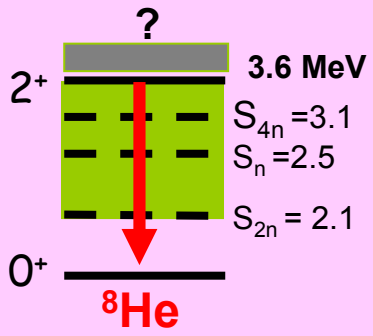
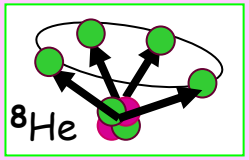
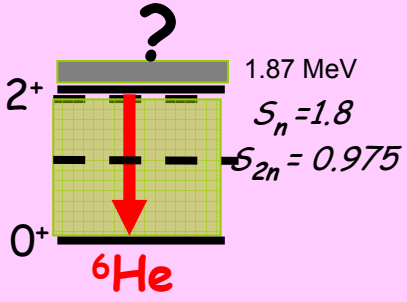
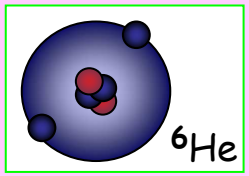






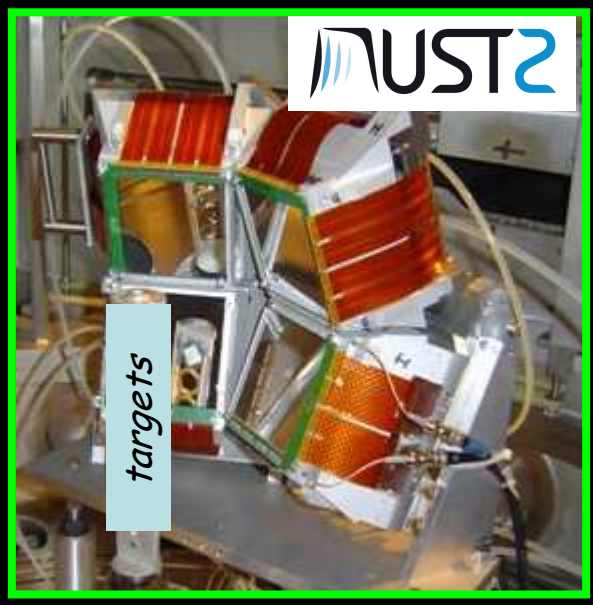


Resonant states of the exotic nuclei ^{6,7,8}He via direct reactions on a proton target

2nd-5th Nov. 08

PISA08

Edifices at the limit of the nuclear binding



vlapoux@cea.fr

Irfu cea saclay

Spectroscopy of dripline nuclei HELIUM 6,7,8 by direct reactions on p

GOAL ?

Extension of systematics of neutron excitation along isotopic chains
Characteristics of structure + low-lying resonances of drip-line nuclei

EXCITATION ENERGY SPECTRUM FOR ^{6}He → ^{8}He(p,t)^{8}He*

Experimental Tools ?

Probe the structure & spectroscopy at large isospin
→ Measure unbound states
→ detection device for particle spectroscopy

Interpretation ?

COUPLED REACTION CHANNEL calculations

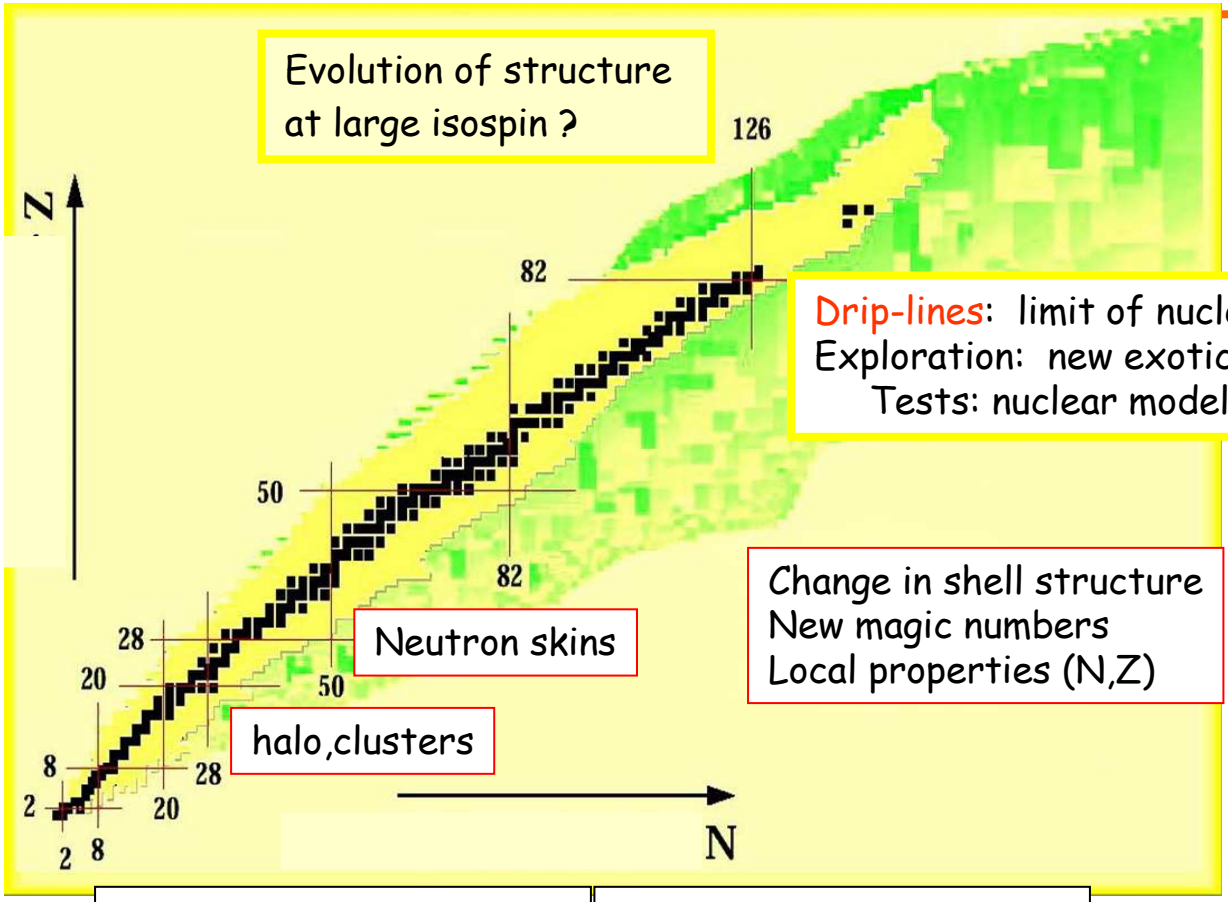
→ **QUESTIONS…**

Perspectives

Understanding of resonant states:
NEED FOR AN IMPROVED THEORETICAL FRAMEWORK
OF STRUCTURE AND REACTIONS

Nuclear structure towards the drip-lines : phenomena to explore & to understand

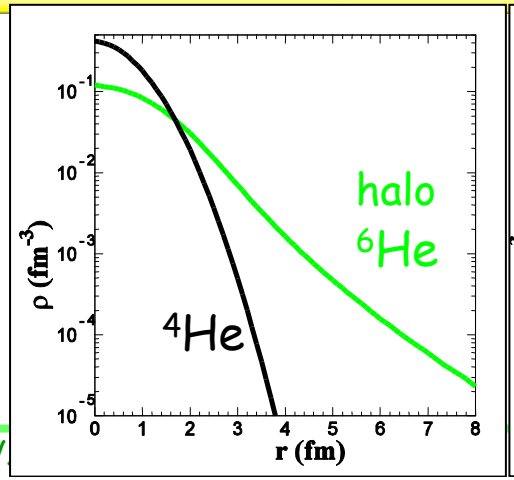
Evolution of structure at large isospin ?

