acta phys. slov. 25 (1975), No. 2—3

PRE-EQUILIBRIUM MODEL ANALYSIS OF NUCLEON AND ALPHA INDUCED REACTIONS[1]

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This report deals with the exciton model which describes the pre-equilibrium decay of a composite nucleus on the basis of a simple statistical approach. The applications of the model to the analysis of nucleon and alpha induced reactions, at intermediate energy, are reviewed and summarized.

I. INTRODUCTION

In the last few years, many authors have shown that several features of reactions induced by intermediate energy particles can be explained by assuming that the reaction products are emitted in the course of the equilibration cascade which follows the projectile-target interaction.

In order to describe the pre-equilibrium emission process, theoretical models have been proposed which have been shown to be successful in describing the general features of intermediate energy reactions. In some cases a satisfactory agreement between the results of calculations and the experimental data has been achieved.

In this report we will discuss only one of these models, the exciton model. Review papers which describe different theoretical approaches for analyzing the experimental data can be found in literature, namely: the recent paper by J. Miller on Pre-equilibrium processes in which the Intranuclear Cascade Monte Carlo calculations and the Master Equation approach are critically reviewed [1], the paper by Bertrand and Peelle, which reports perhaps the most comprehensive analysis performed with the Monte Carlo technique of reactions induced by protons of intermediate energy [2]; the papers by Blann which describe the Hybrid and Geometry Dependent Hybrid Model [3]. Finally one should mention a recent paper by Feshbach [4], who aims to „reconcile pre-equilibrium theory with standard reaction theory", based on the suggestion of Grimes et al. [5], describing pre-equilibrium processes in terms of the statistical theory of doorway states.

II. THE EXCITON MODEL

The exciton model was suggested by Griffin [6] in 1966 and improved by several authors [7—15]. Recent developments make the model able to predict in absolute value, with good accuracy, the cross-sections of neutron and proton induced reactions at incident energies of up to about 60 MeV [11, 12, 14, 16]. In Section IV we hope to be able to show that equally satisfactory results can be achieved in the analysis of α-induced reactions.

In this model, which is a non equilibrium statistical model for nuclear reactions, one assumes that the projectile interacting with the nucleus gives rise to a chain of two-body interactions which eventually lead to the compound nucleus state through a sequence of states characterized by an increasing exciton number. At each stage of this equilibration process there is a competition between particle emission and exciton-exciton interactions leading to an increase in the number of particles and holes sharing the excitation energy. The two processes are characterized respectively by the decay rates $W_c^n(U)$ and $W_{eq}^n(U)$, n being the exciton number of the intermediate state.

II. 1. Decay rates for particle emission

The decay rates for particle emission $W_c^n(U)$ are evaluated by means of the detailed balance principle. This approach leads to the usual Weisskopf expression for decay rates, the only difference being the use of the state densities for p-particle, h-hole states:

$$W_c^n(U) = \frac{1}{\pi^2\hbar^3}\,\frac{A}{A+1}\,\frac{1}{\omega_n(U)}\sum_{\nu}(2s_\nu+1)m_\nu k_\nu(n)\int\limits_0^{E_\nu^{\max}}\sigma_{inv,\nu}(\varepsilon)\varepsilon\,\omega_{n-n_\nu}(U_R)\,\mathrm{d}\varepsilon \tag{1}$$

ν labels the different decay products, $\sigma_{inv,\nu}(\varepsilon)$ are the cross-sections for the inverse processes, $k_\nu(n)$ are numerical factors that take into account that, due to the identity of the projectile and to charge conservation, not all the configurations of the intermediate and residual nuclei, corresponding to a given number of particles and holes, are allowed. The state densities $\omega_n(U)$ and $\omega_{n-n_\nu}(U_R)$ can be calculated for any potential well by taking the finite depth of the potential well explicitly into account [14]. If one assumes, for simplicity,

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[1] Lecture given at the International Symposium on Neutron Induced Reactions at SMOLENICE, September 2—6, 1974.

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a square well, the constraint of reproducing a density of single nucleon states at Fermi energy, consistent with the spacing of slow neutron resonances, forces to choose a value of Fermi energy of $\varepsilon_0 = 20$ MeV, which corresponds to a well depth of about 28 MeV. These state densities are considered to be a reasonable approximation for nuclei far away from closed shell regions. Blann et al. [17] have reported calculations of state densities for nuclei near closed shell regions, based on a realistic set of single particle states.

II. 2. Decay rates for exciton-exciton interactions

An exciton-exciton interaction usually leads to an increase $\Delta n = +2$ in the exciton number. This transition can be triggered by each one of the n excitons of a given configuration. One needs, therefore, to evaluate the probability per unit time that a particle with the excitation energy u interacts with another particle of the Fermi sea, or a hole of the Fermi sea interacts with a hole above the Fermi top. These probabilities per unit time are called respectively the particle and hole collision probabilities per unit time and are given by the product $v\varrho\sigma$, where v is the nucleon velocity ($v = \sqrt{2\varepsilon/m}$, $\varepsilon > \varepsilon_0$ for a particle, $\varepsilon < \varepsilon_0$ for a hole, ε is the exciton energy evaluated from the bottom of the potential well), ϱ is the nuclear matter density, σ the average nucleon-nucleon cross-section in nuclear matter [14].

