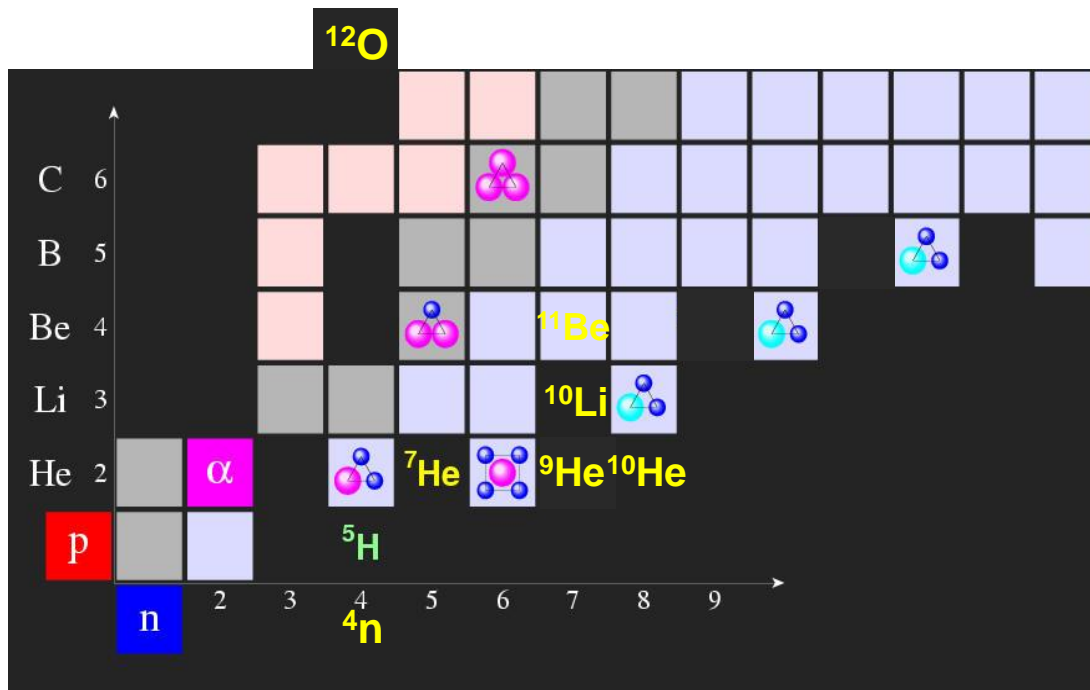


LIGHT EXOTIC NUCLEI

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 $^{11}\text{Li}(d,^3\text{He})$ reaction



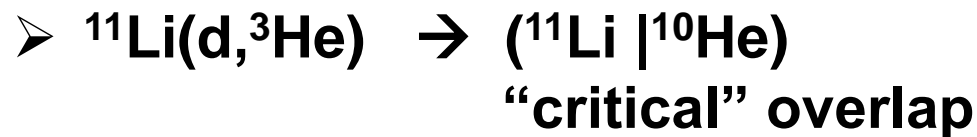
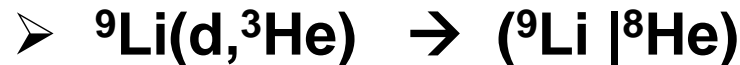
@



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 :



Direct reactions and Nuclear overlaps

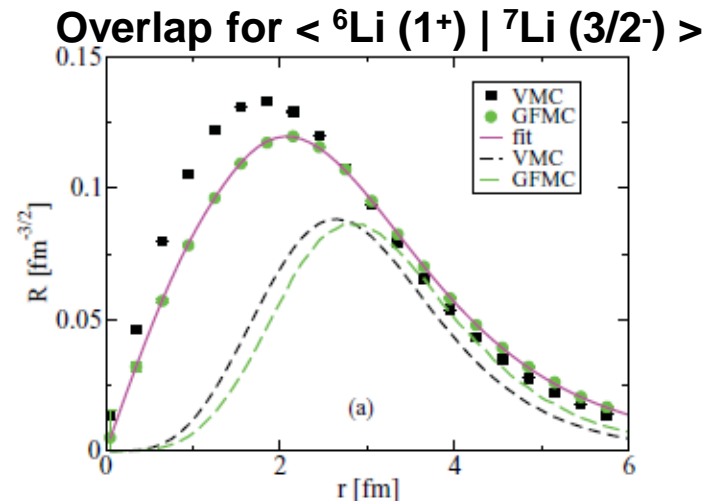
Direct reactions allow to test nuclear overlaps e.g (A/B) B=A± 1 often referred as interface between nuclear structure and reaction

- Can be taken as :

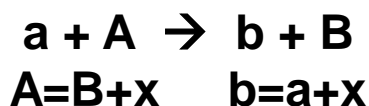
$$I^{A,A+1}(r) \approx S_{l,j} \frac{u_{nlj}(r)}{r}$$

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

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



Case of transfer reactions



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

$$\langle \Phi_b | V_{ax} | \Phi_a \rangle$$

Range function

$$\langle \Phi_B | \Phi_A \rangle$$

Overlap function

χ_{bB}, χ_{aA} : Distorted waves

Direct reactions and Nuclear overlaps

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

L.Lapikas et al., PRL (1999)

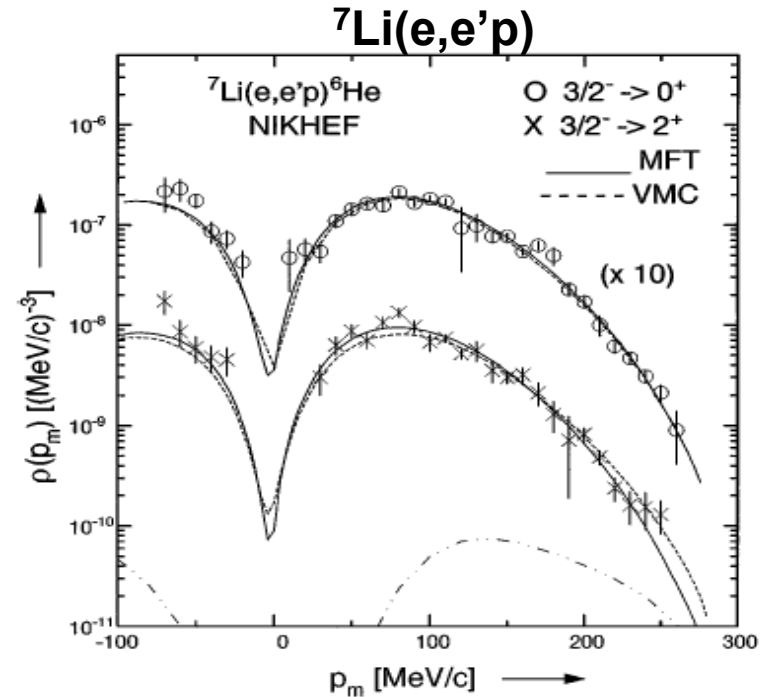
CDWIA calc with **VMC overlap**

Data very well reproduced in both shape and magnitude

Spectroscopic factors for GS:

$S(\text{VMC}) = 0.42(4)$
 $S(\text{SM}) = 0.7$

} **correlations**



Other reactions implemented recently :
(non exhaustive list) :

