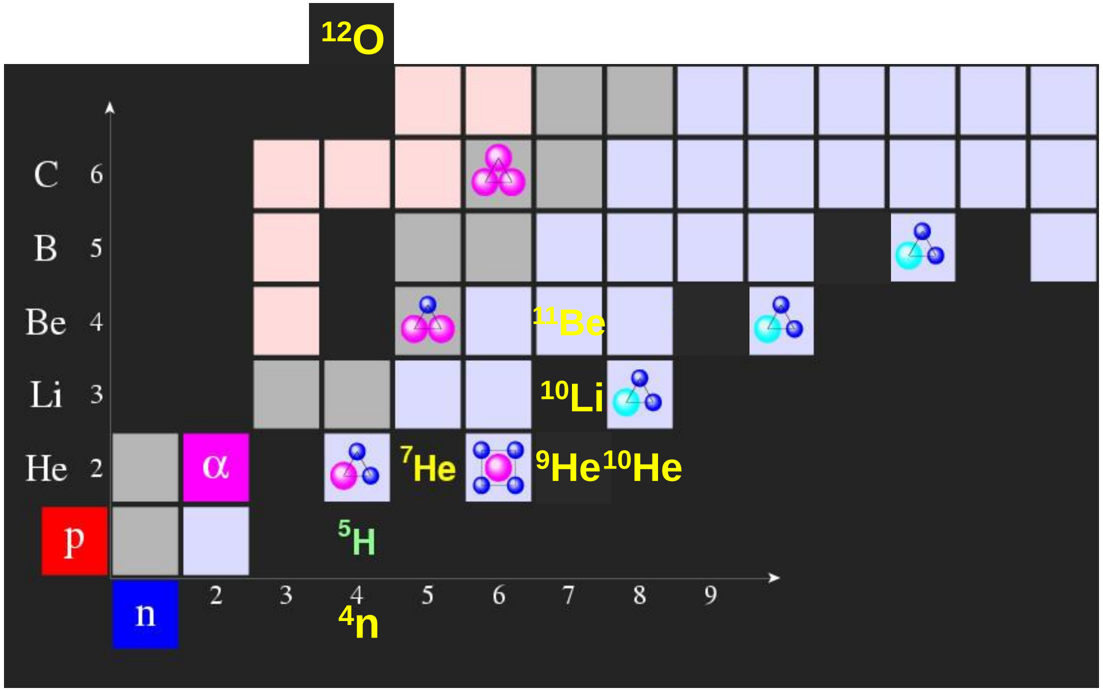
LIGHT EXOTIC NUCLEI

Extensive studies could be performed during the last 15 years by our collaboration (IPN Orsay, CEA/Saclay, GANIL)

- **Missing mass - recoil particle detection**
- **Tools : MUST & MUST2**



- **“Critical” region experimentally accessible**
- ***ab initio* calculations**

Recently : ***make use of ab initio overlaps in cross-section calculations***

Investigation of ^{10}He through ^{11}Li(d,^{3}He) reaction

MUST2 @ RIKEN NISHINA CENTER 独立行政法人 理化学研究所 仁科加速器研究センター

Collaboration: IPN Orsay – RIKEN – GANIL - CEA/Saclay - LPC Caen - JINR Dubna – Kurtchatov Institute - Kyushu Univ. – IPNS KEK – Univ. of Tokyo –Tokyo Inst. of Tech., Univ. Huelva, MSU/NSCL, INP Hanoi

Study of :

- **^{9}Li(d,^{3}He) → (^{9}Li |^{8}He)**
- **^{11}Li(d,^{3}He) → (^{11}Li |^{10}He)**
  "critical" overlap

Direct reactions and Nuclear overlaps

Direct reactions allow to test nuclear overlaps e.g (A|B) B=A± 1
often referred as interface between nuclear structure and reaction

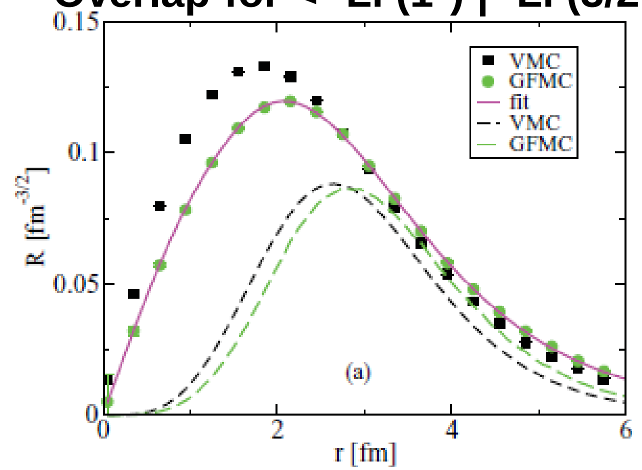
- **Can be taken as :**

$$I^{A,A+1}(r) \approx S_{l,j} \frac{u_{nlj}(r)}{r}$$

$u_{nlj}(r)$ from W.S. potential

- **Can be calculated in *ab initio* models such as VMC ,GFMC,NCSM, …**
  Brida, Pieper, Wiringa, PRC 84 (2011)

Overlap for < ^{6}Li (1$^+$) | ^{7}Li (3/2$^-$) >



Case of transfer reactions **a + A → b + B**
A=B+x b=a+x

$$T_{AB}^{DWBA} = J \int \chi^*_{bB}(\vec{r}_{Bb},\vec{k}_b) \underbrace{<\Phi_B \Phi_b \,|\, V_{ax}(r_{ax}) \,|\, \Phi_a \Phi_A>}\, \chi_{aA}(\vec{r}_{Aa},\vec{k}_a)\, d\vec{r}_{Aa}\, d\vec{r}_{Bb}$$

$<\Phi_b|V_{ax}|\Phi_a>$ $<\Phi_B|\Phi_A>$

Range function **Overlap function**

χ_{bB}, χ_{aA} *: Distorted waves*

Direct reactions and Nuclear overlaps

✓ **Electron scattering $^{7}Li(e,e'p)$**

L.Lapikas et al., PRL (1999)

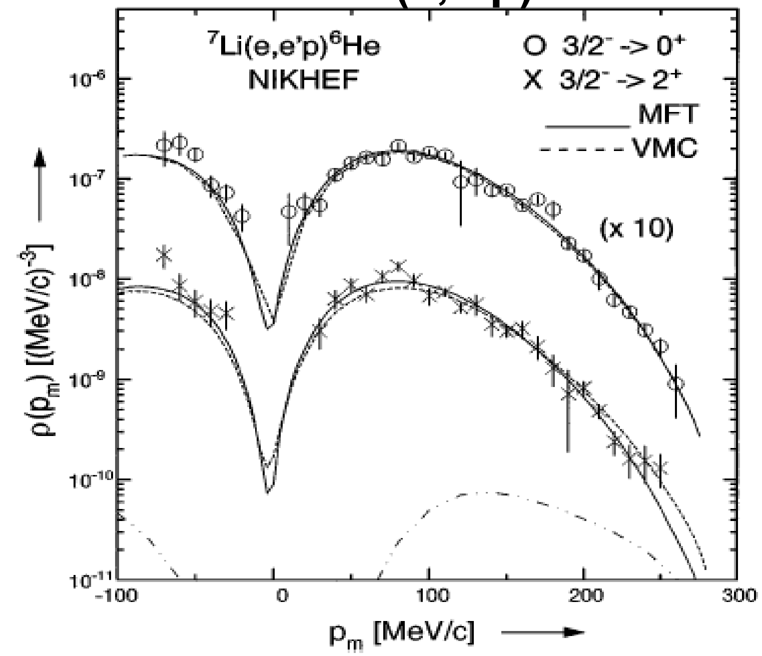
CDWIA calc with VMC overlap

Data very well reproduced in both shape and magnitude

Spectrocopic factors for GS:

S (VMC) = 0.42(4)
S (SM) = 0.7 } **correlations**

$^{7}Li(e,e'p)$



Other reactions implemented recently :
(non exhaustive list) :

✓ **Transfer reactions**

$^{6}He(d,p)$, $^{8}Li(d,p)$ $^{7,8}Li(d,{}^{3}He)$, Wuosmaa et al.,PC(2005), PRL(2005), PRC(2008) **VMC**

$^{9}Li(d,t)$ Kanungo et al., PLB(2008) **VMC**

$^{14}O(d,{}^{3}He)(d,t)$ Flavigny et al, PRL (2013) **SCGF**

✓ **Single nucleon knockout**

(^{9}Li,^{8}Li), (^{9}C,^{8}B),(^{10}Be,^{9}Li), (^{10}C,^{9}C) , … G.Grinyer et al., PRL (2011), PRC (2012)
VMC, NCSM

The < ^{A}Li|$^{A-1}$He> overlaps

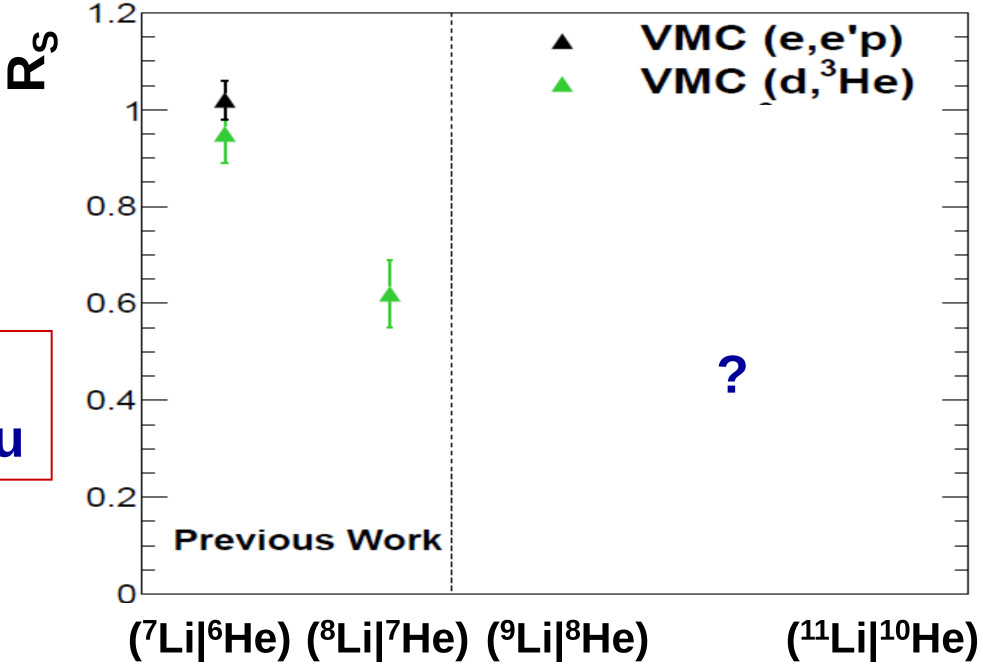
- ✓ **Electron scattering ^{7}Li(e,e'p)**
  CDWIA calc with *ab initio* Variational Monte-Carlo (VMC) overlap
- ✓ **Transfer ^{7,8}Li(d,^{3}He)**
- ✓ **Proton knockout from ^{7}Li**

Generally:
S (< ^{A}Li|$^{A-1}$He>) < S(< ^{A}Li|$^{A-1}$Li>)

PRESENT SITUATION

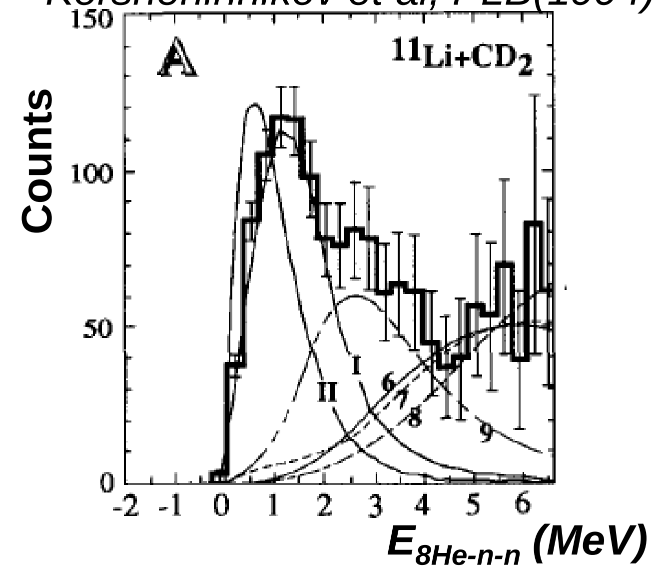
$$R_S = \sigma^{EXP} / \sigma^{\text{React Mod [VMC]}}$$

Our present work:
Study of ^{9,11}Li(d,^{3}He) at 50MeV/u



The ground-state of ^{10}He

Korsheninnikov et al, PLB(1994)

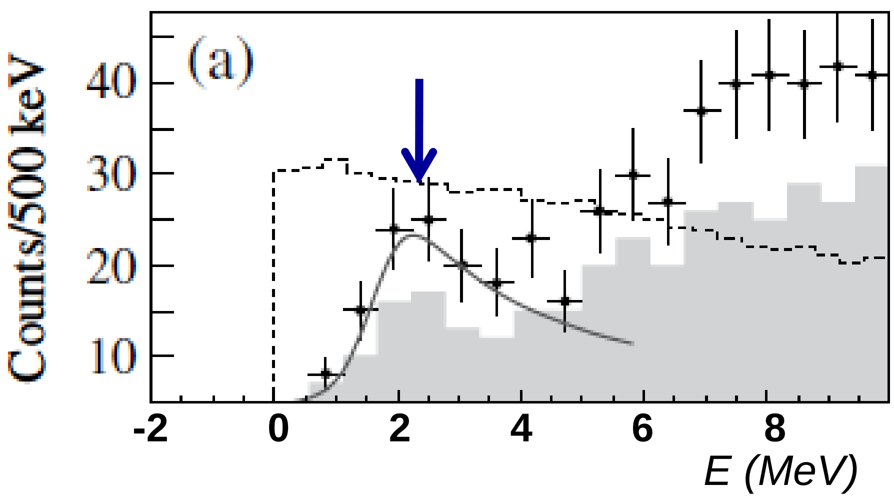


- **Consistent results from ^{11}Li(-1p) expts**
  (Inv. Mass ^{8}He+n+n channel)

  E_{GS} ~ 1.2 – 1.6 MeV above ^{8}He+2n thres.