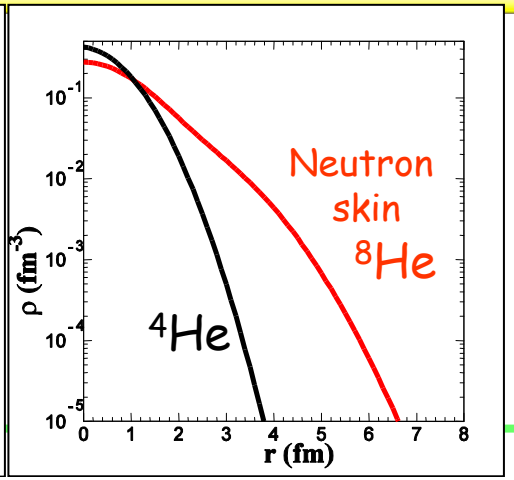


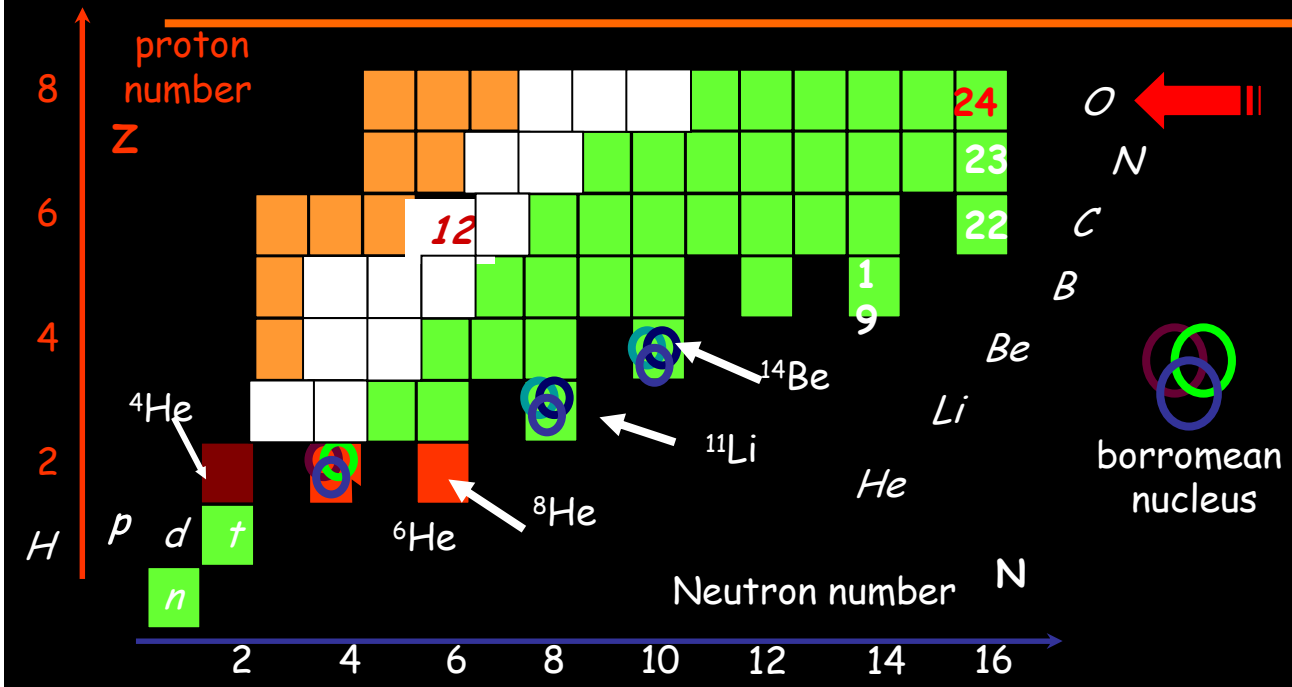
Drip-lines: limit of nuclear binding, large isospin
Exploration: new exotic structures → neutron-skin
Tests: nuclear modelling & interactions $V_{NN}(T_z)$

Change in shell structure
New magic numbers
Local properties (N,Z)

Weakly bound states ?
Continuum **coupling** ?
Isospin dependence ?

