acta physica slovaca vol. 45 No. 6, 725 – 732 December 1995

ON GRADUAL ABSORPTION AND THE VARIETY OF PREEQUILIBRIUM REACTIONS[1]

A. Marcinkowski[2]
Soltan Institute for Nuclear Studies, Hoza 69, 00-681 Warszawa, Poland

Received 23 October 1995, accepted 27 October 1995

The nonelastic direct reactions were devided into the incoherent MSD reactions and the collective reactions that excite coherently nuclear vibrations. This removes the inconsistency in the description of the (n, xn) and (p, xn) reactions in the framework of the MSD model of FKK. The influence of the strong nonelastic direct reactions and of the accompanying gradual absorption on modelling and calculations of the MSD and MSC preequilibrium reactions is discussed.

1. Introduction

In the first semiclassical models of preequilibrium nuclear reactions they were considered as a homogenous reaction mechanism. First in 1980 Feshbach, Kerman and Koonin [1] (FKK) emphasized the distinctly different features of the multistep direct reactions (MSD) and the preequilibrium compound ones, called multistep compound reactions (MSC). In this way FKK have introduced the third reaction mechanism. The remaining two, the direct reactions and the compound nucleus reactions (CN), have been recognized long ago.

The FKK theory assumed the statistical concept of doorway states as being applicable to multistep compound reactions. This means that absorption of the incoming flux into the quasibound compound states was considered to be a onestep process that forms the exclusive $2p1h$ doorway states. Onestep absorption maximizes the preequilibrium compound emission at the expense of compound nucleus formation and provides MSC cross sections that overpredict experimental neutron emission spectra at the intermediate outgoing energies, following the low energy domain of the compound nucleus as shown in Fig. 1. The excessive MSC cross sections originate from the large emission widths $\Gamma^{\uparrow}_{(M+1)pMh}$ and relatively small damping widths $\Gamma^{\downarrow}_{(M+1)pMh}$ predicted by FKK for the initial reaction stages M. The way of reducing the MSC emission and bringing the compound nucleus cross section to fit the data consists in letting less incoming

---

[1] Presented at the International Symposium on Pre-Equilibrium Reactions, Smolenice Castle, 23 – 27 October, 1995

[2] E-mail address: AMAR@FUW.EDU.PL

flux through the $2p1h$ doorway states by allowing gradual absorption to occur directly from the continuum into the more complicated quasibound states which are increasingly damped towards the compound nucleus. This way was suggested and theoretically motivated by Nishioka *et al.* [2, 3] and Arbanas *et al.* [4], and applied by Marcinkowski *et al.* [5, 6] and Chadwick and Young [7].

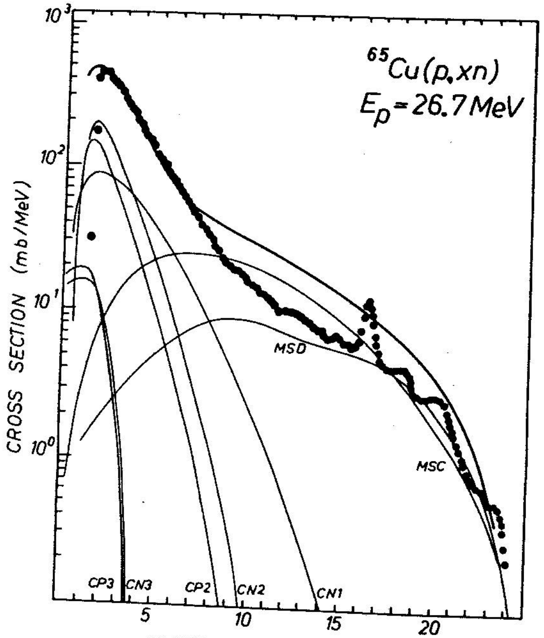

Fig. 1. Comparison of the angle-integrated CM cross section for neutron emission from ^{65}Cu bombarded by 26.7 MeV protons [28] with calculations according to the original FKK theory.