  ^{10}Be(^{14}C, ^{14}O) ^{10}He → E_{GS} = 1.07(7) MeV

- **New results from ^{8}He(t,p) E_{GS} = 2.1 (2) MeV**
  S.Sidorchuk, PRL 108 (2012)



***Interpretation* :**
E_{GS} dependent on the source size of the reaction
(Grigorenko & Zhukov PRC (2008))

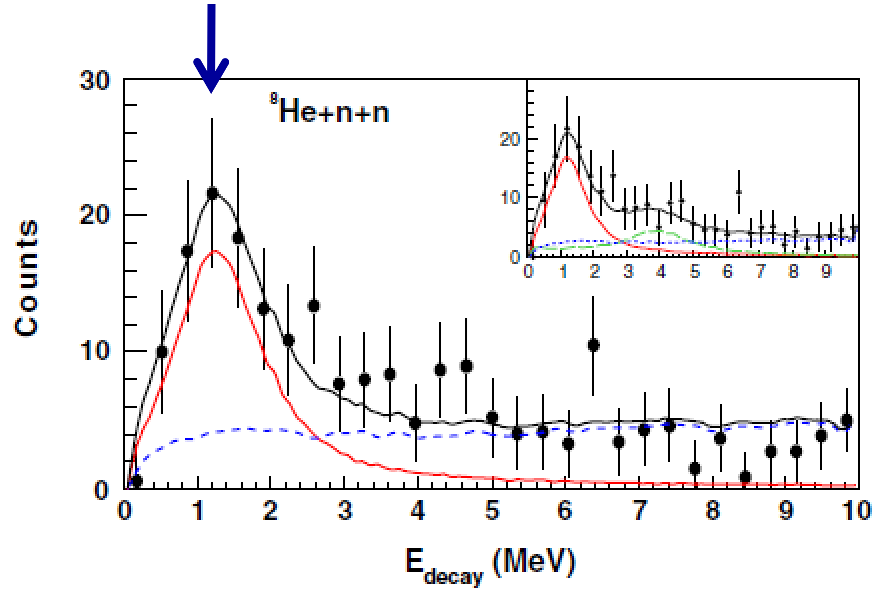
The ground-state of ^{10}He

RECENT STUDY : 2p2n removal from ^{14}Be

Z.Kohley et al., PRL 109 (2012)

E_{GS} = 1.60 ± 0.25 MeV
Γ = 1.8 ± 0.4 MeV

Similar as ^{11}Li(-p) results !
But cannot be explained by the "downshift" mechanism
- ✓ **different mechanism**
- ✓ **Less extended source**



THEORY

***a priori* a good case for 3-body models: ^{8}He+n+n**

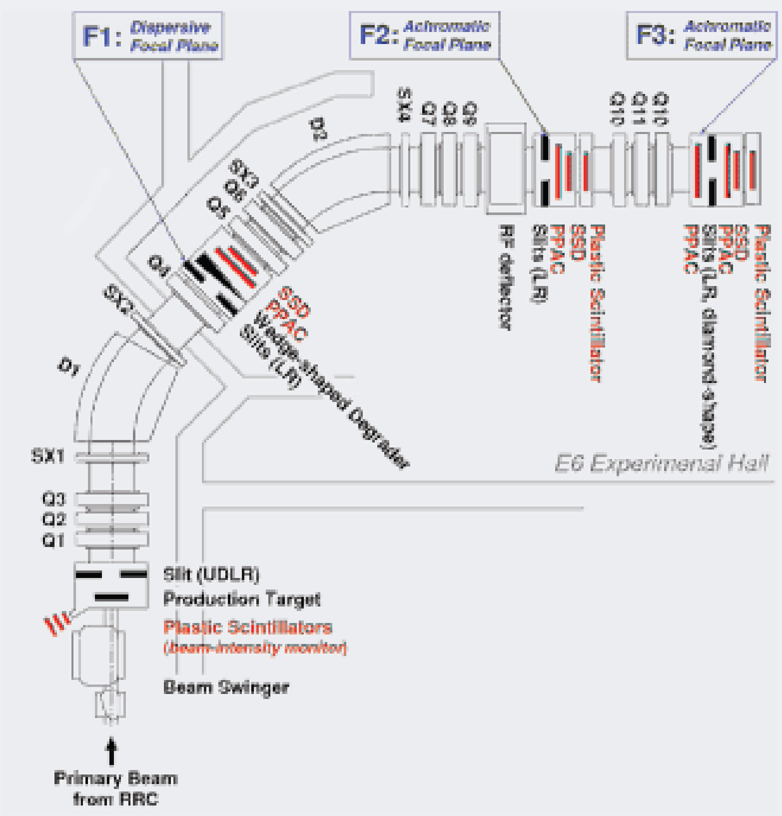
- **Prediction of a ^{8}He ground-state with dominant ^{8}He$\otimes$ $\nu(s1/2)^2$ with halo structure at E = 0.05 MeV**
  S. Aoyama, PRL 89 (2002)
  ACCC method to solve the unbound 3-body problem
- **New 3-body calculations including ^{8}He core excitation**
  H. Kamada et al., PRC (2013) ***GS at 0.8 MeV***

Both models rely on resonances in ^{9}He which are not well established

Study of ^{9,11}Li(d,^{3}He) @ 50 MeV/u at RIKEN/RIPS

- **Spectroscopy of populated states**
- **Decay pattern (branching ratios)**
- **Cross-sections**

RIPS separator



Primary Beam

^{18}O at 100MeV/A

Production Target :10mm Be

^{9}Li

Intensity $= 1.10^{5}$

Purity≈84% (main contaminant ^{3}H)