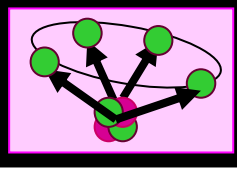


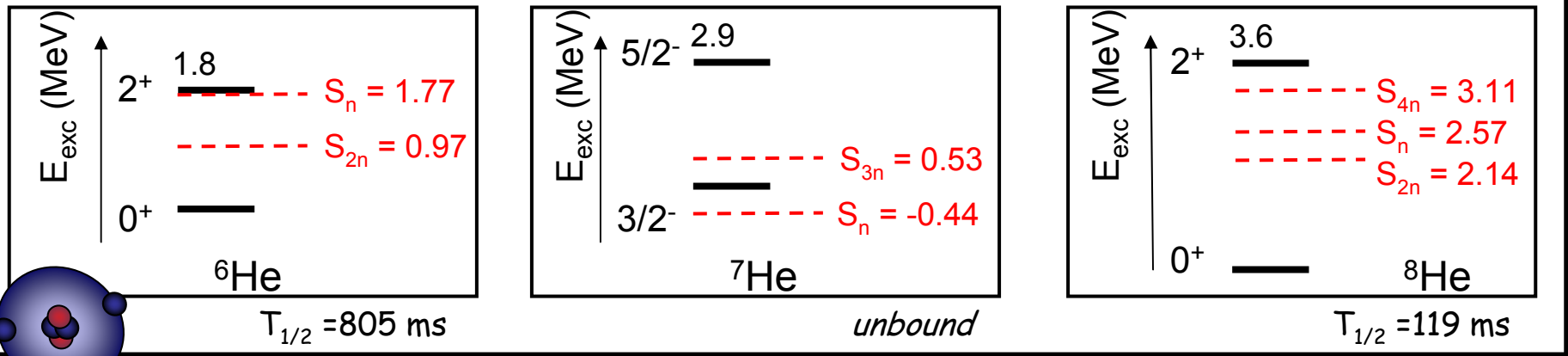




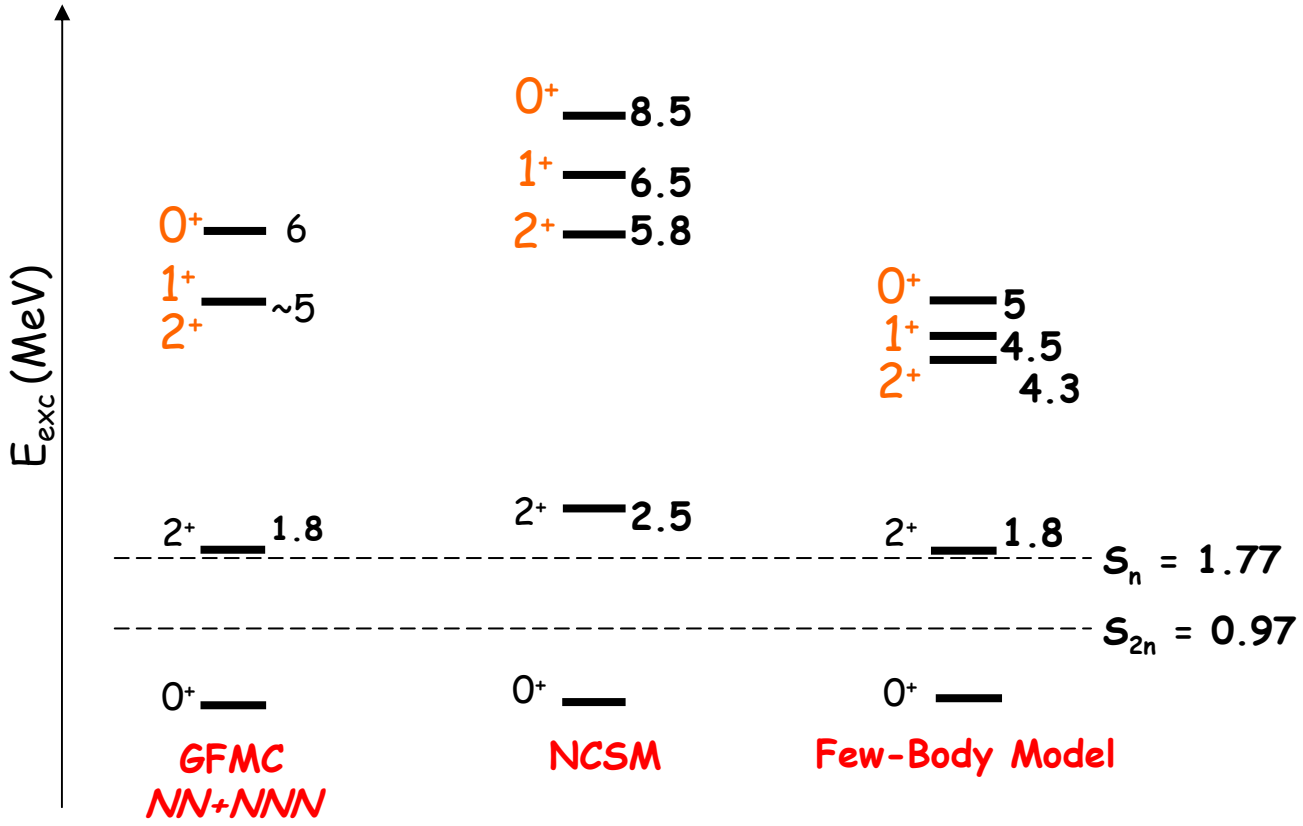
borromean nucleus

^{8}He drip-line nucleus
N/Z =3



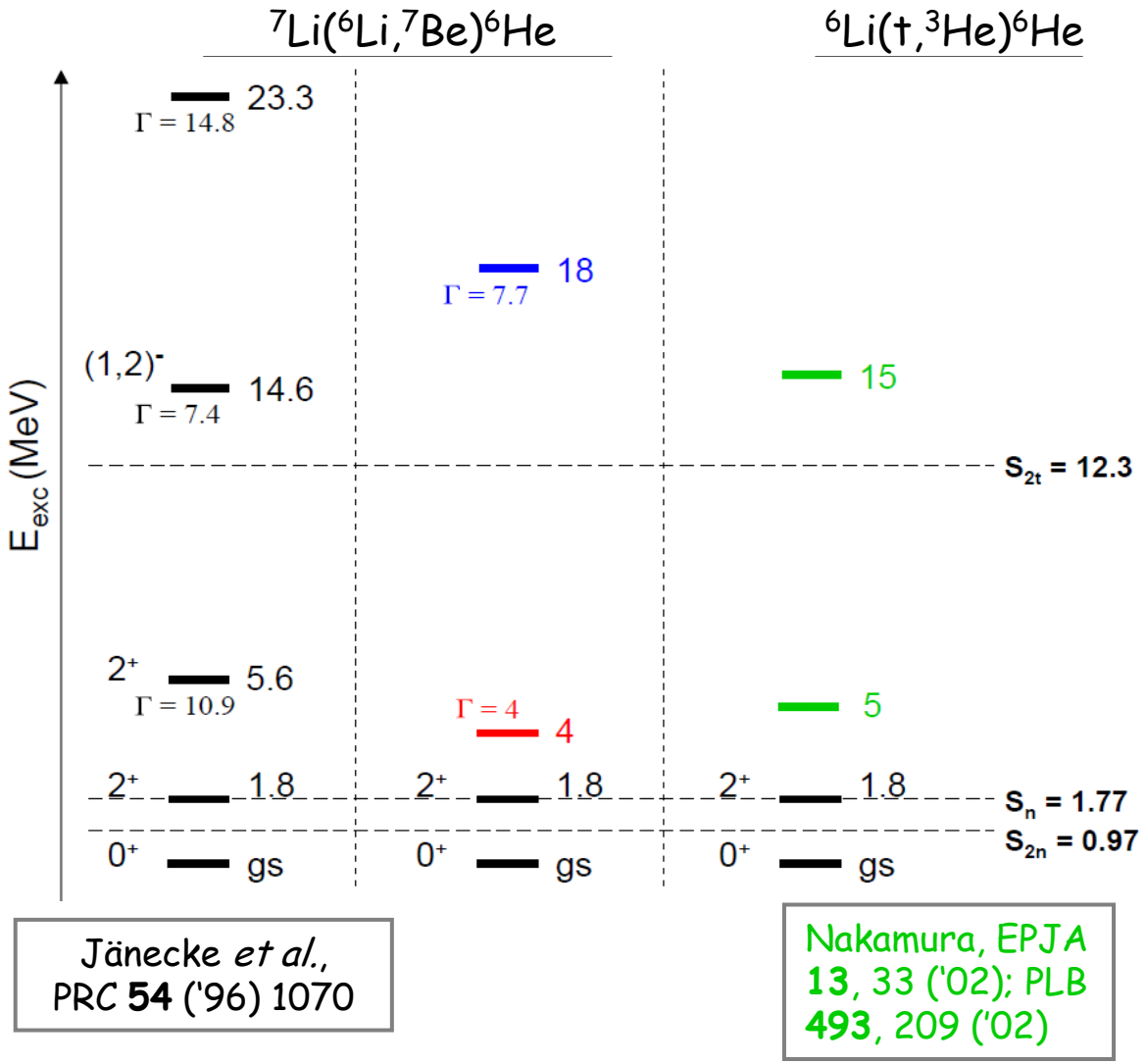


Predictions for ^{6}He spectroscopy



Pieper *et al.*, PRC **70**,054325('04)	Navrátil *et al.*, PRC **54**, 2986 ('96) +priv. Co.	Danilin *et al.*, PRC **55**, 577 ('97)

Experimental spectroscopy of ^{6}He

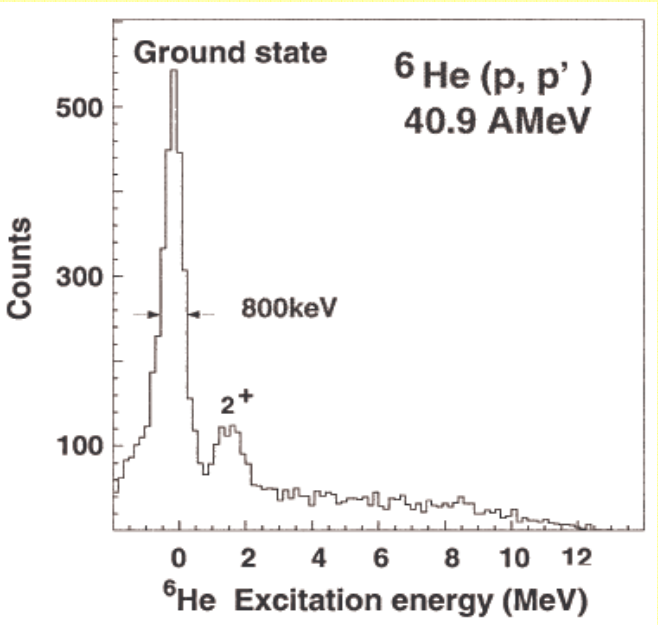


Jänecke *et al.*, PRC **54** ('96) 1070

Nakamura, EPJA **13**, 33 ('02); PLB **493**, 209 ('02)

Nakayama *et al.*, PRL 85, 262 ('00)
Akimune *et al.*, PRC **67**, 051302 ('03)

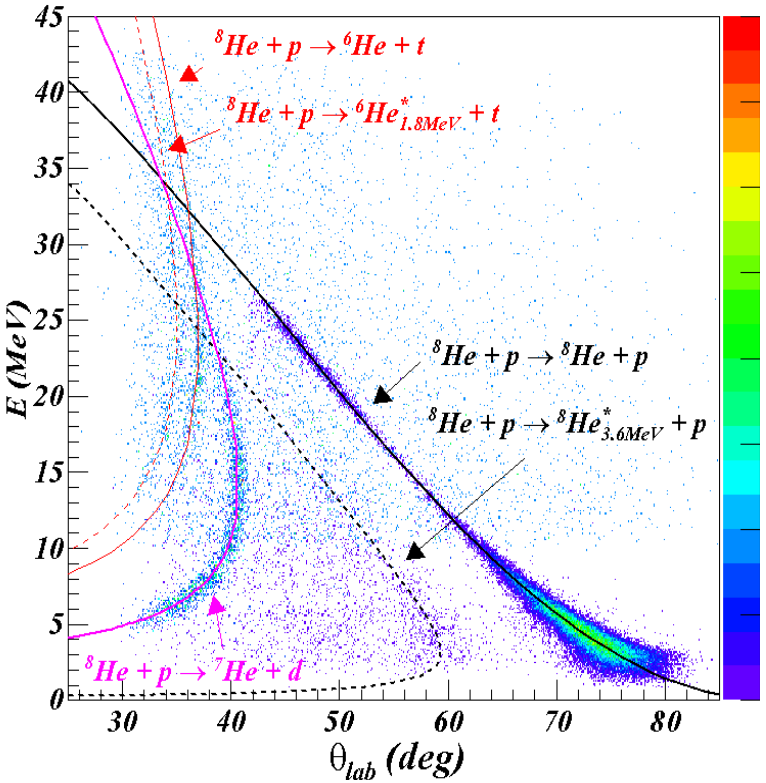
"Natural" probe:
^{6}He(p,p')
MUST(One) @ GANIL
*A. Lagoyannis et al., PLB **518**, 33 (2001)*



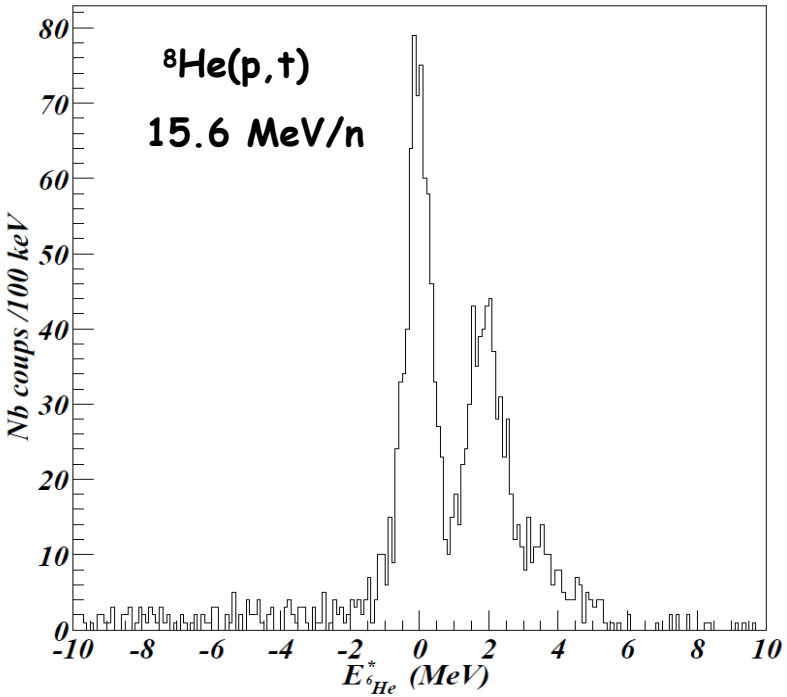
Analysis: No new state was extracted above the first 2+

Results from a previous experiment E405S : ^{8}He + p at 15.6 MeV/n

E405S : goal of the experiment was ^{8}He(p,p')] - MUST array ; SPIRAL ^{8}He beam
Additional data for ^{8}He(p,t)^{6}He



