Configuration mixing in preequilibrium reactions: A new look at the hybrid-exciton controversy

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The physical concepts of the hybrid and exciton models are reexamined and shown to constitute fundamentally different approaches to preequilibrium reactions. The difference in cross section predictions obtained from the models is not attributable—as has often been argued—to inappropriate exciton distribution functions in higher order terms or multiple chance emission. It rather rests with the question of whether or not configuration mixing is assumed to take place during equilibration and what is assumed about hole interactions. A simplified but realistic example is given to illustrate these points, and a test against experimental data is proposed to decide which model is the more appropriate to use.

I. INTRODUCTION

Nuclear reaction models to treat the preequilibrium phase of reactions leading to the formation of a compound nucleus have been around for many years.[1–8] Most of these models are semiclassical in nature and have been used with considerable success in describing experimental data pertaining to the equilibration process, mainly the forward peaked hard component observed in the continuous spectra of light ejectiles and the high energy "tails" seen in the excitation functions of activation cross sections. More elaborate quantum mechanical theories,[9–11] which are not easily applied to routinely calculate measurable preequilibrium cross sections, have tended to support the foundations on which the semiclassical models are built. This has prompted a continued interest in these models as tools both to predict cross sections for a number of practical purposes and to test the adequacy of the underlying physics.

Although quite a variety of model formulations and computational techniques have been employed, most approaches utilize—in one way or another—one or both of two basic concepts which stem from the "grandparents" of preequilibrium theory, the intranuclear cascade (INC) model of Goldberger[1] and Griffin's statistical model of intermediate structure[2] (SMIS). The idea in the INC approach is to treat equilibration as a series of quasifree scattering processes of independent nucleons in the nuclear environment and to follow these processes *explicitly* in a geometric fashion. Nucleon-nucleon kinematics and cross sections are employed and emission is assumed to occur whenever a nucleon follows a trajectory out of the composite nucleus without undergoing another collision. Griffin's idea, on the other hand, was to consider the equilibrating system as a whole, envisioning it to pass through increasingly complex configurations of single particle excitations. His SMIS exploits the assumed two-body nature of the elementary thermalizing process *implicitly* in that it groups the single particle configurations according to the number of single particle degrees of freedom participating in the total excitation. It goes on to assume that, at each stage, all possible configurations are equally likely, so that the occurrence of configurations capable of particle emission into the continuum may be estimated on a statistical basis. This concept has proven extremely fruitful, although the SMIS does not explicitly treat the competition between particle emission and intranuclear collisions and can therefore not predict absolute cross sections as the INC model does. It is, however, a very transparent model, and its formulae can be evaluated on a hand calculator, as compared to the Monte-Carlo technique required by the INC approach.

Much effort has been devoted to combining the advantages of both the INC model and the SMIS into a single one capable of calculating absolute preequilibrium emission cross sections and yet retaining the transparency of the SMIS. As a result, a number of formulations[4–6,19,20] have emerged which are descendents of the SMIS in that they group many-body states of the equilibrating system according to exciton numbers and employ particle hole state densities to estimate the occurrence of configurations capable of precompound particle emission. In addition to the SMIS, however, these models treat the competition between particle emission and intranuclear transitions during the equilibration phase explicitly, and they evaluate the rates at which such intranuclear transitions take place.

Sometimes, all of these models as well as the SMIS are referred to indiscriminately as "the" exciton model. More often, though, the term "exciton model" is used in a narrower sense, namely to denote extensions of the SMIS which employ an *average state lifetime* to calculate precompound emission probabilities. It is in this narrower sense that the term "*exciton model*" is used in this paper. The use of an average state lifetime is to be contrasted to that of a *single particle lifetime* as is employed in the *hybrid model* suggested by Blann.[5]

Some exciton model formulations[19,21] employ an average matrix element to calculate intranuclear transition rates and determine its numerical value as well as its energy and mass dependence through a fit to experimentally

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measured preequilibrium emission data. While this may be a useful procedure to reproduce experimental data and serve the needs of applied physics, it is less suitable to test the underlying basic physics. This is because preequilibrium emission cross sections are smooth, rather structureless functions of incident and ejectile energy as well as of the mass of the composite system. Consequently, even a large amount of experimental data will not readily overdetermine a free parameter such as an average matrix element to anywhere near a desirable degree, especially if it is assigned an arbitrary mass and excitation energy dependence. For this reason, varieties of the exciton model that contain such an adjustable matrix element will not be considered here in detail. Instead, Gadioli's exciton model formulation[6] will be used, which computes the intranuclear transition rates on an *a priori* basis. The conclusions to be presented, however, remain valid for all exciton model varieties as defined by the use of an average state lifetime.

Both the hybrid model and the exciton model (in Gadioli's formulation) compute intranuclear transition rates from nucleon-nucleon quasifree scattering cross sections, much in the spirit of the INC model, and they are essentially parameter-free. Yet they yield closed formulae which are—a heritage from the SMIS—of a remarkably simple structure. This greatly facilitates calculations and has no doubt contributed to the popularity both models enjoy. The formulae also seem to reflect the reasoning on which the approaches are based in a suggestive manner, perhaps so much so that approximations and assumptions inherent in either model are sometimes overlooked. The formulae are not as transparent as they are simple, however, and they give different results. The longstanding[12,13] and continuing[14] debate as to which of the models is "correct" and why conflicting predictions for emission cross sections are obtained indicates that there is only incomplete understanding of the concepts on which the two models rest. As they use the same ingredients—namely quasifree scattering cross sections to calculate intranuclear transition rates, reciprocity expressions for escape rates, and Ericson-type[23] exciton distribution functions—they may be closely compared, and any difference in cross section prediction must rest with the basic ideas that went into their formulations.

It is the purpose of this paper to reexamine the model concepts and to illustrate the different physics and approximations that are employed. As it will turn out, neither model can be proven wrong on an *a priori* basis and either ansatz is useful to explore the physics of the reaction process. It seems possible, however, to conduct a test against experimental data that will show with which concept nature happens to agree better.

For the sake of simplicity, both models are considered in their most basic form in this paper, i.e., without distinction between protons and neutrons and disregarding the extensive refinements that have been made over the years, such as inclusion of effects of the diffuse nuclear edge,[15] isospin conservation,[16] cluster emission,[17] and modifications[18] to the mean free path in nuclear matter, to mention just a few. Furthermore, simplifications will be introduced regarding the energy dependence of intranuclear collision and escape rates. It should be kept in mind that this is just for ease of analytic evaluation and illustration. No comparison with experimental data is given or intended, as this will require more rigorous numerical calculations.

Some of the points that will be discussed below are touched upon or are inherent in a preequilibrium model formulation given by Ernst and Rama Rao[13] in an attempt to reconcile the hybrid and exciton approaches with one another. Their work will not be quoted in detail. Instead, the reader is referred to their paper.[13] Its main conclusion, however, namely that the hybrid and the exciton model can be reconciled once a proper record-keeping of exciton distributions is observed, is at variance with the results to be described below.

