FRESCO: Coupled-channels Calculations

__F__inite-__R__ange with __E__xact __S__trong __CO__uplings.

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Fresco

- Started in 1983 at Daresbury Laboratory
- First for 2-step transfer contributions to $^{17}O^*$.
- Main paper in 1988: *Computer Physics Reports*, Vol **7**, 167-212. Now has 930 citations.
- Source & docs available at www.fresco.org.uk, hosted at Univ. Surrey.
- Versions since 2006: 'public' FRES (3.1), and 'Livermore' FRXY (6l) ⚒
- Textbook (CUP, 2009) "*Nuclear Reactions for Astrophysics*" with Filomena Nunes. Now sold 873 copies.
- Still being maintained, and developed, with queries answered.

2-step transfer contributions to $^{17}O^*$

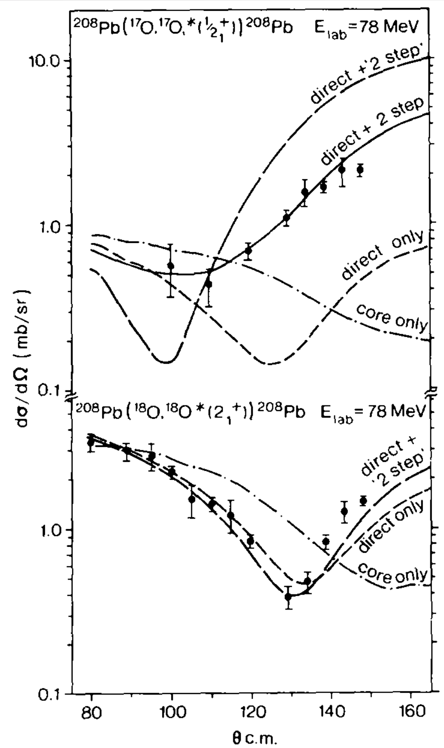


Fig. 2. Differential cross section measurements of the $^{208}Pb(^{17}O, ^{17}O^*(1/2^+))^{208}Pb$ (upper) and the $^{208}Pb(^{18}O, ^{18}O^*(2^+))^{208}Pb$ (lower) reactions at 78 MeV incident energy. The curves are theoretical calculations. The dot–dashed curve includes Coulomb excitation and the nuclear core (^{16}O) excitation only. Adding the valence neutron interaction gives the short-dashed ("direct only") curve. The effect of adding two-step transfer processes using the approximations of ref. [1] is given by the long-dashed curve; the solid curve is the result of a more rigorous calculation described in the text.

Lilley et al, PL 128B, 153 (1983)

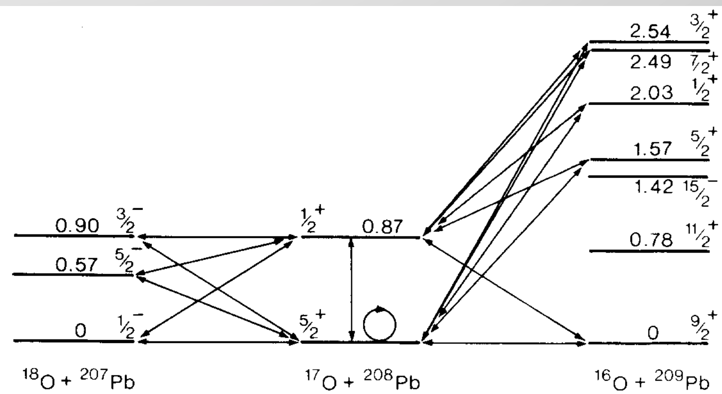


Fig. 6. Channel couplings used in the multistep CRC calculations of the ^{17}O–^{208}Pb interaction at 78 MeV.

Lilley et al, NPA 463, 710 (1987)

Documentation

- *Methods of Direct Reaction Theories*,
  paper in "Scattering" ed. Pike & Sabatier (2001)
- *User Guide*: Appendix A
  of *Nuclear Reactions for Astrophysics*(2009)
- *Coupled Channels Methods for Nuclear Physics,* (1988)
- Input manual

See http://www.fresco.org.uk/documentation.htm

Basic Idea

- Reactions between two nuclei: entrance and exit
- Multiple mass partitions.
- Energy, spin and parity given for all initial and final states of all nuclei.
- Unlimited lists of potentials and couplings.
- Solve coupled equations
- Predict cm cross section distributions.

