Preequilibrium Reactions with Complex Particle Channels

Constance Kalbach Walker

Triangle Universities Nuclear Laboratory, Physics Department, Duke University, Durham NC 27701, USA

Abstract. Existing phenomenological models for direct reactions in the continuum with complex particles in the exit and/or entrance channels have been substantially revised. These models supplement the exciton preequilibrium model and a standard evaporation model in providing a coherent and complete description of experimental energy spectra. The description for nucleon-induced reactions is reasonably complete, but additional work for incident complex particles is needed to properly include the effects of projectile breakup (fragmentation). The present work indicates the importance of allowing for the excitation of extra particle-hole pairs during nucleon transfer; it supports previous systematics with regard to the surface localization of neutron-induced reactions; and it provides insights into key exciton model parameters for complex projectiles. For most of these reactions, direct nucleon transfer is the dominant direct reaction mechanism, while for inelastic channels the consideration of cluster scattering seems important.

THE GOAL

The exciton model has been used for many years to describe preequilibrium reactions with complex particles in the entrance and/or exit channels. What has remained a matter of discussion is the extent to which the exciton model alone should be adequate and what other mechanisms need to be explicitly considered. (See a recent review by Hodgson and Běták [1].) The present work modifies an earlier phenomenological approach to this question, using an extensive database to develop a more comprehensive and reliable description of light particle induced reactions in the continuum.

THE STARTING POINT

The version of the exciton model used in this work was developed in a series of papers and is summarized in the users manual for the computer code, PRECO-2000 [2]. The direct reaction models were developed in 1977 [3] in conjunction with a very early version of the exciton model using very primitive state densities. They were modified for PRECO-D2, and early results from this work were included in PRECO-2000. Angular momentum is not considered in these calculations.

The most important direct reaction mechanism (in addition to the direct part of the exciton model calculations) is the transfer of one to three nucleons. This mechanism includes pickup, stripping, and nucleon exchange. In calculating the energy spectra, the particle-hole state densities in the residual nucleus are multiplied by the usual exit channel energy and inverse cross section, as well as by the spin degeneracy and reduced mass of the outgoing particle. The empirical normalization depends on the nature of the projectile, the $N$ and $Z$ of target nucleus, the incident energy, and the number and type of nucleons being transferred.

The model for knockout and inelastic scattering involving cluster degrees of freedom assumes that a constant fraction of the total reaction cross section is available, and uses rudimentary state densities with cluster degrees of freedom to estimate branching ratios for the possible emissions.

Finally a modification [4] of a simple model [5] for collective excitations (spectroscopic and giant resonance) is now part of the PRECO code system.

The development of reliable phenomenological models requires a broad database. This work uses inclusive continuum energy spectra for charged particles with $A = 1$–4. Incident energies range from 15 to 63 MeV for neutrons, 25 to 90 MeV for protons, 25 to 80 MeV for deuterons, 25 to 41 MeV for He-3, and 35 to 140 MeV for alpha particles. Target nuclides extend from aluminum through uranium. While the database is not exhaustive, it is certainly
comprehensive, comprising over 200 spectra with complex particles in the entrance and/or exit channels. This severely constrains the models and leads to results with significant predictive ability.

NUCLEON INDUCED REACTIONS

This work began with a study of complex particle emission in nucleon-induced reactions, since the exciton model has only been thoroughly tested and benchmarked for incident nucleons. As these reactions are insensitive to the cluster model, the work focused on direct pickup. Shell structure, pairing, isospin conservation, and surface effects are all now included in the exciton model state densities, which are carried over into the direct nucleon transfer model.

Proton Induced Reactions

Only proton-induced reactions were studied in [3], and they were thus considered first here.

The most important change was the evident need to allow for the excitation of additional particle-hole pairs during nucleon transfer. The state densities with the resulting extra degrees of freedom are added to those for the main residual configuration but are multiplied by a scaling parameter; one factor of the parameter for each extra pair. This produces a rapidly converging series. The scaling parameter was found to be proportional to $E_a^{1/2}V_1^{-1}A_t^{-2}$, where $E_a$ is the incident energy, $V_1$ is the potential well depth in the interaction region, and $A_t$ is the target mass. It also contains a factor of $(1.5h^2 + n^2)$, where $h_x$ and $h_y$ are the numbers of hole degrees of freedom left by the picked up protons and neutrons, respectively.