In Sec. II, the models under discussion will be reviewed and reexamined with respect to their similarities and differences. Particular emphasis is put on the question of configuration mixing which seems to have received insufficient attention so far and will be shown to constitute the most important difference. Another aspect by which the models differ, the adequacy of using Ericson-type particle hole state densities to calculate exciton distributions, is discussed in Sec. III in some detail, and more exact distribution function expressions are given for use within the framework of each of the two models. These are employed in an example of a model calculation which is presented and discussed in Sec. IV. The calculation is carried out in both models using the same input data and/or parameters, so as to have any difference in results reflect solely the differences in model concepts and to estimate their importance or unimportance. Section V summarizes the conclusions to the effect that the question of configuration mixing is far more important than that of exciton distribution function approximations. Also, a possible way is suggested to test if or to what extent configuration mixing occurs during equilibration.

II. PHYSICAL AND COMPUTATIONAL CONCEPTS

While the exciton and hybrid models constitute significantly different approaches to—and yield different results for—preequilibrium emission, they are still, to a large extent, built on the same basic assumptions concerning the physics of the reaction.

The fusion of target nucleus and projectile is assumed to result in the formation of an unequilibrated composite system of excitation E, in which only few (n_0-1) degrees of freedom participate in the excitation. These are envisioned to be single particle degrees of freedom and referred to as excitons, which may either be excited nucleons ("particles") or vacant single particle levels below the Fermi energy ("holes"). The equilibration of the system is then assumed to proceed via a series of two-body collisions—hereafter called *thermalizing collisions*—between excited nucleons and nucleons below the Fermi energy. It is further assumed that the thermalizing collisions are of the Markoff-type and that each one will create an additional particle-hole pair. Collisions reducing the number of excitons or leaving it unchanged are neglected. This approximation has been demonstrated[3,4] to be perfectly valid for the part of the equilibration phase that contributes significantly to precompound emission. It is, however, obviously a very poor one as thermal equilibrium is approached, so that neither the exciton nor the hybrid model can be expected to be suitable to treat evaporation. The requirement that a precompound model should include the evaporation limit is, on the other hand, neither a necessary condition for the model to be "correct," nor is it a sufficient one.

During the equilibration cascade, nucleons may occupy single particle levels at energies in excess of the particle's separation energy and Coulomb barrier. Whenever this occurs—hereafter called an *emission chance*—emission of the particle is possible and competes with further thermalizing collisions. The emission rates are calculated from the reciprocity theorem, and the rates at which thermalizing collisions take place are derived from either quasifree nucleon-nucleon scattering or the imaginary part of the optical potential, both approaches giving essentially the same results.[21] These rates, together with the assumptions about the equilibration process outlined above, serve as a common basis to both the exciton and the hybrid model.

The approaches also agree in that they group the emission chances which arise during the equilibration cascade into classes, each class corresponding to a term in the sum by which the preequilibrium emission cross section is eventually given in either formulation. The models differ fundamentally, however, in the way these classes are defined as well as in the physics which is envisioned to underly them and which will now be discussed.

A. The hybrid model concept

In the hybrid model (HM), preequilibrium emission within one class is given as a product of two factors. The first factor is the probability, $\rho_{i,\mathrm{HM}}$, that one out of a total of $n=p+h$ excitons sharing the total excitation E is a particle residing at single particle energy e_p. The second factor is the (conditional) probability that it will then escape into the continuum rather than, and prior to, undergoing a thermalizing collision:

$$W_c^{\mathrm{HM}}(i,e_p)=\rho_{i,\mathrm{HM}}(E,e_p,p,h)\frac{\lambda_c(e_p)}{\lambda_c(e_p)+\lambda_+(e_p)} . \quad (1)$$

(See Table I for notation.) Obviously, the fate of a single exciton is considered in Eq. (1). Its elevation to excitation e_p in the history of the equilibration cascade is contained in the first factor. By definition, this is normalized so that

$$\int_0^E \rho_{i,\mathrm{HM}}(E,e_p,p,h)de_p + \int_0^E \rho_{i,\mathrm{HM}}(E,e_h,p,h)de_h=p+h=n , \quad (2)$$

the total number of excitons in class i. Therefore, evaluating Eq. (1) for all possible energies e_p, will cover emission chances of all p particles, although only one exciton energy is considered at a time. As the second factor in Eq. (1) covers *all* emission chances the exciton under consideration offers prior to undergoing a further thermalizing collision, Eq. (1)—evaluated for all energies $e_p \le E$—exhausts *all* emission chances which arise from *all p particle excitons,* until each of them participates in another thermalizing collision. Trivially, this applies to the h holes as well, since they can never lead to emission prior to undergoing a collision and thereby producing an excited particle. The number of excitons in class i assumed to either be emitted or undergo a thermalizing collision is

$$\int_0^E W_c^{\mathrm{HM}}(i,e_p)de_p+\int_0^E W_+^{\mathrm{HM}}(i,e_p)de_p + \int_0^E W_+^{\mathrm{HM}}(i,e_h)de_h=p+h=n \quad (3)$$

with

$$W_+^{\mathrm{HM}}(i,e_{p/h})=\rho_{i,\mathrm{HM}}(E,e_{p/h},p,h)\frac{\lambda_+(e_{p/h})}{\lambda_c(e_{p/h})+\lambda_+(e_{p/h})} . \quad (4)$$

(See Table I for notation.) Therefore, the structure of the hybrid equation (1) implies that the model groups emission chances according to exciton generations. If, e.g., n_0 excitons (p_0 particles and h_0 holes) are produced in the fusion of projectile and target, they form the first generation of excitons. All emission changes they offer are lumped into one class (class 0) and exhausted by evaluating Eq. (1) with $p=p_0$, $h=h_0$, and for all energies e_p. Further possibilities for emission arise only from excitons which have participated in a thermalizing collision of first generation excitons, i.e., the second generation. It consists of all first generation excitons after they underwent a thermalizing collision (and thus changed their energy e_p, e_h) and their collision partners which were excited in the process. Again, all emission chances which the second exciton generation offers are lumped into one class (class 1) and exhausted by evaluating Eq. (1) with $p=p_1$, $h=h_1$, and for all energies $e_p \le E$, and so on. The total precompound spectrum is then obtained by summing over all generations (classes), i.e.,

$$\frac{d\sigma}{d\epsilon}=\sigma_F\times\sum_i D_{i,\mathrm{HM}}\rho_{i,\mathrm{HM}}(E,e_p,p_i,h_i)\frac{\lambda_c(e_p)}{\lambda_c(e_p)+\lambda_+(e_p)} . \quad (5)$$

$D_{i,\mathrm{HM}}$ is a depletion factor which takes account of the fact that the probability of finding excitons in any subsequent generation is reduced by particle emission from preceding generations.

