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NEUTRON-INDUCED REACTIONS

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FKK Analysis of 14 MeV Neutron-Induced Reactions

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Abstract

The quantum-mechanical theory of Feshbach, Kerman and Koonin (1980) has been applied to analyse neutron-induced reactions, particularly nucleon-emission reactions at 14.1 MeV on ^{51}V , ^{56}Fe , Zr , ^{93}Nb , Mo , and Sb . The analysis is carried out over the whole energy and angle range and aims to account for all the reaction flux. An unambiguous method of isolating the multistep direct component by taking the forward-backward differences in the centre of mass system has been developed and used to obtain the average value for the strength V_0 of the effective N-N interaction. This method has been applied to a wider range of nuclei in order to find the dependence of V_0 on the target mass number.

1. Introduction

The quantum-mechanical theory of preequilibrium reactions proposed by Feshbach, Kerman, and Koonin (1980) (FKK) has been extensively applied during the last decade to analyse a wide range of nucleon-induced reactions. This theory describes a nuclear reaction in terms of a series of nucleon-nucleon interactions in the target nucleus leading to the excitation of nucleons to higher states, from which emission can take place. The theory distinguishes between multistep direct emission (MSD) proceeding through states with at least one unbound particle and multistep compound emission (MSC) from bound particle states. The MSD process is dominant at higher energies (above 30 MeV), giving forward-peaked angular distributions, whereas the MSC contributes at lower energies and gives cross-sections symmetric about 90° .

The MSD theory has been successfully applied to reactions at higher energies (Avaldi *et al*, 1980; Bonetti *et al*, 1981, 1982b, 1994; Marcinkowski *et al*, 1989; Scobel *et al*, 1990; Cowley *et al*, 1991; Richter *et al*, 1992; Chadwick and Young, 1993) and the MSC at lower energies (Bonetti *et al*, 1980, 1982a, 1982b, 1983; Field *et al*, 1986; Chadwick *et al*, 1988, 1989; Koumdjieva and Hodgson, 1992). However, there are rather few analyses that consider the contributions of both MSD and MSC mechanisms (Holler *et al*, 1985; Olaniyi *et al*, 1992; Chadwick and

Young, 1993; Demetriou *et al*, 1993). The aim of the present paper is to study the continuum double-differential cross-sections of several reactions with both MSD and MSC contributions and to require flux conservation.

We analyse the reactions of 14 MeV neutrons with ^{51}V , ^{56}Fe , Zr, ^{93}Nb , Mo, and Sb; these are convenient for such analyses since the MSD and MSC contributions are comparable in magnitude. In addition, we perform a systematic analyses of the MSD component for a more extensive range of targets to explore the dependence of the reaction on the atomic mass number A . We chose for analysis the extensive data of Takahashi *et al* (1992) which are generally in good agreement with those of Pavlik *et al* (1992), and of Vilaithong *et al* (1992).

In section 2 we describe the subtraction method of analysis for the MSD process and in section 3 the analysis of the MSC process. In section 4 we describe the Hauser-Feshbach (HF) calculations of the compound nucleus emission (including multiparticle emission) and of the collective excitations. Adding these contributions allows the whole emission spectrum to be analysed, and the results are shown in section 5. Our conclusions are given in section 6.

The formalism of the MSC and MSD theories has been extensively described by Bonetti *et al*, (1991, 1994).