A reduction of the excessive MSC emission can be obtained using emission and damping widths that provide lower $\Gamma^{\uparrow}_{(M+1)pMh}/\Gamma^{\downarrow}_{(M+1)pMh}$ ratios. However, this option was not intensively investigated except that Bonetti *at al.* [8] calculated the widths including overlap integrals of more realistic wavefunctions than the wavefunctions constant inside the nucleus [1]. The early applications in the original paper of FKK [1] as well as by Herman *et al.* [9] and Kalka *et al.* [10] used the particle-hole state densities of Ericson [11], which do not satisfy the bound-state-only requirement, to evaluate the densities of states $Y^{M+\Delta M}$ accessible in the intranuclear MSC transitions $\Delta M=\pm 1,0$ and this resulted in a reduction of the $\Gamma^{\uparrow}_{(M+1)pMh}/\Gamma^{\downarrow}_{(M+1)pMh}$ ratio. Not until expressions for the densities of the bound-particle-hole states adequate for MSC processes were developed and applied was the excessive emission from the doorway states revealed [12, 13]. It is worth emphasizing that the EXIFON code [14] used in many evaluations of neutron cross sections owes its success to the use of the unrestricted state densities, incorrect for the MSC calculations.

2. Compound reactions in presence of strong multistep direct processes

The optical model reaction cross section σ_r accounts for all the flux removed from the elastic channel. However the removed flux feeds not only the quasibound, compound states of the MSC reaction chain but also the direct nonelastic reactions which do not involve the compound states and thus do not contribute to absorption. The cross sections of these reactions are estimated to be up to 40% of the optical model absorption cross section for neutrons of 26 MeV energy incident on ^{93}Nb [15]. It is this large cross section of the multistep direct nonelastic reactions that enables gradual absorption of the incoming flux via the continuum transitions followed by a transition into the more complicated quasibound states [3, 4]. Therefore to calculate the MSC and the CN cross sections the optical model absorption, $\sigma_c=\sigma_r+\sigma_{el}^{comp}$, has to be reduced by the amount of the direct nonelastic reactions. Let us call the fraction of the optical model absorption cross section due to these reactions (1–R), so that R is the fraction that feeds the MSC reaction chain. Gradual absorption splits R into the partial R_M's that describe feeding of separate reaction stages M [6]. Thus the absorption cross section to be used in MSC calculations is [15],

$$\sigma_a = R\sigma_c = \frac{\lambda^2}{4\pi}\sum_M R_M$$

$$\sum_{J^\pi}\sum_{j=|J-I|}^{J+I}\frac{(2J+1)}{(2i+1)(2I+1)}T_j, \quad (1)$$

with i, I, J, j being the spins of the projectile, the target nucleus, the composite nucleus and the total angular momentum of the projectile, respectively. The partial-wave transmission coefficients T_j come from the standard optical model. The R_M's are determined by a recurrence formula given by Marcinkowski *et al.* [6],

$$R_M = (R - R_1 - ... - R_{M-1})$$
$$\rho^B_{(M+1)pMh}/\rho_{(M+1)pMh}, \quad (2)$$

with R_0=0. The latter was obtained from a phase-space model by considering the densities of the unrestricted states ρ and of the bound-particle-hole states ρ^B.

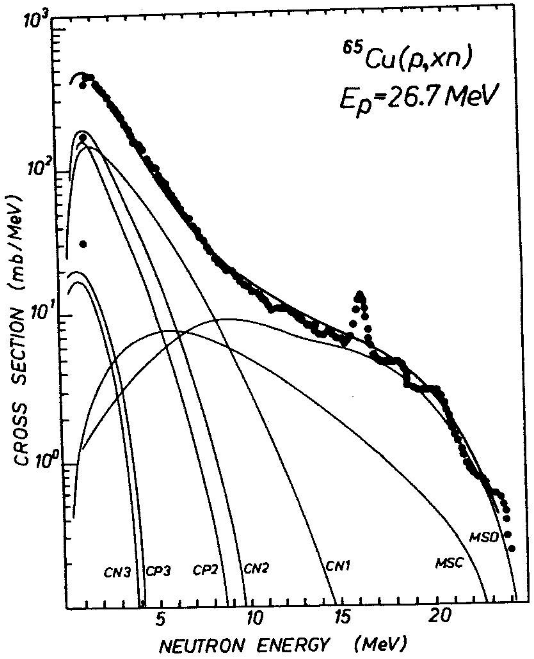

Fig. 2. As in Fig. 1, but the calculations account for gradual absorption from the phase-space model.