In order to evaluate the decay rates for an exciton-exciton interaction, the particle and hole collision probabilities W_{1p} and W_{1h} are averaged according to (2) and (3):

$$\overline{W}_{1p}(p, h, U) = \frac{1}{p\omega_{p,h}(U)} \int_0^U W_{1p}(u)\omega_{p-1,h}(U-u)\omega_{1,0}(u)\,du \qquad (2)$$

$$\overline{W}_{1h}(p, h, U) = \frac{1}{h\omega_{p,h}(U)} \int_0^U W_{1h}(u)\omega_{p,h-1}(U-u)\omega_{0,1}(u)\,du \qquad (3)$$

and, finally, the decay rate for exciton-exciton interactions of a composite nucleus, whose excitation energy is shared by $n(= p + h)$ excitons, is given by:

$$W^n_{eq}(p, h, U) = p\overline{W}_{1p}(p, h, U) + h\overline{W}_{1h}(p, h, U). \qquad (4)$$

The analysis of (p, n) and (p, xn) reactions indicates that the energy and exciton number dependence of the decay rates calculated in this way are reasonable but their absolute value is too high, provided that the decay rates for particle emission are correctly evaluated. This discrepancy is not

surprising due to the approximations one must introduce in order to simplify the calculation. For a careful discussion of this point see Ref. [14].

The required reduction factor (≈ 0.25) is obtained by normalising the theoretical value of the decay rate of a $2p - 1h$ excited system to the experimental one deduced from the analysis of (p, n) excitation functions [12].

In Figs. 1 and 2, the decay rates for exciton-exciton interactions are reported as a function of the composite nucleus excitation energy for different exciton numbers n $(= p + h)$ and respectively $p = h + 1$ and $p = h + 4$. These decay rates have been used in the analysis of the nucleon and α-particle induced reactions discussed later. These decay rates are evaluated for nucleons in a square potential well; the calculation for nucleons in a different potential well can be performed in the same way by evaluating the collision probabilities per unit time in a local density approximation by means of a proper average of the collision probabilities foreseen by the Fermi Gas Model. The figures show that the relation $W^n_{eq} \div 1/(n + 1)$ reported by Williams [8] in the approximation of energy independent matrix elements for residual two body interactions is satisfactory only for excitation energies up to about 10 MeV. The exciton-exciton interaction decay rates are A independent as implicitly

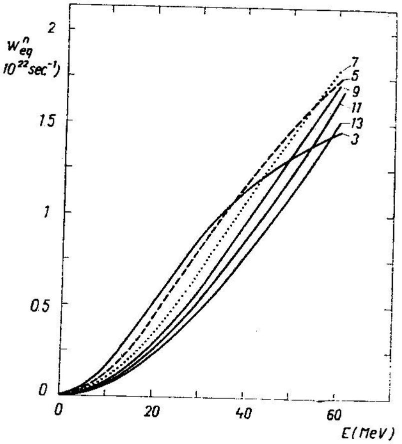

Fig. 1. Decay rates for exciton-exciton interactions, corresponding to different n values ($n = p + h$, $p = h + 1$), reported as a function of the composite nucleus excitation energy E.

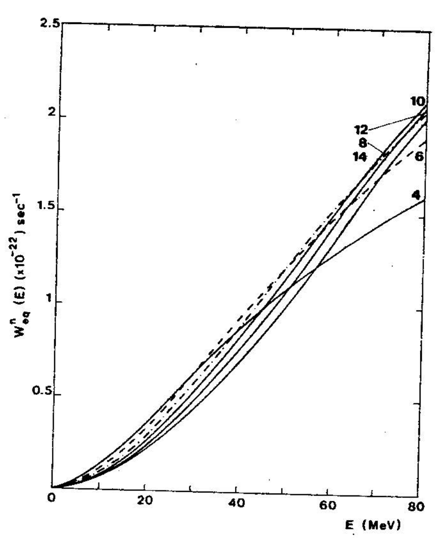

Fig. 2. Decay rates for exciton-exciton interactions, corresponding to different n values ($n = p + h$, $p = h + 4$), reported as a function of the composite nucleus excitation energy.

assumed in all the early applications of the model [15] and explicitly shown in Ref. [11].

Once the decay rates for particle emission and exciton-exciton interactions are known, the cross-section for any given pre-equilibrium process and the compound nucleus formation cross-section are easily evaluated (see e. g. Refs. [12, 15, 16, 20]). The probability that a particle is emitted in a pre-equilibrium process, *PEF* is a strongly increasing function of the excitation energy of the composite nucleus, according to the above quoted calculations. As a typical figure, at an excitation energy of $U \approx 20$ MeV, the *PEF* ≈ 0.1 both in the case of a nucleon and α-induced reactions, and rises to ≈ 0.6 at $U \approx 60$ MeV.