Two additional changes improve the realism and accuracy of the calculations without introducing any new parameters. The first allows for nucleon transfer at the Fermi level. The corresponding states were not being counted in the state densities because the Fermi level moves down during particle emission. Therefore their state densities must be explicitly added in. The second change adjusts the pairing corrections to allow for the transfer of two neutrons or protons with their spins paired.

Finally, the sensitivity of these reactions to isospin conservation was studied. The results, combined with those from nucleon spectra and from some of the complex particle-induced reactions discussed later, indicate that isospin conservation should be assumed during energy equilibration when the excitation energy in the intermediate nucleus is less than four times its symmetry energy ($E < 4E_{\text{sym}}$). At higher excitation energies, isospin appears to be mixed.

Neutron Induced Reactions

Neutron-induced reactions were studied to look for any projectile charge dependence in the model. The per-nucleon normalization factor (one such factor for each nucleon transferred) had to be increased by 45% relative to the value for incident protons. Further, while it was known that a large neutron excess in the target hinders proton pickup, incident neutrons allow the pickup of two protons to be studied and also show a weaker $2Z/A$ dependence. This leads to an exponent of $2(Z+2)h_n$, where any contributions from stripped nucleons is still unknown.

These reactions also relate to recent results [6] on the surface localization of the initial target-projectile interaction obtained from proton and neutron spectra. That work indicated that incident neutrons generally interact further out in the target nucleus ($V = 7$ MeV) than is the case for incident protons ($V = 17$ MeV), but that for heavier targets, as the incident energy increases, the neutron-proton interactions tend to occur further and further into the nucleus, with $V$ becoming as large as 30 MeV. Complex particle emission for light targets, where $V = 7$ MeV, now confirms the use of $V$ in the scaling parameter for extra pair excitation in the nucleon transfer model. With that established, the general trend of $V$ for heavier targets was confirmed at bombarding energies of 49 and 63 MeV.

COMPLEX PARTICLE INDUCED REACTIONS

While a fairly comprehensive and definitive description of nucleon-induced reactions can now be achieved, the same is not true for reactions initiated by complex particles. A greater variety of reaction mechanisms must be considered, and, in particular, projectile breakup has not yet been included in a consistent way. Still, good progress has been made.

The Exciton Model

The exciton model components, particularly for incident alpha particles, were sometimes found to be too large even without any direct reaction contributions. This indicates that the effective mean square matrix elements for the residual interactions
that produce energy equilibration were too small. The alternate form that seemed to give the best overall agreement with experiment is

\[ M^2_{ij} = K_{ij} A_n A^{-3} \left( 21 + E / 3 A_n \right)^3. \]  

(1)

where the subscripts \(i\) and \(j\) refer to the kinds of interacting particles (neutrons or protons), \(K_{ij}\) is a normalization constant, \(E\) is the excitation energy in the equilibrating nucleus, and \(A\) is its mass number. The \(A\)_dependence of Eq. (1) the only change.

The other unique parameter in the exciton model is the number of particle and hole degrees of freedom in the initial configuration. The work of [3] indicated that particle emission should only be allowed to occur after the first particle-hole pair excitation. The initial configuration is thus specified by \((p_0, h_0) = (A_x+1, 1)\). This implicitly assumes that a complex projectile does not disintegrate into its constituent nucleons prior to that interaction. Alternatively, emission could begin from states with \((p_0, h_0) = (A_x, 0)\). For incident nucleons this is not an issue because states with \((p, h) = (1, 0)\) can only emit into the elastic scattering channel, which is not calculated in the exciton model.

While the present work continues to assume a \((p_0, h_0) = (A_x+1, 1)\) initial configuration, it is likely that this will change once projectile breakup is included. Preliminary estimates show that, especially for deuterons, projectile breakup can account for close to half of the total reaction cross section. This will reduce the cross sections going into the exciton model calculations, lowering their intensity. This fact plus a deficit in the calculated cross sections at high emission energies, particularly for proton emission, point to both the possibility and desirability of having emission begin from states with \((p_0, h_0) = (A_x, 0)\).