The predictions based on the phase-space model were supported by Sato and Yoshida [16], who investigated the influence of the imaginary optical potential on the transitions into the compound states and very recently Arbanas *et al.* [4] provided a quantum mechanical justification of gradual absorption by using the non-normal DWBA matrix elements for the continuum transitions and included it successfully into the calculations of neutron emission cross sections. Calculations in which the partial R_M's are used provide best fits to experimental data [4, 15, 17], shown in Fig. 2, although application of $R_1=\rho^{B}_{2p1h}/\rho_{2p1h}$ as an overall reduction factor [7] results also in a good description of experimental cross sections [18].

It is worth emphasizing that gradual absorption is not in line with the concept of statistical doorway states in MSC reactions. Since gradual absorption is justified by strong multistep direct transitions, which require the use of non-normal DWBA matrix elements in MSD calculations [4], it also questions the argumentation in favour of the normal DWBA matrix elements by Feshbach [19].

3. The nonelastic direct reactions

It has been shown recently that the nonelastic direct reactions can not be described consistenly in the framework of the MSD reaction model of FKK.

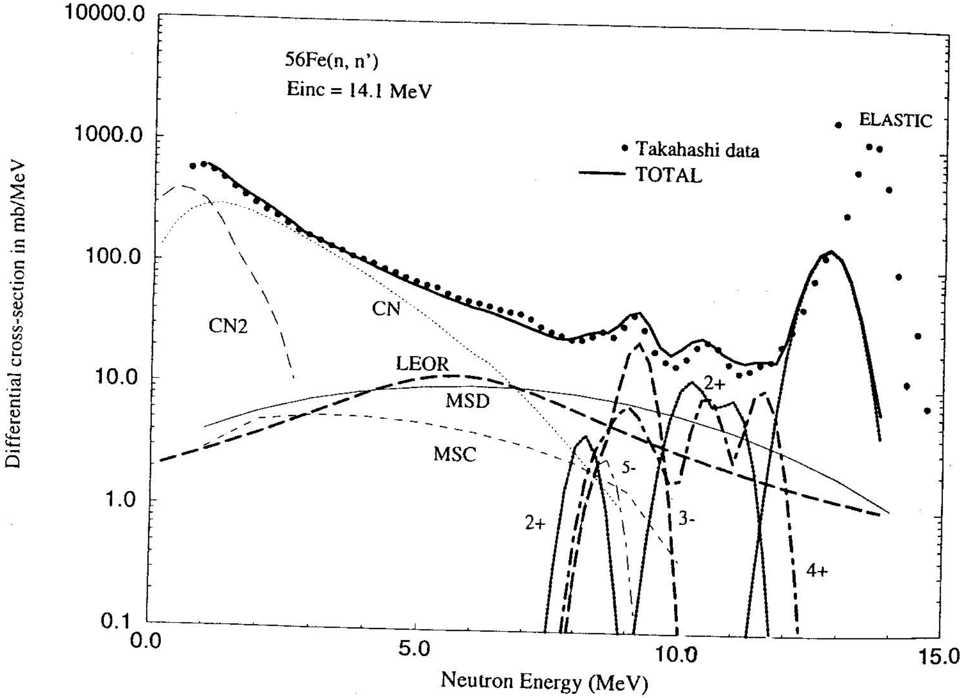

Fig. 3. Comparison of the angle-integrated CM cross section for neutron emission from ^{56}Fe bombarded by 14.1 MeV neutrons [29] with calculated cross sections for excitation of collective vibrations of different multipolarity and the MSD cross section with parameters from the fit in figure 2, together with CN and MSC cross sections including gradual absorption from the phace-space model.