For all practical purposes, only very few terms of the sum have to be calculated, as—from generation to generation—the total excitation energy E of the system is shared among more and more excitons, and emission probabilities decrease rapidly. As each particle in a generation will lead to a two particle-one hole subsystem in the next generation, and each hole to a one particle-two hole subsystem, the daughter generation will comprise (except for depletion)

$$p_{i+1}=2p_i+h_i \text{ particles}$$

and (6a)

$$h_{i+1}=2h_i+p_i \text{ holes} .$$

Consequently, a daughter generation consists of

$$n_{i+1}=p_{i+1}+h_{i+1}=3n_i \tag{6b}$$

excitons, i.e., three times as many as the parent generation and not, as the original hybrid formulation, misleadingly, suggests,

$$n_{i+1}=n_i+2 \; . \tag{7}$$

The structure of Eq. (1) implies more, however, than just the way in which emission chances are grouped. As the probability for a particle to escape into the continuum is expressed as a branching ratio of single particle rates, $\lambda_c(e_p)$ and $\lambda_+(e_p)$, pertaining to an exciton under consideration and of a given single particle excitation, e_p, excitons are assumed to have well-defined energies between thermalizing collisions. This means that the n-exciton states through which the composite nucleus passes are envisioned to be combinations of single particle excitations $e_1,e_2,\ldots,e_k$ which are independent of one another except for the condition that

$$\sum_{k=1}^{n_i} e_k=E \; . \tag{8}$$

Such combinations will be referred to hereafter as *configurations,* in the sense that the n-exciton wave function can be written as a product of single particle wave functions with eigenvalues e_k. The hybrid model assumes that no "intrinsic" mixing of configurations is produced by the nuclear forces which can rather be entirely described by a potential well and two-body collisions of independent excitons. So in an individual composite nucleus, the attainment of any two n-exciton configurations is mutually exclusive. The model does allow, however, for statistical configuration mixing in the trivial sense that the equilibration cascade may, alternatively, proceed through large numbers of different configurations. Thus, the probability $\rho_{i,\mathrm{HM}}(e_p,p,h)$ of finding a particle at energy e_p—i.e., the probability that an n-exciton configuration with one particle at that excitation is attained—is an average over a

TABLE I. Definition of symbols.

p,h	Number of particles or holes, $n=p+h$ number of excitons.
$e_{p/h}$	Single particle (or hole) excitation, measured from the Fermi energy.
E	Total excitation energy in the composite system.
$\lambda_c(e)$	Probability per unit time that a particle of excitation e is emitted into the continuum, ("escape rate"), identically zero in the case of holes and calculated from reciprocity for particles.
$\lambda_+(e)$	Probability per unit time that a particle (or hole) of excitation e undergoes a thermalizing collision ("transition rate"), taken as resulting from intranuclear quasifree scattering in this work.
B	Separation energy.
ϵ	Ejectile channel energy.
σ_F	Entrance channel fusion cross section.
i	Index denoting classes of emission chances, $i+1$ denotes generations.
$\rho_i,(^{\mathrm{HM}}_{\mathrm{EM}})(e)$	Probability of finding an exciton at excitation e in generation $i+1$ in the hybrid or exciton model ("exciton distribution functions").
g	Single particle level density.
$W_c(^{\mathrm{HM}}_{\mathrm{EM}})(i,e_p)$	Probability of emitting a particle of energy e_p from generation $i+1$ into the continuum as calculated in the hybrid or exciton model.
$W_+(^{\mathrm{HM}}_{\mathrm{EM}})(i,e_{p/h})$	Probability that a particle-hole of energy $e_{p/h}$ in generation $i+1$ undergoes a thermalizing collision in the hybrid or exciton model.
$D_i,(^{\mathrm{HM}}_{\mathrm{EM}})$	Depletion factor in either model.
$\dfrac{d\sigma}{d\epsilon}$	Preequilibrium emission cross section.
$\omega(E,p,h)$	Particle hole level density.
$\Lambda_{i,p/h}$	n exciton state average decay rate due to particle-hole transitions.

large ensemble of "microscopically" different equilibration cascades. So while the hybrid model does not group emission chances according to n-exciton states, but rather according to generations of independent excitons, it does imply that the n-exciton states are "pure" configurations and that no intrinsic configuration mixing occurs.

There is only a loose correspondence between the succession of generations in the hybrid model and the time elapsed since formation of the composite system. In particular, excitons which are members of different generations may coexist at a given time. Owing to their independence, no exciton "knows," if, when, and how other excitons were emitted before—out of its own generation or out of another—and if it is still in the original composite system rather than a daughter nucleus formed by a previous preequilibrium emission. Consequently, no distinction can be made in the hybrid approach between single and multiple precompound emission. Instead, inclusive spectra are calculated with the approximation that all precompound ejectiles are emitted from the same composite system, and the number of particles emitted from generation i,

$$\int_0^E W_c^{\mathrm{HM}}(i,e_p)de_p \ , \tag{9}$$

may even be larger than one. As long as multiple emission is unlikely (up to some tens of MeV of total excitation), this does not present a problem, and it certainly suits the many experiments in which inclusive spectra are measured. If multiple precompound emission is important, however, and if activation cross sections for specific nuclides are to be calculated, a hybrid calculation is not adequate without additional consideration of the multiple chance emission problem.[22,26]

To evaluate the average probability $\rho_{i,\mathrm{HM}}(E,e_p,p,h)$—often called the exciton densities or distribution functions—the hybrid model approach employs Griffin's assumption that (on the average) each of the configurations which are possible in a system of n excitons is attained with equal probability. Under this assumption, the well-known Ericson[23] state densities

$$\omega(E,p,h)=\frac{g(gE)^{n-1}}{p!h!(n-1)!} \ , \tag{10}$$

or a modification thereof,[24] yield

$$\rho_{i,\mathrm{HM}}(E,e_p,p_i,h_i)=\frac{g\omega(E-e_p,p_i-1,h_i)}{\omega(E,p_i,h_i)} \ . \tag{11}$$

The hybrid model uses

$$\begin{aligned} p_{i+1}&=p_i+1 \ , \\ h_{i+1}&=h_i+1 \ , \\ n_{i+1}&=n_i+2 \ , \end{aligned} \tag{12}$$

instead of the relation (6) implied by grouping emission chances according to exciton generations. Moreover, Eqs. (10)–(12) are not generally consistent with the nucleon-nucleon collision mechanism which the model assumes to mediate the transition between any two generations of excitons. Also, an incorrect depletion factor $D_{i,\mathrm{HM}}$ is used in the original hybrid formulation,[5] improvements being suggested in Ref. 22. Consequently, the use of Eqs. (10)–(12) must be considered an approximation. While all this is important from a conceptual point of view, the chosen approximations are very good for most of the practical model applications. A more detailed discussion of this point is given in Secs. III and IV.

B. The exciton model picture

In the exciton model (EM), preequilibrium emission within one class is given as the ratio

$$W_c^{\mathrm{EM}}(i,e_p)=\frac{\rho_{i,\mathrm{EM}}(E,e_p,p,h)\lambda_c(e_p)}{\Lambda_{i,p}+\Lambda_{i,h}} \ , \tag{13}$$

with

$$\Lambda_{i,p}=\int_0^E \rho_{i,\mathrm{EM}}(E,e_p,p,h)[\lambda_c(e_p)+\lambda_+(e_p)]de_p$$

and

$$\Lambda_{i,h}=\int_0^E \rho_{i,\mathrm{EM}}(E,e_h,p,h)\lambda_+(e_h)de_h \ .$$

(See Table I for notation.)

