## Howework day 3: Transfer calculations with DWBA and ADWA

# Useful resources:

- FRESCO and XFRESCO: `fresco.org.uk`
- TWOFRNR (Surrey version by Jeff Tostevin) `http://www.nuclear theory.net/NPG/code.htm`
- TUNL Nuclear Data Project: `http://www.tunl.duke.edu/NuclData/`
- RIPL-3 database (optical potential parameters): `http://www-nds.iaea.org/RIPL-3/`
- Lund database for masses, $S_n$, $S_p$ values, Q-values `http://nucleardata.nuclear.lu.se/database/`

# Introduction:

The programs front TWOFNR and BRUSH are useful in interactively assembling transfer reaction data sets for TWOFNR and FRESCO. These prompt for all of the inputs that need to be specified to carry out such calculations. In such calculations, the Johnson-Soper adiabatic approximation is an approximate but very efficient way to deal with the effects of breakup on a transfer reaction for the cases of an s-state projectile wave function (such as for the deuteron and $(d,p)$ and/or $(p,d)$ nucleon transfer reactions).

The codes permit different kinds of approaches for the numerical evaluation of the transfer amplitude. For a $(d,p)$ reaction, using the post-form representation, the integral is dominated by the product $D(r) \equiv V_{pn}(r)\phi_d(r)$, which is referred to as *vertex function*. For $s$-wave states (as is the case of the deuteron to a very good approximation), the simplest approximation is to assume that $V_{pn}(r)$ is of zero range,

$$D(r) \approx D_0\delta(\mathbf{r}) \quad \text{(zero-range approximation)} \tag{1}$$

where $D_0$ (called *zero-range constant*) is estimated from

$$D_0 = \sqrt{4\pi}\int dr\ r^2 V_{pn}(r)\phi_d(r) \simeq (1.5\times 10^4)^{1/2}\ \text{MeVfm}^{3/2} \tag{2}$$

A finite range-correction is can be obtained using the *effective zero-range coupling*,

$$D = \sqrt{4\pi}\int_0^\infty \frac{\sinh(kr)}{k}\ V_{pn}(r)\phi_d(r)dr \tag{3}$$

where $k$ is the deuteron linear momentum. The value of $D$ can be estimated using a realistic model for the deuteron.

The code FRESCO permits three kinds of calculations: zero-range, zero-range with finite correction, and exact finite-range, so we can assess the validity of the former two against the *exact* calculation (note, however, that the inclusion of exact-finite range in the front-end BRUSH is in progress and only for (d,p) and (p,d) reactions so far).

# Exercise:

Consider the transfer reaction $^{12}$C(d,p)$^{13}$C at a deuteron laboratory energy of 25 MeV, populating the following states in $^{13}$C: $1/2^-$ (ground state), $1/2^+$ (3.09 MeV), $3/2^-$ (3.68 MeV) and $5/2^+$ (3.85 MeV). This reaction was measured by Hidenori Toyokawa *et al.* (Ph.D. thesis, RCNP/Osaka University, 1995). The measured cross sections are given as a function of the angle of the outgoing proton in the c.m. frame. These data can be found in the website of this course in the files `12Cdp12-25.exp`, `12Cdp12+25.exp`, `12Cdp32-25.exp` and `12Cdp52+25.exp`.

1. Write a table including the following information for each final state: c.m. kinetic energy, separation energy of the least bound neutron, the expected dominant single-particle configuration ($n$, $\ell$, $j$) for the states populated in $^{13}$C, according to the standard level scheme.

2. Use FRONT to construct data sets `tran.xxx` (or BRUSH in case you plan to use FRESCO) for **zero-range** DWBA and zero-range Johnson-Soper adiabatic model calculations for the $^{12}$C(d, p)$^{13}$C reactions at 25 MeV deuteron incident energy that populate the $1/2^-$ (ground state), $1/2^+$ (3.09 MeV), $3/2^-$ (3.68 MeV) and $5/2^+$ (3.85 MeV) final states of $^{13}$C. The experimental $^{13}$C spectrum can be fetched from the TUNL database, and is given also in the file `c13_spectrum.pdf` for convenience.

3. Perform the actual transfer reaction calculations using TWOFNR (or FRESCO) and compare the quality of agreement of both the DWBA and the Johnson-Soper calculations with the experimental data of Toyokawa et al. The cross section calculated by TWOFNR is written to the file `21.xxx`. With FRESCO, the transfer cross section is written in `fort.202` (the output contains some header lines for the plotting package `xmgrace`; if you are plotting with a different utility, you will need to remove these header lines).

4. Estimate the spectroscopic factors for the ground state and first excited state in $^{13}$C, scaling your calculation to the data, at the smaller angles.

5. Repeat the calculations including the **finite-range correction** (with the default parameters suggested by the code for the finite- range correction parameter) corresponding to the $\langle d|p\rangle$ vertex. If you are using FRESCO, perform also the calculation using **exact finite-range**. In view of the results, what conclusions can be drawn about the accuracy of the zero-range and corrected zero-range calculations regarding both the shape and the absolute value of the calculated cross sections?

6. Plot the transfer cross section, for each total angular momentum $J$ of the system, as a function of $J$ (with FRESCO, last column in `fort.56` file). What can we conclude from this plot regarding the nature of the transfer process?