✓ Transfer reactions

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

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

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

✓ Single nucleon knockout

$({}^9\text{Li}, {}^8\text{Li})$, $({}^9\text{C}, {}^8\text{B})$, $({}^{10}\text{Be}, {}^9\text{Li})$, $({}^{10}\text{C}, {}^9\text{C})$, ... G.Grinyer et al., PRL (2011), PRC (2012)

VMC, NCSM

The $\langle {}^A\text{Li} | {}^{A-1}\text{He} \rangle$ overlaps

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

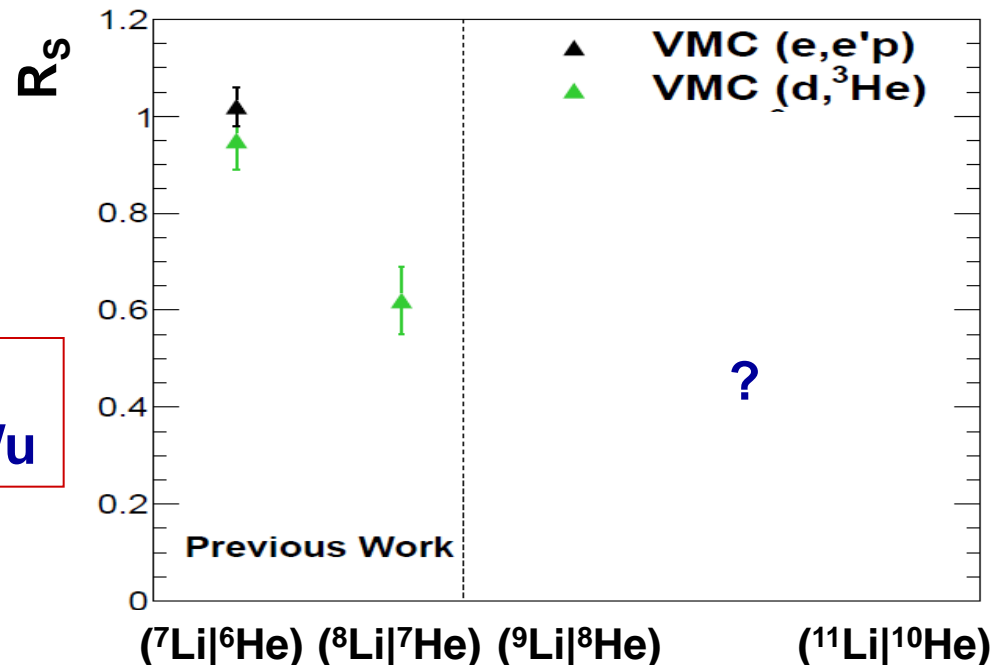
Generally:

$$S(\langle {}^A\text{Li} | {}^{A-1}\text{He} \rangle) < S(\langle {}^A\text{Li} | {}^{A-1}\text{Li} \rangle)$$

PRESENT SITUATION

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

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



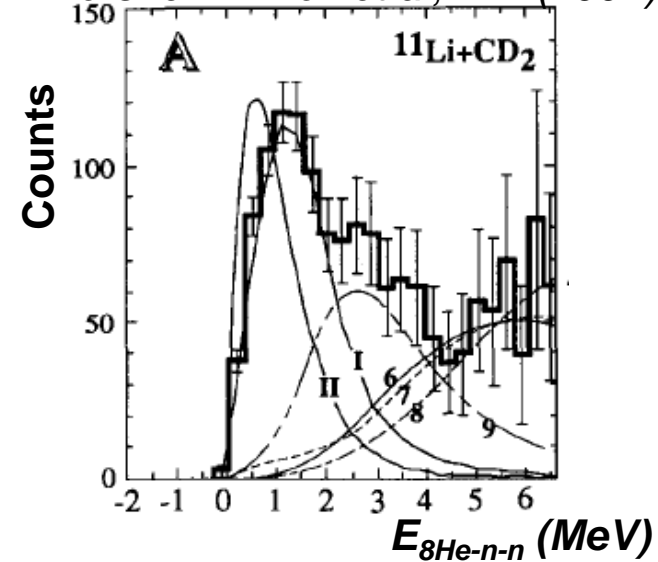
The ground-state of ^{10}He

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

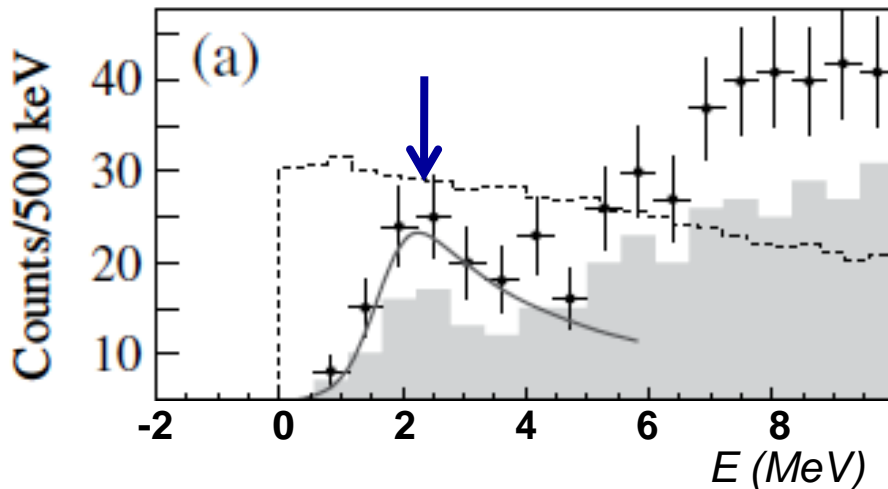
$E_{\text{GS}} \sim 1.2 - 1.6 \text{ MeV}$ above $^8\text{He}+2n$ thres.

$^{10}\text{Be}(^{14}\text{C}, ^{14}\text{O})^{10}\text{He} \rightarrow E_{\text{GS}} = 1.07(7) \text{ MeV}$

Korshenninnikov et al, PLB(1994)



- New results from $^8\text{He}(t,p)$ $E_{\text{GS}} = 2.1 (2) \text{ MeV}$
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

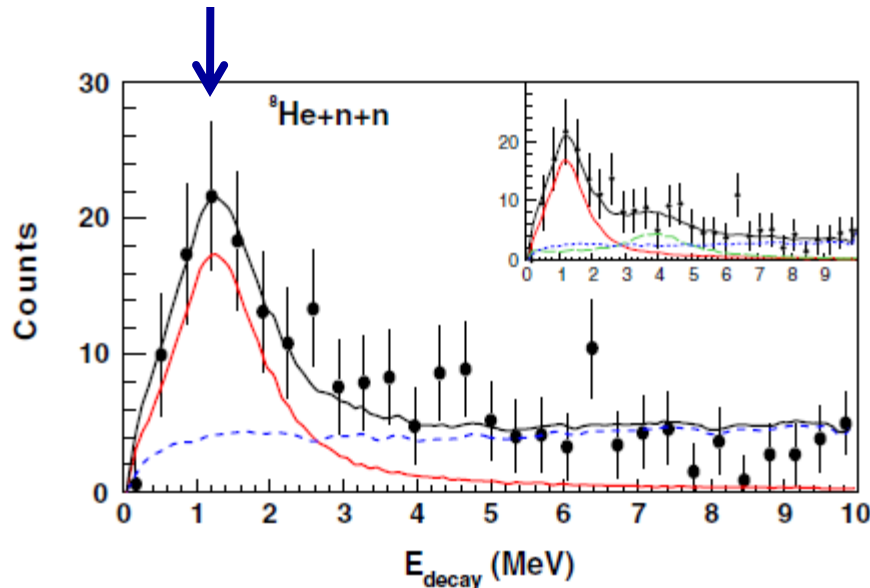
RECENT STUDY : $2p2n$ removal from ^{14}Be