F. Skaza *et al.*, NP *A 788* (2007) 260c

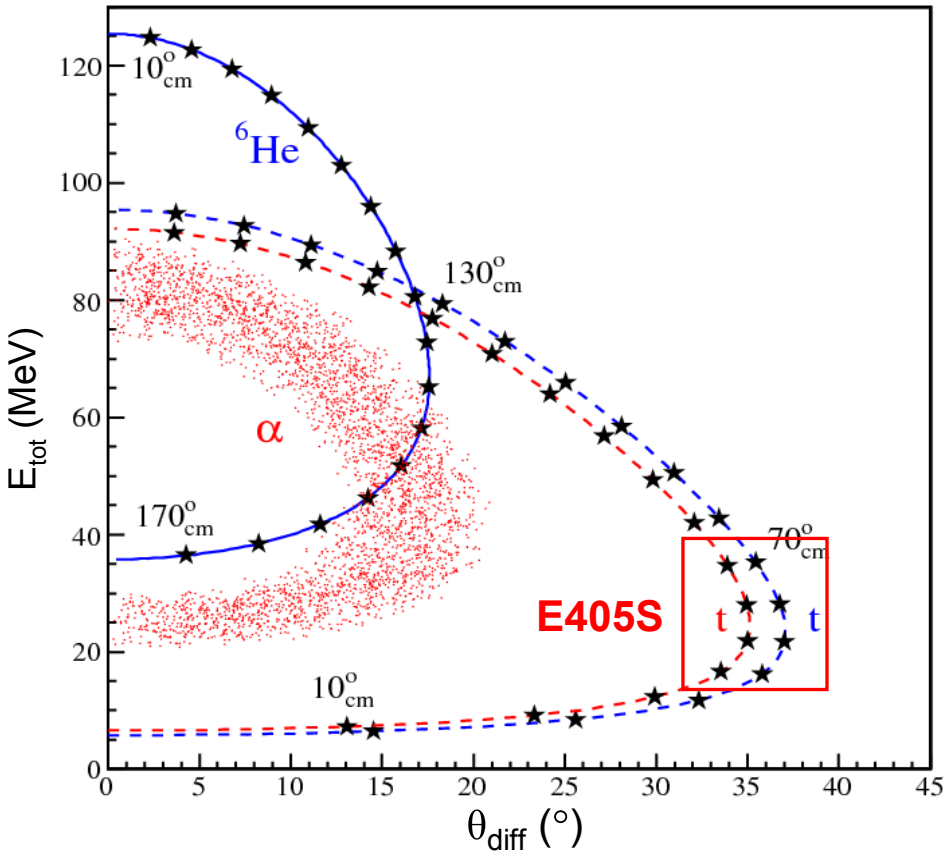


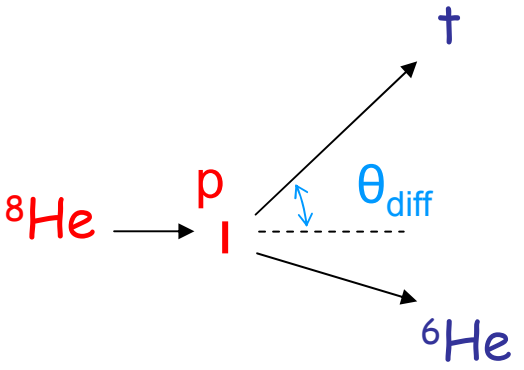
F. Skaza, CEA-Saclay SPhN, PhD (2004)

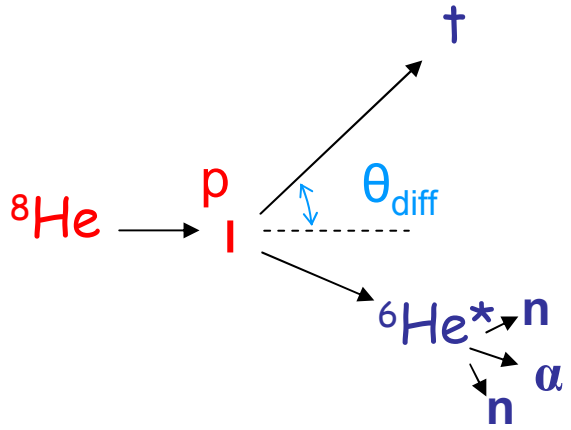
dσ/dΩ > 1 mb/sr
for ^{6}He(0^{+}) **and** ^{6}He(2^{+}) !
N. Keeley *et al.*, PLB **646**, 222('07)

^{8}He(p,t) as a spectroscopic tool for ^{6}He

Kinematics of the (p,t) reaction







(E,x,y,t) + identification for each particle ⇨ Kinematics (E_{tot},θ_{diff}) missing ⇨ mass ⇨ Spectra E* + $d\sigma/d\Omega$

a short advertisement page

MUST2

March 2007-1st campaign
E525S-Spectroscopy of ^{6}He via ^{8}He(p,t)
Spokesperson SPhN; collaboration MUST2
PhD Thesis: X. Mougeot (SPhN) [→ Sept 08]

Direct reactions with exotic beams

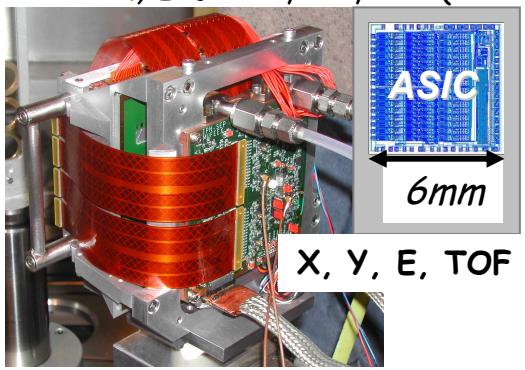
Light charged particle spectroscopy

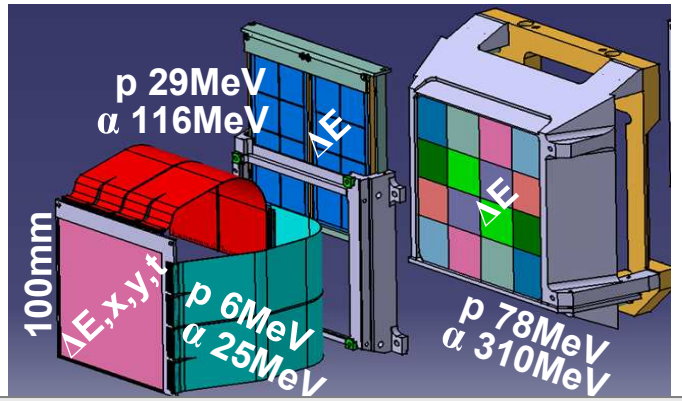
- project *achieved in* 2006
- collaboration DAPNIA/SPhN, IPN Orsay, GANIL
- 6 telescopes 10×10 cm² Si-strips / SiLi / CsI
- high granularity 128 (X,Y)

ASIC electronics 'MATE' Time and Energy for each channel developed by DAPNIA/SEDI

- Compact geometry - 1400 channels (E,T)
- front-end electronics under vacuum

E. Pollacco *et al.*, EPJA **25**, s01, 287 (2005)





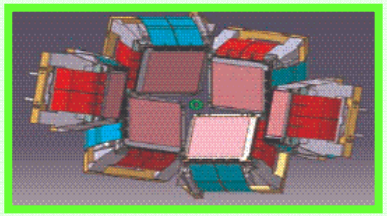
Si 300 μm [SiLi 4.5 mm] ; CsI 40 mm ; 128(X,Y)

Resolutions : dx,dy ~ 0.53mm → $d\theta_{lab}$ ~ 0.2° à 15cm

DE (Si): 40keV at 5.5 MeV ; CsI crystals ~ 200 keV

direct reactions : (p,p'), (p,d) (p,t)
(d,d') (d,p) (d,t)

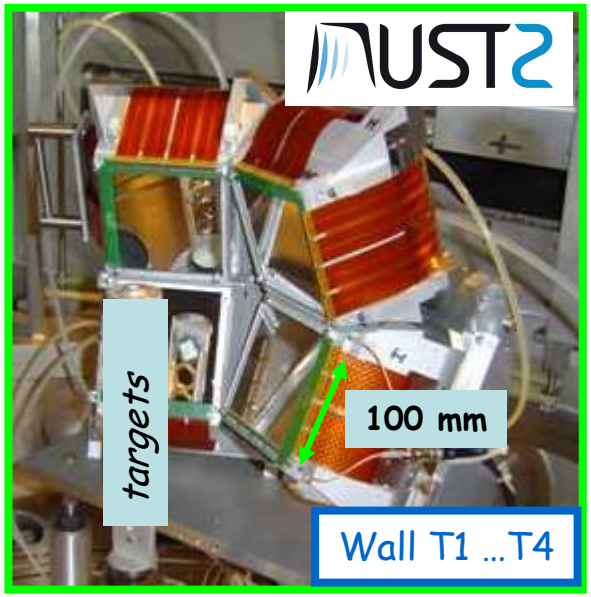
I (> 5. 10³/s)



