Ecole Joliot Curie 2012
Lecture topic: Direct reactions at low energies
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Preamble – scene setting

Direct reaction methods provide certain standard tools, and also some newly-developing ones, that are suited to describe (at some level of precision) reactions in which only a *small number of degrees of freedom* (either collective or those of individual clusters or nucleons) are excited/changed in a collision. The usual aim - particularly in the present era of reactions using short-lived secondary beams of radioactive nuclei - is to derive new and if possible *quantitative spectroscopic information* on these exotic projectile nuclei. Both the approximations that can be made and the reactions chosen for the physics of interest (usually dictated by the magnitudes of the cross sections) depend on the choice of beam energy. The aims of this short lecture series will be to make the connection between physical observables for a selected set of often-used lower-energy reactions (e.g. transfer, fusion and projectile breakup) and the wave functions, potential and other necessary parameters that enter the *direct reaction* model descriptions of these processes. The key approximations and physical assumptions behind the models will be discussed. Many of the relevant texts can be found at: http://www.nucleartheory.net/DTP_material/texts.htm

Lecture 1: Fundamentals of direct reaction model descriptions

This lecture will aim to review the assumptions and ideas that underpin quantum mechanical and semi-classical models of direct nuclear reactions at lower energies, i.e. near the Coulomb barrier energy of the reacting systems. We will first review the use of *potential models* for the description of bound, scattering, virtual, resonant, continuum bin, and distorted wave states of *point-like particles* (e.g. nucleons and/or clusters). The key ideas of global or microscopically-derived optical potentials (e.g. Feshbach's approach and g-matrix, e.g. JLM methods), the mean free path, and of point-particle scattering models will be reviewed. These include the phase shift, the T- and S-matrix elements and associated transmission coefficients, and their relationship to elastic, absorption, and total reaction cross-sections. The roles played by Coulomb forces, angular momentum and absorption (and their energy dependences) will be outlined. Generalizations of such approaches for the construction of interactions between *composite* systems, i.e. folding-like models (or channel coupling interactions in non-diagonal cases) and their generic features (volume integrals, root mean squared radii, etc.) will be outlined. The connection of these reaction ingredients to few- and many-body nuclear structure models, specifically the concepts of nucleon *overlap functions*, and of spectroscopic factors and asymptotic normalization constants/coefficients (ANCs) will be introduced.

[Pre-reading/concepts: The use of an imaginary part in the nuclear optical potential to represent loss of flux from the elastic channel, and its formal (Feshbach) derivation in terms of projections on and off the space of reaction channels of interest: The effects of imaginary potentials on the results of quantum mechanical scattering: The appearance of resonances and virtual states in a real potential model, their location in the complex energy/k-plane and the definitions of resonance widths, scattering lengths and of the

effective range: The quantum theory of scattering of point particles: Material is available in the texts list above and at: http://www.nucleartheory.net/DTP_material/index2.htm]

Lecture 2: Specific concepts/examples of direct reaction models

The formulation of direct reactions methods (eventually into computer codes) often relies heavily on more formal, perturbation theory expansions – their order depending on the nature and the strength of the particular transition(s) of interest. The necessary reaction amplitudes are expressed (and computed) both as T-matrix elements (i.e. in integral form) or using solutions of coupled equations methods within a suitable basis of states (the differential form). Analyses of elastic and inelastic scattering use exact, coupled channels and DWBA and higher-order methods. Cluster transition strengths are used to describe excitations and/or breakup of weakly-bound systems, and B(E1) and B(E2) strengths for provide valuable semi-classical estimates of Coulomb excitation (discrete) and breakup (continuum) calculations for particle-core and of halo systems. For fusion reactions, barrier penetration and transmission coefficients concepts are important, with ingoing wave or absorptive boundary conditions. The role played by projectile excitations (the source of coupling-enhanced-tunneling) can be critical, and will be discussed. These methods also connect to astrophysically-interesting direct and resonant capture reactions and S-factors, and to B(E1) and B(E2) distributions. DWBA-like transfer channel methods will be introduced before being extended in Lecture 3. Topical examples will be used that illustrate recent applications of the methods discussed.

[Pre-reading/concepts: The Born approximation and the Born series: The integral form of the quantum mechanical scattering problem – including *propagators* and the *Green's operator*: the differential and integral forms of the scattering problem.]

Lecture 3: Transfer and breakup degrees of freedom

This lecture aims to provide an introduction to reactions of weakly bound (e.g. very neutron-rich) systems and of the importance and treatment of their breakup, including their effects on other reaction channels - such as transfer. The methods of Alder and Winther and other (semi-classical) *time-dependent approaches* for breakup/excitation will be outlined. The formulation of breakup using the *adiabatic* and the coupled discretised continuum channels (*cdcc*) methodologies for effective two- and three-body projectiles, and recent applications, will be presented and, for the cdcc, to include a consideration of the choice of model spaces and of truncation strategy. The different commonly-used calculation schemes for transfer reactions will be discussed, including momentum and angular momentum matching/mismatch considerations and their implications for direct reaction models. This involves considerations of zero-range (ZR) and approximate finite range interaction treatments and their applicability. The use of *adiabatic* and the *cdcc* approximation methods for transfer reactions will be discussed and the (relatively simple) ADWA approximation implementation discussed. Topical examples will be used to illustrate recent applications/advances of the methods discussed.

[Pre-reading/concepts: There is much work in the recent literature. Relevant reading and orientation can be found in the textbooks referred to earlier and in the notes of Johnson and others at http://www.nucleartheory.net/DTP_material/index3.htm]