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

$$E_{\text{GS}} = 1.60 \pm 0.25 \text{ MeV}$$

$$\Gamma = 1.8 \pm 0.4 \text{ MeV}$$

Similar as $^{11}\text{Li}(-p)$ results !
But cannot be explained by the
“downshift” mechanism
✓ different mechanism
✓ Less extended source



THEORY

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

- Prediction of a ^8He ground-state with dominant $^8\text{He} \otimes \nu(s1/2)^2$ with halo structure at $E = 0.05 \text{ MeV}$

S. Aoyama, PRL 89 (2002)

ACCC method to solve the unbound 3-body problem

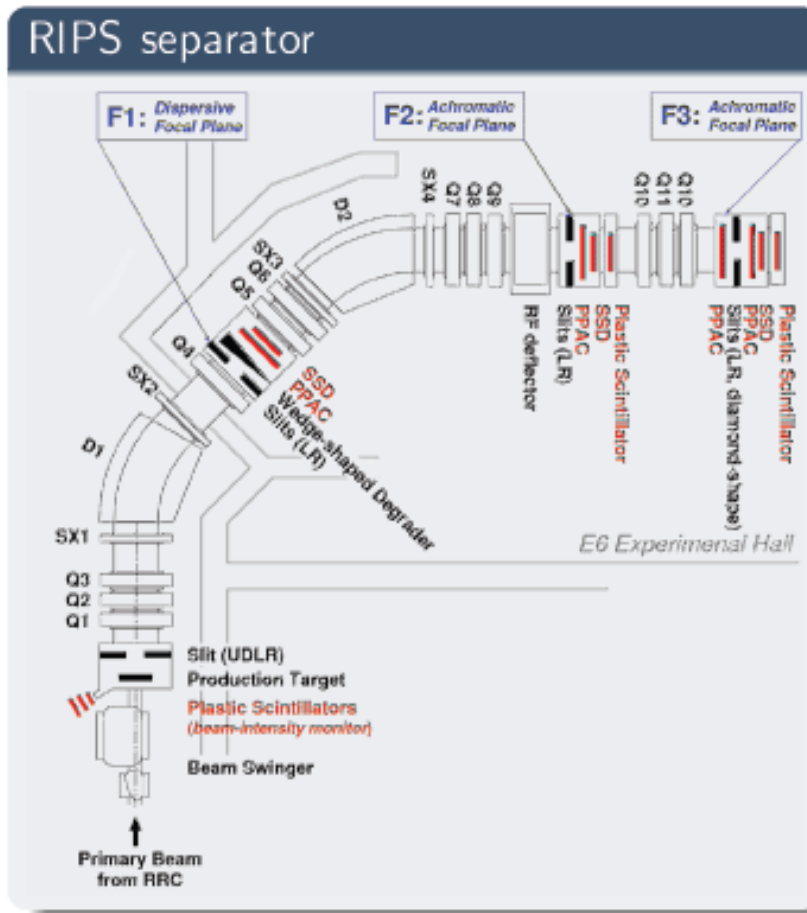
- New 3-body calculations including ^8He core excitation

H. Kamada et al., PRC (2013) **GS at 0.8 MeV**

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

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

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



Primary Beam

${}^{18}\text{O}$ at 100MeV/A

Production Target :10mm Be

${}^9\text{Li}$

Intensity = 1.10^5

Purity \approx 84% (main contaminant ${}^3\text{H}$)

Count during 35h

${}^{11}\text{Li}$

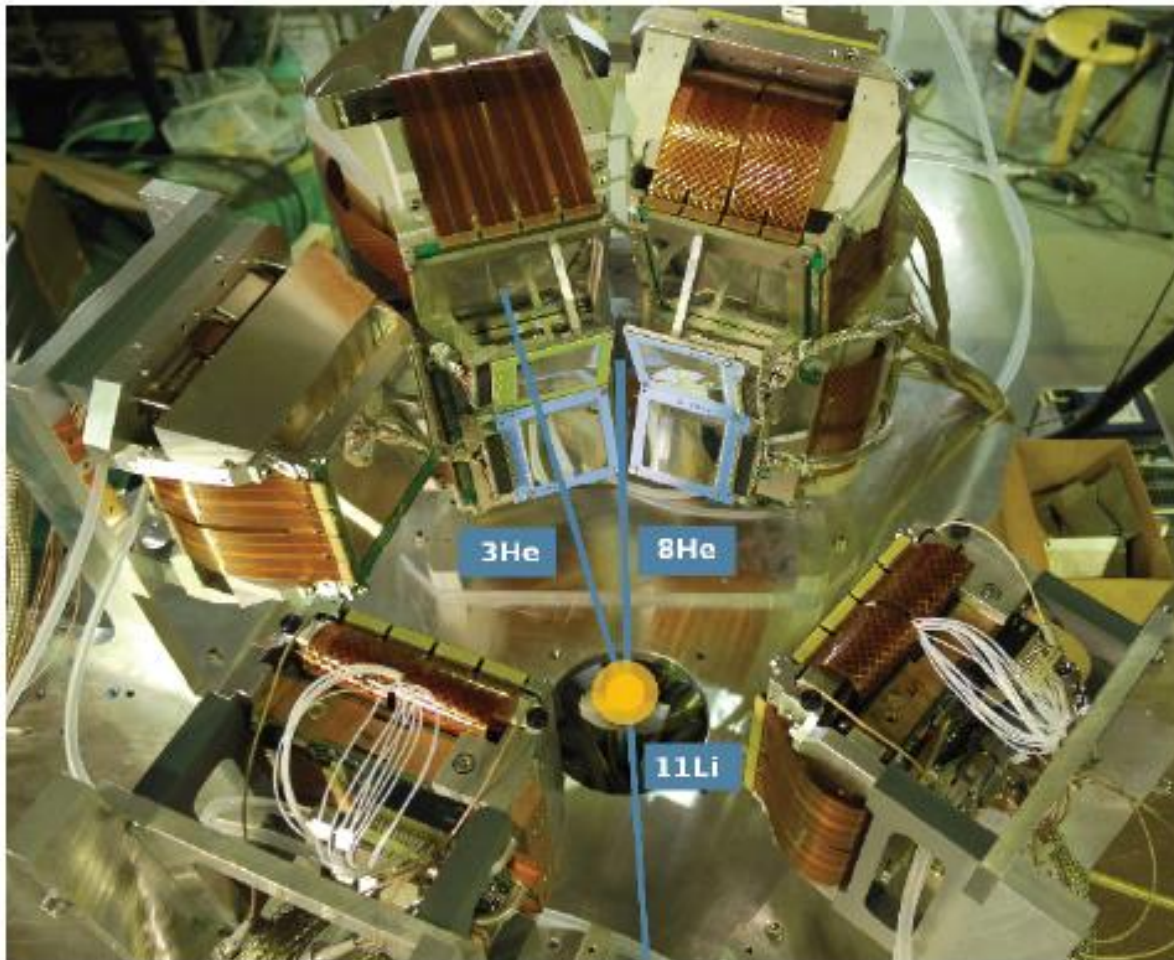
Intensity = $1.7.10^4$

Purity \approx 7% (main contaminant ${}^{15}\text{B}$)