The number of excitons which—in each class—is assumed either to be emitted or to undergo a thermalizing collision is easily verified to be

$$\int_0^E W_c^{\mathrm{EM}}(i,e_p)de_p+\int_0^E W_+^{\mathrm{EM}}(i,e_p)de_p + \int_0^E W_+^{\mathrm{EM}}(i,e_h)de_h=1 \ , \tag{14}$$

with

$$W_+^{\mathrm{EM}}(i,e_{p/h})=\frac{\rho_{i,\mathrm{EM}}(E,e_{p/h},p,h)\lambda_+(e_{p/h})}{\Lambda_{i,p}+\Lambda_{i,h}} \ . \tag{15}$$

Action of one and only one exciton is considered in each class, although any of the n excitons is given the chance to play that role. As the thermalizing collision of one exciton will produce an additional particle hole pair, Eq. (12) holds, and each exciton model class covers the emission chances arising from all states of the composite system that have the same exciton number. The transition between any two n-exciton state generations is mediated by a thermalizing collision of one and only one exciton, increasing the exciton number by $\Delta n=2$, and the total precompound spectrum is obtained by summing over all generations:

$$\frac{d\sigma}{d\epsilon}=\sigma_F\sum_i D_{i,\mathrm{EM}}\frac{\rho_{i,\mathrm{EM}}(E,e_p,p_i,h_i)\lambda_c(e_p)}{\Lambda_{i,p}+\Lambda_{i,h}} \ . \tag{16}$$

(See Table I for notation.)

Again, only few terms of the sum have to be calculated for practical purposes, as emission probabilities decrease rapidly with exciton number. Exciton numbers grow less rapidly ($n_{i+1}=n_i+2$) in the exciton model than they do in the hybrid model ($n_{i+2}=3n_i$), however. Consequently, Eq. (16) converges more slowly than the corresponding hybrid model expression (5).

As the depletion factor $D_{i,\mathrm{EM}}$ is correctly computed in the framework of the exciton model formulation,[6] and as action of one and only one exciton is considered in each generation of Eq. (16), the preequilibrium spectrum obtained is that of the first precompound particle out. The exciton model produces exclusive spectra, as opposed to the inclusive spectra calculated in the hybrid approach. The calculation may, however, be extended to daughter nuclides to include multiple emission *without losing the distinction between single and multiple emission.*

The exciton distribution functions, $\rho_{i,\text{EM}}(E,e_{p/h},p_i,h_i)$, are evaluated using the same equations (10)—(12) that the hybrid model employs. In the framework of the exciton model, too, they are inconsistent with the nucleon-nucleon scattering mechanism envisioned to mediate the transition from one n-exciton generation to the next. Again, they must be considered an approximation, as will be discussed in Sec. III. They may be used, however, to demonstrate an additional fundamental implication of Eq. (13). Substitution of Eq. (11) into (13) yields

$$W_c^{\text{EM}}(i,e_p)=\frac{g\omega(E-e_p,p_i-1,h_i)\lambda_c(e_p)}{\int_0^E g\omega(E-e_p,p_i-1,h_i)[\lambda_c(e_p)+\lambda_+(e_p)]de_p+H}\ , \tag{17}$$

where H is an analogous term for holes, and $\omega(E-e_p,p_i-1,h_i)/g$ is the number of (distinguishable) configurations[23,24] of p_i-1+h excitons and energy $E-e_p$. So the numerator in Eq. (17) comprises the rates of emitting a particle of energy e_p for those $(n_i=p_i+h_i)$-exciton configurations in which one particle is excited to energy e_p. They compete with the rates comprised in the denominator, namely those of either emission or thermalizing collision of *all* excitons (at any energy $e_{p/h}$) for *all* n_i-exciton configurations possible at total excitation E, because

$$\int_0^E \omega(E-e_p,p_i-1,h_i)de_p+H=n\omega(E,p_i,h_i)\ , \tag{18}$$

H being, again, an analogous hole term.

In particular, the emission of a particle at excitation e_p from a configuration containing such a particle competes against the decay of configurations in which *all* excitons are excited to energies *other* than e_p. This is impossible if the configurations are assumed to be "pure" as in the hybrid model. Therefore, the exciton model implies thorough intrinsic configuration mixing, caused by a part of the nuclear Hamiltonian represented neither by the nuclear well nor by quasifree collisions of independent nucleons, and the exciton model exciton distribution functions $\rho_{i,\text{EM}}$ must be interpreted as the average statistical weight which the "pure" configurations carry in the "real" n_i-exciton wave functions. This is to be contrasted to the ensemble average character of the corresponding (and numerically identical) distribution function $\rho_{i,\text{HM}}$ in the hybrid model concept.

As stated in the Introduction, these findings are valid for all exciton model varieties, including those[19,20] which utilize an average matrix element to compute the average state lifetime. This is inherent in the final state densities used in these approaches both for intranuclear transition and for escape rates. The expression used for escape rates requires that all possible final states be accessible from all initial states, even from those that may not have an exciton at the single particle energy under consideration. The intranuclear transition rates are averages over all possible transitions including those, e.g., which are mediated by interaction of a hole that cannot coexist with the single particle excitation necessary for emission because of energy conservation. Unfortunately, however, the effect on predicted cross sections that results from these assumptions is masked by the absolute value and excitation energy dependence that the average matrix element is arbitrarily assigned in order to fit the data.

C. Important and less important differences

Of the differences between (and the approximation used in) the hybrid and the exciton models, as outlined above, some will be shown to be relatively unimportant in practical applications by the realistic example given in Sec. IV. These differences will include the question of multiple versus single preequilibrium emission and the approximations used for the exciton distribution functions in higher order $(i>0)$ terms of either model. The single difference between the approaches, which is of the foremost significance *practically* and *conceptually,* is that of *zero* versus *maximum* intrinsic configuration mixing. It is also, perhaps, the most elusive one and worth demonstrating in an (unrealistic but) illustrative example, as depicted in Fig. 1. Consider a two particle-zero hole system in which only the two configurations denoted A (open circle excitons) and B (full dots) are energetically possible. Assume that they are attained with equal probability (in the hybrid picture) or carry equal average statistical weight in the two-exciton wave functions (in the language of the exciton model). Then the probability of finding a particle at the highest possible single particle level, e_m (i.e., just above the emission threshold), is

$$\rho_{i,\text{EM}}(E,e_m,2,0)=\rho_{i,\text{HM}}(E,e_m,2,0)=0.5\ , \tag{19}$$

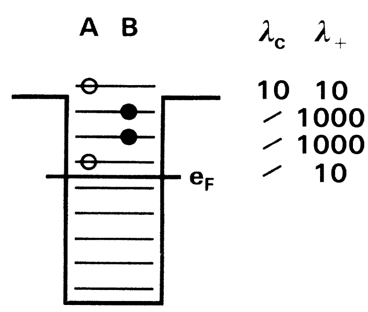

FIG. 1. An illustrative (but unrealistic) example for zero versus strong configuration mixing. Only two configurations of excited particles are possible and denoted A and B. Each single particle level is assigned a value for the escape rate, λ_c, and for the transition rate, λ_+. Consequences of configuration mixing under these and other assignments are discussed in the text.