**Nucleon Transfer**

The \((d, t), (d, ^{3}\text{He}), (d, ^{6}\text{He}, \alpha\), and \((^{3}\text{He}, \alpha)\) reactions serve to test the pickup formalism derived from nucleon induced reactions. The normalization factor for proton projectiles works well for deuterons and for the limited He-3 data. At incident energies around 25 MeV, agreement with experiment is good, while the 70-80 MeV incident deuteron data suggest that the scaling factor for the state densities from extra pair excitation needs to be reduced. Stripping reaction data reinforce this need and point to replacing \(E_a\) with \(E_a/A_n\), the energy per nucleon in the scaling factor.

Data from stripping reactions were sparse when the nucleon transfer model was first developed. With the current, expanded database, significant changes are needed. First, the factor of 12 enhancement for \((N, \alpha)\) and \((\alpha N, N)\) reactions (where \(N\) is a nucleon) appears to decrease and eventually disappear in the latter case as the alpha particle energy gets much larger than its internal binding energy. The form chosen is \(12 - 11(e_\alpha / 20) e_a\), where \(e_\alpha\) is the incident channel energy. In addition, the overall normalization seems to vary with \((1/E_a)^{1/2}\), rather than \(1/E_a\) as for pickup. Finally the exponent of the \((2Z/A)\ factor for stripping could be investigated for the first time. The full exponent now becomes \(2(Z_a+2) h_\pi + 2 p_\pi\), indicating that a large neutron excess hinders both proton pickup and neutron stripping. This could reflect a neutron-rich region at the nuclear surface.

Nucleon exchange can occur in complex-particle inelastic scattering and in the one \((^{3}\text{He}, xt)\) spectrum studied. Unfortunately, the inelastic spectra can have contributions from cluster scattering, making results on these two mechanisms difficult to disentangle. Nevertheless, it appears that the nucleon transfer model works well if the incident energy dependence in the normalization is taken from stripping rather than pickup and if the normalization is reduced by a factor of two. The normalization is, however, tentative.

**Cluster Reactions**

For inelastic scattering and knockout reactions involving cluster degrees of freedom, the only change made was to decrease the normalization from 1/12 to 1/14 of the total reaction cross section. This inherently assumes that a loosely bound deuteron is just as likely as a more tightly bound alpha particle to maintain its cluster identity while exciting a particle-hole pair, whereas the probability might be expected to depend on the projectile energy relative to its internal binding energy. Investigating that possibility will require additional \((^{3}\text{He}, xt)\) or \((t, ^{3}\text{He})\) spectra to better define the normalization of the nucleon exchange component.

**WHAT HAS BEEN ACHIEVED**

With all of the changes made in the models—and most were made based on subsets of the data—a full set of calculations for all the available spectra was carried out. Sample comparisons with experiment are shown in Figs. 1 and 2. The calculations include secondary emission (both preequilibrium and evaporation) of nucleons following primary nucleon.
emission, but otherwise only the emission of the first particle is calculated. Thus the evaporation peaks and, in some cases, the cross section at emission energies just above the evaporation peak are underestimated. Otherwise the agreement seen is generally quite good.

The incident proton results shown in Fig. 1 are typical of those at lower energies, as well as those for incident neutrons up to 63 MeV and incident alpha particles up to 60 MeV. For 90 MeV incident protons, however, the shapes of the triton and alpha particle spectra are not as well reproduced. Likewise for 140-MeV incident alpha particles, the proton spectra show what may be a significant breakup component, while the calculated triton, He-3 and alpha particle spectra are deficient in high energy particles.

In summary, this work has produced a description of direct nucleon transfer and cluster reactions that complements the exciton model in providing a more comprehensive, reasonable and accurate description of measured continuum energy spectra. It has shown the importance of allowing extra particle-hole pairs to be excited during nucleon transfer processes; indicated the importance of the neutron excess in the target nucleus; increased our understanding of when isospin is conserved in a preequilibrium reaction; and confirmed trends with regard to the surface localization of the initial interaction that had been observed in nucleon spectra.

Much work remains to be done for complex projectiles, particularly with regard to the inclusion of projectile breakup contributions and unraveling the relative contributions of nucleon exchange and cluster scattering processes. Yet the current formalism, in addition to yielding physical insights, should provide a useful tool for the description of unmeasured or unmeasurable reactions.

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**REFERENCES**