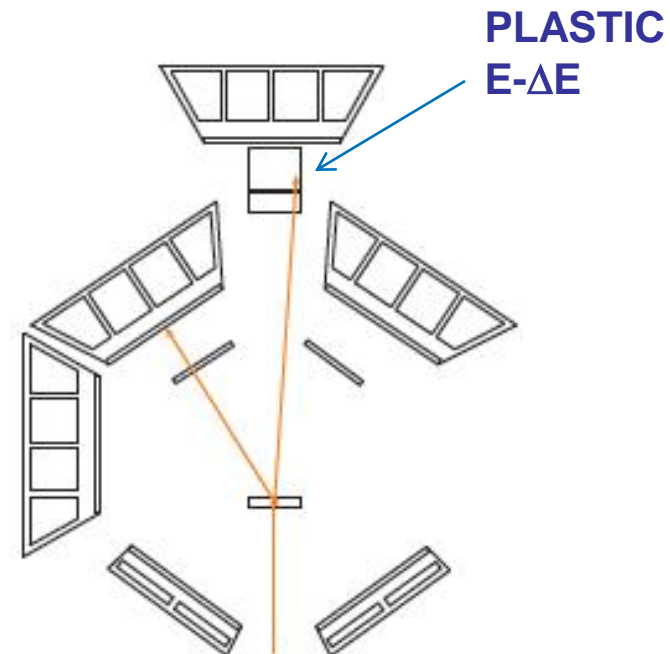
Count during 140h

Detector's setup

- Beam tracking detectors (PPAC) upstream of CD2 target
- 8 MUST2 telescopes around the CD2 target + thin ($20\mu\text{m}$) Si layer (fwd)
- Plastic telescope at zero degrees