Count during 35h

^{11}Li

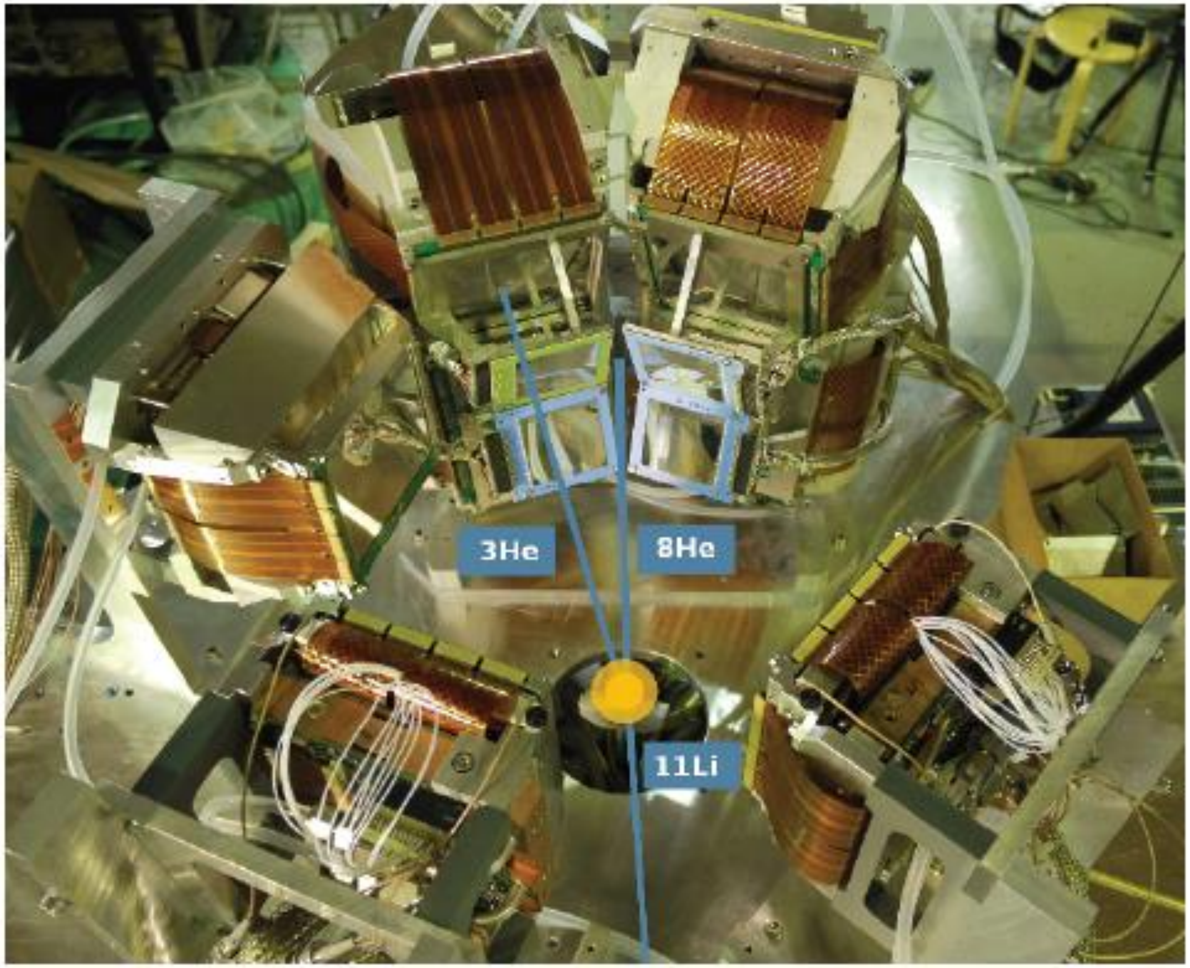
Intensity $= 1.7.10^{4}$

Purity≈7% (main contaminant ^{15}B)

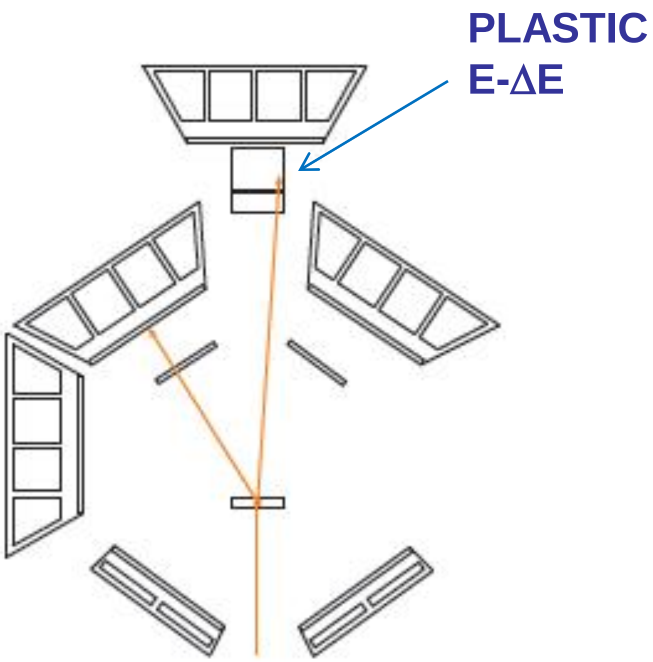
Count during 140h

Detector's setup

- Beam tracking detectors (PPAC) upstream of CD2 target
- 8 MUST2 telescopes around the CD2 target + thin (20μm) Si layer (fwd)
- Plastic telescope at zero degrees



