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Multi-step direct reactions

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SUMMARY

In nucleon–induced nuclear reactions, one conventionally distinguishes between fast, direct processes and slow, compound processes. However, for reactions with incident energies between 10 and 200 MeV per nucleon, it is found that emission can take place after the direct stage but long before the attainment of statistical equilibrium in the compound stage. Such processes are called pre–equilibrium reactions and account for a significant fraction of the total reaction cross section. This thesis concerns the quantum–mechanical description of this no man's land between direct and compound reactions.

Quantum–mechanical pre–equilibrium theory distinguishes between multi–step compound processes (all particles remain bound throughout the successive stages of the reaction) and multi–step direct reactions (at least one particle remains in the continuum). We have attempted to cover both theoretical and practical aspects of multi–step direct reactions. Starting from distorted wave theory, we have derived in chapter 2 a panoply of existing and new MSD reaction models on the basis of two different statistical postulates. The first postulate, that we call leading-particle statistics, is based on the assumption that many states are accessible to the leading particle and that the associated DWBA matrix elements are randomly distributed. The alternative postulate is called residual-system statistics, which represents random configuration mixing due to the residual interaction within the residual nucleus. It does not make any statistical assumption about the interactions of the leading particle. Applying these physically different random postulates on first and higher order distorted wave theory leads to two distinct classes of statistical MSD theories, as depicted in the MSD family tree of fig. 2.6. From this analysis several interesting conclusions follow for the quantum theory as well as for the computational phenomenology of MSD reactions. The TUL [1] and NWY [2] models appear to be based on residual-system statistics, whereas the FKK model [3] can be derived using *only* leading-particle statistics. For the latter, we have shown that there is no need to invoke residual-system statistics, although this was explicitly mentioned in [3,4]. Furthermore, we have argued that conceptually the generalized exciton models are actually quite close

to the FKK model.

These multi–step direct reaction models have been implemented in a single computer code system called KAPSIES. In this way, we were able to perform a consistent practical comparison of the FKK, TUL and NWY model, on the basis of the same set of parameters and the same set of numerical techniques for the MSD calculations. Various experimental data of energy spectra and angular distributions in the pre–equilibrium region have been analyzed. The MSD model comparison is the subject of chapter 3, while in chapter 4 the KAPSIES system is discussed.

In sum, the major results of this work are:

- All MSD models can be derived from two alternative types of statistics, leading-particle statistics and residual-system statistics, respectively.
- The expression for the FKK multi–step cross section can be obtained using *only* leading-particle statistics. We regard the FKK model as the quantum–mechanical equivalent of the generalized exciton model since they can both be understood on the basis of our concept of leading-particle statistics.
- The one–step contribution to the MSD cross section is the same for all MSD models.
- In general, the one–step contribution dominates the total continuum cross section. The first two steps are sufficient for the explanation of the data over the whole outgoing energy range. This is in line with [1] but in disagreement with [5,6,7].
- The problem of the underestimation of the angular distributions at backward angles by the classical (exciton) models is solved by the quantum–mechanical MSD approaches. Good agreement with the experimental data is obtained, especially at the highest outgoing energies.
- Theories based on leading-particle statistics appear to be computationally much simpler than those based on residual-system statistics, while they have essentially the same predictive power. For routine calculations, we therefore consider the FKK model as the most appropriate.

In general, we feel that this thesis has contributed to a better understanding of the quantum–mechanical pre–equilibrium models as well as to making them amenable for practical nuclear data applications.