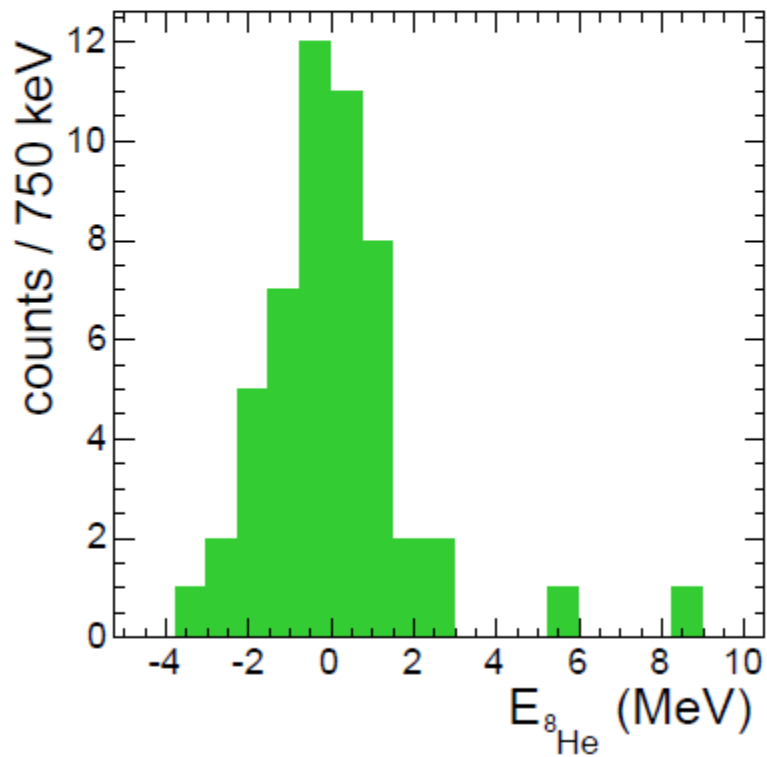
TOP VIEW SCHEME



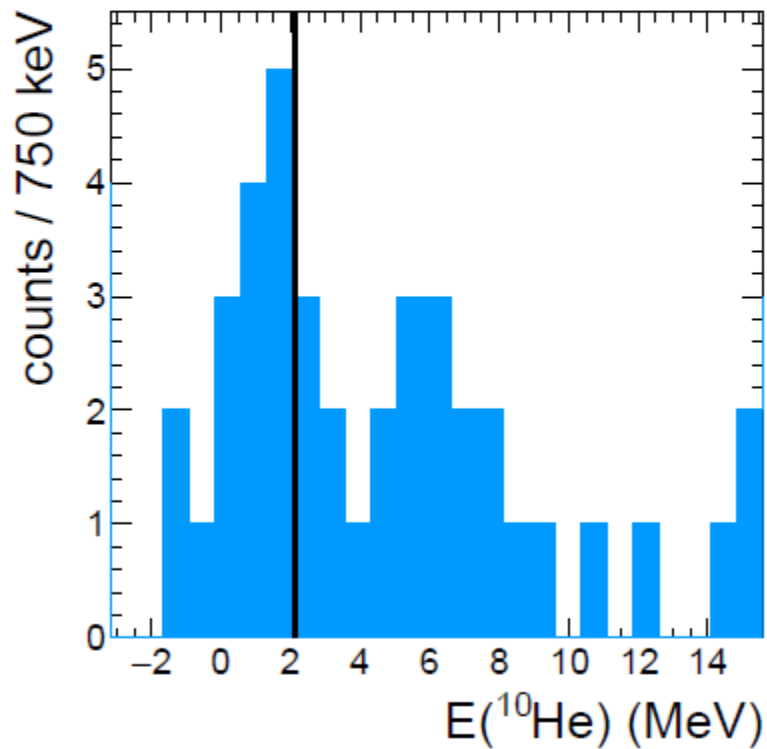
CD2 : 1.9 mg/cm^2

Excitation Spectra

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



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



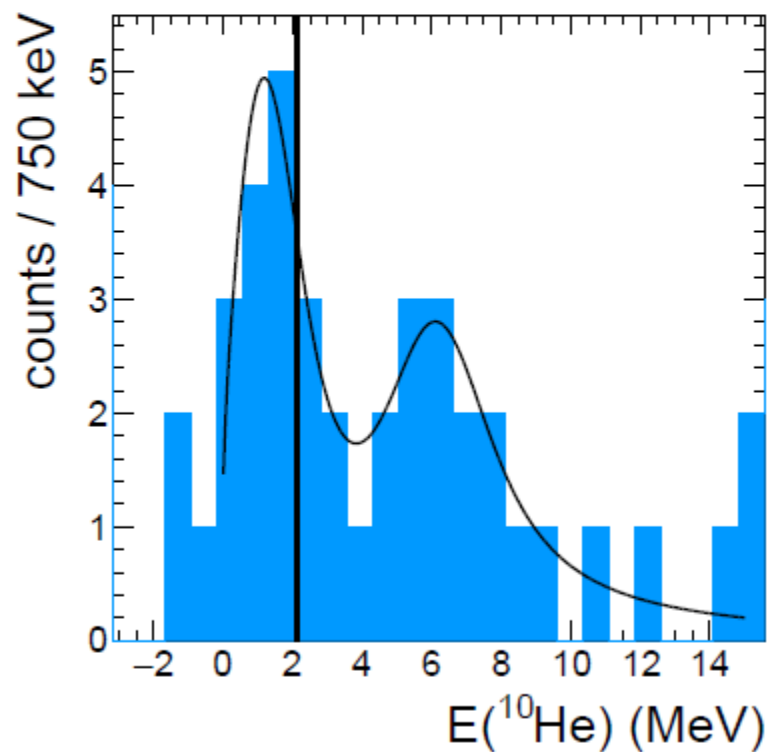
Excitation Spectra

$^8\text{He}+2n$ decay

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

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

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



Excitation Spectra

$^8\text{He}+2n$ decay

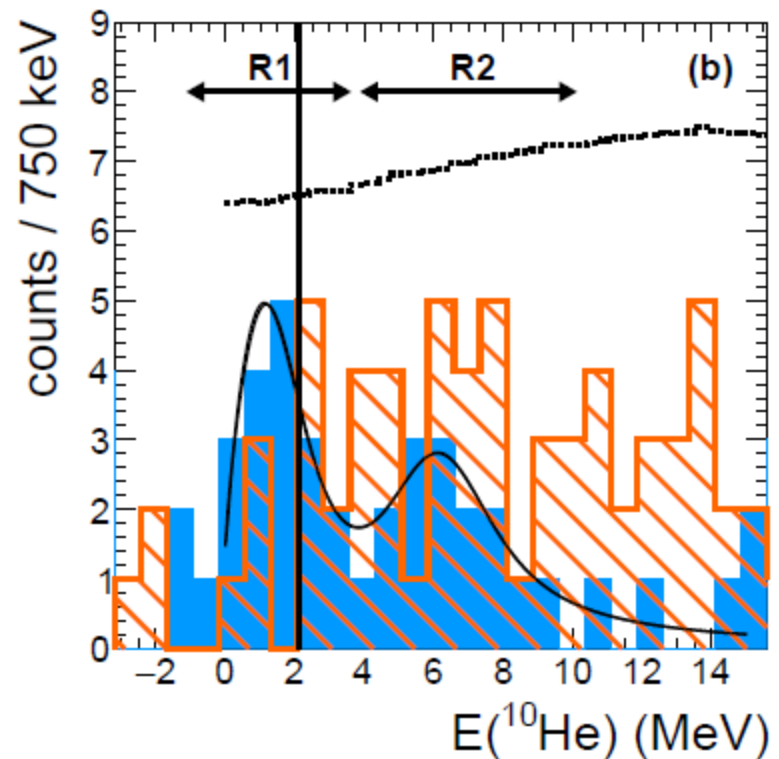
$$\Gamma(E) = \frac{\Gamma_R}{(\pi M \rho_{ch}^2)} \frac{2}{(J_{K+2}^2(\epsilon) + N_{K+2}^2(\epsilon))}$$

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

$^6\text{He}+4n$ decay:

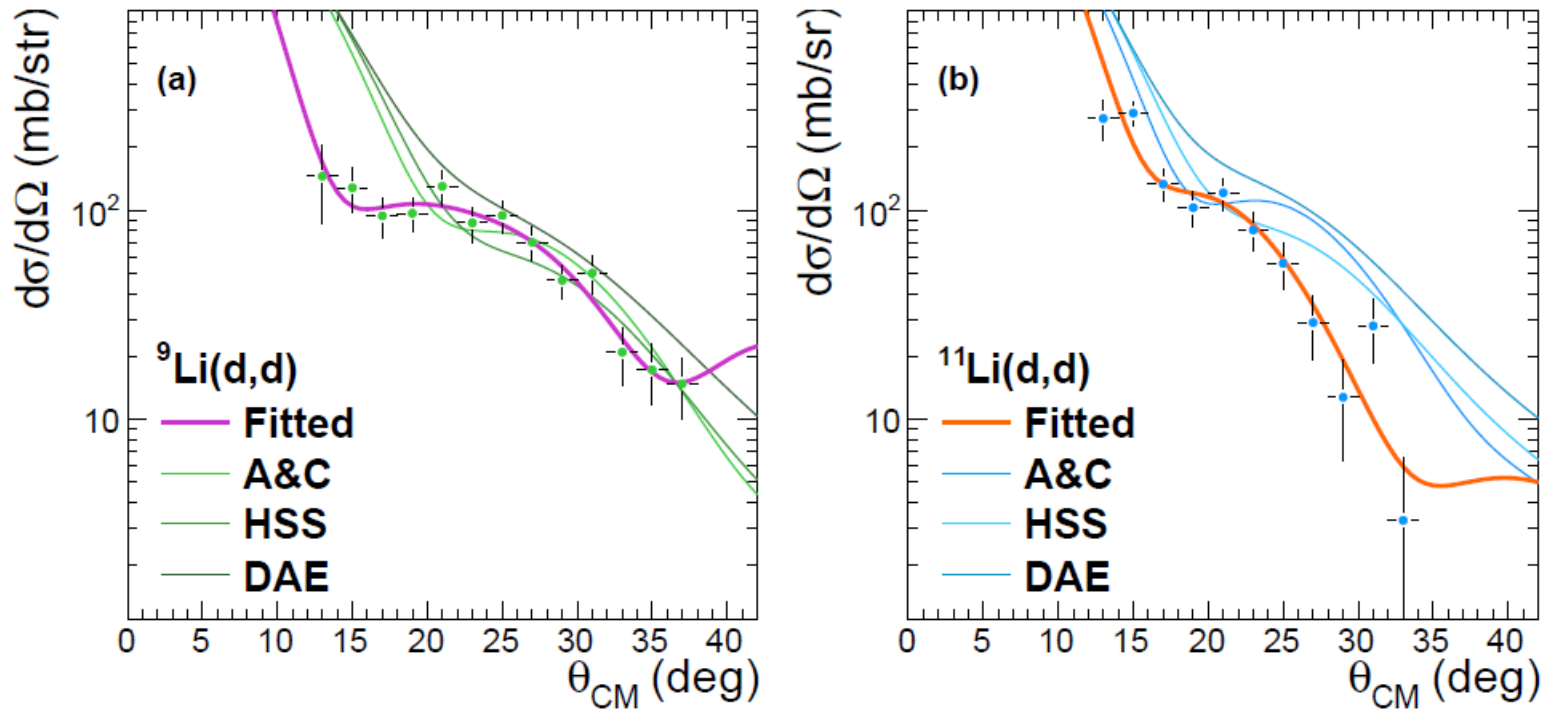
- R1 BR: 64(18)%
 - R2 BR: 46(8)%
- Core excitation in g.s.
- Many states at higher energy

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



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

Fitted and global potentials



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

Available overlaps

Standard Potential Model (SPM)

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

Source Term Approach (STA)