- Standard forms for
  - optical potentials,
  - bound states,
  - inelastic, transfer and capture mechanisms,
  - etc
- Written in Fortran 90
  - Tested on wide range of compilers

The Coupled Equations

For each total spin J_{tot} and parity π

$$[T_{xL}(R) + V_c(R) - E_{xpt}]\psi_\alpha(R) + \sum_{\alpha'} \langle\alpha|V|\alpha'\rangle \psi_{\alpha'}(R') = 0.$$

with

$$\hat{T}_{xL}(R_x) = -\frac{\hbar^2}{2\mu_x}\left[\frac{\mathrm{d}^2}{\mathrm{d}R_x^2} - \frac{L_x(L_x+1)}{R_x^2}\right]$$

and

$\langle\alpha|V|\alpha'\rangle$ either local R=R', or non-local $R \neq R'$

satisfying the boundary conditions

$$\psi^{J_{\text{tot}}\pi}_{\alpha\alpha_i}(R_x) = \frac{\mathrm{i}}{2}\left[H^-_{L_i}(\eta_\alpha, k_\alpha R_x)\,\delta_{\alpha\alpha_i} - H^+_L(\eta_\alpha, k_\alpha R_x)\,\mathbf{S}^{J_{\text{tot}}\pi}_{\alpha\alpha_i}(\right]$$

Optical and Binding Potentials

- Central, spin-orbit and tensor forces.
- WS, Gaussian (etc) shapes, or read in.
- Deformation by rotational model, or by arbitrary strengths
- Linear energy interpolations.

- L-, J-, and parity-dependent potentials.
- Effective masses m*(r)
- Lane isospin couplings

Coupling Mechanisms

- Inelastic
  - Deformed optical potls.
  - Single-particle excitations
- Transfers of a cluster
  - Zero range, LEA.
  - Finite range
  - Non-orthogonality terms.
- Two-nucleon transfers
  - From & to correlated 2N wfs from correlated 1N wfs, or read in from 3-body code.
  - Sequential and Simultaneous
- Capture to γ channels
  - Ek in Siegert approx.
  - Mk magnetic transitions
    - (both in localized approx.)
- R-matrix phenomenology
- General LSJ couplings
  - Local or non-local
  - Numerical forms read in
- ⚒ General partial wave couplings
  - Numerical local or nonlocal

Solving the Coupled Equations

- Numerov integration of equations with local couplings: 'exact'
- Iteration on non-local couplings (eg. transfers).
- Use Pade acceleration if *n*-step DWBA diverges.
- Use James Christley's coupled-Coulomb wave functions CRCWFN for long-range multipoles
- Isocentrifugal approx.

- R-matrix solutions:
  - Expand on eigenstates of diagonal optical potls
  - Need Buttle corrections.
  - More stable numerically
- Lagrange-mesh method:
  - From Daniel Baye (ULB)
  - No Buttle correction needed
- MPI: to solve J^{π} sets in parallel.
- OPENMP: to solve coupled equations for given J^{π}.

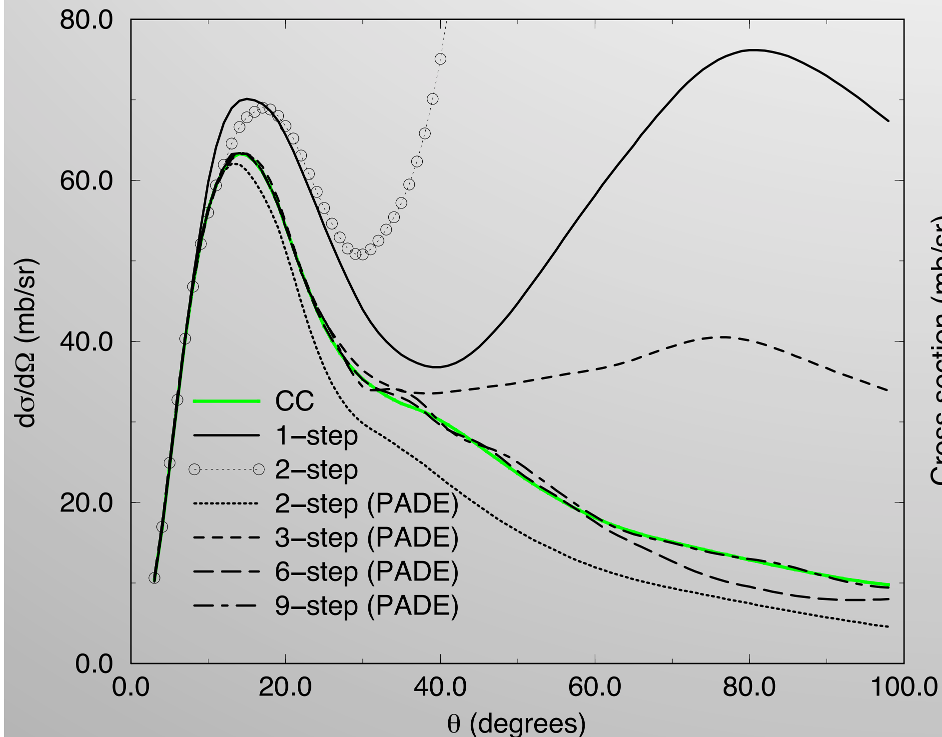
Breakup: beyond 2-body channels

- CDCC:
  - Use continuum single-particle states
  - Orthonormalized in segments.
  - Post-processing by Jeff Tostevin for coincidence breakup cross sections.
  - Converges ok (if no transfer bound states!)

