086	0.1275	0.1280	0.0608	0.0612	0.0886	0.0888
Integral (b)	1.4962	1.5044	1.8630	1.8669	0.9095	0.9130	1.4045	1.4037

Table 4 **The comparision of the cross sections for inelastic scattering the first excited state (U=0.1 MeV, 2^+)**

Unit: b/sr

Model	HF	HF	WHF	WHF	HF	HF	WHF	WHF
Code	MUP2	WIL6	MUP2	WIL6	MUP2	WIL6	MUP2	WIL6
$\theta_c \backslash E_n$ (MeV)	0.2	0.2	0.2	0.2	0.5	0.5	0.5	0.5
0^0	0.0323	0.0313	0.0205	0.0197	0.0707	0.0695	0.0448	0.0441
10^0	0.0326	0.0316	0.0207	0.0199	0.0712	0.0700	0.0451	0.0445
20^0	0.0334	0.0325	0.0212	0.0204	0.0726	0.0715	0.0462	0.0455
30^0	0.0348	0.0338	0.0220	0.0211	0.0748	0.0736	0.0477	0.0470
40^0	0.0365	0.0354	0.0230	0.0221	0.0775	0.0762	0.0494	0.0488
50^0	0.0383	0.0372	0.0240	0.0231	0.0802	0.0790	0.0512	0.0505
60^0	0.0399	0.0388	0.0250	0.0240	0.0827	0.0814	0.0527	0.0520
70^0	0.0413	0.0401	0.0257	0.0247	0.0847	0.0834	0.0538	0.0531
80^0	0.0422	0.0410	0.0262	0.0252	0.0860	0.0847	0.0545	0.0538
90^0	0.0425	0.0413	0.0264	0.0254	0.0864	0.0851	0.0548	0.0541
Integral (b)	0.4909	0.4770	0.3073	0.2954	1.0221	1.0062	0.6501	0.6414
$\theta_c \backslash E_n$ (MeV)	1.0	1.0	1.0	1.0				
0^0	0.0950	0.0943	0.0598	0.0594				
10^0	0.0957	0.0951	0.0604	0.0599				
20^0	0.0979	0.0972	0.0620	0.0615				
30^0	0.1010	0.1002	0.0642	0.0637				
40^0	0.1043	0.1036	0.0665	0.0660				
50^0	0.1074	0.1066	0.0686	0.0680				
60^0	0.1099	0.1091	0.0701	0.0696				
70^0	0.1116	0.1107	0.0710	0.0705				
80^0	0.1125	0.1117	0.0715	0.0710				
90^0	0.1128	0.1120	0.0716	0.0711				
Integral (b)	1.3568	1.3466	0.8633	0.8568				

Table 5 **The comparision of the cross sections for inelastic scattering the second excited state (U=0.3 MeV, 4^+)**

Unit: b/sr

Model	HF	HF	WHF	WHF	HF	HF	WHF	WHF
Mode	MUP2	WIL6	MUP2	WIL6	MUP2	WIL6	MUP2	WIL6
$\theta_c \backslash E_n$ (MeV)	0.5	0.5	0.5	0.5	1.0	1.0	1.0	1.0
0^0	0.0004	0.0004	0.0008	0.0007	0.0076	0.0074	0.0075	0.0073
10^0	0.0004	0.0004	0.0008	0.0007	0.0077	0.0074	0.0076	0.0074
20^0	0.0004	0.0004	0.0008	0.0008	0.0079	0.0076	0.0078	0.0076
30^0	0.0005	0.0004	0.0008	0.0008	0.0081	0.0079	0.0080	0.0078
40^0	0.0005	0.0005	0.0008	0.0008	0.0083	0.0081	0.0082	0.0080
50^0	0.0005	0.0005	0.0009	0.0008	0.0085	0.0082	0.0084	0.0082
60^0	0.0005	0.0005	0.0009	0.0008	0.0085	0.0083	0.0084	0.0082
70^0	0.0005	0.0005	0.0009	0.0008	0.0085	0.0082	0.0084	0.0082
80^0	0.0005	0.0005	0.0009	0.0008	0.0085	0.0082	0.0084	0.0081
90^0	0.0005	0.0005	0.0009	0.0008	0.0084	0.0082	0.0083	0.0081
Integral (b)	0.0061	0.0058	0.0106	0.0102	0.1053	0.1019	0.1039	0.1013

3. Conclusions

The comparisons made in this report show that the accuracy of MUP2 is comparable with that of similar international codes for optical model calculations and Hauser-Feshbach calculations to the discrete states. The comparison also shows that the calculations[1,7,8] made using the Chinese optical model and statistical theory codes are reliable.

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