The physically justified parameters that fit the cross sections of the (p,xn) reactions [17] determine MSD cross sections that are too low to fit the measured (n,xn) reaction data. To restore the fit it was just sufficient to calculate and add the cross sections for the direct excitation of the isoscalar collective states including the giant resonances in the continuum (see fig. 3) [18, 20]. This means that the direct inelastic scattering reaction can be divided into two different types of reactions, the ones involving incoherent particle-hole excitations and the other exciting coherently the collective vibrations of the whole nucleus. The former are to be identified with the MSD reactions of FKK whereas the latter can be calculated from the macroscopic model by the DWBA [21].

Practically this division is approximate since the strengths of the giant resonances are taken from the EWSR's which contains an unseparated contribution due to incoherent excitations and vice versa the MSD cross section includes some of the coherent ones. The total nonelastic MSD cross section and the total collective cross section determine the reduction factor $R=(\sigma_c-\sigma_{MSD}-\sigma_{COLL})/\sigma_c$ in (1). For the (n,xn) reaction on ^{93}Nb, at incident energies 14 MeV, 20 MeV and 26 MeV, the factors R amount to 0.82, 0.72 and 0.59, respectively [20]. The increasing contribution of the direct reactions is entirely due to the rise of the MSD cross sections since the fraction of the collective cross sections changes from 0.12 to 0.15 only, mainly due to the fall of the optical model absorption cross section, in the incident energy range considered.

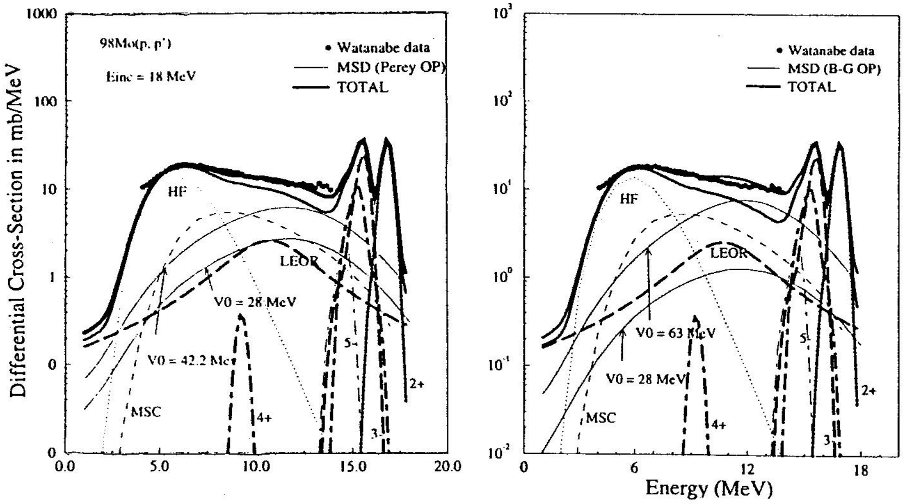

Fig. 4. As in Fig. 3, but for proton emission from ^{98}Mo bombarded with 18 MeV protons [23]. Best fits correspond to the artificial V_0=42.2 MeV when the optical potential of Percy [30] is used and V_0=63 MeV when the potential of Becchetti and Greenlees [31] is used. The realistic V_0=28 MeV results in MSD cross section that underestimates the experimental proton emission spectrum.