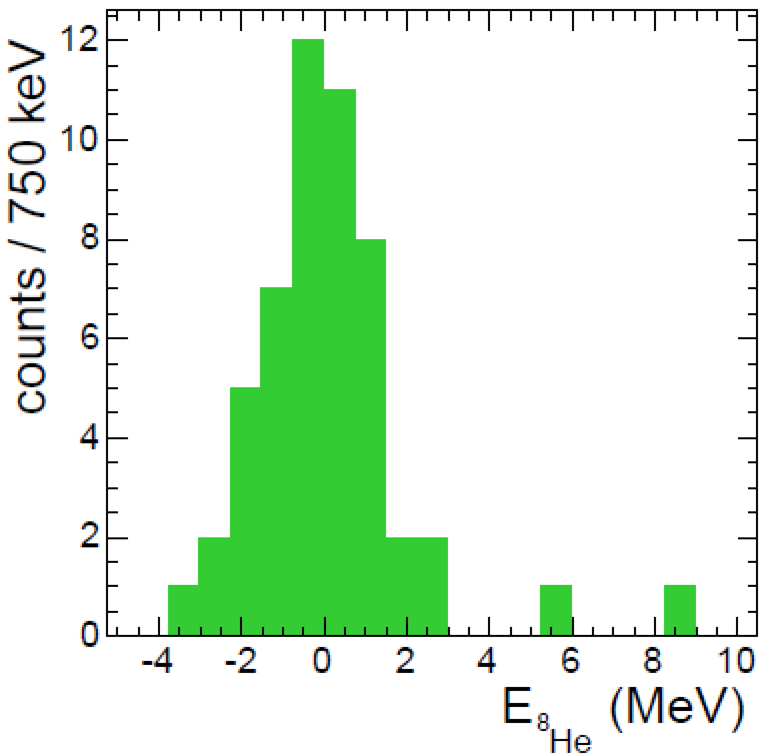
TOP VIEW SCHEME



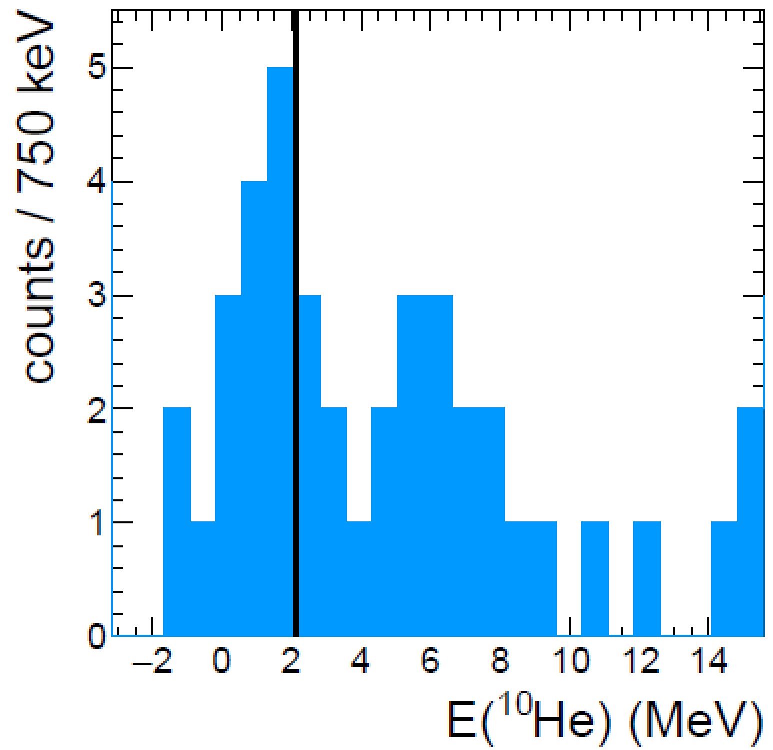
CD2 : 1.9 mg/cm^2

Excitation Spectra

$^{9}Li(d,^{3}He)^{8}He$



$^{11}Li(d,^{3}He)^{10}He$



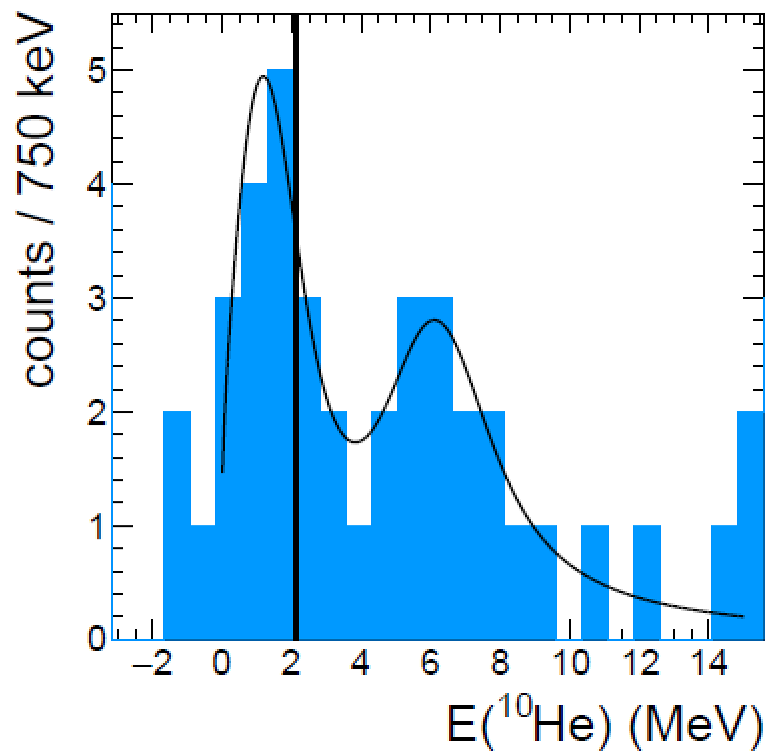
Excitation Spectra

^{8}He+2n decay

$$\Gamma(E) = \frac{\Gamma_R}{(\pi M \rho_{ch}^2)} \frac{2}{(J_{K+2}^2(\varepsilon) + N_{K+2}^2(\varepsilon))}$$

- $E_R = 1.4(3)$ MeV Γ_R=1.4(2) MeV
- $E_R = 6.3(7)$ MeV Γ_R=3.2(2) MeV

^{11}Li(d,^{3}He)^{10}He



Excitation Spectra

^{8}He+2n decay

$$\Gamma(E) = \frac{\Gamma_R}{(\pi M \rho_{ch}^2)} \frac{2}{(J_{K+2}^2(\varepsilon) + N_{K+2}^2(\varepsilon))}$$

- $E_R = 1.4(3)$ MeV Γ_R=1.4(2) MeV
- $E_R = 6.3(7)$ MeV Γ_R=3.2(2) MeV

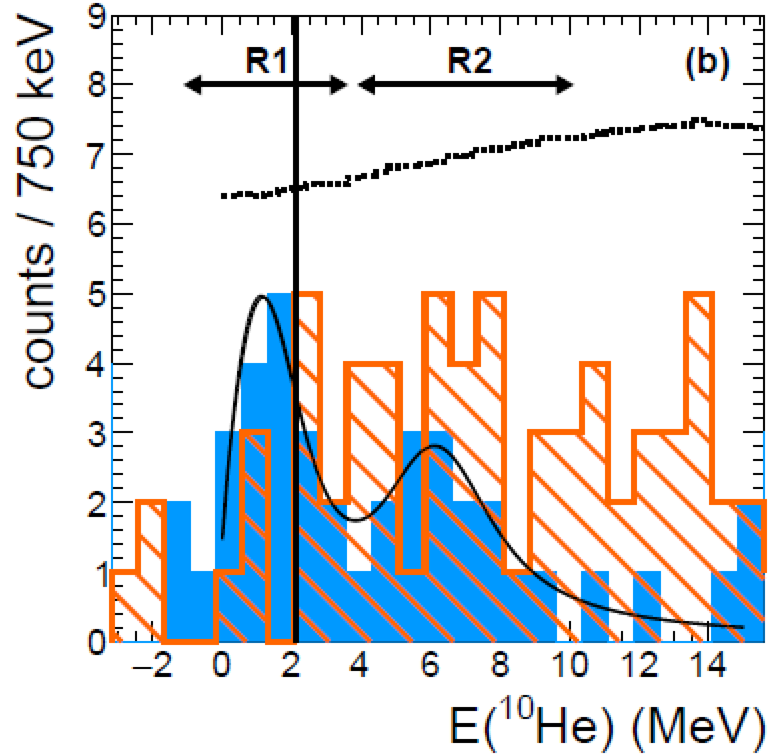
^{6}He+4n decay:

- R1 BR: 64(18)%
- R2 BR: 46(8)%

→ Core excitation in g.s.