III. ANALYSIS OF NUCLEON INDUCED REACTIONS

III. 1. Neutron induced reactions

Analyses of (n, p) reactions on the basis of the exciton model have been reported by **Braga Marcazzan** et al. [11] and **Decowski** et al. [18]. The former authors through a fitting of 74 (n, p) cross sections, measured by the activation technique at $E_n \approx 14$ MeV, induced on target nuclei with $A > 100$, showed that the $2p - 1h$ decay rate W^3_{eq} is really mass independent and its value for an excitation energy of ≈ 21 MeV amounts to about $\approx 0.41 \times 10^{22}$ sec^{-1} in very satisfactory agreement with the same value estimated from the analysis of (p, n) reactions (see later and Fig. 1). The calculations of these authors show that the exciton model satisfactorily reproduces also the spectral shape of the emitted protons.

The exciton model has proved to be successful also in reproducing, in absolute value, the pre-equilibrium contribution to (n, n') reactions, on nuclei spanning from Mg to Au, at $E_n \approx 14$ MeV. In fact, the analysis [19, 20] of the neutron spectra measured by D. **Hermsdorf** et al. shows that the exciton model, using the estimate of W^3_{eq} obtained from the analysis of (n, p) reactions, allows to estimate within 10 % the absolute value of this contribution.

Analyses of (n, α) reactions, at $E \approx 14$ MeV, have been reported by L. **Milazzo Colli** et al. [21], **Caplar** et al. and **Glowacka** et al. [22]. The best agreement between the predictions of the model and the experimental data has been obtained by assuming that the emitted α-particle is preformed in the target nucleus [21]. In this way the spectral distribution of emitted α-particles can be satisfactorily reproduced. The absolute value of the cross-sections sensitively depends on the probability φ for the incoming particle to strike an α-particle preformed in the target nucleus. The values of φ reported in Ref. [21] range in value from 0.8 to 0.1 fluctuating around an average value slowly decreasing from ≈ 0.5 for target nuclei with $A \approx 150$ to ≈ 0.2 for target nuclei with $A \approx 200$.

III. 2. Proton induced reactions

Analyses of the spectral shape of neutrons emitted in (p, n) reactions, induced by 12–20 MeV energy protons on nuclei spanning from $A \approx 50$ to $A \approx 200$, have been reported by **Griffin** [6, 23], **Grimes** et al. [5, 24], **Blann** et al. [15], **Verbinski and Burrus** [25], **Cline and Blann** [9], **Kalbach** et al. [26].

The results of these analyses indicate that the model, taking properly in to account pairing and shell effects, can satisfactorily reproduce the spectral distribution of the highest energy emitted neutrons. A satisfactory agreement between the predictions of the model and the experimental results has been obtained in the analysis of (p, xn) excitation functions.

Birattari et al. [12] have shown that the energy dependence of the high energy tails of the excitation functions of (p, n) reactions is explained by the model in a very natural way.

The use of the decay rates for exciton-exciton interactions reported in Fig. 1 allows to reproduce in absolute value, with good accuracy, all the measured (p, n) excitation functions reported in literature for target nuclei ranging from $A \approx 50$ up to $A \approx 170$ and energies extending, in some cases, up to 80 MeV.

A typical fit is shown in Fig. 3 for reaction ^{65}Cu(p, n) ^{65}Zn [27]. A very satisfactory fit is also obtained in the analysis of (p, xn) reactions, [14, 16, 28] see for instance in Fig. 4 the theoretical fit to the reactions $^{1\;1}$Ta$(p, 3n)$ ^{179}W and ^{181}Ta$(p, 4n)$ ^{178}W.

While the analysis of (p, xn) reactions is successful, the exciton model seems to fail to answer for the emission of high energy protons in (p, p') reactions.

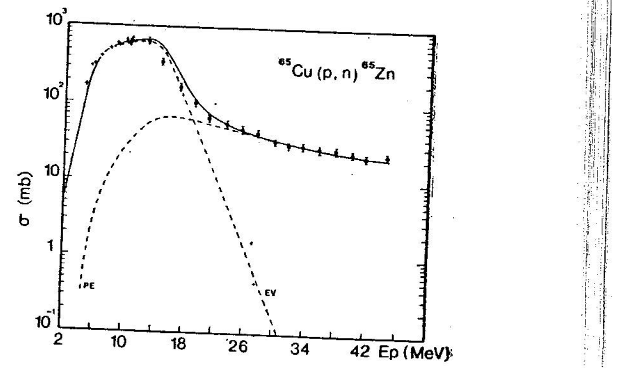

Fig. 3. Comparison between experimental data and theory for the excitation function of the reaction ^{65}Cu(p, n) ^{65}Zn [27].

The (p, p) spectra are harder than (p, n) spectra and cannot be satisfactorily reproduced by the model if one assumes a $2p - 1h$ initial configuration.

This does not mean that the exciton model fails at all in predicting the proton yield in (p, p') reactions. For instance, at $E \approx 60$ MeV in the case of heavy nuclei, according to the calculations of Refs. [15] and [16], the model accounts for about 80 % of the proton emission.