2. Analysis of MSD reactions.

2.1 Determination of V_0 by the Subtraction Method

The MSD theory gives the double-differential DWBA cross-sections in the continuum for several energies and transferred angular momenta ℓ . To evaluate them we use the program DWUCK4 with a Yukawa effective nucleon-nucleon potential of range 1 fm and strength V_0 for $1p1h$ excitations. These DWBA cross-sections are processed by the MSD code (Olaniyi, 1992) by averaging over a 6 MeV energy range to remove unphysical fluctuations and Gaussian smoothing of width 2 MeV for each ℓ transfer, averaging over 12 ℓ values. The wave functions in the form factors for unbound states were obtained from optical potentials. For neutron scattering we used the Wilmore-Hodgson (1964) parameters and for proton scattering those of Becchetti and Greenlees (1969). For bound states we used a real Woods-Saxon potential with radius parameter 1.2 fm, diffuseness 0.6 fm and depth fixed to give the experimental separation energy. These parameters together with those defining the scattering wavefunctions are given in Table I. The state density formulae of Williams are used with the single-particle spacing given by $g = A/13$ with the pairing corrections of Dilg *et al* (1973). A Gaussian angular momentum distribution is assumed with spin cut-off $\sigma_n^2 = 0.24nA^{2/3}$ (Gruppelaar, 1983). Only the one-step cross-section is calculated since the two-step cross-sections are negligible at 14 MeV (Chadwick and Young, 1993).

Table I. Potential parameters with depths in MeV, radii and diffuseness in fm.

	V_R	r_R	a_R	W_V	W_S	r_W	a_W	V_{SO}	r_{SO}	a_{SO}
$n^{(1)}$	42.9	1.279	0.66		8.78	1.245	0.48			
$p^{(2)}$	55.9	1.17	0.75	0.369	9.73	1.32	0.59	6.2	1.01	0.75
b.s. ⁽³⁾	55	1.2	0.6							

⁽¹⁾ Wilmore and Hodgson (1964). ⁽²⁾ Becchetti and Greenlees (1969). ⁽³⁾ Bound state depths adjusted to fit the experimental separation energies.

The direct components of nuclear reactions give cross-sections that are generally asymmetric in the centre of mass (CM) system, whereas the compound nucleus components, both MSC and HF, are symmetric. If therefore we subtract the CM cross-sections at complementary angles we remove all the MSC and HF cross-sections, leaving only the asymmetric part of the direct cross-sections. For the reactions considered here, these come from the MSD reactions and the inelastic scattering reactions exciting the collective states which give neutrons of higher energies. The subtracted spectra for lower emitted energies are therefore due to MSD only, and comparison with the **similarly-subtracted** calculated MSD spectra enables the theory to be tested and the value of V_0 determined (Demetriou *et al*, 1993). This analysis was applied to the data for seven nuclei, and some of the results are shown in figure 1. The FKK theory gives the cross-sections of reactions to the fragmented single-particle states in the continuum, but not that to individual low-lying collective states. We therefore do not expect to fit the peaks at high emission energies.

Table II. Values of V_0 in MeV for each pair of complementary angles and the average obtained by the subtraction method.

Angles($^\circ$)	^{51}V	^{56}Fe	^{nat}Zr	^{93}Nb	^{nat}Mo	^{nat}Sb
30–150	70 $\pm$ 3	81 $\pm$ 3	48 $\pm$ 2	40 $\pm$ 2	44 $\pm$ 1	35 $\pm$ 2
40–140	61 $\pm$ 3	72 $\pm$ 2	41 $\pm$ 2	34 $\pm$ 2	38 $\pm$ 1	31 $\pm$ 1
50–130	53 $\pm$ 4	59 $\pm$ 3	27 $\pm$ 2	34 $\pm$ 2	32 $\pm$ 1	19 $\pm$ 2
60–120	46 $\pm$ 5	41 $\pm$ 5	21 $\pm$ 4	33 $\pm$ 2	32 $\pm$ 2	13 $\pm$ 4
Average	61 $\pm$ 6	66 $\pm$ 7	41 $\pm$ 5	35 $\pm$ 2	38 $\pm$ 5	30 $\pm$ 6

This method of analysis enables the MSD theory to be checked in three ways : (i) by the goodness of the fit of the normalised calculations to the experimental data (see figure 1), (ii) by the agreement between the values of V_0 extracted from several pairs of complementary angles (see Table II and figure 1) and (iii) by the symmetry of the cross-sections obtained by subtracting the MSD cross-section from the experimental data. A value of V_0 is obtained from the analysis of the data over the energy range 5-8 MeV for each pair of complementary angles, and