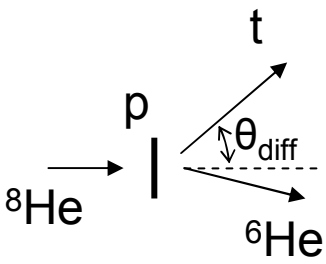
MUST2

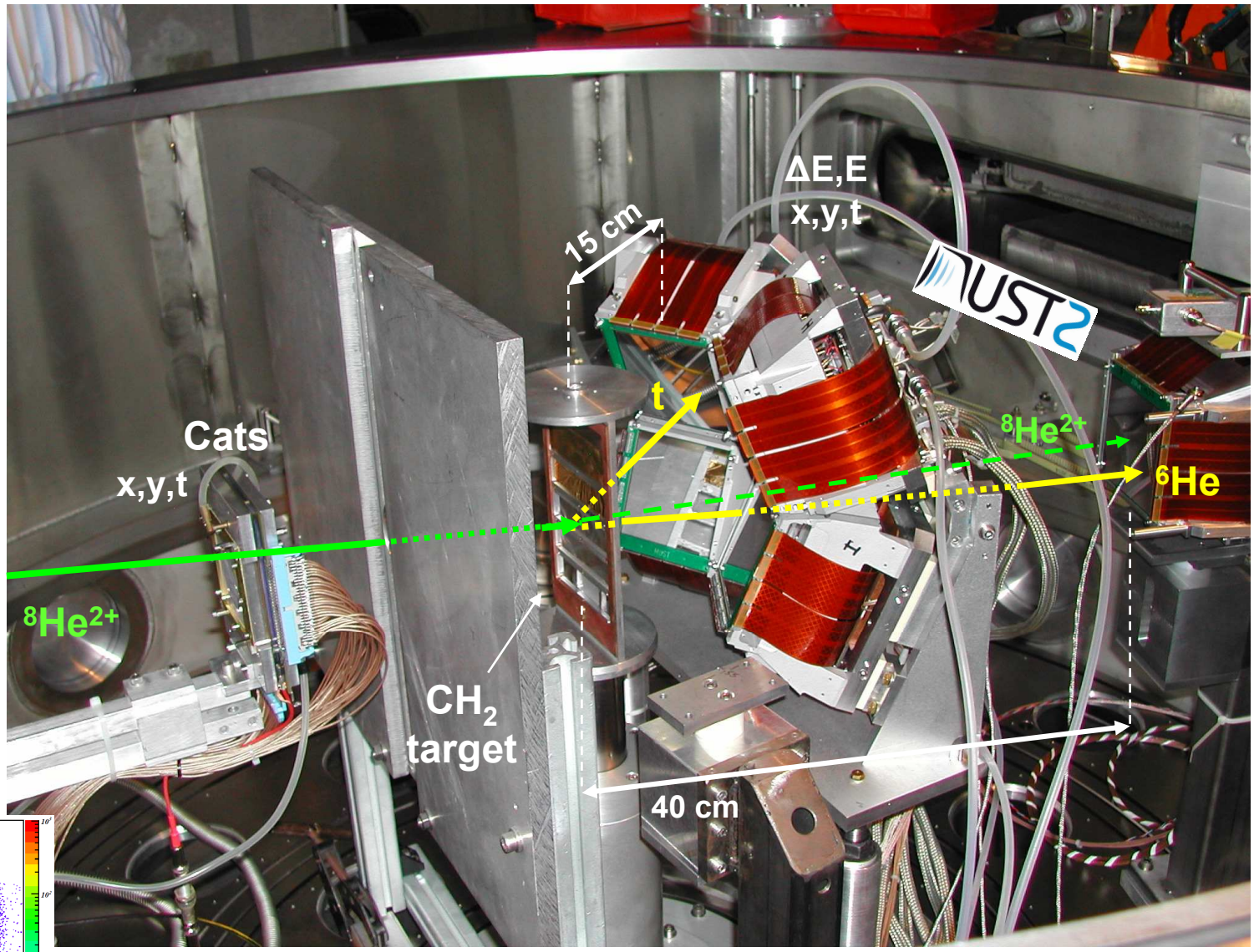
+ EXOGAM + VAMOS

(d,pγ)



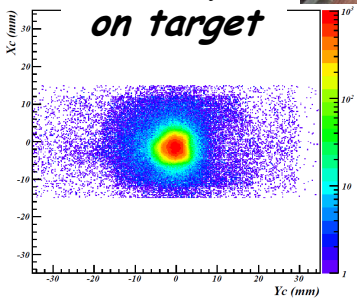
E525S : ^{8}He+p @ GANIL





SPIRAL beam
@ 15.4 MeV/n
<I> ~ 18500 pps

Beam spot on target



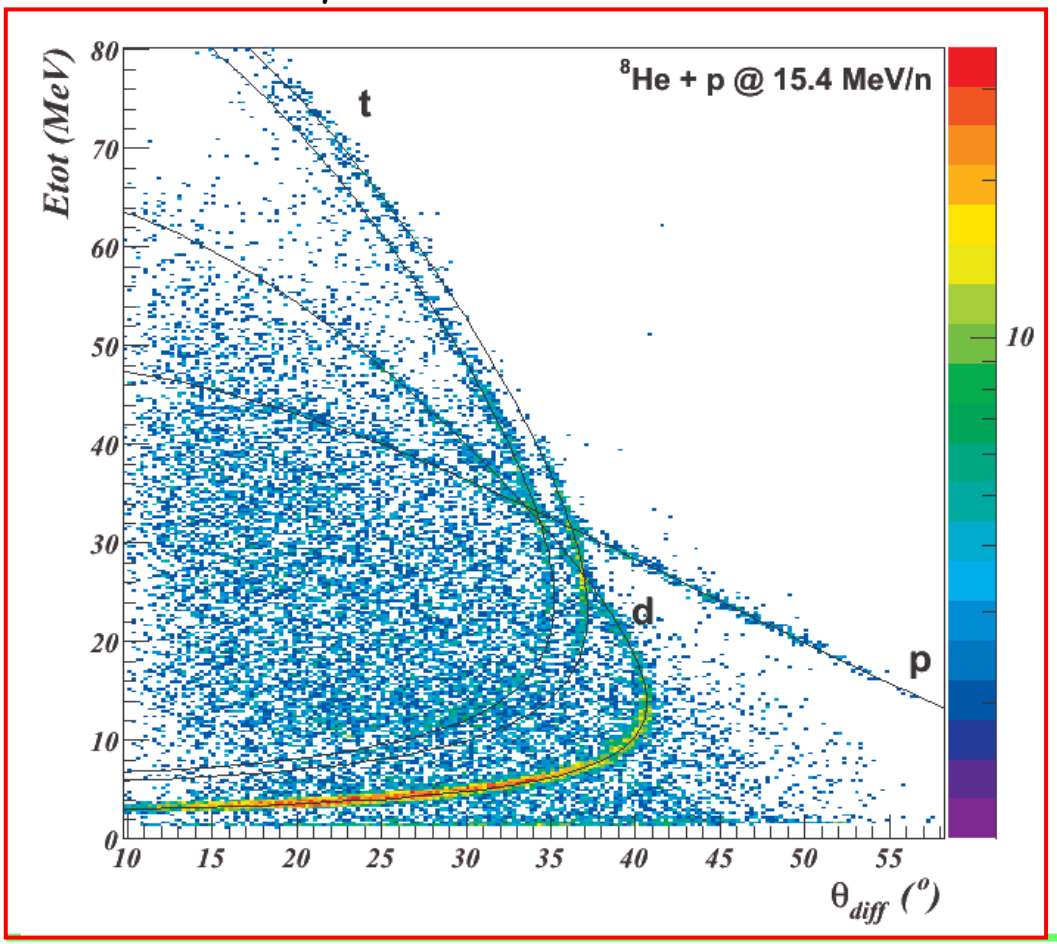
FWHM ΔX_c ~ 4 mm et ΔY_c ~ 5 mm
Incident angles ~0.5°