and it is the same for any of the other levels. Assume further that the escape and collision rates λ_c and λ_+ pertaining to the various single particle levels are as indicated in the figure in arbitrary units. Then the hybrid model predicts a probability of

$$W_c^{\mathrm{HM}}(i,e_m)=0.5\times\frac{10}{10+10}=0.25 \tag{20}$$

[see Eq. (1)] for particle emission, while the exciton model will yield

$$W_c^{\mathrm{EM}}(i,e_m)=\frac{0.5\times 10}{0.5\times 10+0.5\times 1000+0.5\times 1000+0.5\times(10+10)}\simeq 0.005 \tag{21}$$

[see Eq. (13)]. The striking difference in the model predictions is entirely due to opposing assumptions about configuration mixing which are employed. In the hybrid model, no intrinsic configuration mixing is assumed. So in 50% of all equilibration cascades in an ensemble, configuration A is attained and suffers no interference from the existence of configuration B as a possible alternative. In configuration A, the higher energy particle has a 50% chance of escape (irrespective of what the lower energy particle will do), and the total hybrid prediction for emission is just the product of these two independent probabilities. In the exciton model, on the other hand, strong intrinsic configuration mixing is assumed, so that the "real" two-exciton wave functions are linear combinations of the configurations A and B, each of which contributes with the same average strength. Consequently, each "real" two-exciton state has a chance to decay through its configuration B component, and it will do so with overwhelming probability, as the collision rates λ_+ associated with configuration B are so large. Configuration A—although it offers a 33% escape chance for emission of the higher energy particle when considered separately in the exciton model framework—does not contribute appreciably to the average two-exciton state decay. Its contribution to the total average decay rate is only

$$0.5\times(10+10)+0.5\times 10=15\ , \tag{22}$$

as opposed to

$$0.5\times 1000+0.5\times 1000=1000 \tag{23}$$

for configuration B.

Assume now, that the collision rates indicated in Fig. 1 are changed to be $\lambda_+=1$ for all single particle levels. Under this assumption, the hybrid model prediction changes to

$$W_c^{\mathrm{HM}}(i.e_m)=0.5\times\frac{10}{10+1}\simeq 0.45\ , \tag{24}$$

while the exciton model gives

$$W_c^{\mathrm{EM}}(i,e_m)=\frac{0.5\times 10}{0.5\times 14}\simeq 0.71\ . \tag{25}$$

The probability of emitting a particle of energy e_m in the exciton model framework is thus seen to be possibly greater than the probability of finding it at that excitation in the first place. Furthermore, the exciton model result was changed by two orders of magnitude versus only a factor of 2 in the hybrid result. Now add a hole to configuration A and assign it a transition rate of $\lambda_+=2000$. That leaves the hybrid result unchanged, whereas the exciton model prediction drops to $W_c^{\mathrm{EM}}(i,e_m)\simeq 0.01$. The decay of the states now proceeds predominantly through this configuration A component, but via interaction of a hole, which is, of course, incapable of nucleon emission.

Obviously, none of the examples just studied resembles a real nucleus. They serve to illustrate, however, the effects which intrinsic configuration mixing can have on a preequilibrium calculation. Whether or not such configuration mixing is assumed is of great conceptual significance, as it makes for the difference between the purely quasifree scattering picture of the hybrid model approach and an *additional* part of the nuclear interaction, which is assumed to produce intrinsic configuration mixing. It is also, however, of great practical importance. As is familiar to practitioners of both models and has been pointedly stated by Chiang and Hüfner,[8] the first term in Eqs. (5) and (16) strongly dominates the high energy part of the preequilibrium spectrum. Most of the differences between the models which have been outlined in subsections A and B do not (or only marginally so) affect this first term. Intrinsic configuration mixing, on the other hand, does affect the first term, and particularly so through hole interaction, which thus comes to play a crucial role. This has just been shown in an illustrative fashion, and the example given in Sec. IV will demonstrate that the same finding results when a more realistic case is considered. The example in Sec. IV will also show that inconsistencies from which both models suffer with respect to higher terms ($i>0$) have only a small effect on the predicted spectra compared to the influence exerted by intrinsic configuration mixing. These inconsistencies arise from using Ericson-type[23] exciton distribution functions, and they will now be discussed.

III. EXCITON DISTRIBUTION FUNCTIONS

Both in the hybrid and in the exciton model, exciton distribution functions are assumed to be given by Eqs. (10)–(12), although they have different meanings in either model and are inconsistent with the way the hybrid model groups emission chances. Moreover, Eqs. (10)–(12) require that all possible n-exciton configurations be populated with the same probability. Blann[22,25] has shown that all possible ($n+2$)-exciton configurations are accessible through quasifree nucleon-nucleon scattering from all (although not each of the) n-exciton configurations. They are not populated with equal probability, however, with one notable exception. If a single particle exciton of excitation e_p scatters off some nucleon below the Fermi surface, the exciton distribution function for the resulting two particle-one hole system will be, within about 20% error margin,

$$\rho(e_p,e_p',2,1)=\frac{4(e_p-e_p')}{e_p^2}\ , \tag{26}$$

i.e., in agreement with Eqs. (10)—(12), evaluated for total excitation e_p, $p=2$, and $h=1$. This was demonstrated by Blann[22,25] in a quasifree scattering calculation. His result can be used to calculate [within the accuracy of Eq. (26)] the exciton distribution functions in both the hybrid and the exciton model framework, which should be used instead of Eqs. (10)—(12). Suppose in some generation (e.g., in $i=0$) the distribution functions are given by Eqs. (10) and (11) and that they comprise $n_0=p_0+h_0$ excitons. Then, the distribution functions for the next generation ($i=1$), i.e., the probabilities of finding a particle at energy e_p' are

$$\rho_{1,\mathrm{HM}}(E,e_p',2p+h,2h+p)=\int_{e_p'}^{E}\rho_{0,\mathrm{HM}}(E,e_p,p,h)\frac{\lambda_+(e_p)}{\lambda_+(e_p)+\lambda_c(e_p)}\rho(e_p,e_p',2,1)de_p+H \tag{27}$$

in the hybrid model, and

$$\begin{aligned}\rho_{1,\mathrm{EM}}(E,e_p',p+1,h+1)=&+\int_{e_p'}^{E}\frac{\rho_{0,\mathrm{EM}}(E,e_p,p,h)\lambda_+(e_p)}{\Lambda_{0,p}+\Lambda_{0,h}}\rho(e_p,e_p',2,1)de_p\\&+\int_0^{E-e_p'}\frac{\rho_{0,\mathrm{EM}}(E,e_p,p,h)\lambda_+(e_p)}{\Lambda_{0,p}+\Lambda_{0,h}}\rho_{0,\mathrm{EM}}(E-e_p,e_p',p-1,h)de_p+H\end{aligned} \tag{28}$$

in the exciton model. In either equation, only the part of the particle distribution arising from particle scattering is explicitly written. The part H which arises from hole scattering is analogous and must be added. Completely analogous expressions are valid for the hole distribution in class 1. The exciton distribution functions given by Eqs. (27) and (28) are correctly depleted with respect to first generation (class 0) particle emission. The structure of the exciton equation (16) still requires the use of a depletion factor for the calculation of class 1 (second generation) preequilibrium emission, as depleted exciton distributions are used both in the numerator and the denominator, so that the depletion contained therein cancels out. The depletion factor needed is the same as in the original formulation.[6] In the hybrid model, on the other hand, the depletion factor contained in the original formulation[5] is obsolete when Eq. (27) is used.