DOUBLE DIFFERENTIAL CROSS SECTION (mbarns/MeV sr)

Figure 1. Subtracted double differential cross-sections in the CM system for 14 MeV neutrons scattered by ^{51}V , ^{56}Fe and ^{93}Nb for four pairs of complementary angles, compared with the similarly subtracted cross-sections calculated with the multistep direct theory of FKK (1980). The triangles are the subtracted cross-sections calculated using the average value of the effective interaction strength $\bar{V}_0$ for the four angle pairs. The data are obtained from Takahashi *et al* (1992).

these are combined to give an average value $\overline{V}_0$ by weighting by $\sin \theta_i$ and by the statistical weights ω_i of the data for each angle pair so that

$$\overline{V}_0 = \sqrt{\sum_i \omega_i V_{0i}^2 \sin \theta_i / \sum_i \omega_i \sin \theta_i}$$

This value is used in the calculations of the angle-integrated spectra. The value of V_0 obtained by the subtraction method is obtained only from the asymmetric part of the MSD cross-section but this introduces no uncertainty since the V_0 affects only the magnitude of the cross-section and not the reaction dynamics. The symmetric part is not small; indeed at incident energies around 14 MeV it amounts to about two-thirds of the total MSD cross-section for ^{93}Nb . The average values of V_0 for ^{51}V , ^{56}Fe , Zr , ^{93}Nb , Mo , and Sb found in this way are shown in Table II. We emphasise that the subtraction method does not assume that the MSD cross-section is negligible in the backward direction.

The values of V_0 obtained from different angle pairs show a definite tendency to increase for the pairs with the smaller forward angle. This could indicate asymmetry in the compound nucleus cross-section, as discussed by Kun (1993). We think it is more likely, however, that it is attributable to measurement difficulties because (i) analyses of (p, n) and (p, p') reactions by Watanabe *et al* (1994) fit the data very well and show no such effect and (ii) measurements of the same reaction by different groups often show significant differences in the small angle region. We consider that the excess at low energies for ^{56}Fe in figure 1b has the same explanation.

Figure 2 shows the $\overline{V}_0$ values obtained for a large number of targets, some of which are included in Table II. There is an overall tendency for $\overline{V}_0$ to decrease with A , and this is in agreement with the results of Richter *et al* (1992).

3. Analysis of MSC Reactions

When both MSD and MSC processes contribute, the incident reaction flux going to the Q- chain is reduced by the factor R^{MSC} , and following Chadwick and Young (1993) we assume that this is given by the ratio of the bound to the total $2p1h$ phase space

$$R^{MSC} = \frac{\omega^B(2p, 1h, E)}{\omega(2p, 1h, E)}$$

where the $\omega(2p, 1h, E)$ are calculated using the formula of Williams (1971).

The wavefunctions of the bound and unbound states are assumed to be constant following FKK. The V_0 factors in the MSC cross-section cancel, so the MSC emission is obtained without any free parameters. The reduction factors R^{MSC} for the targets considered in the analysis are shown in Table III.

Figure 2.

Figure 2. The effective interaction strength $\bar{V}_0$ as a function of the atomic mass A of the target nucleus for the MSD component of inelastic neutron scattering at incident energy 14 MeV.

Table III. Reduction factors R^{MSC} , excitation energies ω_λ and deformation parameters β_λ of two low-lying phonon states of multipolarity 2^+ and 3^- for ^{51}V , ^{56}Fe and ^{93}Nb .

