INTERPRETATION OF PRECOMPOUND REACTION DATA

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ABSTRACT

The main assumptions at the basis of phenomenological pre-equilibrium models are briefly reviewed. Results of analyses of experimental data are discussed.

It is undoubted that the phenomenological models introduced to describe the equilibration process of an excited nucleus, and the emission of fast particles in the course of such process, have now become very serviceable tools for the analysis and interpretation of nuclear reactions at energies greater than some ten MeV. These models have prompted new researches, both experimental and theoretical, and have considerably contributed to clarify our ideas on reaction mechanisms.

All the models that we shall call, broadly speaking, pre-equilibrium models - i.e., the Intranuclear Cascade Montecarlo (I C M) model, the Exciton model, the Harp-Miller-Berne Master Equation approach, the Hybrid and Geometry Dependent Hybrid models (including their Quasi Free version) - while differing in specific and even important points, introduce certain common hypotheses to describe the generic nuclear process (1 - 4).
These hypotheses are, briefly, the following: (a) The projectile or one of its constituent nucleons if the projectile is a complex particle, interacts with a nucleon (or possibly with a small number of correlated nucleons) of the target giving rise to states of a simple configuration.
(b) The particles and the holes excited in the first stage of the process originate a cascade of two body interactions that brings about the distribution of the excitation energy among an ever increasing number of particles and holes. In this second stage of the process fast particles may be emitted which, by retaining (at least partly) a memory of the direction of the incident projectile, have asymmetric (forward peaked) angular distributions. Emission during this stage are called pre-equilibrium emissions.
(c) The statistical equilibrium is finally reached between all the states corresponding to a given energy, parity and angular momentum. Now the mean energy of the excited particles is low (assuming that the residual excitation energy is small

in comparison to the total binding energy of the nucleus), and the subsequent emission of particles takes place through the well known evaporation mechanism.

In respect to the differences among the various models, we shall limit ourselves to a few remarks.
In the I C M model the interaction cascade is calculated by following explicitly the trajectories of the excited nucleons inside the nuclei. An extraction of random numbers decides where inside a nucleus an interaction (which is assumed, except for limitations due to Pauli principle, identical with the free interaction) can take place, and it likewise decides the direction and momentum of the struck nucleon as well as the direction and energy of the particles after the collision. The calculation follows all the nucleons, excited in the course of the cascade, that are emitted when - on reaching the nuclear surface - are not reflected there, and it terminates when the energy of every nucleon drops below a predetermined value. In conventional versions of the I C M models one takes into account only the interactions that involve excited particles. It has to be mentioned that in a recent version by Iljinov *et al.* (5) account is taken, although in a rather schematic and artificial way, also of the interactions that involve excited holes.
In the other models the probability of a given process taking place is calculated with the methods of quantum statistical mechanics, and is expressed by means of decay rates (&).
The decay rate for emission of a particle of a certain energy is evaluated from the particle and hole energy distribution inferred on the basis of apposite statistical hypotheses, and from the probability per unit time that a particle in the continuum be emitted by the nucleus; usual assumptions introduced for the evaluation of this decay rate are that all possible states corresponding to a given configuration are equiprobable and that the detailed balance principle is usable.

(&) It is well known, however, that the procedures adopted by the authors who have contributed to the develement of the various models are not always equivalent. E. g., discussion in regard to the differences in the assumptions used in the Exciton model, in comparison to those made in the Hybrid model and a comparison of the results obtained by means of the Exciton model and the I C M model can be found in refs. (6 - 8) and (9 - 11), respectively.

The decay rates for two body interactions, leading in the most probable case to a re-distribution of the energy among a number of excitons increased by two units, are calculated starting from the mean nucleon-nucleon interaction cross section in nuclear matter.

The pre-equilibrium models have been employed with increasing success as their sophistication grew and the knowledge of the required parameters become more precise, in the study of reactions induced by light particles (n, p, d, α) and less usual projectiles (γ , $\pi^{\pm}$, μ) as well.
Just as an example we can show in Figs. 1 - 3 and Table I, the results of some recent calculations with the Hybrid, the Exciton and the I C M models at excitation energies up to ∼ 200 MeV (12 - 15). These results indicate that by means of such models it is possible now to reproduce with quite good precision the amount of practically all the contributions of the various reaction channels to a given nuclear process, also in the case of low probability processes with cross sections of 1 mb or less.

One might rightfully enquire about the relative importance of pre-equilibrium phenomena. In this connection let us remind that the probability of emissions during the pre-equilibrium stage rises with the excitation energy; so that for energies higher than 50 - 60 MeV, in most reactions one gets the emission of at least one particle from the pre-equilibrium stage. Such emissions lower considerably the excitation energy of the system, which afterwards decays essentially through evaporation. To make a numerical example, consider a reaction induced by a π^- at rest in a nucleus of A∼150:on the average one gets from the pre-equilibrium stage an emission of∼1.4 neutrons of∼42 MeV mean energy, and of∼.22 protons of∼40 MeV mean energy. Therefore the pre-equilibrium emissions (in this example) reduce, on the average, the excitation energy from the initial∼140 MeV to about 60 MeV (16).