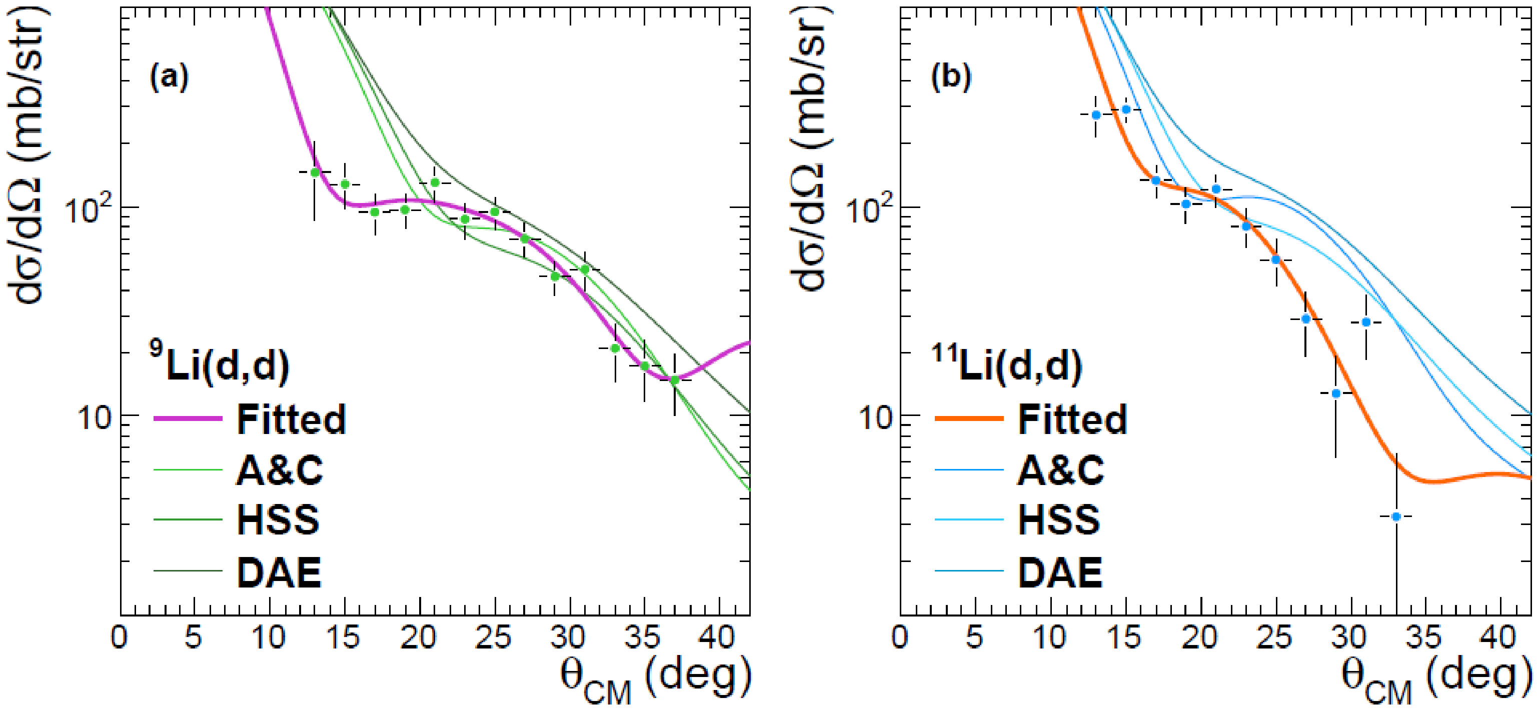
- Many states at higher energy

^{11}Li(d,^{3}He)^{10}He



Analysis of ^{9}Li(d,d) and ^{11}Li(d,d) @ 50 MeV/u

Fitted and global potentials



- ➢ **For ^{9}Li, global potential do not work well**
- ➢ **Better agreement in the case of ^{11}Li for some of them**

Available overlaps

Standard Potential Model (SPM)

- Fixed geometry WS well
  $\rightarrow r_0 = 1.25$ fm $a_0 = 0.65$ fm
  $\rightarrow$ Adjust the depth to reproduce the binding energy

Source Term Approach (STA)

- Restoring missing correlations from the shell model
  $\rightarrow$ start with shell model s.p. wave function
  $\rightarrow$ resolve inhomogeneous equations using a given NN int.

N.K. Timofeyuk, Phys. Rev. C 88, 044315

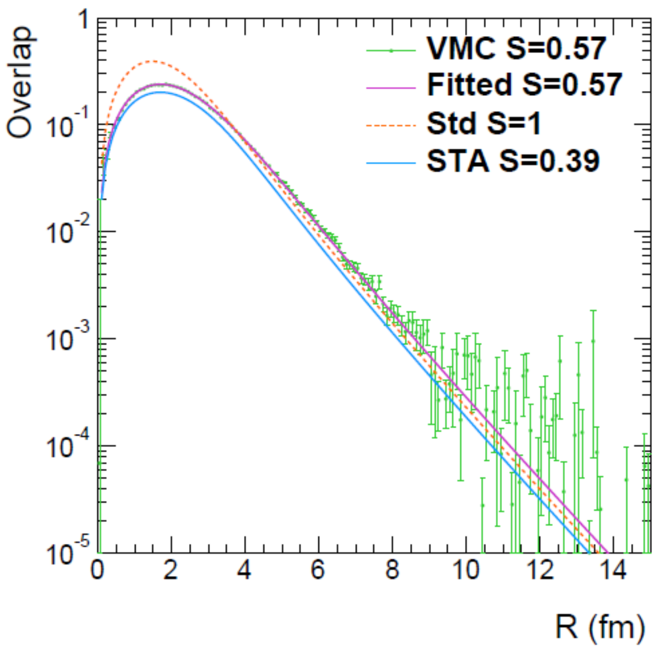
Variational Monte Carlo (VMC)

- Numerical variational *ab initio* method
  $\rightarrow$ Difficult calculations
  $\rightarrow$ Limited cases tractable

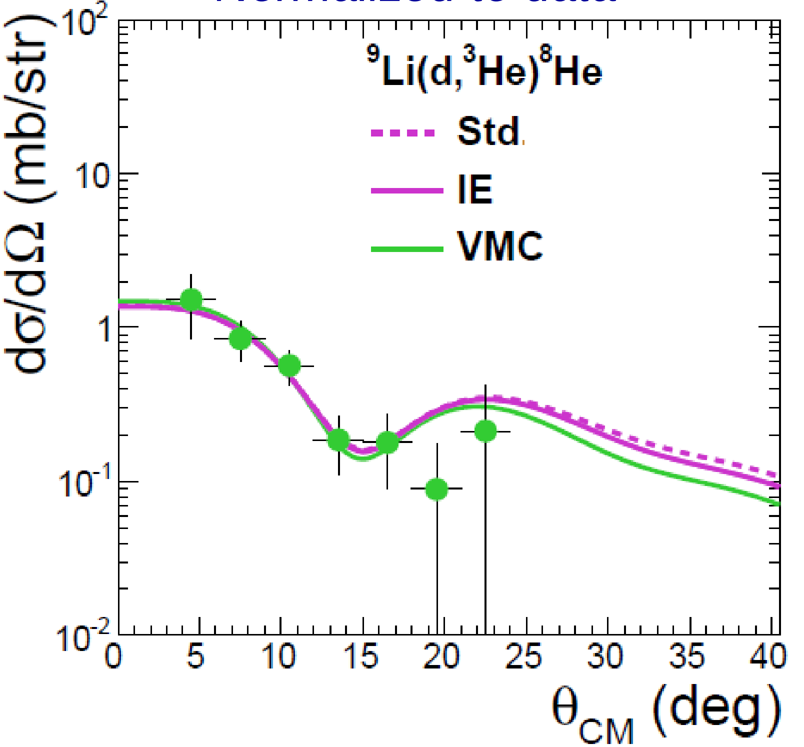
R. Wiringa, http://www.phy.anl.gov/theory/research/overlap/

Differential cross-sections

- **Full finite range calculations using DWUCK5**
- **(d|^{3}He) overlap from GFMC (***Brida, Pieper, Wiringa, PRC84 (2011))*
- **Entrance potential : Determined from elastic scattering data**
- **Exit potential : from Global formula**
  Non-locality corrections for both potentials
- **Overlaps:**
  1. **Standard (s.p wave function) ($S^{th} = S^{SM} = 0.93$)**
  2. **Source term approach ($S^{th} = 0.38$)**
  3. **VMC ($S^{th} = 0.57$)**