Note that the integration limits in Eqs. (27) and (28) ensure energy conservation for each possible nucleon-nucleon scattering process and that the distributions—neglecting emission—are normalized to

$$\int_0^E\rho_{1,\mathrm{HM}}(E,e_p',2p+h,2h+p)de_p'=2p+h \tag{29}$$

and

$$\int_0^E\rho_{1,\mathrm{EM}}(E,e_p',p+1,h+1)de_p'=p+1 \tag{30}$$

in accordance with the different kinds of generations into which emission chances are grouped in the models.

In Eq. (28), the first term is the contribution arising from the particles that participated in the collision mediating the transitions from n-exciton states to those with $n+2$ excitons, whereas the second term covers the contribution of particles that remained spectators to that collision. This second term contains the probability $\rho_{0,\mathrm{EM}}(E-e_p,e_p',p-1,h)$ that after one particle of energy e_p is singled out to undergo a thermalizing collision, the rest of the system contains another particle at energy e_p'. If all configurations are equally likely in class 0, as was assumed to be the case here, it is readily evaluated according to Eqs. (10)—(12). In general, however, it is more tedious to calculate and becomes increasingly complex as one goes on to further generations. It also prevents Eq. (28) from becoming truly recursive, as is the corresponding hybrid equation (27), but no conceptual difficulties arise.

Expressions analogous to (28) can be written for exciton distributions in daughter nuclides produced by precompound emission in the exciton model framework. They also become increasingly lengthy the further one follows the chain of thermalizing collisions and emission processes. In principle, however, Eqs. (27) and (28) provide the recipe to substitute the currently used expressions (10) and (11) with more exact approximations which are consistent with two-body collisions and the way in which emission chances are grouped in the hybrid and the exciton models.

In the case of the exciton model, evaluation of Eq. (28) results in the Ericson-type distributions (10)—(12) if (and only if)

$$\lambda_c\ll\lambda_+\propto e_{p/h}^2\ . \tag{31}$$

This may be a good approximation[24] for low energies but becomes increasingly poor as one goes to tens of MeV in excitation. In either model, the exciton distribution function assumed to be valid for the first generation of excitons or exciton configurations, respectively, must be justified as resulting from the fusion of projectile and target. In the case of a nucleon induced reaction, e.g., Blann's quasifree scattering result[25] may be used to justify an equal probability assumption for all initial two particle-one hole configurations, i.e., the use of Eqs. (10), (11) or, more specifically, Eq. (26) for class 0 emission chances.

Equations (27) and (28) may now be used to see whether the approximative use of Ericson-type exciton distribution functions—as given by Eqs. (10) and (11)—in both the exciton and the hybrid model has an important impact on model predictions, and how its impact compares to that of other model differences. These questions will now be addressed.

IV. THE SENSITIVITY OF MODEL CALCULATIONS TO CONCEPTUAL MODEL DIFFERENCES —A "REALISTIC" EXAMPLE

In order to assess the practical significance of the differences between the exciton and the hybrid models and of the approximations employed, a near realistic numerical example will now be discussed. It is a simplified case and not intended for comparison with experimental data, but it is realistic in that reasonable or reasonably demonstrative transition rates and functional dependences are used. It is meant to show what sorts of effects result on a typical preequilibrium calculation as consequences of the model differences which were discussed from a conceptual point of view in Secs. II and III, namely

(a) that the hybrid model works in terms of generations of independent excitons and yields inclusive spectra, whereas the exciton model envisions generations of exciton configurations and predicts exclusive spectra;

(b) that exciton distribution functions for generations other than the first are neither the same in both models nor given solvely by state density considerations, but that they are given by Eq. (27) for the hybrid model and by Eq. (28) in the exciton model framework; and

(c) that maximum configuration mixing is assumed in the exciton approach versus no configuration mixing in the hybrid model.

This last difference has already been shown to affect preequilibrium emission from the first generation of excitons or configurations thereof in Sec. II C. The illustrative case considered there showed that the hole interaction strength will influence first generation preequilibrium emission if configuration mixing is assumed (exciton model) but will leave it unchanged if no such mixing is assumed (hybrid model). To show this influence (or lack thereof) more quantitatively, three kinds of transition rates for holes, $\lambda_+(e_h)$, are considered in the example to be presented. They are depicted on the left-hand side of Fig. 2. The full curve will be referred to as strong hole interaction $[\lambda_+(e_h)\propto e_h^2]$ and approximates a nucleon-nucleon scattering calculation by Gadioli *et al.*,[24] whereas the dashed $[\lambda_+(e_h)\propto e_h]$ and dotted $[\lambda_+(e_h)=0]$ lines will be called medium and zero hole interaction, respectively, and are picked arbitrarily, although roughly in line with approaches found in the literature. This meaning of curves will be retained throughout the example.

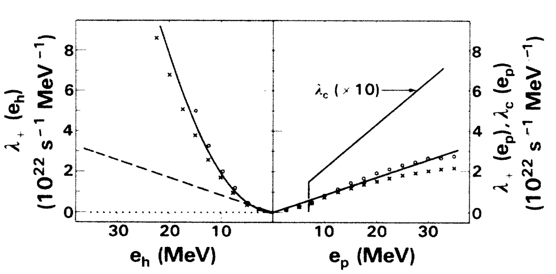

FIG. 2. Single particle escape and transition rates used in the demonstrative, realistic example in this work. The full, dashed, and dotted curves on the left-hand side represent hole transition rates for strong, medium, and zero hole interaction, respectively. The full lines on the right-hand side represent the particle transition (λ_+) and escape rates (λ_c) adopted. The crosses correspond to results of detailed calculations (Ref. 24) assuming a truncated harmonic oscillator potential and the open circles correspond to results (Ref. 24) assuming a Fermi gas with 20 MeV Fermi energy.

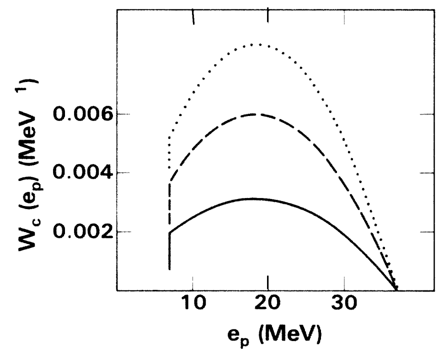

FIG. 3. First generation (class 0) preequilibrium emission probabilities obtained from the exciton model for strong (full curve), medium (dashed line), and zero (dotted line) hole interaction, as are depicted in Fig. 2.