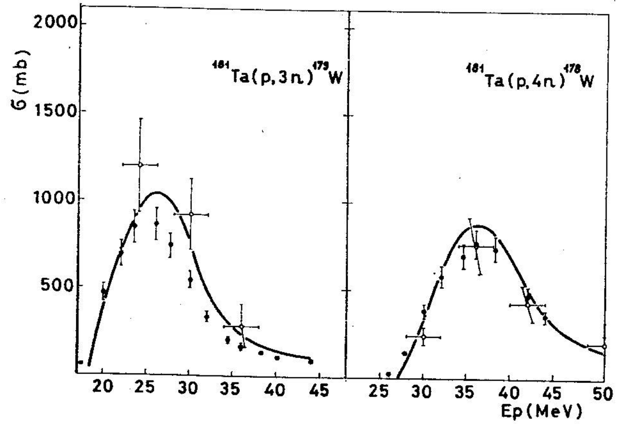

Fig. 4. Comparison of theory and experimental data for the reaction ^{181}Ta$(p, 3n)$, $(p, 4n)$. The experimental data are from Ref. [28] (black points) and Ref. [31] (open points).

Bertrand and **Peelle** [29] and **Cohen** et al. [30] have shown that good resolution experiments reveal the presence of structures in the hardest part of the proton spectra. **Cohen** et al. in their most interesting paper show that these structures correspond to excitations of groups of levels, of a collective nature, in the residual nucleus and show that a complete correspondence exists between the structures appearing in the proton spectra and the structures appearing in deuteron spectra in (d, d') reactions on the same target nuclei. This correspondence — taking into account that it is unlike for deuterons feeding the observed levels to be emitted in evaporation processes from the compound nucleus or in a pre-equilibrium process — strongly suggests that the reaction mechanism responsible of the emission of high energy protons in (p, p') reactions is a direct process.

In contrast with the conclusion of **Cohen**, **Kalbach** et al. [26] try to reproduce proton and neutron spectral distributions in (p, p') and (p, n) reactions, at $E_p \approx 18$ MeV on odd proton-even neutron target nuclei by the exciton model, assuming that the initial configuration of the composite system is a 2 proton — 0 hole configuration. In this case proton spectra which can be fed starting from the initial configurations are almost flat in good agreement with the data; neutron spectra which can be fed only starting from 3 particle — 1 hole configurations, of the type 2 proton — 1 neutron — 1 neutron hole, are softer than proton spectra and in fair agreement with the data. However, this assumption seems to contradict one of the basic assumptions of the model and, at the same time, implies the presence of odd-even effects in (p, p') and (p, n) reactions that are not observed. In fact, the exciton model is based on the assumption that the matrix elements for two-body interactions are not strongly dependent on the quantum numbers of the interacting particles. If this assumption is correct, the probability of sharing the excitation energy between two protons, at the first interaction of the incident proton with the target, is given by:

$$P_{2\pi} \approx \frac{\omega_{2\pi}(U)}{\omega_{2\pi,1\pi^-}(U)+\omega_{1\pi,1\nu,1\nu^-}(U)} \approx \frac{4}{3}\,\frac{U-\Delta}{g(U-2\Delta)^2} \tag{5}$$

where U is the composite nucleus excitation energy and g the density of single nucleon states at the Fermi energy (we have indicated, respectively, by means of π, ν, π^-, ν^- a proton, a neutron, a proton hole and a neutron hole, and we have assumed, for simplicity, that the neutron and proton pairing energies are equal to Δ). In the three cases examined by these authcrs (^{103}Rh, ^{159}Tb, ^{169}Tm, $E_p = 18$ MeV) $P_{2\pi}$ ranges from about 0.4×10^{-2} to 0.2×10^{-2} and it appears extremely improbable that in the initial configuration, the excitation energy is shared only by the incident and the unpaired proton. In addition, the spectra of emitted protons should be markedly different for odd-even and even-even target nuclei. The proton spectra measured by **Bertrand** and **Peelle** [29] do not show such odd-even effect as

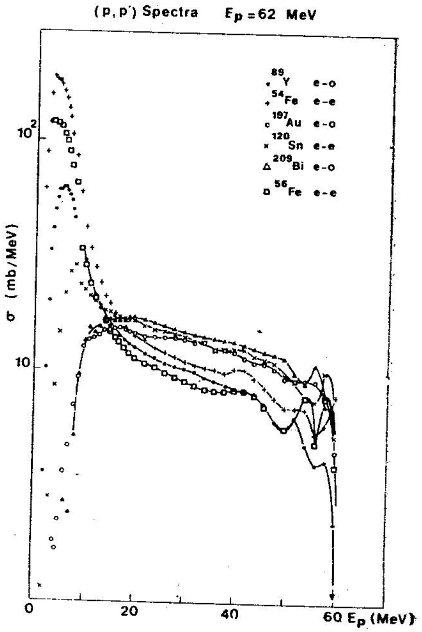

Fig. 5. Energy spectra of protons emitted in (p, p') reactions at $E_p \approx 62$ MeV, as measured by **Bertrand** and **Peelle** [29].

shown in Fig. 5. An analogous odd-even effect should be revealed by the slope and the absolute value of (p, n) excitation functions induced in odd and even target nuclei,* while in all cases the slope and the absolute value of these excitation functions is consistent with the hypothesis of a $2p - 1h$ initial configuration [12].