Kinematical reconstruction

CATS
impact on target
θ_{inc}

MUST2
identification
E_{tot}, θ

Resolution : 0.6 mm
Efficiency : 94 %



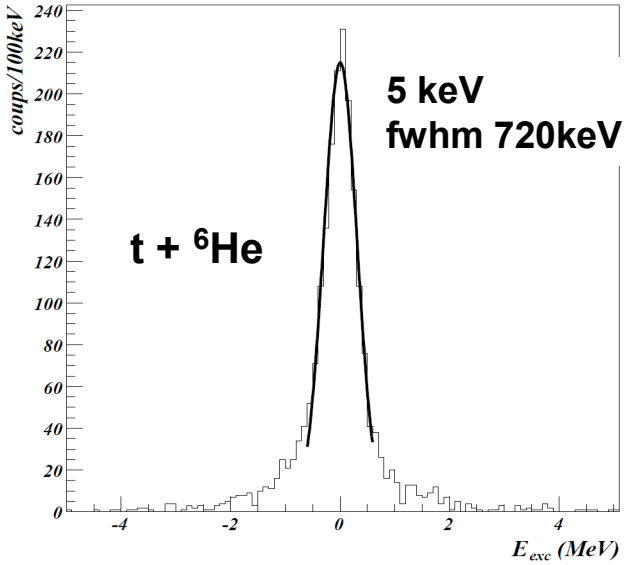
^{8}He + p → ^{6}He + t

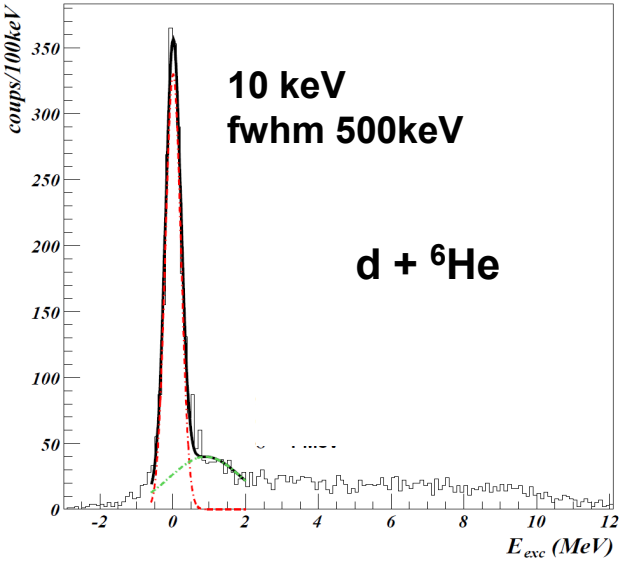
^{8}He + p → ^{7}He + d

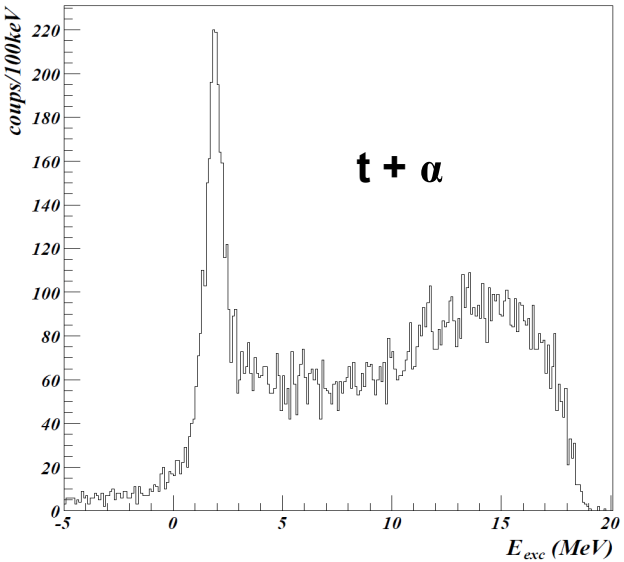
Missing mass method

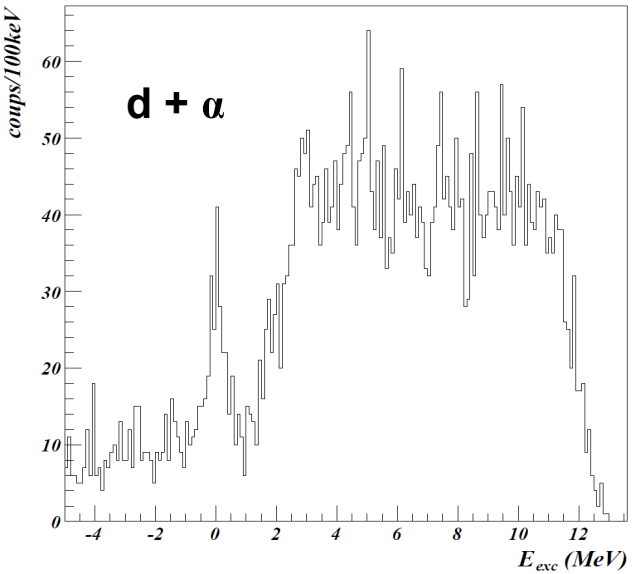
Spectra E_{exc} + $d\sigma/d\Omega$

Excitation energy spectra with particle coincidences



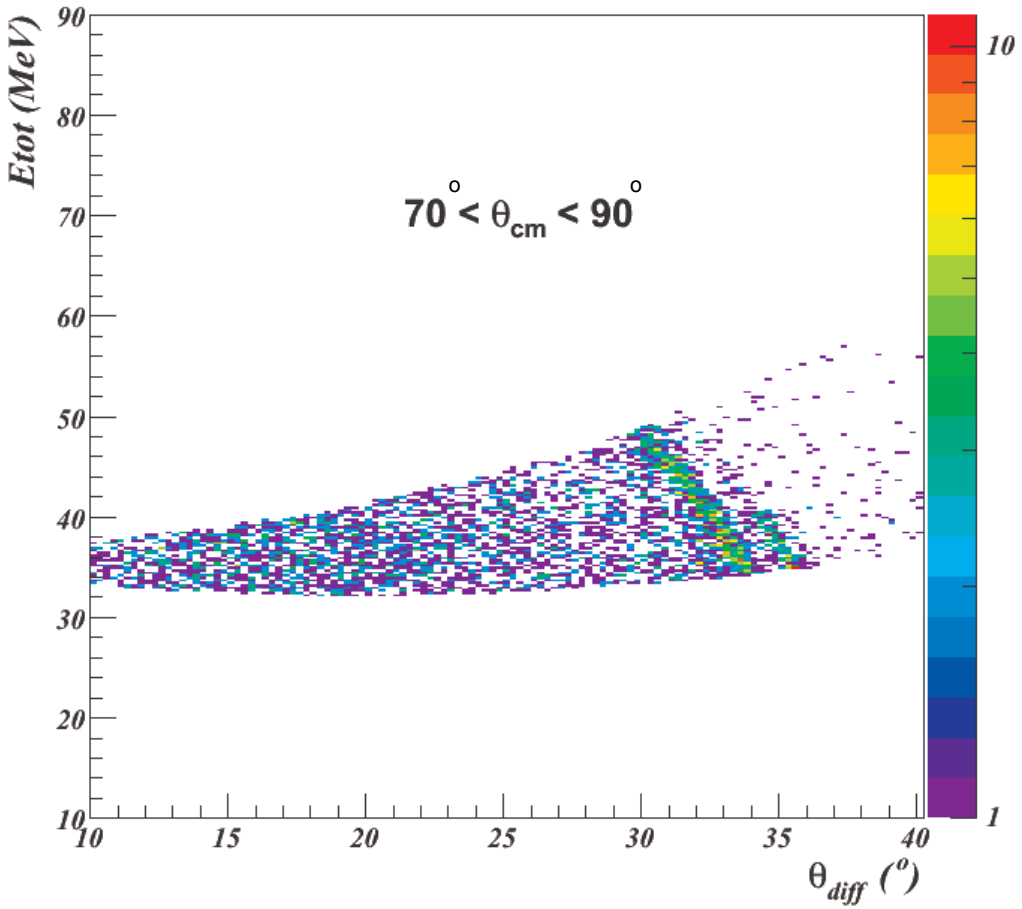


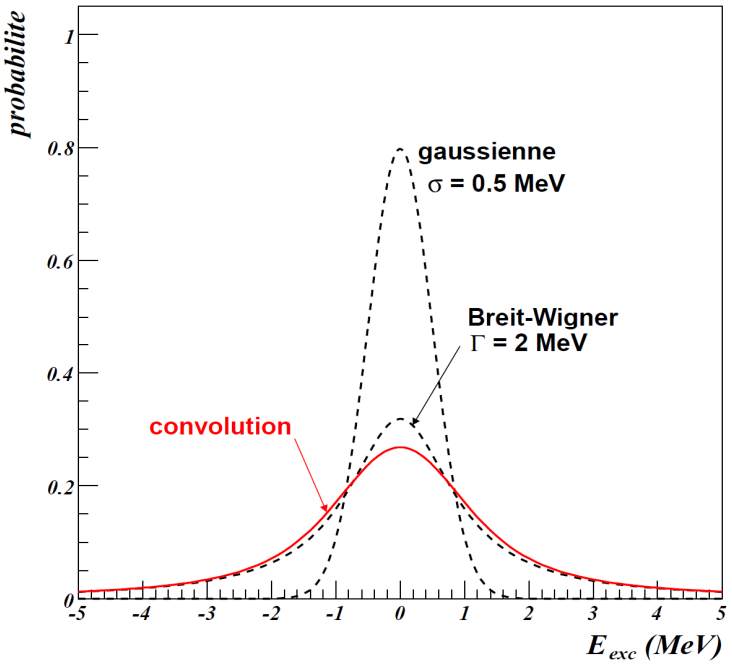




All data on the 50 µm target

Criteria for a resonant state





Breit-wigner parametrization $$f(\mathrm{E}) = \frac{1}{\pi}\frac{\Gamma_R/2}{(\mathrm{E}-\mathrm{E}_R)^2 + (\Gamma_R/2)^2}$$

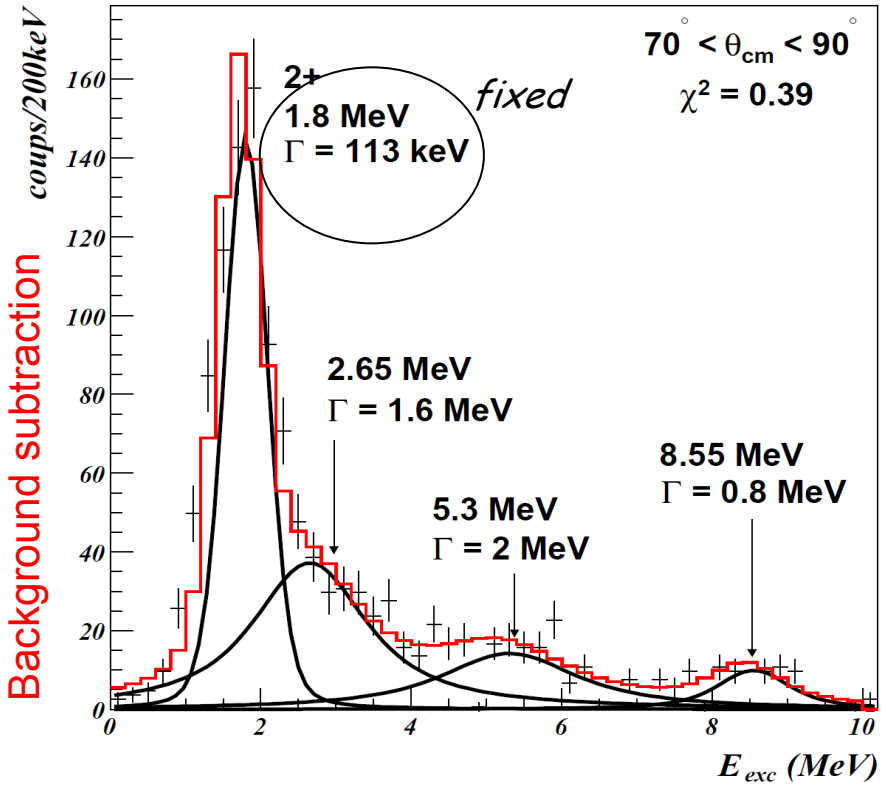
Effect of the experimental resolution: folding with a Gaussian function

Analysis of the ^{6}He spectra: resonances

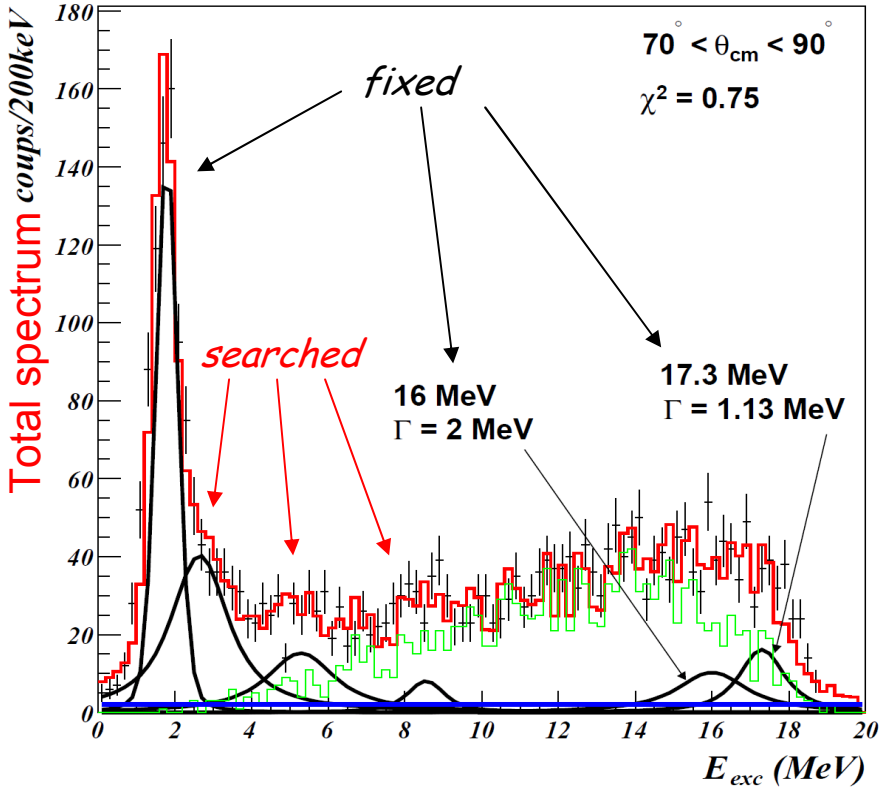
Sources of physical background
Few-body kinematics in exit channel → Alpha+n+n background
C content in target → possible reactions producing alpha in coinc with t