The consistent description of the (n,xn) and (p,xn) reactions, including gradual absorption and the collective reactions, is a partial success only since the very recent analyses of Demetriou *et al.* [22] and of Watanabe *et al.* [23] show that this approach fails to fit the proton emission channels. In particular the MSD cross sections for the (p,xp) reaction are too low when the parameters V_0=28 MeV, $g=A/13$ and $\sigma_2^2=0.56A^{2/3}$ that have proved successful in describing the neutron emission channels

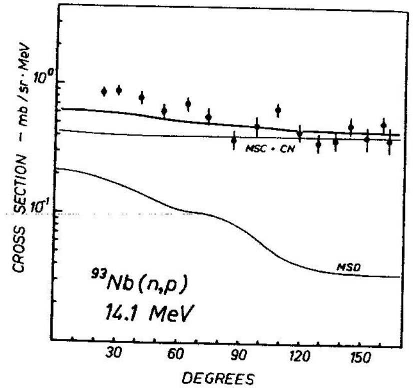

Fig. 5. Comparison of the angular distribution of protons of outgoing energy from 6 MeV to 8 MeV, emitted from ^{93}Nb bombarded with 14.1 MeV neutrons [26], with calculations including gradual absorption from the sphase-space model.

are used. Several possible reasons for this were investigated including neutron-proton distinguishability, sensitivity to optical potentials and nonlocality effects but the cross sections for proton emission remain low at the intermediate outgoing energies, as shown in Fig. 4.

The (n,xp) reaction was studied by Kielan *et al.* [24, 25], who investigated the excitation functions at incident energies from 13 MeV to 16.6 MeV and analysed also the proton spectra from the ^{63,65}Cu and ^{93}Nb targets bombarded with neutrons of energy close to 14 MeV. These authors found that fitting the proton emission cross sections at such low incident energy is rather inconclusive. Although satisfactory agreement between the calculated MSD emission spectra and the measured data can be obtained when the parameters given above were used, there are some questions concerning agreement with the forward peaked angular distributions observed in experiments also at the low outgoing proton energies [26]. The MSD cross section, which is in case of the (n,xp) reaction the only one that shows forward peaked angular distribution, contributes little at low proton energies (see Fig. 5). The calculated cross section of the (n,xp) reaction is also less sensitive to the presence of gradual absorption [25].

4. Conclusions

Gradual absorption is an effect of strong MSD transitions which can be explained only when the non-normal DWBA matrix elements are used. Best fits are obtained by calculating the gradual absorption at successive reaction stages from the phase-space model. However, according to Feshbach the calculations of the MSD cross sections are commonly based on the normal DWBA matrix elements. Since gradual absorption is needed to fit experimental data there is a contradiction inherent in using simultaneously gradual absorption and these MSD cross sections. On the other hand, recent calculations of the MSD cross sections including the non-normal DWBA matrix elements have proved true at incident energies below 30 MeV [4] but encountered difficulty in describing the ^{90}Zr(p,xn) reaction at incident proton energy of 80 MeV. In this case the multistep contributions at low outgoing energies are too large and result in an incorrect neutron spectrum shape [27]. Thus the question: "Is gradual absorption a significant, physical phenomenon?" remains still open.

The absorption cross section as defined in the optical model is inadequate for MSC and CN calculations since up to 40% of it is due to direct nonelastic reactions even at relatively low incident energies. These direct reactions do not involve formation of the quasibound particle-hole states and therefore do not feed the MSC and CN reactions. At energies lower than 30 MeV much of the inelastic scattering cross section comes from a direct excitation of the isoscalar collective vibrations of different multipolarity. These collective direct reactions contribute throughout the entire spectrum of scattered nucleons and show angular distributions that differ from the angular distributions of the MSD reactions. They can be extended to include two-phonon excitations [10] and viewed as a separate preequilibrium reaction mechanism [18, 20]. This is the fourth type of reactions beside the incoherent MSD, the MSC and the CN reactions that contribute appreciably to nucleon scattering cross sections.

The (n,xn), (p,xn) and (n,xp) reaction data are fitted with the physically justified V_0=28 MeV, $\sigma_2^2 = 0.56A^{2/3}$ and g=$A/13$ [17], whereas describing of the (p,xp) reaction requires an adjustable parameter in the MSD reaction model of FKK. This inconsistency needs further studies.