A different approach is proposed by **Blann**. Following the results of **Bertini** [32] and **Chen** et al. [33], **Blann** suggests that the most important contribution to a simple reaction like (p, p') is due to interactions of the projectile with nucleons on the outer edge of the target in a low density region, an tries to describe this process by means of his Geometry Dependent Hybrid Model [3]. It can be shown in a local density approximation that due to the small depth of the potential well, no energy is supplied to the holes in this nuclear region. The state density of the composite nucleus strongly resembles $\omega_{2p,0h}(U) \div g^2U$ and the residual nucleus density becomes equal to the density of single nucleon states g. The proton spectra, according to this model, are almost flat in fair agreement with the experimental results. However, it can be shown that this model overestimates the yield of high energy neutrons in the competing (p, n) reaction. In addition, for processes occuring on the surface of the nucleus in a region of low density ($\lesssim 0.15$ of its interior value) and high density gradient, the assumption of two-body interactions and of the validity of the Thomas Fermi approximation, upon which both the exciton and the hybrid model rely, is doubtful [34—36].

To conclude, in our opinion the exciton model can hardly account for high energy proton emission in (p, p') reactions. Arguments will be given later to support the hypothesis that proton interactions on the outer edge of the nucleus result in the excitation of low energy collective levels.

Measurements and exciton model analyses of (p, α) reactions have been reported by several authors [20, 22, 37—40]. The best fits to measured α-spectra have been obtained by assuming, as in the case of (n, α) reactions, that the emitted α-particle is preformed in the target nucleus. The φ factors estimated by **L. Milazzo Colli** et al. [20] from the analysis of the reactions induced on nuclei ranging from ^{115}In to ^{176}Yb, at incident proton energies in the interval of 16—18 MeV, agree very satisfactorily with the ones estimated by analysing (n, α) reactions at $E_n \approx 14$ MeV. On the other hand, the φ factors estimated by **Chevarier** [38] from the analysis of reactions induced by 43—50 MeV energy protons on nuclei ranging from Co to Bi appear to be mass independent and ≈ 0.2.

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* i.e. a steeper slope of (p,n) excitation function tails for odd target nuclei ($\sigma_{p,n} \div E_{inc}^{-3}$, at high energy) than for even target nuclei ($\sigma_{p,n} \div E_{inc}^{-2}$); a smaller cross-section for (p,n) reactions on odd target nuclei than for (p,n) reactions on even target nuclei.

III. 3. Nucleon mean free path

The nucleon mean free path corresponding to the decay rates reported in Figs. 1 and 2 is reported in Fig. 6. This figure shows that in all the energy range considered the mean free path is comparable with the diameter of a heavy nucleus. One could wonder, as a consequence, whether the nuclei would not appear too transparent to incident nucleons. The problem has been faced by **Gadioli** et al. [41] who have shown that the values of the neutron and proton absorption cross sections estimated by utilising the above reported mean free path is correct provided that the absorption of the incident nucleons occurs in a nuclear volume which includes also the regions where the density has fallen off to ≈ 0.01 of the interior value. This outcome is consistent with the results of Monte Carlo calculations [32, 33] which show that the diffuse surface region of the nucleus is very effective in contributing to the absorption of incident nucleons.

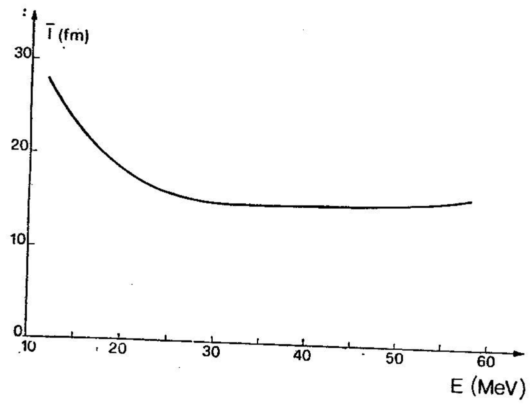

Fig. 6. The mean free path of a nucleon in the nucleus, reported as a function of the nucleon energy ε evaluated from the Fermi energy.

IV. ANALYSES OF α-INDUCED REACTIONS

As previously stated, the study of pre-equilibrium processes involving „complex“ particles, like α-particles, appears to be more complicated than the one of reactions involving simple nucleons. The analysis of (n, α) and (p, α) reactions, for instance, seems to indicate that the emitted α-particle is preformed in the target nucleus. The theoretical expressions for the cross-sections contain the unknown factor φ, to be extracted by experimental data, and further assumptions concerning the interaction of the α-particle with a nucleon of the Fermi sea and of the α-hole with a hole above the Fermi top are to be introduced in order to evaluate the decay rates. The study of processes induced by „complex“ particles seems to be simpler than the study of processes considered above. In this case the preformation probability has not to be taken into account. Further simplification arises if processes to which only the first stage of the equilibration cascade contributes are considered. Processes satisfying the above condition are (α, n) or (α, p) processes which leave the residual nucleus unable to emit further particles. These processes should constitute a powerful tool to study the configuration of the composite nucleus just after the α-target interaction.