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

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

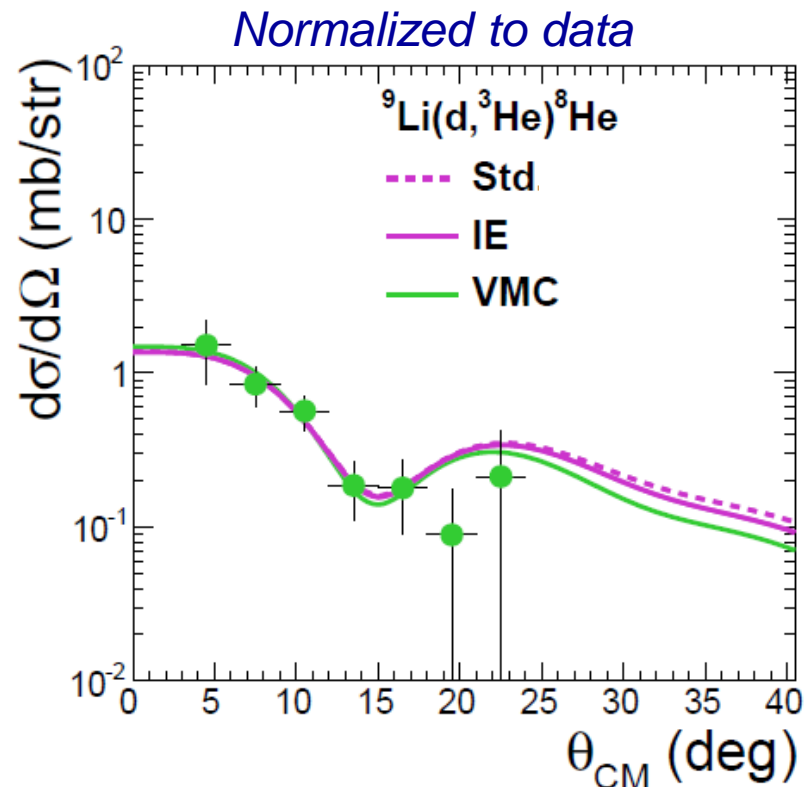
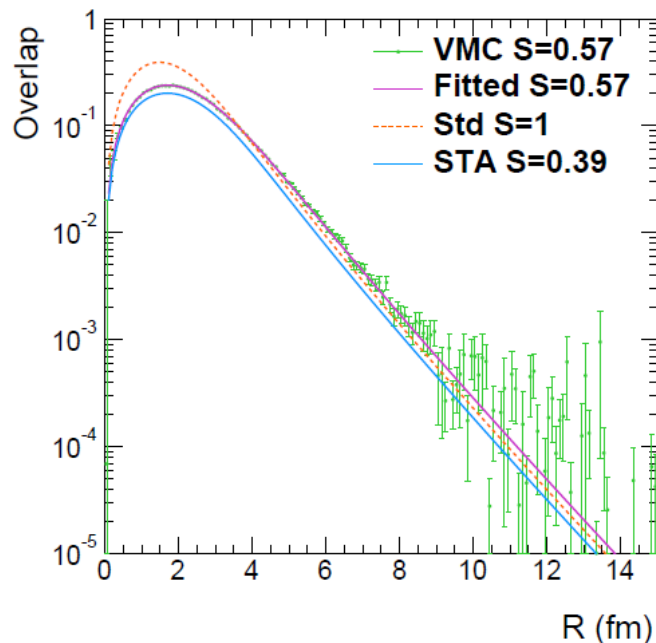
Variational Monte Carlo (VMC)

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

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

Differential cross-sections

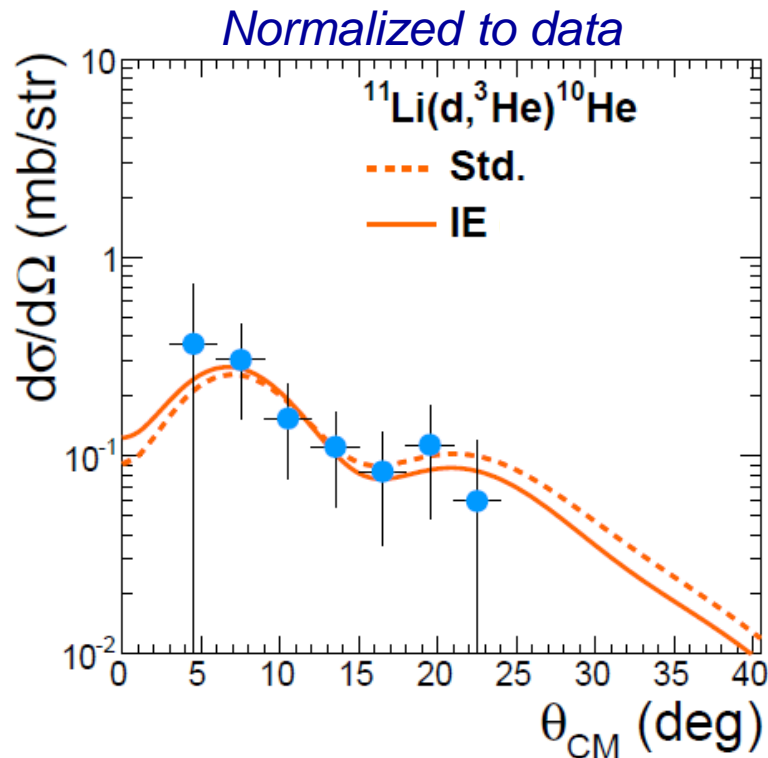
- Full finite range calculations using DWUCK5
- $(d|^3\text{He})$ overlap from GFMC (*Brida, Pieper, Wiringa, PRC84 (2011)*)
- Entrance potential : Determined from elastic scattering data
- Exit potential : from Global formula
- Non-locality corrections for both potentials
- Overlaps:
 1. Standard (s.p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