Normalized to data

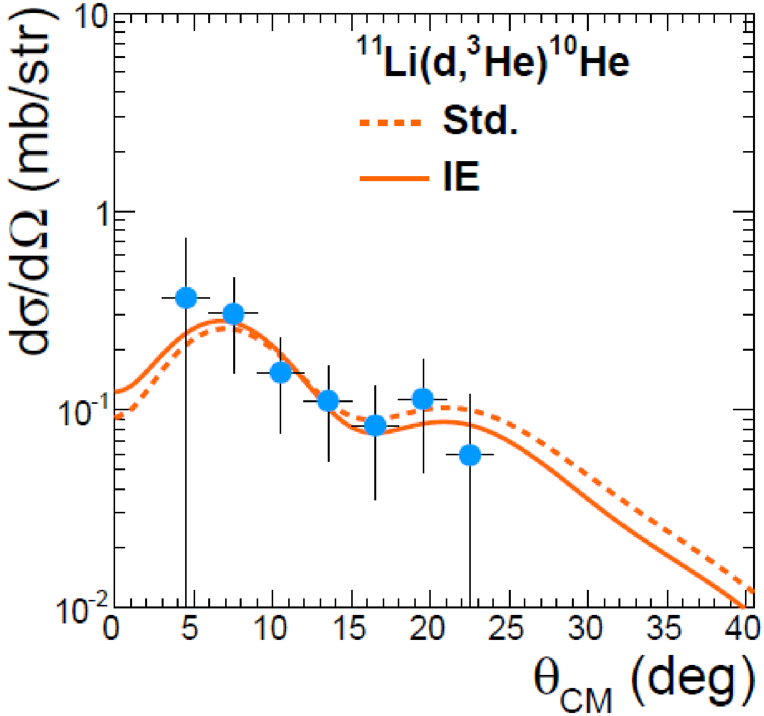


Shape well-reproduced by DWBA calculations (l=1 transfer)

Differential cross-sections to ground-state

- **Full finite range calculations using DWUCK5 (and FRESCO)**
- **(d|^{3}He) overlap from GFMC (***Brida, Pieper, Wiringa, PRC84 (2011))*
- **Entrance potential : From fit of elastic scattering**
- **Exit potential : from Global formula**
- **Overlaps:**
  1. **Standard (s.p wave function) (S^{th} = 0.65)**
  2. **Inhomogenous equation [simplified] (S^{th} = 0.58)**

Normalized to data



Shape well-reproduced by DWBA calculations (l=1 transfer)

Differential cross-sections to ground-state

DWBA calculations NOT normalized to the data

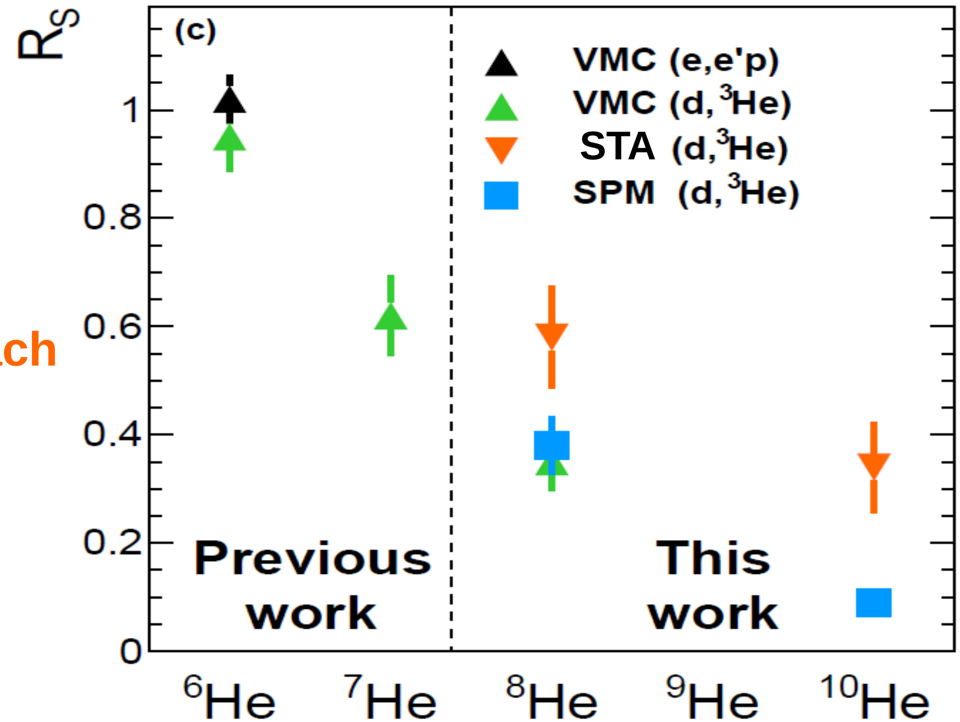
Cross-sections stronglyTf 3(d)uETc[(se[W-3( )e)3(pc)3(tal) Tffor

Normalization factors

$R_S = \sigma^{EXP} / \sigma^{React\ Mod}$

VMC : Variational MC

STA: Source term Approach
(corrected by geometr.
mismatch factor)



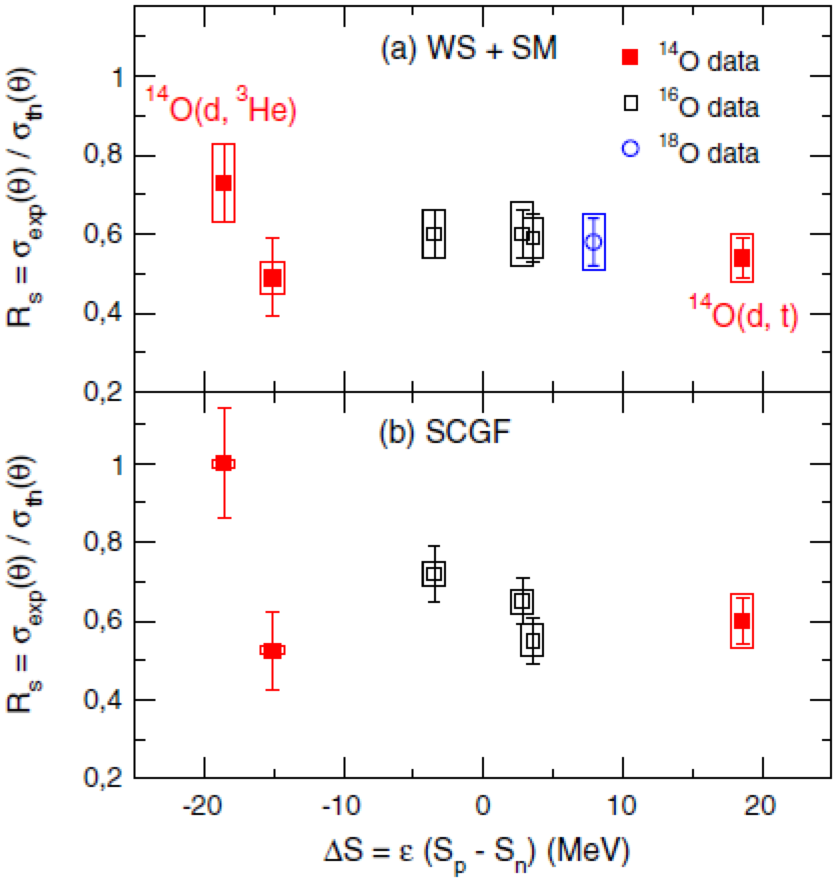
Asymmetry
$\Delta S = S_p - S_n$ ΔS (MeV) = 2.5 9.9 10.4 15.1