The energy distribution of neutrons emitted in (α, n) reactions induced by 14—23 MeV α-particles has been measured and analysed by Magda et al. [42] and Grimes et al. [5] Magda et al. show that the contribution of pre-equilibrium processes to (α, n) reactions at $E_\alpha \approx 20$ MeV is of the order of 10 % in fair agreement with the estimate of *PEF* of Section II. These authors also report that their analysis gives some support to the hypothesis that the α-particle behaves like an exciton. This result is at variance with the results of the analyses of (α, p) reactions that will be discussed later and conflicts with the measurements of the yield and the spectral distribution of the α' s emitted in (α, α') processes, at $E_\alpha \approx 40-90$ MeV, as reported by Chevenert et al. [43]. In fact, if the α-particle behaves like an exciton, the yield of the α' s emitted in a pre-equilibrium (α, α') process should be greater than the measured one and their spectral distribution should greatly differ from the one measured by these authors. In addition one could hardly account for the absolute value of (α, n) excitation functions on light target nuclei at $E_\alpha \gtrsim$ $\gtrsim 25$ MeV.

Though one could not exclude that the interaction of an α-particle with a target nucleus could strongly differ at low and high incident energies, it should be stressed that the analysis of neutron spectra in terms of pre-equilibrium contributions strongly depends, at such a low α-particle energy, from the evaluation of the evaporative contribution; in fact the conclusions of Magda et al. concerning the reaction ^{56}Fe(α, n) are at variance with the ones of Grimes et al. according to which the α behaves like four uncorrelated nucleons.

Analyses of (α, xn) excitation functions on odd target nuclei in terms of the exciton model have been reported by Blann and Lanzafame [44] and Demeyer et al. [45]. The initial configuration is assumed to be a 3π, 2ν configuration according to a suggestion by Griffin [46].

Since 1955 various authors have reported that the analysis of proton spectra in (α, p) reactions, at $E_\alpha \gtrsim 20$ MeV, gives results not consistent with the predictions of the statistical model concerning the evaporation of protons from the compound nucleus [47]. The level density parameter a, extracted from a reduced plot of the proton distributions is much smaller than expected and does not show the expected increase with the mass number. Neither do the angular distributions, peaked forward, agree with the ones expected for an evaporative process. A far reaching suggestion (relying on previous work by Weisskopf [49] and Igo and Wegner [50]), by Sidorov [48] was that processes intermediate between a direct interaction and complete compound nucleus formation and decay could contribute to (α, n) and (α, p) reactions. In fact recent analyses of (α, p) reactions in terms of the exciton model constitute one of the most brilliant successes of the theory. Griffin [46] has analysed the proton spectra from (α, p) reactions on odd target nuclei, measured by Swenson and Cindro (a few of the following experiments may be mentioned) [47], suggesting a 3π, 2ν initial configuration. The same initial configuration was assumed in (α, xn) excitation function analyses [44, 45] as reported above, but later Blann and Mignerey [51] analysing the West data [47] assumed a 2π, 2ν initial configuration both for odd and even nuclei. The recent work by Chevarier et al. [52] who have measured and analysed proton spectra from (α, p) reactions at $E_\alpha \approx 54.8$ MeV is based on the hypothesis of 3π, 2ν and 2π, 2ν initial configurations for (α, p) reactions induced respectively on odd and even target nuclei. The recent paper by Bertrand et al. [53], who analysed charged particle spectra in reactions of 58 MeV α-particles with ^{12}C, ^{16}O, ^{54}Fe, is based on the hypothesis of a 2π, 2ν initial configuration.

The presence of odd-even effects in α-induced reactions is, in our opinion, hard to accept within the framework of the exciton model which is based on a statistical approach. 3π, 2ν states can arise from the interaction of the α-particle with the unpaired proton. The interaction of the α-particle with a proton or a neutron of the Fermi sea could give rise to 3π, 2ν, $1\pi^-$ and 3ν, 2π, $1\nu^-$ states. At a high excitation energy E, when the influence of the pairing effects should be reduced, the ratio R of the densities $\omega_{3\pi,2\nu}$ and $(\omega_{3\pi,2\nu,1\pi^-} + \omega_{3\nu,2\pi,1\nu^-})$ is $\approx 5/gE$. For nuclei with $A \gtrsim 50$ and $E \gtrsim 15$ MeV, $R \lesssim 0.088$ and only the assumption of strongly hindered interactions of the α-particle with the nucleons of the core could justify the presence of odd-even effects. Also the experimental evidence of the effect appears to be doubtful. A discussion by Chevarier et al. [52] shows that a pairing correction to the excitation energies could account for the effect. In addition the excitation functions of the (α, n) reactions do not show odd-even effects. The effect should reveal itself in two different ways: by an increased slope of the excitation function tails and, more important, by a sensitively smaller cross-section for odd target nuclei. These effects are hardly recognized in the measured excitation functions.