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

Differential cross-sections to ground-state

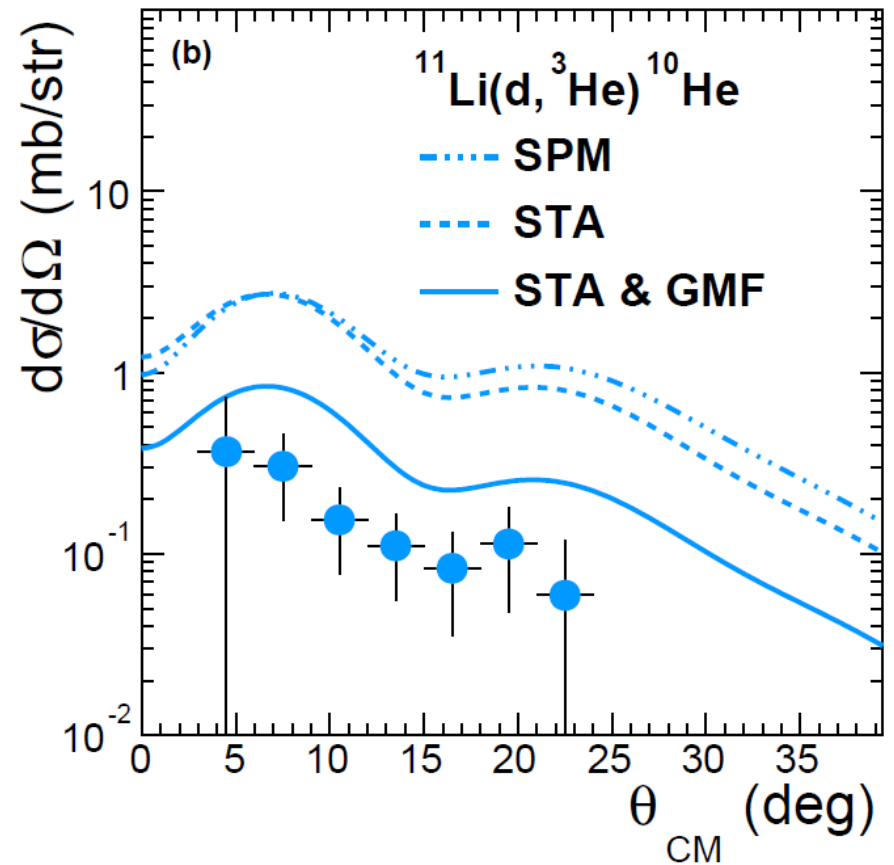
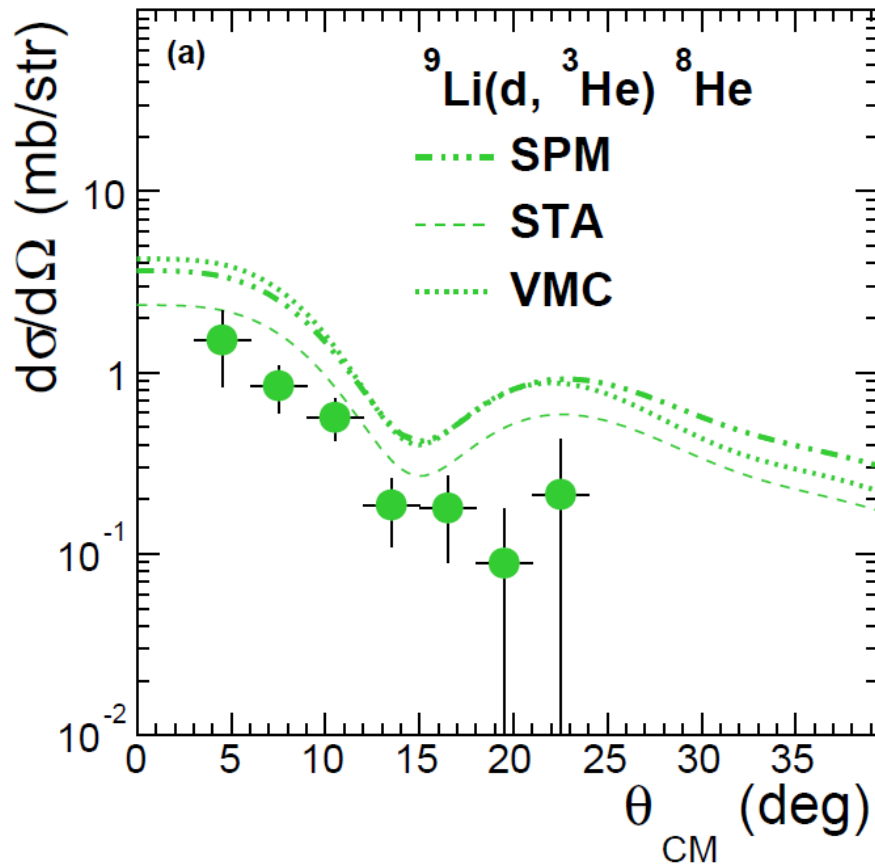
- Full finite range calculations using DWUCK5 (and FRESCO)
- $(d|{}^3\text{He})$ overlap from GFMC (*Brida, Pieper, Wiringa, PRC84 (2011)*)
- Entrance potential : From fit of elastic scattering
- Exit potential : from Global formula
- Overlaps:
 1. Standard (s.p wave function) ($S^{\text{th}} = 0.65$)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



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

Differential cross-sections to ground-state

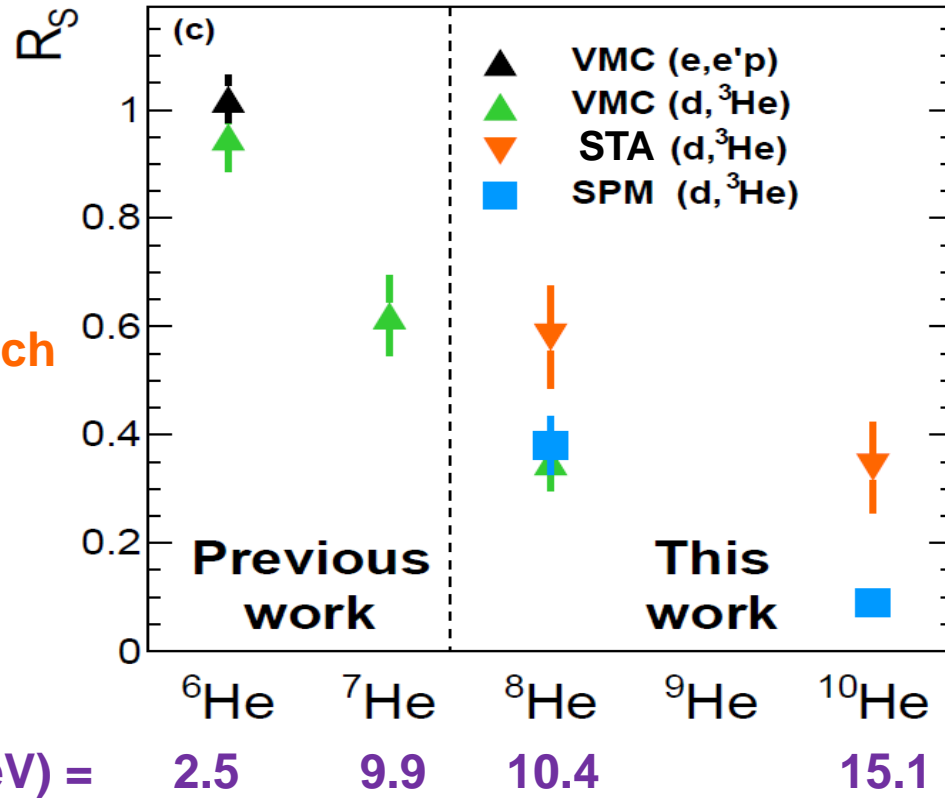
DWBA calculations NOT normalized to the data



Cross-sections strongly reduced, especially for ${}^{10}\text{He}$ production
Especially for ${}^{11}\text{Li}$