The lines on the right-hand side of Fig. 2 show the particle transition rates $\lambda_+(e_p)$ and escape rates $\lambda_c(e_p)$ adopted, the transition rates approximating Gadioli's calculation[24] mentioned above and the escape rates corresponding to a sharp cutoff reciprocity expression.

The example chosen is that of a 30 MeV nucleon incident on a medium mass nucleus with a nucleon separation energy of 7 MeV. The assumption of equal *a priori* probability of all two-particle—one-hole configurations in the first generation of excitons or configurations thereof is then justified,[22,25] if a nucleon-nucleon scattering excitation mechanism is assumed. Consequently, nucleon emission from the first generation $(i=0,\ n=n_0)$ is readily calculated according to Eqs. (5) and (16), and the influence of model differences (a) and (b) will show only when subsequent generations are treated.

Figure 3 shows the result obtained for first generation emission in the exciton model using zero (dotted line), medium (dashed line) and strong (full curve) hole interaction. The results vary by a factor of 3—4, depending upon the hole interaction which is assumed, and Fig. 4 illustrates the reason for these pronounced differences: In the

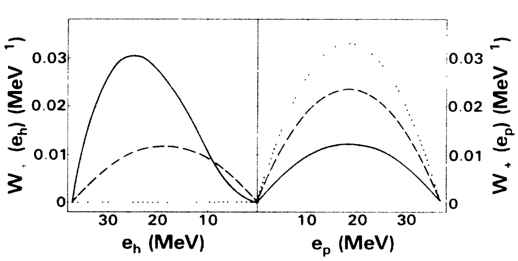

FIG. 4. Probabilities $W_+(e_{p/h})$ for decay of $2p\,1h$ states through a thermalizing collision of an exciton of energy $e_{p/h}$, as obtained in the exciton model. The different curves pertain to the different assumptions about hole interaction which are shown in Fig. 2, full curves for strong, dashed curves for medium, and dotted curves for zero hole interaction.

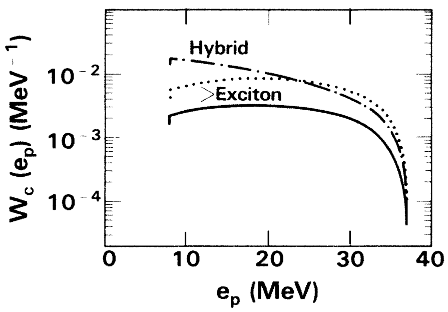

FIG. 5. First term or generation (class 0) preequilibrium emission probabilities. Exciton model results for no hole interaction (dotted line) and strong hole interaction (full curve) are compared to a hybrid model result (dash-dotted curve), which is independent of the hole interaction assumption.

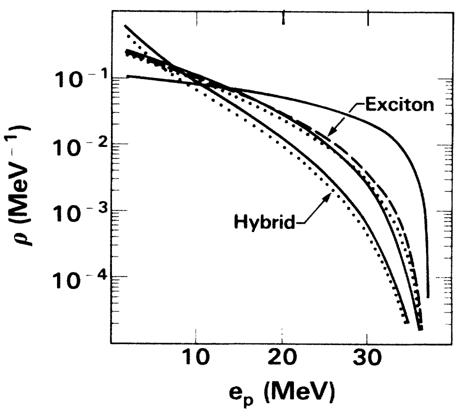

FIG. 6. Exciton distribution functions, ρ, resulting from Eqs. (27) and (28) for the second generation (class 1) emission chances under zero, medium, and strong hole interaction assumptions (dotted, dashed, and full lines labeled "exciton," respectively). The full and dotted curves labeled "hybrid" show corresponding hybrid model results with strong and zero hole interaction, respectively. For comparison, the first generation (class 0, $n=n_0$) distribution function is also indicated (upper full curve).

case of strong hole interaction (full line) the initial three-exciton states decay predominantly via hole interactions, reducing particle interaction and emission accordingly. If, on the other hand, zero hole interaction is assumed (dotted line in Fig. 4), the three-exciton states decay exclusively by particle emission or particle-particle intranuclear collision, and the probability of either is correspondingly high (dotted line in Figs. 3 and 4). Medium hole interaction produces an intermediate result both for particle emission and for a particle thermalizing collision to occur (dashed lines in Figs. 3 and 4). In Fig. 5, the preequilibrium emission probability from class 0—i.e., the first generation and the first term in Eqs. (5) and (16)—in the hybrid and exciton models are compared with one another. The exciton model result varies by about a factor of 4, as the assumption about hole interactions is changed from zero to strong (dotted and full curve), whereas the hybrid model result is the same under both assumptions (dash-dotted line). In the high energy part of the spectrum, which is most important for comparison with experimental data pertaining to precompound decay, the exciton model predicts emission probabilities (full curve) which are down by a factor of about 2 from the hybrid model result if strong hole interaction is assumed. On the other hand, if no hole interaction is assumed in the exciton model (dotted curve), larger preequilibrium emission probabilities result than are obtained from a hybrid calculation at high ejectile energies. These differences are almost exclusively due to the influence of the intrinsic configuration mixing envisioned by the exciton model as opposed to no mixing in the hybrid model concept, as it is through configuration mixing that hole interaction exerts its influence on first generation emission.

Under the assumptions used in this example for the transition rates, the integrals (27) and (28) can be solved analytically to yield the second generation exciton distribution functions, ρ, which are shown in Fig. 6. Inspection of the figure shows that the rather accurate results obtained from Eqs. (27) and (28) do not depend very much on what is assumed about hole interaction in either model. The figure also shows that the hybrid distribution functions are much softer than those obtained in the exciton model and that both are much softer than the first generation distribution function which is the same in either model. In terms of high energy ejectile emission this means that the second term in the exciton model formula [Eq. (16)] contributes only a fraction of the first term, and that in the hybrid model [Eq. (5)] that fraction is still smaller. If Eqs. (10)–(12) were used to calculate the second generation distribution functions, they would overpredict or underpredict the more exact results of Eqs. (27) and (28) by factors $F_<$ and $F_>$, respectively, which are shown in Fig. 7. At the maximum particle energies, e.g., Eqs. (10)–(12) will give an exciton density four times as large as calculated with Eq. (27) in the hybrid model. While these differences are serious from a conceptual point of view, they are of no great practical importance to high energy preequilibrium emission. This is seen in Fig.

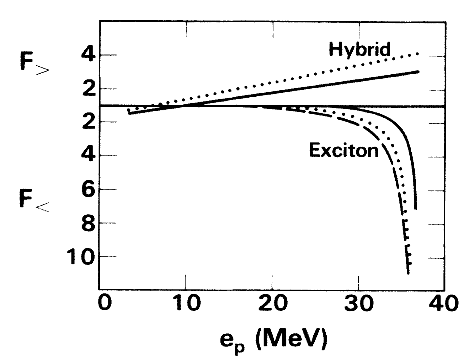

FIG. 7. Factors by which Eqs. (10)–(12) will overpredict ($F_>$) or underpredict ($F_<$) the more exact second generation exciton densities obtained with Eqs. (27) and (28) in both the hybrid and the exciton model frameworks. Full, dashed, and dotted curves refer, again, to strong, medium, and zero hole interaction.