A comprehensive analysis of (α, n) excitation functions [54] has been undertaken by the present authors and G. Tagliaferri [55]*. The initial configura-

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* These reactions have been also analysed by Ribanský et al. [73].

tion was assumed to be a 2π, 2ν configuration. The decay rates for exciton-exciton interactions are the ones reported in Fig. 2. The inverse cross-sections for neutrons and protons are evaluated according to Ref. [41]. The binding energies are taken from Wapstra and Gove [56], the pairing energies from Nemirovski and Adamchuck [57], $g \approx (A/13.3)\,\mathrm{MeV}^{-1}$. The α-particle absorption cross-section is assumed to be $\approx 85\,\%$ of the total reaction cross-section according to the results of Chevenert et al. [43], which attribute $\approx 15\,\%$ of the reaction cross-section to processes that cannot be explained by a pre-equilibrium emission process.

The agreement of the calculations with the experimental excitation functions is reasonably good for medium-heavy target nuclei, far from closed shell regions (see in Figs. 7—9 the fit to the excitation functions of ^{138}Ba, ^{139}La and ^{165}Ho (α, n) reactions (the cross-section values are taken from [58—60]). For nuclei like ^{181}Ta and ^{197}Au the cross-sections, calculated using for the parameters the values quoted above are, at $E_\alpha \gtrsim 25$ MeV, markedly larger than the experimental ones [61, 62], (by approximately a factor 2), but a very reasonable agreement between calculation and experiment is achieved by taking into account a shell effect correction to the state densities of composite and residual nuclei according to the simple model of Ref. [63].

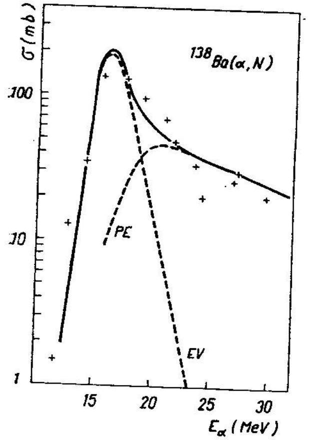

Fig. 7. Comparison between experimental data [58] and theory for the excitation function of the reaction ^{138}Ba(α, n) ^{141}Ce.

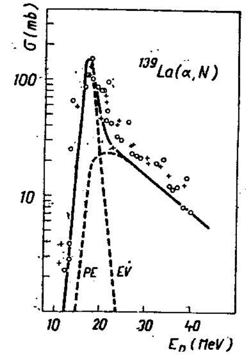

Fig. 8. Comparison between experimental data and theory for the excitation function of the reaction ^{139}La(α, n) ^{142}Pr. The experimental data are from Furukawa (crosses) and Verdieck and Miller (open points) [59].

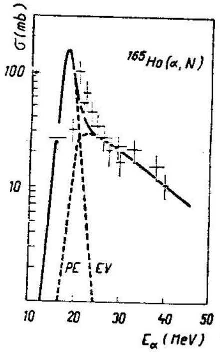

Fig. 9. Comparison between experimental data [60] and theory for the excitation function of the reaction ^{165}Ho(α, n) ^{168}Tm.

In the case of light nuclei ($A \approx 40—65$) the calculated excitation functions appreciably differ from the experimental ones at $E_\alpha \gtrsim 25$ MeV, showing a reduced slope and a higher cross-section. A much better agreement could be obtained by assuming a $5p$, $0h$ initial configuration, both for odd and even target nuclei. An alternative and, in our opinion, more satisfactory way of obtaining a reasonable fit to the data is to allow for an admixture of $5p - 1h$ states. Assuming that the composite nucleus state density ω^* is given by $\omega^* = k\omega_{4p,0h} + (1 - k)\omega_{5p,1h'}$ a very reasonable fit to the experimental excitation functions, for nuclei ranging from ^{41}K to ^{65}Cu, is obtained by assuming for k the values of Table 1. As an example, in Figs. 10 and 11, the comparison between the measured and calculated excitation functions of ^{55}Mn and ^{64}Zn(α, n) reactions is reported. An equally satisfactory fit to the measured (α, p) spectra [52, 53] is obtained using the same parameters and the k values of Table 1 (see Figs. 12 and 13).*

Table 1

Reaction	Reference	k
^{41}K (α, n) ^{44}Sc	[64]	0.991
^{45}Sc (α, n) ^{48}V	[65]	0.987
^{51}V (α, n) ^{54}Mn	[66]	0.997
^{54}Fe (α, n) ^{57}Ni	[67]	0.994
^{55}Mn(α, n) ^{58}Co	[64, 68]	0.990
^{60}Ni (α, n) ^{63}Zn	[69]	1.000
^{64}Zn (α, n) ^{67}Ge	[70]	0.996
^{65}Cu (α, n) ^{68}Ga	[71]	1.006

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* It should be mentioned that spin dependent level density calculations, according to the usual theory which assumes that the rotational energy of the residual nucleus is dissipated by the emission of γ rays on the assumption that no levels of spin J exist at energies less than the classical rotational energy [66, 72], overestimate the evaporative contribution to the excitation functions for $A \approx 40—65$ target nuclei at $E_\alpha \lesssim 40$ MeV if the moment of inertia is lower or equal to the spherical nucleus rigid body value J_{RS}. The theory, in this case, is unable to explain the long tails of (α, n) excitation functions, as already shown by Blann [68], and the spectral distribution of high energy protons in (α, p) reactions at $E_\alpha \approx 42$ MeV [47]. To obtain a satisfactory fit to the data there should be $J \geq 2J_{RS}$. Deformations of these nuclei could hardly account for this high value of the moment of inertia. It seems to be more plausible that the usual theory should be modified to take into account in a more realistic way the level density spin distribution.