References

[1] H. Feshbach, A. Kerman, S. Koonin: *Ann.Phys. NY* **125** (1980) 429
[2] H. Nishioka, H.A. Weidenmuller, S. Yoshida: *Ann. Phys. NY* **183** (1988) 166
[3] H. Nishioka, H.A. Weidenmuller, S. Yoshida: *Z. Phys. A* **336** (1990) 197
[4] G. Arbanas, M.B. Chadwick, F.S. Dietrich, A.K. Kerman: *Phys. Rev. C* **51** (1995) R1078
[5] A. Marcinkowski, J. Rapaport, R.W. Finlay, X. Aslanoglou, D. Kielan: *Nucl. Phys. A* **530** (1991) 75
[6] A. Marcinkowski, J. Rapaport, R.W. Finlay, C. Brient, M. Herman, M.B. Chadwick: *Nucl. Phys.* **A561** (1993) 387
[7] M.B. Chadwick, P.G. Young: *Phys Rev. C* **47** (1993) 2255
[8] R. Bonetti, L. Colli-Milazzo, M. Melanotte: *Lett. Nuovo Cim.* **31** (1981) 33
[9] M. Herman, A. Marcinkowski, K. Stankiewicz: *Nucl. Phys. A* **430** (1984) 69
[10] H. Kalka, M. Torjman, D. Seeliger: *Phys. Rev. C* **40** (1989) 1619
[11] T. Ericson: *Adv. Phys.* **9** (1960) 425
[12] A. Marcinkowski: *IAEA Report INDC(NDS)-214/LJ* (1989) 79
[13] M.B. Chadwick: *Ph.D. Thesis, Oxford University, Oxford* (1989)
[14] H. Kalka: *Report INDC(GDR)-060/L IAEA, Vienna* (1990) 1
[15] A. Marcinkowski, D. Kielan: *Nucl. Phys. A* **578** (1994) 168
[16] K. Sato, S. Yoshida: *Phys. Rev. C* **49** (1994) 1099
[17] A. Marcinkowski, P. Demetriou, P.E. Hodgson: *J. Phys. G* **21** (1995) 1089
[18] P. Demetriou, A. Marcinkowski, P.E. Hodgson: *Nucl. Phys. A* (1995, *(in press)*)

[19] H. Feshbach: *Phys. Rev. C* **8** (1994) R2553 : *Ann. Phys. (NY)* **159** (1985) 150

[20] A. Marcinkowski, B. Marianski, P. Demetriou, P.E. Hodgson: *Phys. Rev. C* **52** (1995)

[21] G.A. Needham, F.P. Brady, D.H. Fitzgerald, J.L. Romero, J.L. Ullmann, J.W. Watson, C. Zanelli, N.S.P. King, G.R. Satchler: *Nucl. Phys.A* **385** (1982) 349

[22] P. Demetriou, P.E. Hodgson, A. Marcinkowski, Y. Watanabe: *to be published*

[23] Y. Watanabe, A. Aoto, H. Kashimoto, S. Chiba, T. Fukatori, K. Hasagawa, M. Mizumoto, S. Meigo, M. Sugimoto, Y .Yamanouti, N. Koori, M.B. Chadwick, P.E. Hodgson: *Phys. Rev. C* **51** (1995) 1891

[24] D. Kielan, A. Marcinkowski, U. Garuska: *Nucl. Phys.A* **559** (1993) 333

[25] D. Kielan and A. Marcinkowski: *Acta. Phys. Pol.B* **25** (1994) 1219

[26] G. Traxler, A. Chalupka, R. Fischer, B. Strohmaier, M. Uhl, H. Vonach: *Nucl. Sci. Eng.* **90** (1985) 174

[27] M.B. Chadwick, P.G. Young, F.S. Dietrich: *private communication*

[28] Y. Holler, A. Kamisky, R. Langkau, W. Scobel, M. Trabandt: *Nucl. Phys.A* **442** (1985) 79

[29] A. Takahashi, M. Gotoh, Y. Sasaki, H. Sugimoto: OKTAVIAN Report A-92-01. JAERI 1992

[30] F.G. Perey: *Phys. Rev.* **131** (1963) 745

[31] F.D. Becchetti, G.W. Greenlees: *Phys. Rev.* **182** (1969) 1190