- XCDCC
  - Neil Summers extended CDCC method to deal with <u>deformed core states</u> in single-particle states.
  - Example for breakup of $^{11}Be = {}^{10}Be(0^+,2^+) + n$

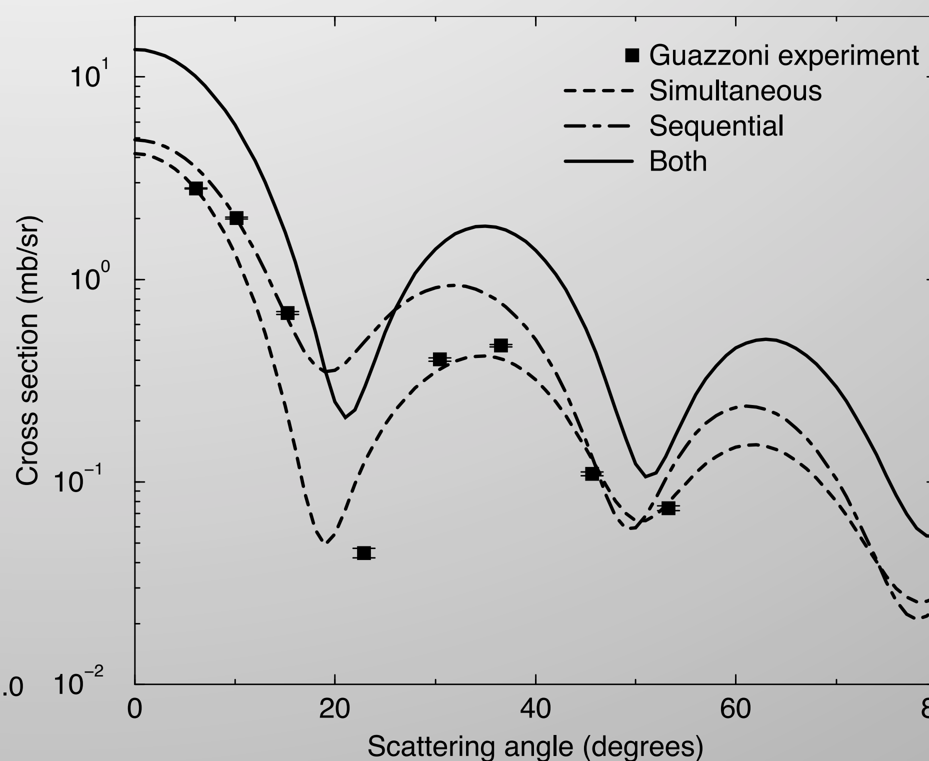
Coherent multistep effects

$^{8}B + ^{58}Ni$ breakup at 26 MeV



Nunes & Thompson, PRC 59, 2652 (1999)

$^{124}Sn(p,t)$ at 25 MeV



Thompson, in Broglia et al (2013)

Input Formats

- OLD style #1:
  - Card inputs cols 1—72
- NAMELIST style #2:
  - Fortran var=value text
- CDCC style #3:
  - Generate easily the NAMELIST sets of bins and couplings for CDCC calculations.

Output Formats

- Cross sections $\sigma(\theta)$
- Amplitudes $f_{mM:m'M'}(\theta)$
- CDCC amplitudes for post-processing.

Sfresco: searching for χ^2 minimums

- Define data with errors:
  - Energy and/or angle data
  - Polarization data
  - Angle-integrated data
  - Phase shifts in given channel
  - Fitted bound state parameters
- Define parameters

  Initial values and limits of:
  - Optical parameters
  - Spectroscopic amplitudes
  - R-matrix pole energies & widths
  - Data normalizations

- Searching
  - Interactive or given method
  - Uses MINUIT
  - Plot initial or final fits
  - Trace χ^2 progress
  - Restart at any trial set.

Current Developments

- LLNL:
  - General nonlocal potentials
  - Effective masses m*(R)
  - Lane couplings for IARs
  - IAR non-orthogonality (p,p′)
  - Semi-direct capture step
  - Surface operator for transfer
- Jeff Tostevin:
  - Breakup coincidence cross sections with core excitation in XCDCC
  - Simple zero-range transfers
- Alex Brown
  - Using shell-model two-nucleon overlaps for transfers (seq+sim).
- Antonio Moro:
  - Stabilizing the solutions from Numerov method
  - More NN standard forms for tensor forces
  - Deformations in optical potentials in transfer operator

Missing Capabilities

- Core transitions in electromagnetic particle steps.
- Perey-Buck nonlocality in optical potentials.
- Spin-dependence of optical potentials in transfer operators.
- Energy-dependence of optical potentials in transfer operators.
- Uniform treatment of antisymmetrization and identical particles
- <u>Convergence problems</u>: CDCC breakup with all-order couplings to transfer channels.

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