Nuclei	^{51}V	^{56}Fe	^{93}Nb
$R^{MSC(1)}$	0.305	0.366	0.214
$\omega_2^{(2)}$ (MeV)	1.55	0.85	0.93
$\beta_2^{(2)}$	0.17	0.24	0.13
$\omega_3^{(2)}$ (MeV)	3.00	4.52	2.30
$\beta_3^{(2)}$	0.14	0.18	0.18

(1) MSC5X-code (Chadwick and Young, 1993)

(2) Kalka *et al* (1989)

In this analysis we aim to include the cross-sections from all the contributing processes and satisfy flux conservation following a different method of determining the MSC contribution from that used by Demetriou *et al* (1993). In that work the MSC component was calculated using the n-n effective interaction strength as a free parameter and fitting the MSC + MSD contributions to the experimental data in the preequilibrium energy region. The compound nucleus cross-section we obtained in this way was quite low and led to the violation of flux conservation. This disagreement was due to the neglect of transitions from P to Q chain after the first step, which are not included in the original FKK formalism. To include these transitions, we follow the method of Chadwick and Young (1993) and determine the flux going into the Q-chain with the R-factor in the above expression. Our results show a considerably smaller MSC contribution even in the low energy region compared with that of Demetriou *et al* (1993). This means that the flux going directly into the Q-chain has to be reduced and the contribution of the P to Q transitions increased significantly in order to satisfy flux conservation. This is in agreement with other work which stress the importance of these transitions (Chadwick and Young, 1993; Marcinkowski *et al*, 1991, 1994). Finally, the use of a phase-space reduction factor (R^{MSC}) as given in the above expression has been further tested (Sato and Yoshida, 1993) and can be used as a reliable method of determining the partitioning of the flux in the two primary channels (P and Q).

The MSC5X computer code of Chadwick and Young (1993) was used with the same input parameters as those used in the MSD calculations.

4. Other Contributions

4.1 Compound Nucleus emission

After the first few preequilibrium stages, the energy of the projectile has been shared statistically among so many nucleons that the compound nucleus can be regarded as equilibrated. Emission from the compound nucleus stage is calculated by the Hauser-Feshbach (1952) theory using the code STAPRE-H (Uhl and

Strohmaier, 1976; Avrigeanu *et al*, 1994). The contributions from multi-particle emission reactions such as $(n, 2n)$, (n, pn) , $(n, \alpha n)$ are also calculated by this code.

4.2 Collective Excitations

At low excitation energies, inelastic scattering with excitation of collective modes gives prominent peaks in the cross-section. The most important of these are excitations of the 2^+ and 3^- states along with the less probable excitation of the low energy octupole resonance. These contributions are calculated using the expression of Kalka *et al*, (1989) for one-phonon and two-phonon transitions to the continuum. The one-phonon cross-section is:

$$\frac{d\sigma_{f,i}}{dU_{f\text{phonon}}} = \left(\frac{mV}{2\pi\hbar^2}\right)^2 \frac{4\pi}{(k_i R)^2} \delta_{i,f} \sum_{\lambda} \bar{\beta}_{\lambda}^2 V_R^2 \delta(U - \omega_{\lambda}) \frac{k_f}{k_i} P_f(\epsilon_f) P_i(\epsilon_i)$$

where V_R is the real potential depth, $V = \frac{4}{3}\pi R^3$, $R = r_0 A^{1/3}$, $\bar{\beta}_{\lambda} [4\pi(2\lambda + 1)]^{1/2} = \beta_{\lambda}$ is the nuclear deformation parameter, and ω_{λ} is the excitation energy of the excitation mode with angular momentum λ . The penetrability factor $P_i(\epsilon_i)$ is equal to one for neutrons. The angular distribution was obtained by a DWBA calculation of the collective excitation cross-section using DWUCK4 (Kunz). The deformation parameters β_{λ} were taken from Kalka *et al* (1989) and are shown in Table III.

5. Results

The multistep, compound nucleus and collective excitation contributions to the inelastic scattering of 14.1 MeV neutrons by ^{51}V , ^{56}Fe , Zr, Nb, Mo and Sb have been calculated as described in the previous sections, and the results for the angle-integrated spectra for ^{51}V , ^{56}Fe and ^{93}Nb are compared with the data of Takahashi *et al* in figure 3. The angular distributions for the same nuclei for two emission energies are compared with the data in figure 4.