1st step :subtraction of the physical background to find out the possible resonance location

2nd Step : search for the resonances on the total spectra



χ² between 0 and 10 MeV

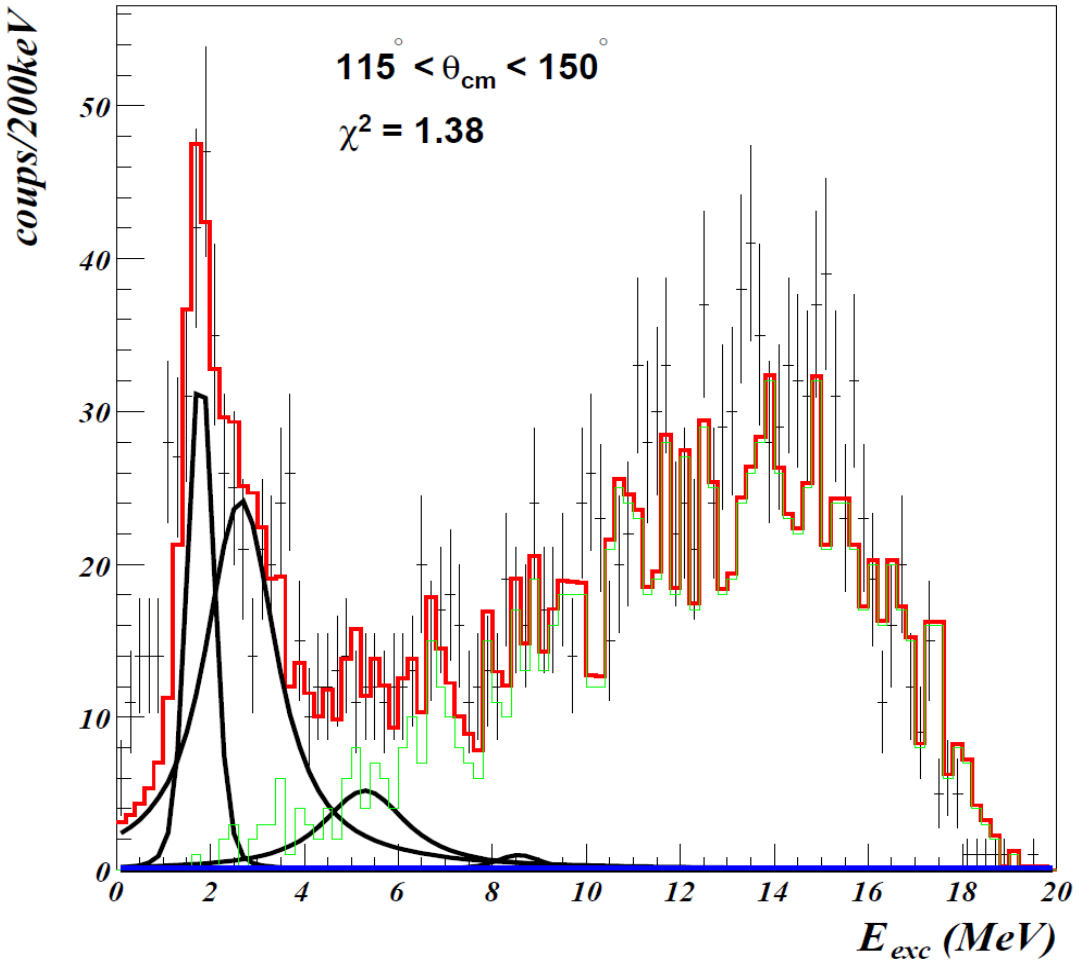


χ² between 0 and 20 MeV

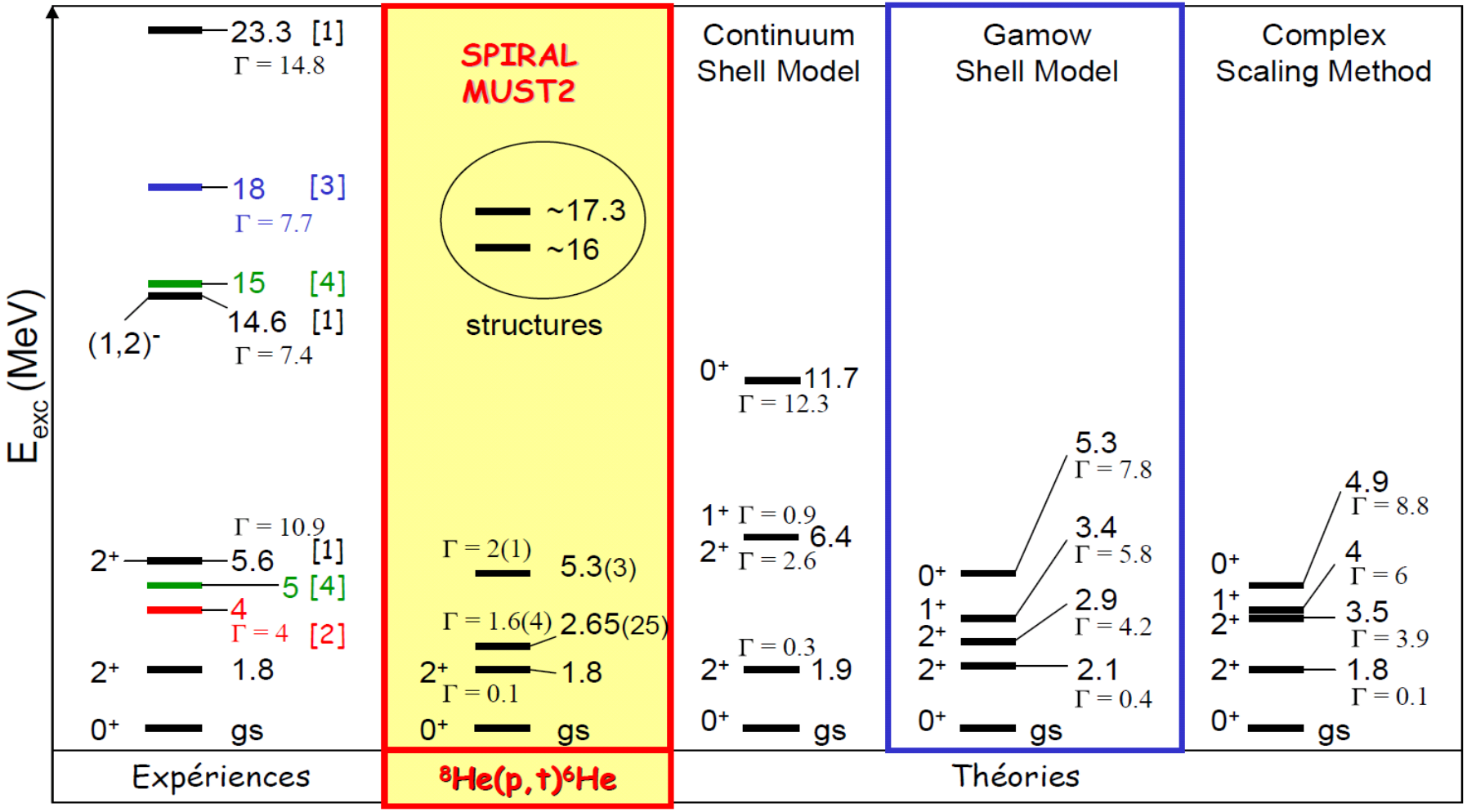
Analysis of the ^{6}He spectra: resonances

→ *Operations repeated for all Eexc spectra [c.m. slices in the kinematics]*

3rd step : checking that the parameters of the resonances are conserved at the various c.m. angles



Summary of the ^{6}He spectroscopy



[1] Jänecke *et al.*, PRC 54 (1996) 1070
[2] Nakayama *et al.*, PRL 85 (2000) 262
[3] Akimune *et al.*, PRC 67 (2003) 051302
[4] Nakamura, EPJA 13 (2002) 33

