Breakup Reactions on Deformed Nuclei

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Motivation

Compound nuclear reaction calculations of deformed nuclei require input from direct reactions. The amount of compound nucleus formed in the reaction is determined from the direct reaction component, i.e. the imaginary part of the optical potential. Also the transition matrix elments from direct reactions are required inputs into the Hauser-Feshbach calculation. Inelastic excitations of the deformed target are coupled via rotational/vibration couplings. The transition potentials are obtained by calculating the scattering of nucleons from the deformed target via a coupled channels code. This is limited to rotational/vibrational bands. Other states are included via a weak coupling DWBA model or by the weak coupling model for odd-A nuclei.

The coupled channels model employed in typical Hauser-Feshbach calculations can only couple the ground state rotational or vibrational bands. Other levels are then included uncoupled only to first order.
A more complete description of the direct reactions would involve including the other levels on the same footing as rotational bands. This involves calculating the transition potentials of inelastic states from particle-hole excitations. The scattering of nucleons from the deformed target can then be calculated using coupled channels where more complete set of channels is included in the calculation.

Here we consider the breakup of deformed projectile, which consists of a deformed core+particle. The breakup of this deformed core+particle from the scatting off a nucleon is a similar problem as the scattering of nucleons from deformed targets. We consider the elastic scattering and breakup of ^{11}Be from a proton target using an extended coupled channels model, which can include deformation of one of the fragments
[N.C. Summers *et al*., Phys. Rev. C 76, 014611 (2007)].

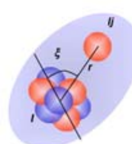
eXtended Coupled Discretized Continuum Channels (XCDCC)

The eXtended Coupled Discretized Continuum Channels (XCDCC) method was developed [N.C. Summers *et al*., Phys. Rev. C 73, 031603(R) (2006); 74 014606 (2006)] to extend the traditional CDCC method to include deformation of one of the fragments. The normal CDCC method treats the projectile as a pure single particle state. To include deformation in XCDCC involves 2 steps. 1) A couple channels description of the projectile provides the projectile wave function for both the bound states and continuum bins. Using a particle rotor model excited states of the core can be introduced. 2) Dynamical coupling potentials which include deformed optical potential allow the deformed fragment to change states during the reaction.

1) Coupled channels description of projectile

$$V_{a:a'}(r) = \langle (ls)j, I; J_p | V_{vc}(r,\xi) | (l's)j', I'; J_p \rangle$$

$$[E_k - \epsilon_a + \epsilon_n - T_a] f_{a:n}(k_{an};r) = \sum_{a'} V_{a:a'}(r) f_{a':n}(k_{a'n};r)$$



$a = \{l, j, I\}$

Bin wave function over momentum interval

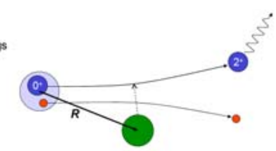
$$u^i_{a:n}(r) = \sqrt{\frac{2}{\pi N^i_n}} \int_{k_{i-1}}^{k_i} dk\, g_n(k) f(k_{an};r)$$

Sum coupled channels to make projectile state

$$\phi^i_{J_p n}(r,\xi) = \sum_a u^i_{a:n}(r) \varphi_I(\xi) | (ls)j, I; J_p \rangle$$

2) Dynamical reaction couplings

$\alpha = \{L, J_p, J, J_t, i, n\}$



$$[E_\alpha - T_R - U^{J_T}_{\alpha:\alpha}(R)] \Psi^{J_T}_\alpha(R) = \sum_{\alpha \neq \alpha'} U^{J_T}_{\alpha:\alpha'}(R) \Psi^{J_T}_{\alpha'}(R)$$

$$U^{J_T}_{\alpha:\alpha'}(R) = \langle \alpha; J_T | U_{ct}(R,r,\xi) + U_{vt}(R,r) | \alpha'; J_T \rangle$$

$U_{ct}(\mathbf{R},\mathbf{r},\xi)$ is a deformed core-target optical potential which is fitted to elastic and inelastic scattering

The resulting coupled channels equations can be solved in the usual way, using a modified version of the computer code FRESCO. This version includes parallelism to cope with the increased model space needed to describe the deformed fragments.

Structure of ^{11}Be

^{11}Be is the archetype of a one neutron halo nucleus. The ^{10}Be core is a highly deformed nucleus with a β_2 = 0.67. The 0$^+$ ground state of ^{10}Be is strongly coupled to the 2$^+$ first excited state at 3.4 MeV, via a collective rotational model. ^{11}Be can be described well by particle-rotor model [Nunes *et al*., Nucl. Phys. A609 (1996) 43].