In this analysis, we have included all the major contributions to the reactions initiated by 14.1 MeV neutrons on a range of nuclei. The cross-sections of the remaining reactions such as $\sigma(n, \alpha)$ are calculated by STAPRE-H (Uhl and Strohmaier, 1976; Avrigeanu *et al* 1994). This enables us to sum the cross-sections in all the contributing reaction channels and to compare with the total reaction cross-section (see Table IV).

On the whole the calculations fit the experimental data particularly for ^{93}Nb . For the other two nuclei, ^{51}V and ^{56}Fe , a more detailed evaluation of the collective contributions to higher outgoing energies is required.

6. Discussion

This paper describes a complete analysis of the principal reactions of 14.1 MeV neutrons on a range of nuclei. The multistep compound and multistep direct

Figure 3.

Figure 3. Angle-integrated energy spectra for the reactions $^{51}\text{V}(n,n')$, $^{56}\text{Fe}(n,n')$ and $^{93}\text{Nb}(n,n')$ at 14 MeV compared with the calculated MSD (dashed curve), MSC (dot-dashed curve), HF (dot-long dashed curve) and collective excitation (dotted curve) calculations. The solid line shows the sum of all these contributions. The experimental points are from the data of Takahashi *et al* (1992).

Figure 4.

Figure 4. Angular distributions for the reactions $^{51}\text{V}(n,n')$, $^{56}\text{Fe}(n,n')$ and $^{93}\text{Nb}(n,n')$ at 14 MeV for outgoing energies of 3 ± 1 and 8 ± 1 MeV compared with the MSD (dashed curve), MSC (dot-dashed curve) and HF (dotted curve) calculations. The solid line includes all contributions and the experimental points are those of Takahashi *et al* (1992).

contributions to inelastic scattering are calculated using the theory of Feshbach, Kerman and Koonin, and the compound nucleus contributions by that of Hauser and Feshbach. Adding these together, and including the collective excitations, accounts well for the double-differential cross-section for neutron emission and inclusion of the cross-sections of several other reactions enables flux conservation to be confirmed within the uncertainties. We have confirmed the dependence of V_0 on A and our values are in accord with the known energy dependence. It would be desirable to improve the calculations by using realistic bound state wavefunctions for the MSC contribution and to include a two-component formulation for proton-neutron distinguishability.

Since the FKK theory has been successful in describing nucleon inelastic scattering for a wide range of nuclei, especially at the low and intermediate incident energies, it would be useful to extend it to include the emission of composite particles. These are important reactions for nuclear data applications in fusion technology and in cancer radiation treatment.

Table IV. Cross-sections in mbarns calculated for each contribution and comparison of the total reaction cross-sections with those obtained from optical model calculations.

Nuclei Reaction	⁵¹ V		⁵⁶ Fe		⁹³ Nb	
	Th	Exp	Th	Exp	Th	Exp
MSD	278	—	237	—	281	—
MSC	55	—	35	—	66	—
Coll.Exc ^c	55		116	144±6 ^e	114	100±10 ^e
H-F ^d	797		902		1221	
γ emission ^f	5		5		5	
(n, px)	114 ^d	91±14 ^b	35 ^d		22.3 ^d	42.4±2 ^a
(n, αx)	21 ^d	17±3 ^b	17 ^d		11.6 ^d	14±3 ^b
Total	1325±85 ^g		1347±94 ^g		1721±100 ^g	
σ _R (OM)	1384		1419		1745	

^a Fischer *et al* (1988). ^b Grimes *et al* (1978). ^c Kalka *et al* (1989). ^d STAPRE-H (Uhl and Strohmaier, 1976; Avrigeanu *et al*, 1994). ^e Takahashi *et al* (1992). ^f GNASH Chadwick and Young (1993). ^g theoretical estimate.

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