The Griffin Model, Complex Particles and Direct Nuclear Reactions

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The basic approximations of the Griffin model for nuclear reactions are reexamined. Proton-neutron distinguishability and the Pauli exclusion principle are treated in an improved way. Several improvements in the model input values are suggested. Direct reaction mechanisms are systematically considered, and semi-empirical descriptions are proposed for those not included in the Griffin model calculations (knockout and inelastic processes involving alpha particles and stripping and pickup). When all of these points are considered, good agreement with experimental energy spectra for emitted particles are obtained without arbitrary and unphysical factors in the particle emission rates and without the artificial projectile dependence previously needed for the average residual two-body matrix element.

I. Introduction

The Griffin preequilibrium reaction model was originally formulated for nucleon induced reactions and with the principle aim of calculating the energy spectra of emitted nucleons. Yet in recent years a desire to extend the range of validity of model calculations has led to studies of reactions involving complex particles. While much has been learned from this work, several questions, problems and even misconceptions have resulted. It is time for a new and more general consideration of the field of complex particles in preequilibrium reactions.

In this paper we attempt to show that many of the apparent problems and inconsistencies existing in the Griffin preequilibrium model may be attributed to an inadequate consideration of the influence of direct reactions. In analyzing nucleon induced reactions, groups have tended to consider at most one class of direct mechanisms in describing complex particle emission. In the study of alpha particle induced reactions they have been virtually ignored!

II. Improvements to and Clarifications of the Griffin Model

II.1. Summary of the Extended Griffin Model

The basic formulation of the Griffin model described here is the one used by our group and incorporated into the computer code PRECO-A [1]. It has been modified, however, in light of recent results appearing in the literature.

The states of the composite nucleus are classified according to the numbers of particle, \( p \), and hole, \( h \),
degrees of freedom they contain, with the initial composite state being specified by \((p_0, h_0)\). The corresponding state densities \([2]\) have been modified \([3]\) to take into account the existence of passive particles and holes (adjacent to the Fermi surface) as well as the degrees of freedom. This gives

\[
\omega(p, h, E) = \frac{g_0^2 (E - A_{p, h})^{n-1}}{p! \cdot h! \cdot (n-1)!},
\]

\[
A_{p, h} = E_{\text{pauli}}(p, h) - \frac{p^2 + h^2 + n}{4g_0},
\]

\[
E_{\text{pauli}} = \frac{\hbar^2}{g_0}
\]

where \(g_0\) and \(E\) are the single particle state density and excitation energy, respectively, for the composite nucleus, and \(E_{\text{pauli}}\) is the minimum energy required by the Pauli exclusion principle for a state with given numbers of particles and holes. The quantity \(n\) is referred to as the exciton number of the system and is defined as \(n = p + h\), while \(\omega = \max(p, h)\).

Corrections for the finite depth of the nuclear potential well \([4]\) have been found to be small and have been included only for the initial composite nucleus configuration. For a well depth of \(V = 38\,\text{MeV}\) we find that the state density can be approximated as

\[
\omega(p_0, h_0, E, V) = \omega(p, h, E) \left[1 - \frac{(E - V)}{E}\right]
\]

for \(E > V\). (4)

For smaller excitation energies (1) still applies. The rates for the pair creation and destruction interactions which bring about equilibration are \([1, 5]\) for a given initial state \((p, h)\) are

\[
\lambda_+(p, h, E) = \frac{2\pi}{M^2} \frac{g_0^2 (E - E_{\text{pauli}}(p + 1, h + 1))^2}{2(n+1)},
\]

\[
\lambda_-(p, h, E) = \frac{2\pi}{M^2} \frac{g_0 p h (n-2)}{2} \left[1 - \frac{(n-1)(p-1)(p-2) + (h-1)(h-2)}{8g_0E - E_{\text{pauli}}(p, h)}\right].
\]

The quantity \(M^2\) is the square of the average matrix element for the effective, residual, two-body interaction. It has been evaluated empirically \([6]\) and found to vary as

\[
M^2 = K_s A^{-3} E^{-1}
\]

for \(E \geq 20\,\text{MeV}\). The quantity \(K_s\) has sometimes been taken to be projectile dependent. For the initial composite state of \(E > V\) we again use a result corrected for the finite well depth \([4]\) and analogous to (4).

The probability per unit time for emitting particles of type \(b\) and energy \(\epsilon\) averaged over a given class of composite states is \([7]\)

\[
W_b(p, h, \epsilon) d\epsilon = \frac{(2s_b + 1) \mu_b \epsilon \sigma_b \omega(p, h, U)}{\pi^2 h^3} \frac{R_b(p)}{\omega(p, h, E)} \frac{\omega(p - p_b, h, U)}{\omega(p, h, E)}
\]

where \(s_b\), \(\mu_b\), \(\sigma_b\) and \(p_b\) are the spin, reduced mass, inverse reaction cross section and mass number of the emitted particle. The quantity \(U\) is the excitation energy of the residual nucleus while \(R_b(p)\) takes account of the distinguishability of protons and neutrons. Additional factors of \(\gamma_b\) \([7]\) or \(\gamma_b \omega(p_b, 0, E - U)/g_0\) \([8]\) have sometimes been used but cannot be derived from microscopic reversibility and so have been omitted here.

The reaction is described by solving the appropriate set of master equations for the system and obtaining the values of the occupation probabilities, \(P(p, h, t)\), for the various classes of states at different times, \(t\), during the equilibration process. The master equations include terms for particle emission as well as pair creation and destruction. The occupation probabilities are then used to calculate the energy spectra of the emitted particles, according to the relations

\[
\frac{d\sigma}{d\epsilon}(a, b)_{\text{PRE}} = \sigma_a \int_0^{\tau_{eq}} W_b(p, h, \epsilon) P(p, h, t) dt,
\]

\[
\frac{d\sigma}{d\epsilon}(a, b)_{\text{EQ}} = (\sigma_a - \sigma_{\text{PRE}}) \frac{\sum_p W_b(p, h, \epsilon) P(p, h, \tau_{eq}) P(p, h, \epsilon)}{\sum_p \sum_{\epsilon} W_b(p, h, \epsilon) P(p, h, \tau_{eq}) d\epsilon}
\]

where \(\sigma_a\) is the composite nucleus formation cross section, \(\tau_{eq}\) is the time at which the system has achieved equilibrium and \(\sigma_{\text{PRE}}\) is the total cross section which has gone into preequilibrium emission.

Differences between using the assumed constant single particle state density, \(g_0\), and one that increases with increasing energy in the well has been considered by Gadioli et al. \([9]\). The effects are small. We apply a similar correction to the initial composite state assuming a Fermi gas with a 38 MeV deep potential well. This gives

\[
g(p_0, h_0, E) = g_0 \left(1 + \frac{E}{n \cdot 38\,\text{MeV}}\right)^\frac{n}{2}
\]

\[
+ h \left(1 - \frac{E}{n \cdot 38\,\text{MeV}}\right)^\frac{n}{2}
\]

\(n\).