Normalization factors

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



VMC : Variational MC

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

Asymmetry

$$\Delta S = S_p - S_n$$

$$\Delta S \text{ (MeV) =}$$

2.5

9.9

10.4

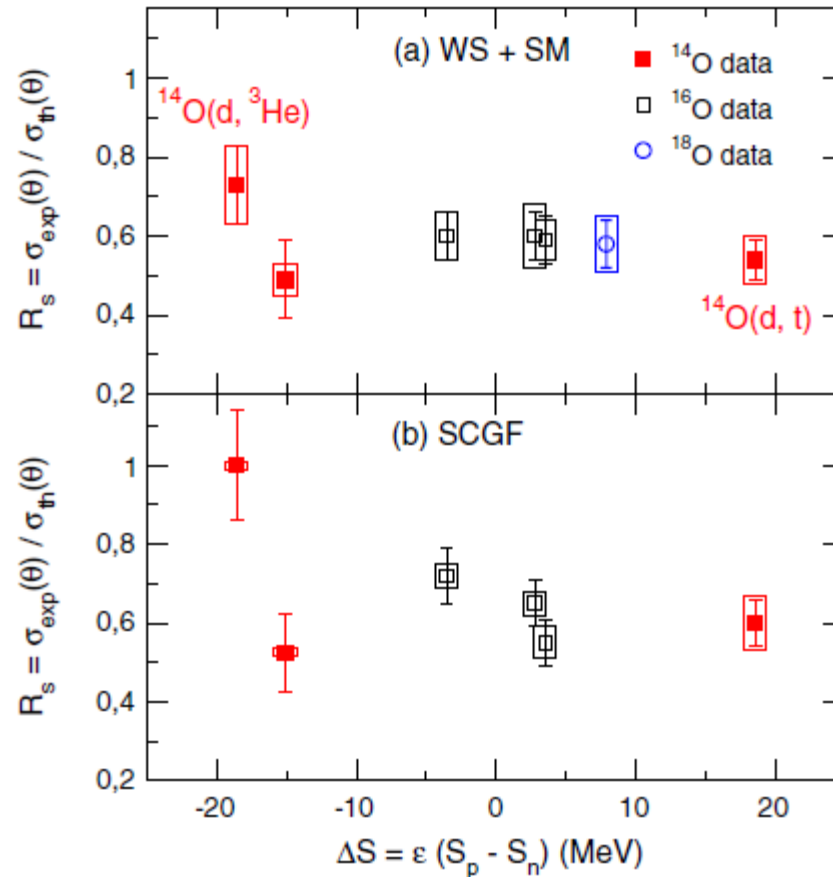
15.1

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

Reduction factors in recent transfer studies

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

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

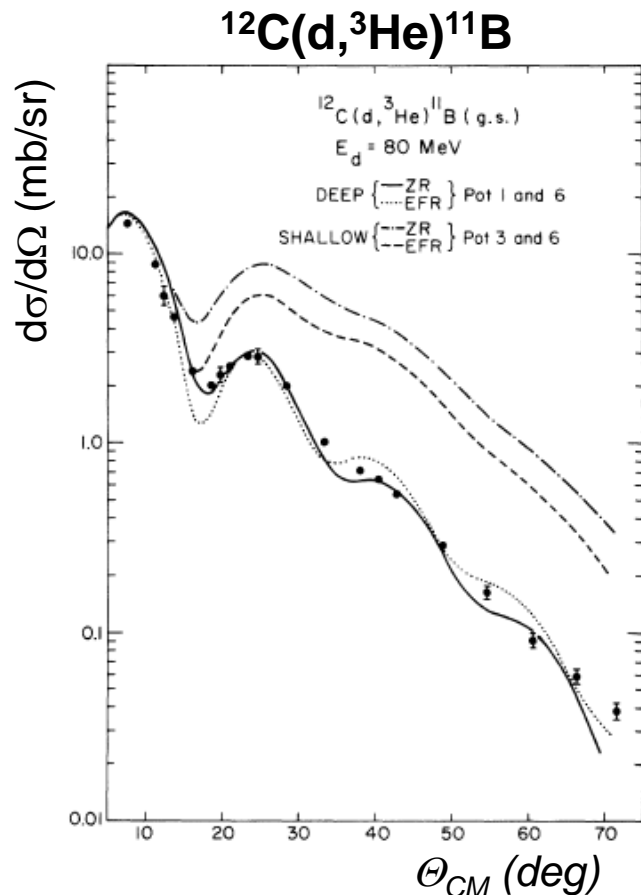


➤ **Very weak asymmetry dependence of reduction factors**

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

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

(d,³He) studies at 40 MeV/u



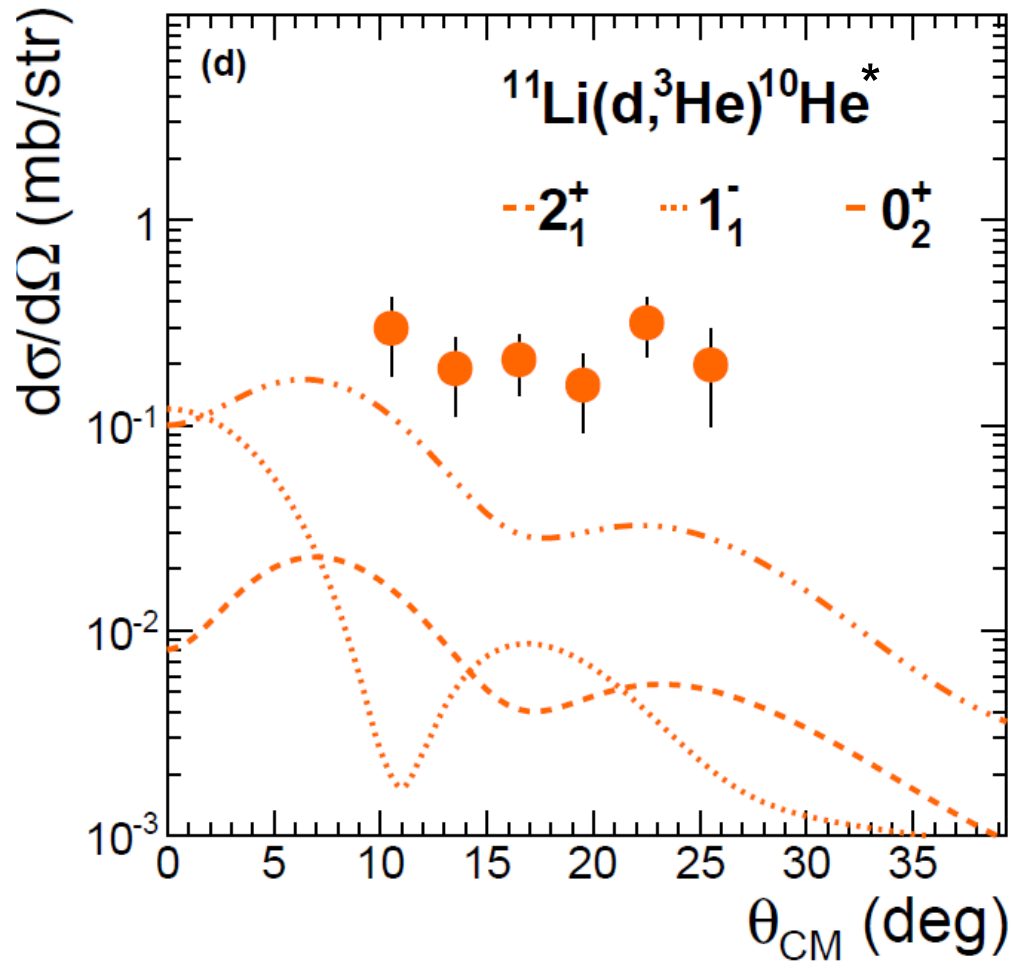
J.P. Didelez et al., PRC 13(1976)

**Spectroscopic factors found
in fair agreement with SM
Provided the 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 ¹¹Li(d,³He), residue is unbound
Also the case for ⁸Li(d,³He)
and in other studies e.g. ⁸He(p,d)⁷He**

Differential cross-sections to excited states



DWBA calculations
(FF from $2h\omega$ Shell
Model)

Enhanced !

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

HIGHLIGHTS

Tests of Nuclear overlaps

- Shape of differential Xsection of ${}^9\text{Li}(d, {}^3\text{He}){}^8\text{He}$ well-reproduced by calculations using several overlaps including *ab initio* VMC
Magnitude strongly reduced
- Even more reduced for ${}^{11}\text{Li}(d, {}^3\text{He}){}^{10}\text{He}$

Available overlaps fail away from stability

${}^{10}\text{He}$ structure

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

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

NEXT :

- ${}^{10}\text{He}$ populated by ${}^{14}\text{Be}(p, p\alpha)$
First study of $6n$ (decay channel of ${}^{10}\text{He}^*$)

Collaboration

- **IPN Orsay, France**
A.Matta, D.Beaumel, M.Assié, N. de Séréville, S.Franchoo, F.Hammache, E. Rindel, P. Rosier, J.-A. Scarpaci, I.Stefan
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R.Wolski
- **Institute for Nuclear Physics, Hanoi**
L.H.Khiem
- **University of Surrey**
N.K Timofeyuk