

# Challenges in Reaction Theory

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# Spectrum of Reactions

- ◆ Direct Reactions
  - In & outgoing channels – quantum scattering theory
- ◆ Compound nucleus production & decay
  - Particles,  $\gamma$  emission, fission – use statistical theories
- ◆ Heavy ion reactions
  - high  $\rho$ ,  $T$  – use transport theories
- ◆ Subnucleonic:
  - quarks, mesons, etc – use field theories

# Modelling Direct Reactions

- ◆ Beyond Few-body Structure for light neutron-rich nuclei
- ◆ Bound and Continuum Overlaps
- ◆ Few-body Reactions with light neutron-rich nuclei
- ◆ Predicting what is actually measured.

# No “universal” model!

- ◆ Only models & techniques depending on:
  - reaction (beam) energy
  - target (Coulomb or nuclear dominant?)
  - structures involved (important degrees of freedom; deformation, breakup etc)
- ◆ Calculation of reactions requires knowledge of structures involved + model for reaction.
  - Simple mechanism => deduce structure (eg at high energy!)
  - Structure and model => reaction rate

# New Developments

- ◆ Many-body (microscopic) structure
- ◆ Three- and Four-body continuum
- ◆ Direct Reactions
  - Inelastic: bound  $\rightarrow$  bound' states, same nucleus
  - Transfer: bound  $\rightarrow$  bound states in partner
  - Breakup: bound  $\rightarrow$  continuum states
  - Multistep direct processes?
    - some of: Adiabatic, Eikonal, CRC, CDCC
- ◆ Fusion!

# Related Structure Challenges

- ◆ Nuclear structure:
  - ${}^6\text{Li}$  quadrupole moment?
  - ${}^8\text{B}$  E2 transitions ?
  - Intruder states in  ${}^{11}\text{Be}$ ,  ${}^{11}\text{Li}$ ,  ${}^{12}\text{Be}$  etc ?
    - Can these be found in a model beginning with a NN force?
    - Are tensor and/or 3-body forces required?
  - Thresholds: are these fitted simultaneously?

# 'Overlap' Challenges

- ◆ Reaction models need few-body degrees of freedom (dof) in structure models.
  - Solve a few-body model directly, or
  - Extract few-particle dof from microscopic model
    - Difficult for: GFMC,
    - for HFB, QRPA and RMF structure models
    - Do we transfer quasi-particles, or particles?
  - **Collective** and **giant-resonance** degrees of freedom ('semi-direct' reactions)

# Nucleon-Nucleus Reactions

- ◆ Optical potentials
  - Microscopic derivation?
- ◆ Particle-hole excitations (like breakup)
  - 1p1h, 2p2h, etc?
- ◆ Pre-equilibrium reactions
  - Avoid: on-shell approximations
  - Examine: decoherence approximations

# Few-body Challenges

- ◆ One nucleon with core excitation:
  - solve problem of E2 breakup in  ${}^8\text{B}$ ?
- ◆ Two nucleons with core excitation:
  - eg.  ${}^{12}\text{Be}$ ,  ${}^{14}\text{Be}$ 
    - Solve underbinding problems? In  ${}^6\text{He}$  too perhaps?
    - **Is it possible** to have an *s*-wave resonance at +0.6 MeV in  $n+{}^{12}\text{Be}$  scattering?
    - Or must it be a *p*-wave?
  - How to do Pauli blocking without closed shells?

# Reaction Challenges

- ◆ Need reaction models with some/all of:
  - Recoil & Finite Range of projectile vertex.
  - Final-state (partial wave) interference
  - Nuclear and Coulomb mechanisms
  - Core excitation (initial and/or dynamic)
  - Final-state interactions:
    - between halo fragments (needed if resonances)
    - between fragments and target (needed if close in)
  - Multistep Processes (higher order effects)

# CDCC (3-body) method

- ◆ So we need Coulomb+Nuclear coupling,
  - eg DWBA, MST breakup, or (better)
  - CDCC calculations (3-body),
- ◆ To predict e.g.  $d^3\sigma/dE_1d\Omega_1d\phi_{12}$ 
  - fold with detector apertures & efficiencies
- ◆ Theory Challenge:
  - Include core excitation of  $^{10}\text{Be}^*$  in continuum as well as ground state wave functions.

# 4-body Reaction Models

- ◆ High Energies (first order & all order):
  - T-matrix multiple scattering (Crespo)
  - Eikonal+Adiabatic (Tostevin, Al-Khalili)
  - Eikonal(Exact fragment) (Brooke, Tostevin, Al-Khalili)
  - Adiabatic (Johnson, Christley et al)
- ◆ All Energies (all orders):
  - 4-body pseudostate CDCC (Kamimura)
  - 4-body bin-state CDCC (???)

# Fusion Theory (!?)

- ◆ Fusion is a small fraction of total reaction.
- ◆ Theory Challenges:
  - Converged breakup in CDCC?
    - Nuclear & Coulomb couplings for fine bins
    - Continuum-continuum couplings.
    - Measure all breakup fragments at all angles
  - Distinguish complete vs incomplete fusion!
    - Do we need another formalism, to track second fragment even after first is 'absorbed' ?

# Grand Challenges?

- ◆ *Ab initio* grand challenges in reactions
  - Using structure of light nuclei (GFMC; NCSM; CC) for overlaps & resonances
  - Calculating the optical potential
  - Breakup of few-body projectiles
  - Pre-equilibrium ( $n$ -particle-hole) reactions
  - Fission

Computers are bigger now!  
Why not Parallel Computation?

# Way Forward

- ◆ Many calculations to do!
  - (and so few theorists!)
- ◆ New challenges to connect new structure theories with reactions
  - Need to solve reaction models accurately, so comparisons with theory tells us about initial physics, not approximations used.
- ◆ 'Grand challenges' in theory of reactions