To conclude this summary exposition, we would like to remark that although at energies lower than those cited above the phenomena taking place during the equilibration are on the whole less relevant, still certain processes can occur only because there is a pre-equilibrium stage. Such is the case, e. g., of the emission of charged particles in reactions induced in heavy nuclei at comparatively low excitation energies (17).

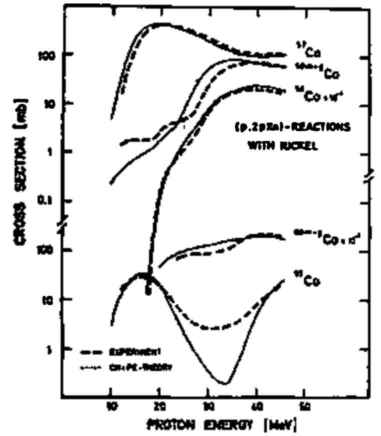

FIG. 1 - Experimental excitation functions for (p,2pxn) reactions on Ni and predictions of the Hybrid model. (From ref. (12)).

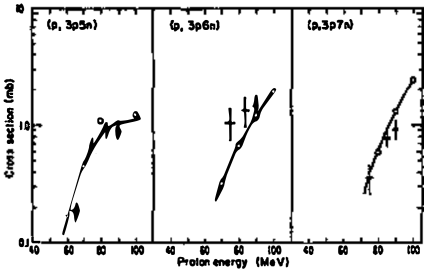

FIG. 2 - Experimental excitation functions for (p,3pxn) reactions on Th (black dots with error bars)and predictions of the Exciton model (open points and line through them). (From ref. (13)).

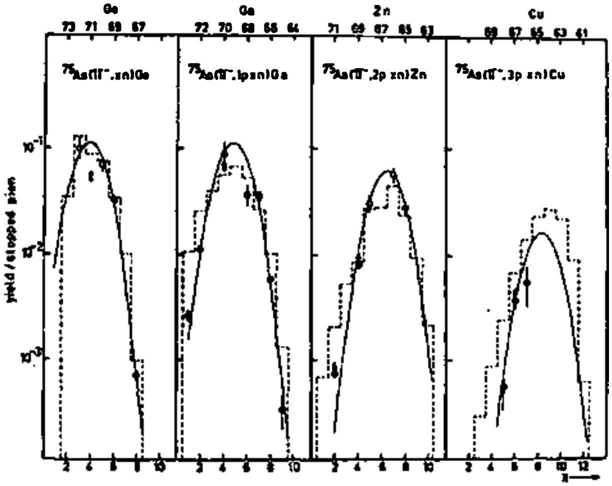

FIG. 3 - Yield of isotopes produced after π^- absorption in ^{75}As. Open and black circles are the results obtained from in-beam and activation measurements,respectively. The dashed histograms are the results from Exciton model calculations.

RESIDUAL NUCLEUS	EXP. YIELD (mb)	TH. YIELD (mb)
62 Zn	2.4 ± 1.1	3.0 ± 0.9
61 Cu	25.0 ± 3.0	34.0 ± 3.1
57 Ni	1.7 ± 0.2	5.44± 1.23
55 Co	2.0 ± 0.2	6.4 ± 1.4
56 Co	12.4 ± 1.3	21.7 ± 2.5
57 Co	37.5 ± 4.0	37.3 ± 3.1
58 Co	44.6 ± 5.0	28.5 ± 2.8
61 Co		2.8 ± 0.9
52 Fe	0.1 ± 0.02	0.5 ± 0.37
59 Fe	1.3 ± 0.13	1.43± 0.66
52 Mn	5.56± 0.6	12.3 ± 2.0
54 Mn	17.4 ± 1.8	16.4 ± 2.1
56 Mn	2.3 ± 0.3	3.7 ± 1.0
48 Cr	0.07± 0.01	0.03± 0.09
49 Cr	0.74± 0.08	1.65± 0.75
51 Cr	12.2 ± 1.3	14.7 ± 1.0
48 V	2.4 ± 0.3	2.8 ± 0.9
44 Sc	0.33± 0.04	0.25± 0.26
46 Sc	0.61± 0.07	0.06± 0.13
47 Sc	0.36± 0.04	0.03± 0.09

TABLE I - Cross sections for proton induced spallation of Cu at 200 MeV. The theoretical predictions are based on the Los Alamos version of VEGAS code. (From ref. (15)).

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