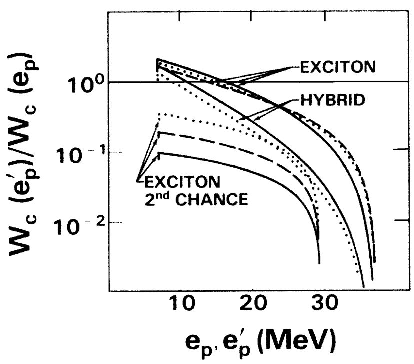

FIG. 8. Second generation (and second chance, in the exciton model) preequilibrium emission as a fraction of first generation emission and resulting from the expressions given in Sec. III. Full, dashed, and dotted curves are, once again, for strong, medium, and zero hole interaction.

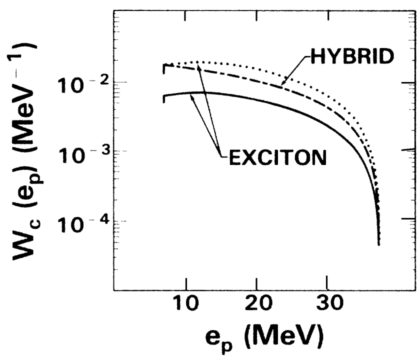

FIG. 9. Emission probabilities obtained from roughly comparable parts of hybrid and exciton model calculations. The first generation hybrid term (dash-dotted curve) is compared to the sum of first and second generation (and second chance) emission in the exciton model, assuming strong (full curve) or zero (dotted curve) hole interaction.

8, which shows the probabilities of preequilibrium emission from the second generation, $W_c(e_p')$, as a fraction of emission for the first generation, $W_c(e_p)$. For the exciton model, all three assumptions on hole interaction yield essentially the same result: For particle energies above 25 MeV, the second term contributes about 40% or less of what the first term yielded, and second chance emission is even less important. Terms other than $i=0$ are thus seen to affect mostly the lower ejectile energies, for which Eqs. (10)–(12) are a good approximation according to Fig. 7. Consequently, using Eq. (28) instead of (10)–(12) will leave the total exciton model prediction for the preequilibrium spectrum essentially unchanged. In the hybrid model, the second generation contribution is even less significant than in the exciton approach, as is seen in Fig. 8. Only in roughly the lower half of the emission spectrum will it give any appreciable contribution. Therefore, using Eq. (27) instead of using the simpler Ericson state densities [Eqs. (10)–(12)], will change the overall result of a hybrid calculation only marginally.

As emission chances are grouped according to different kinds of generations in either approach, no rigorously meaningful comparison can be made between contributions of individual generations in the two models. Nevertheless, a rough comparison was made in Fig. 5 on the pretext that the first term plays a dominating role and can be used, perhaps, as a zero order approximation to a full calculation. More nearly equivalent to the hybrid first generation, however, is the sum of the first and second generation and of second chance emission in the exciton model, as this choice covers chances up to the point that two thermalizing collisions have occurred in either model, and that a maximum of two particles could have been emitted. Such a comparison is shown in Fig. 9, using the more rigorous exciton distributions given by Eq. (27) rather than expressions (10) and (11) for second generation and second chance emission in the exciton model. Inspection of the figure shows that the shapes of the spectra which are predicted, are more similar to one another than they are in Fig. 5, but that the difference in absolute magnitude visible at the high energy end in Fig. 5 are seen to persist in practically the entire spectrum when the "fairer" comparison shown in Fig. 9 is made.

The example just presented may be summarized to show that the use of Ericson-type exciton distribution functions as an approximation in both the exciton and the hybrid model affects the predicted precompound spectra only marginally. On the other hand, the example demonstrates that in a typical precompound calculation the hole interaction plays an important part. If configuration mixing is assumed (exciton model), the hole interaction strongly influences the all important first generation emission, whereas no such influence exists if no configuration mixing is assumed (hybrid model).

V. CONCLUSIONS

The exciton model and the hybrid model have been shown to differ fundamentally in several ways. The hybrid approach groups emission chances according to generations of independent excitons and yields inclusive spectra. The exciton model groups emission chances according to generations of n-exciton configurations and yields exclusive spectra. It is a systems rather than an independent particle approach. Both models use the same closed form expressions as exciton distribution functions. These are inconsistent with two-body thermalizing collisions in the framework of either model. More accurate and consistent exciton distribution functions were given (Sec. III) but shown to have only marginal impact on the results of a simplified but realistic calculation in Sec. IV. This finding is expected to be generally valid and is due to the overwhelming importance of first generation emission, which is not affected by the approximations made for higher terms. Exceptions may possibly be reactions where first generation emission is suppressed by the nature of the entrance channel, e.g., proton preequilibrium emission induced by capture of negative pions.

The difference between the models, however, which is by far the most important—conceptually and numerically—is that no intrinsic configuration mixing is assumed in the hybrid model, whereas the exciton model implies strong mixing. This mixing, which is restricted to occur only among configurations of the same exciton number, affects the (dominating) first generation emission. As a consequence, an exciton model calculation is very sensitive to what assumption is made about the interaction of holes.

There is no obvious *a priori* basis on which to estimate the amount of configuration mixing likely to occur during equilibration. It is incompatible with a pure concept of two-body collisions of independent nucleons moving in a potential well as it would require collisions which leave the exciton number unchanged, and these can easily be estimated to be very unlikely. Rather, it must be produced by a part of the nuclear Hamiltonian which is not described by the potential well and two-body collisions. In addition, the question of hole interaction has, perhaps, not been studied sufficiently well to base a decision between the model concepts on a comparison of absolute cross sections to experimental data. As—unlike the hybrid model predictions—the exciton model results will strongly depend on hole interaction, agreement or disagreement with experimental data may just reflect the choice of a favorable or unfavorable hole interaction. The models differ, however, in the trend the preequilibrium spectra follow as a function of the total excitation. This trend is only partly influenced by the hole interaction and can most likely be used to decide whether or not there is configuration mixing in preequilibrium processes. If ratios of higher ejectile energy emission cross sections obtained with a number of different projectile energies are considered, the uncertainty resting with hole interaction assumptions is considerably reduced. In addition, the question of hole interaction might be studied in the same way Blann[25] has used to justify Eq. (26).

The difference in preequilibrium emission cross section predictions obtained from the hybrid and exciton models rests almost exclusively with the question of intrinsic configuration mixing. Past comparisons,[12] which have led to adverse conclusions about the mean free path of nucleons in nuclei, were affected by differences in the single particle state densities used and other inconsistencies beyond the conceptual difference of the models. Once the latter is recognized (and, perhaps, decided) and the former eliminated, a unique set of mean free paths may be shown to result from preequilibrium analysis.

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