- Decreasing trend of N_f toward the drip line
- $N_f = 0.35$ for $^9Li(d,^3He)^8He$ using VMC
  $N_f \approx 1.$ for $^8Li(d,p)^9Li$ using VMC
- N_f for ^{11}Li correspond to standard SF of only 0.08

Reduction factors in recent transfer studies

Study of $^{14}O(d,t)(d,^{3}He)$ with MUST2

F. Flavigny et al., PRL 110 (2013)



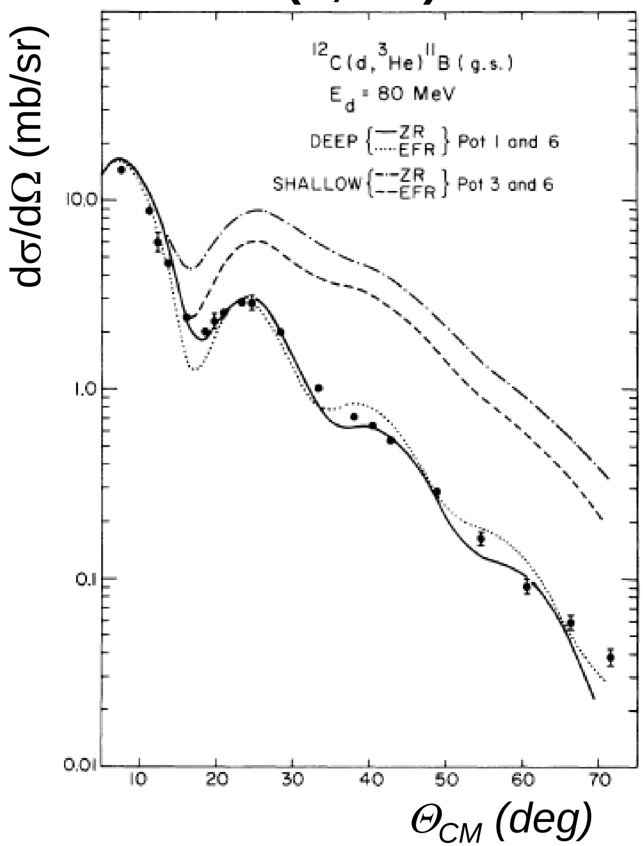
- **Very weak asymmetry dependence of reduction factors**

Similar conclusions in (p,d)(d,p)

J.Lee et al. PRC 75 (2007), J.Lee et al. PRC 83 (2011)

(d,^{3}He) studies at 40 MeV/u

^{12}C(d,^{3}He)^{11}B



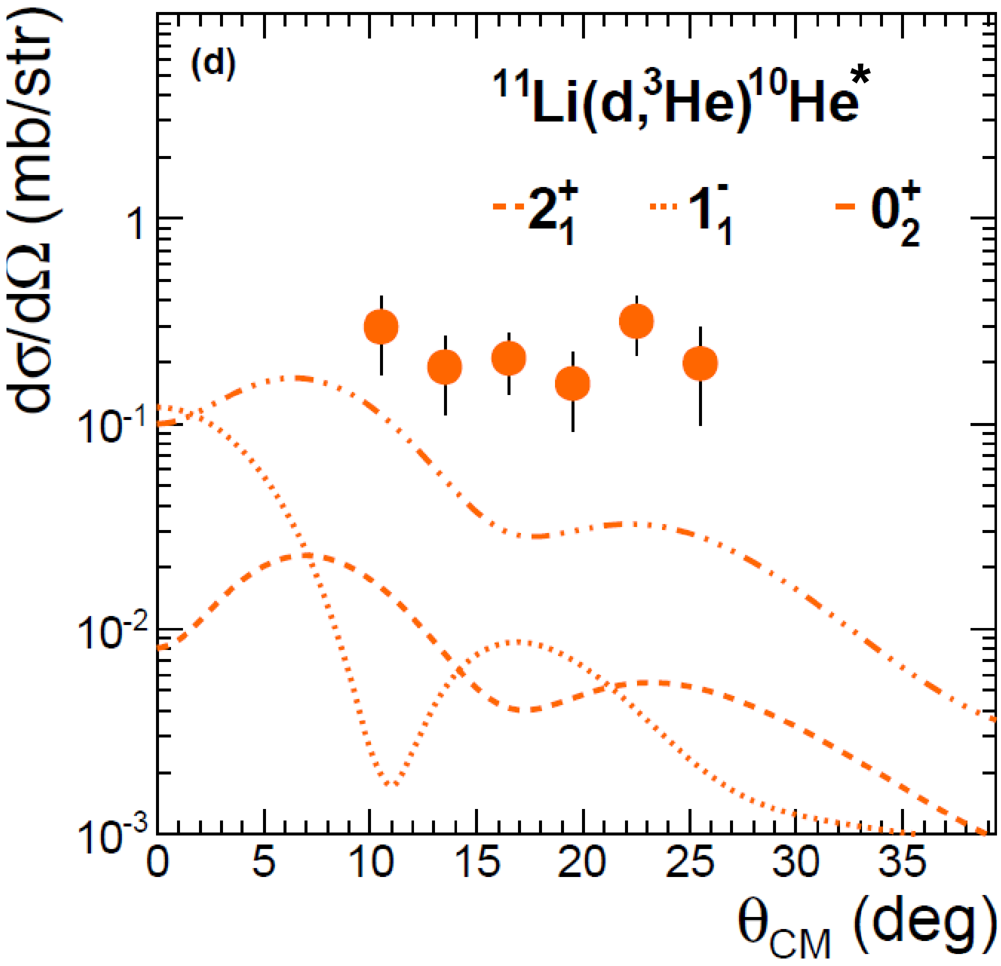
J.P. Didelez et al., PRC 13(1976)

Spectroscopic factors found in fair agreement with SM Provided he optical potential allow to reproduce differential cross-sections.

J.P. Didelez et al. PRC 13 (1976)
N.S. Chant et al., PRC15 (1977)

NB: in ^{11}Li(d,^{3}He), residue is unbound
Also the case for ^{8}Li(d,^{3}He)
and in other studies e.g. ^{8}He(p,d)^{7}He

Differential cross-sections to excited states



DWBA calculations (FF from 2hω Shell Model)

Enhanced !

Importance of many-body dynamics in ^{11}Li

HIGHLIGHTS

Tests of Nuclear overlaps

- **Shape of differential Xsection of ^{9}Li(d,^{3}He)^{8}He well-reproduced by calculations using several overlaps including *ab initio* VMC Magnitude strongly reduced**

- **Even more reduced for ^{11}Li(d,^{3}He)^{10}He**

Available overlaps fail away from stability

^{10}He structure

- **Two resonances at 1.4(3) MeV and 6.3(7) MeV**
- **^{6}He+4n decay channel preferred to 8He+2n**

Role of many-body dynamics in ^{10}He (and ^{11}Li)

NEXT :

^{10}He populated by ^{14}Be(p,pα)

First study of 6n (decay channel of ^{10}He*)

Collaboration

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- **University of Surrey**
  N.K Timofeyuk