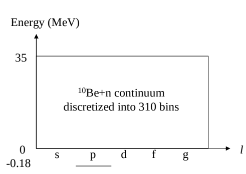
The ground state of ^{11}Be is very weakly bound by 504 keV below the ^{10}Be+n continuum and is predominantly (about 80%) a $s_{1/2}$ neutron coupled to the ground states of ^{10}Be. There is only one bound excited state at 320 keV. The ^{10}Be+n continuum is included in the calculations by discretizing into bins. The continuum is truncated at 35 MeV in energy and up to *l*=4 in partial waves.

^{11}Be has a number of low lying resonances in the continuum. The lower energy resonances (<3 MeV) are thought to be predominantly single particle resonances built on the ground state of the core. The higher energy resonances (3-5 MeV) are more exotic and possibly contain large excited core contributions.

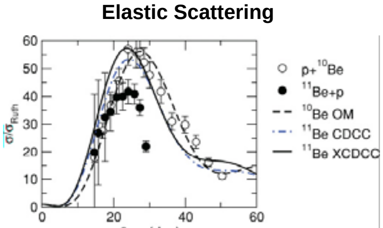
Table 1
States populated in the ^{11}Be(p, p') reaction [2,5,18,19]. E^* denotes the excitation energy. Spin assignments in brackets are unconfirmed experimentally. The suggested dominant structures are mostly those of Liu and Fortune [19]

E^* (MeV)	J^π	Suggested dominant structure
gs	$1/2^+$	^{10}Be$(0^+) \otimes (s_{1/2})$
0.320	$1/2^-$	^{10}Be$(0^+) \otimes (p_{1/2})$
1.778	$(5/2^+)$	^{10}Be$(0^+) \otimes (d_{5/2})$
2.67	$(3/2^-)$	^{10}Be$(0^+) \otimes (p_{3/2})$
3.41	$(3/2^-)$	^{9}Be$(3/2^-) \otimes (sd)^2_{0^+}$
3.89	$(3/2^-)$ [19] $(5/2^-)$ [2]	^{10}Be$(2^+) \otimes (s_{1/2})$
3.96	$3/2^-$	^{9}Be$(3/2^-) \otimes (sd)^2_{2^+}$
5.25		

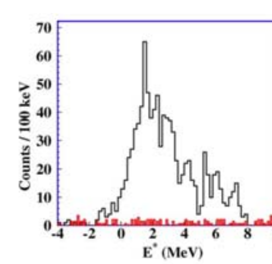
[Shrivastava et al., Phys. Lett. B596, 54 (2004)]



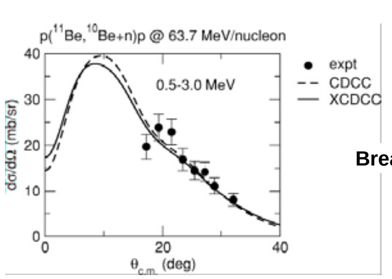
Elastic Scattering

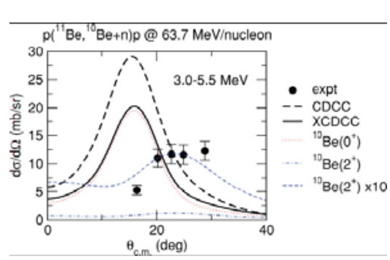


The experimental data is from Shrivastava et al., Phys. Lett. B596, 54 (2004). The breakup data (right) has relatively poor statistics and therefore was summed into two broad energy bins. The first from 0.5-3.0 MeV covers a region where the resonances are predominately single particle states coupled to the ground state of ^{10}Be. The higher energy bin from 3.0-5.5 MeV covers the resonances that have exotic structures where excited states of the core are significant. The lower energy bin (lower left) is well reproduced by the single particle CDCC model and the inclusion of deformation in the XCDCC calculations has little effect as expected. The inclusion of deformation lowers the cross section for the higher energy bin (below), but does not change the energy of the peak as the data suggests. Looking at the excited core distribution of the breakup fragments in the calculation suggests that the data does match the angular distribution of excited core breakup, but the particle rotor-model does not reproduce the resonance with sufficient strength to attract cross section to this energy region. This is also a possibility as to why the elastic distribution (left) is over-estimated by the calculation. It would be interesting to include a better structure model which can describe the exotic resonances as well lower energy states.



Breakup





Computational Requirements

Coupling potentials : radial integrals – trivial parallelization
Sparse matrix :
- ~4,000,000 integrals (only need to store 60,000)
- Memory requirements $\propto$ NR.NC^2

Coupled channels equations:
- NR=400 radial steps
- NC=1800 α channels
- NJ=30 J_T channels
- Computational time $\propto$ NR.NC^3 .NJ

Parallel solution of coupled channels equations
- independent solution for each J_T

CPUs=16 walltime = 4 days memory = 120 Gb total
(can be reduced by sharing coupling integrals over nodes)

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