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Panel Discussion

on

Heavy Ion Transfer

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Heavy Ion Transfer Reactions - Status and Prospects*

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Abstract. Some comments are addressed to the current status of and possible future directions for transfer reactions induced by heavy ions.

In this talk I shall present some impressions of the current status of heavy ion transfer reactions in the vicinity of the Coulomb barrier and prospects for the future experimental and theoretical developments in this area.

Heavy-ion induced reactions differ from those of light ions in the increased importance of couplings between reaction channels. The most obvious of these couplings arises from the increased strength of inelastic scattering as compared to light ions but couplings between fusion and deep-inelastic processes and transfer are also important. These strong couplings imply an intertwining of nuclear structure and reaction dynamics which is not present in the light ion case. This may be thought of as either a blessing or an undesirable complication depending on one's point-of-view. On one hand, the strong couplings are what give heavy ion reactions their diversity of phenomena and also present the opportunity to study new modes of collective nuclear excitations and other new aspects of nuclear structure. On the other hand, the simple separation of reaction mechanism and structure which occurs for light ion projectiles, is in large part responsible for the relative ease with which spectroscopic information could be extracted from the experimental data and which has played such an important role in furthering our understanding of the structure of nuclei.

In the case of projectiles such as ^{16}O incident on targets which are closed shell nuclei like ^{208}Pb there now exist complete bodies of data for essentially all reaction channels; elastic, inelastic, transfer and fusion - together with complete analyses in the framework of coupled-channels formalism. In these cases, where the coupling between individual channels is not too strong and the number of channels is not too large, a satisfactory description of the experimental results is generally obtained.

A further observation which may now be said to be understood is the origin of the effect of the opening of new reaction channels on one-channel scattering potentials used to fit the experimental data. The first example of this is the observed energy dependence of the real and imaginary parts of the optical potential used to fit elastic scattering data. In the vicinity of the barrier, i.e. the opening of the fusion

channel, the strong increase in the real potential well depth is correlated with the rise in the strength of the absorptive potential, connected in a quantitative way by a simple dispersion relation. In this respect, theory is in relatively good shape. A question which arises is - did we learn any new nuclear structure? The answer appears to be that we knew it all anyway and it would have been difficult to extract new information from the data. Exceptions to this may be the importance of multi-phonon excitations and some aspects of pair transfer strengths.

The situation becomes more cloudy when the target nuclei become deformed. Experimentally, the problem of resolving the closely spaced levels in these nuclei has perhaps limited the number of studies carried out. There are some data for lighter projectiles such as ^{16}O or ^{12}C in which detailed inelastic scattering and transfer data exist. These have been successfully analyzed in the coupled channels framework and some qualitatively new phenomena such as the interference between direct and two-step population of final states has been observed and accounted for. Data and analysis of the quantity and quality of the spherical target cases do not in general exist.

Moving to heavier projectiles. On simple targets it is still possible to resolve individual levels and the strengths of these transitions can be accounted for by current theory. At higher excitation energies, however, there are very large fractions of the reaction strength which remain unaccounted for. This cross-section presumably corresponds to multi-step excitation of complex states which cannot be included in any simple way in the coupled channels calculations. Instead, the tendency has been to describe the qualitative features of these data in terms of global parametrizations such as "Q-windows", binding energy dependences and model based on semi-classical considerations of the scattering and transfer processes. These approaches have been rather successful in describing the overall features of the data although significant deviations, presumably reflecting real nuclear structure effects, are observed.

Transfer between nuclei at large distances has been investigated by several groups and is currently an area of active research. A primary motivation is the similarity that may exist between solid-state junctions and two nuclei separated by a large distance at their point of closest approach in a collision. The semi-classical model leads us to expect a rather simple dependence of the probability of nucleon transfer on the distance of closest approach and the falloff of the wavefunction of the transferred particles in the region outside the nucleus. In some cases it has been observed that the transfer probability falls off more slowly with increasing distance of closest approach than expected on the basis of the semi-classical tunneling model - particularly in the case where it is a pair of nucleons that is transferred. This enhancement or "slope-anomaly", represents an intriguing observation which may have relevance to the proposed parallels between solid-state and nuclear physics. A word of caution is, however, in order. It has been pointed out that in some cases the data leading to the "slope anomaly" was obtained under conditions which would violate some of the assumptions of the semi-classical model and that the observed effects may arise from diffractive effects not included in the simple model.

One of the goals of transfer reaction studies with heavy projectiles is the extraction of information relating transfer on excited states of the target nucleus. If this were possible it would represent a qualitatively new aspect of transfer reaction spectroscopy and would give us a method of studying, for example, the influence of rotation on single-particle and pairing aspects of the wavefunctions of the transferred particles. This goal has not yet been attained although progress is being made and hints of interesting phenomenon appear in data for Ni + Dy. From the experimental point-of-view, the driving force is the need for energy resolution sufficient to resolve individual final states and thereby extract their population strengths. This need has led to the development of particle-gamma coincidence technique which show considerable promise although, at their present level, the experimental data are lacking in statistics. It is likely, however, that the new generation of gamma-ray arrays with near 4π efficiency and excellent energy resolution, will allow data of the needed quality to be obtained. On the theoretical side, guidance is needed on what signatures one might expect to see in the data as a consequence of physical effects such as band crossing, the disappearance of pairing etc. In this way the experimental parameters can be fine-tuned to give maximum sensitivity to the underlying physics.

Finally, I would like to add some words on the question of missing degrees of freedom in our physical description of transfer reactions and their relation to other reaction channels. The current view is that a description of transfer reactions can be obtained using a model (coupled-channels) which describes the process in terms of the relative motion of the colliding ions and the coupling of this motion to excited states of the target and projectile. Other reaction channels, such as fusion, are accounted for by the inclusion of an absorptive component in the scattering potential or by the use of incoming-wave boundary conditions inside some critical radius. Little is said however, on the multitude of steps which must connect the simple rearrangement of the target and projectile to the complete amalgamation called fusion. For heavy systems the qualitatively different phenomenon of deep-inelastic or strongly-damped processes displays some of the degrees of freedom which must be important in the transition between transfer and fusion. At present, however, our microscopic understanding of this transition is, at best, rudimentary and in no sense included in our model description of heavy ion fusion.

Generically, such processes might be called "di-nuclear" and we might therefore expect that the physics of the di-nucleus might manifest itself in the connection between quasi-elastic processes, damped-processes and fusion. Particularly intriguing in this respect is the possibility that shell effects at extreme deformations might play a role. Such shell effects can influence the mass distributions of damped fragments - as is known in the case of fission. They might also influence the nature of the energy dissipation process itself through changes in the level density as the nuclei coalesce and by the provision of relatively long-lived sets of very deformed "doorway" states through which the system must pass on its pathway to fusion. The inclusion of these effects in our description of the transfer of nucleons is a challenge for the future.

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