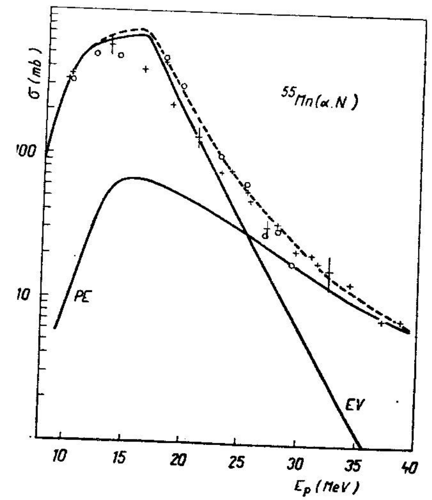

Fig. 10. Comparison between experimental data and theory for the excitation function of the reaction ^{55}Mn(α, n) ^{58}Co. The experimental data are from Matsuo et al. [64] (open points) and Tanaka et al. [68] (crosses).

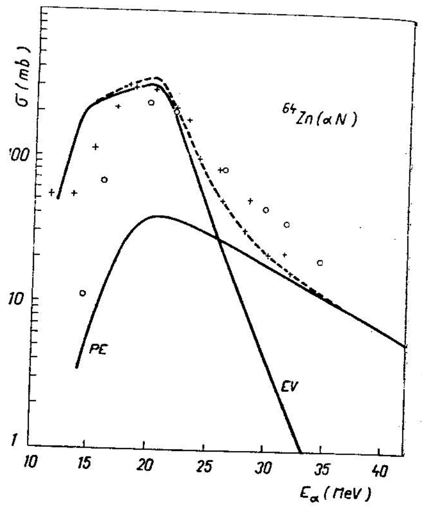

Fig. 11. Comparison between experimental data and theory for the excitation function of the reaction ^{64}Zn(α, n) ^{67}Ge. The experimental data are from Porile [70] (crosses) and Ruddy and Pate [70] (open points).

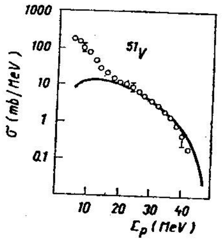

Fig. 12. Comparison between the spectrum of protons emitted in the reaction ^{51}V (α, xp), measured by Chevarier et al. [52] at $E_\alpha \approx 54.8$ MeV, and the one foreseen by the exciton model. The contribution due to protons evaporated from the compound nucleus is not reported.

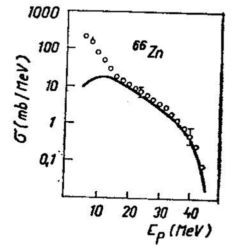

Fig. 13. Comparison between experimental data and theory for the spectrum of protos emitted in the reaction ^{66}Zn(α,xp) [52].

A 2π, 2ν initial configuration can be explained by assuming that the incident α-particle dissolves in the coulomb and nuclear field of the target nucleus. The 3π, 2ν, $1\pi^-$ and 3π, 2ν, $1\nu^-$ configuration admixture in the case of lighter target nuclei for which $N \approx Z \approx A/2$ seems to indicate a small, but not negligible probability that the α dissolves only in the interaction with a nucleon of the target nucleus.

V. CONCLUSION

The analyses of experimental data summarized in this report seem to indicate that the exciton model can satisfactorily account for most of the reactions induced by incident nucleons and α-particles. In both cases experimental evidence exists of direct interactions which cannot be accounted for by the model [30, 43]. The fraction of reaction cross-section which cannot be accounted for by the model amounts to ≈ 10 % in the case of proton induced reactions, at $E_p \approx 20-60$ MeV, according to our calculations [15, 16], the same fraction in the case of 40—90 MeV α-particles is estimated, according to Chevenert et al. [43] data, to amount to $\approx$ 15 %. The approximately equal values of these estimates, confirmed by the comparison of the absolute values of the high energy tails of (α, $\alpha' n$) and (p, $p' n$) excitation functions* seems to indicate the same origin for these direct effects. A possible explanation could be to assume that these effects originate in the interactions of the incident particles with nucleons of the outer edge of the target nucleus. These interactions are expected to strongly contribute to the excitation of low lying collective states of the residual nucleus which are really observed. In addition, arguments most of the reactions induced by the incident nucleon or α-particle could hardly account for these interactions.

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* See, for instance, Ref. [54] at the pgs. 192 and 331, for reactions induced on a gold target. As a rough rule, according to exciton model calculations [15, 16], ≈ 0.5 of the (p, pn) cross-section in the plateau region is due to effects which cannot be explained by the exciton model. In the case of the (α, αn) reaction the pre-equilibrium process contribution to this reaction is assumed to be small since the α usually dissolves in the coulomb and nuclear field of target nucleus.

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Received September 9th, 1974