Volya *et al.*, PRL**94** (2005) 052501

Hagen *et al.*, PRC **71** (2005) 044314

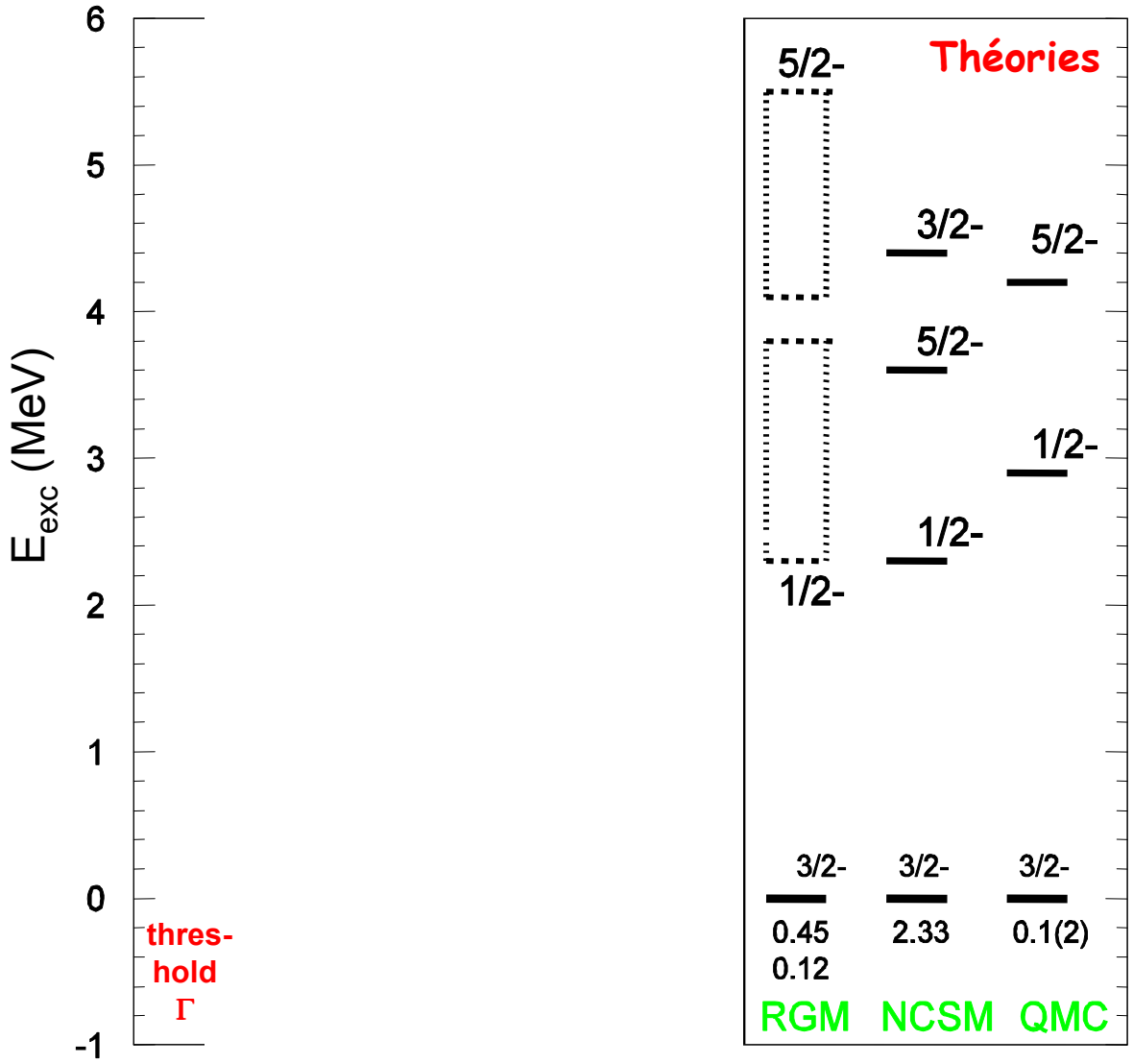
Myo *et al.*, PRC **76**(2007) 054309

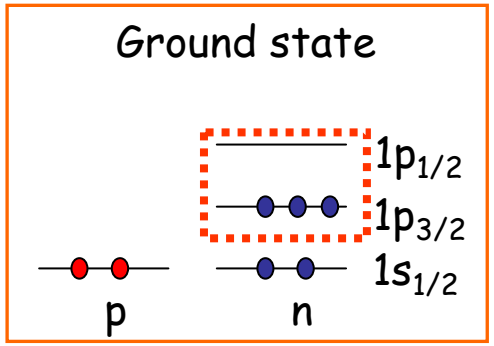
Unbound

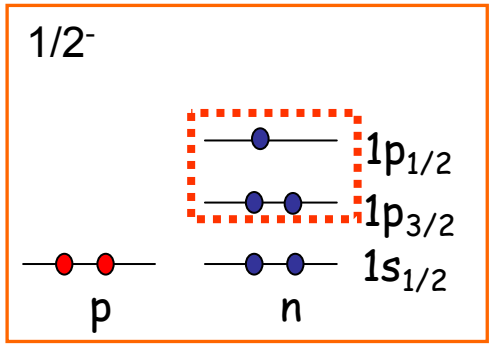
^{7}He

Controversy/debate:
existence of the low-lying state ~ 1 MeV?

Spectroscopy of ^{7}He, summary



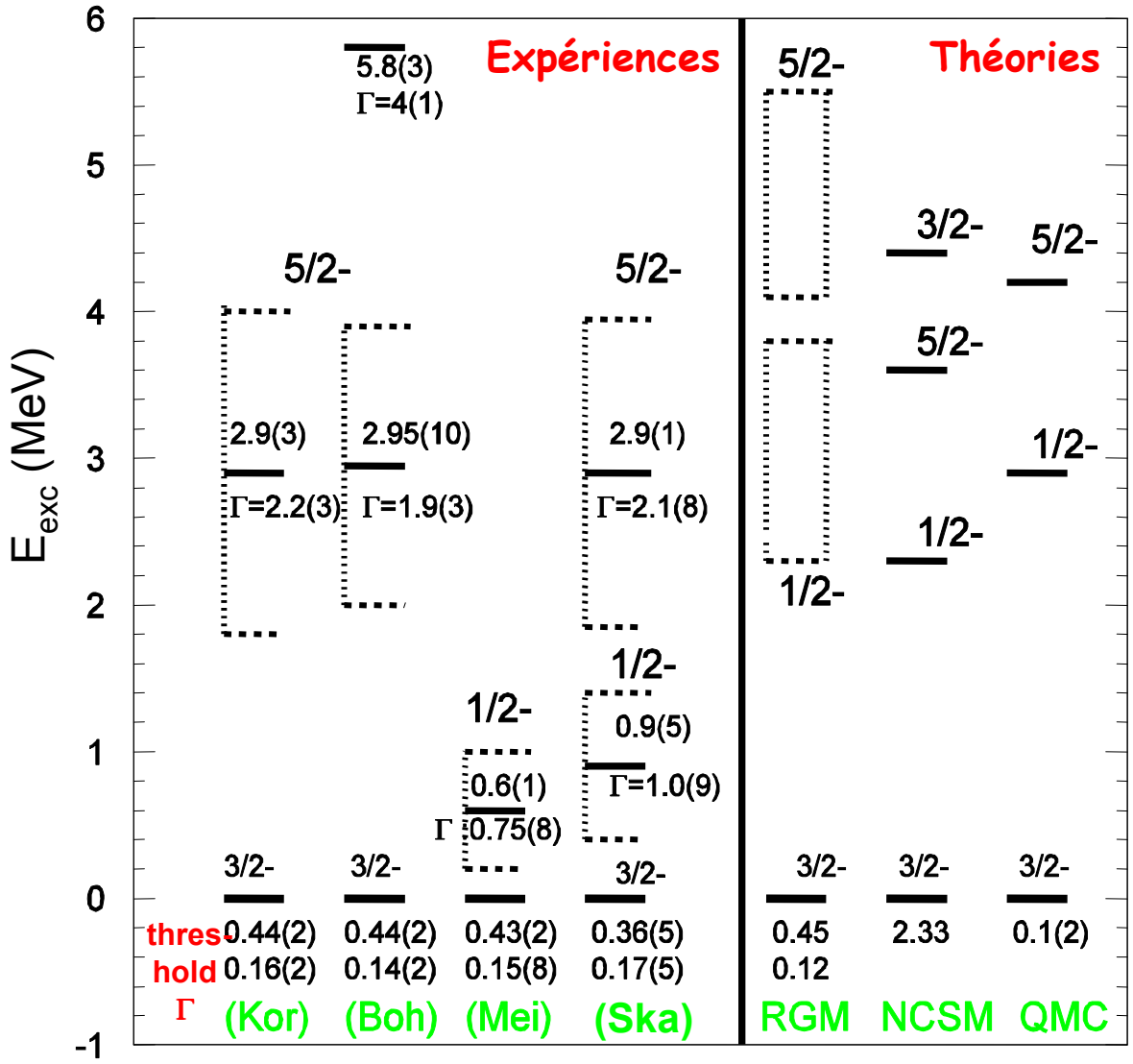


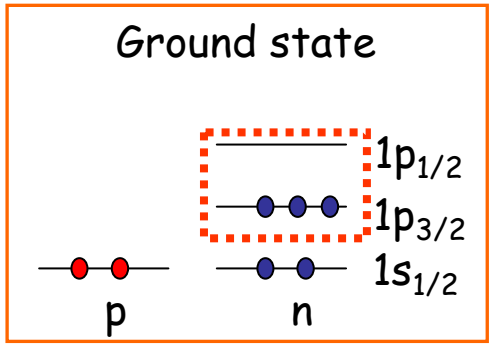


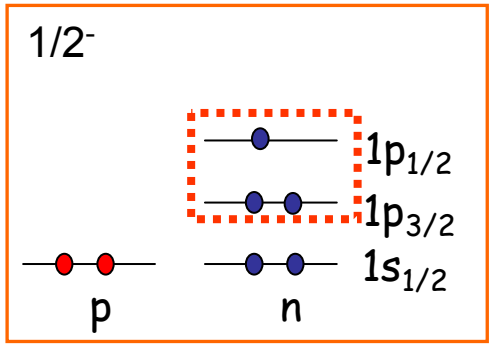
RGM
Wurzer *et al.*, PRC **55** (1997) 688
NCSM
Navrátil *et al.*, PRC **57** (1998) 3119
QMC
Wiringa *et al.*, PRL **89** (2002) 182501

(Kor) Korsheninnikov *et al.*, PRL **82** (1999) 3581 (Boh) Bohlen *et al.*, PRC **64** (2001) 024312
(Mei) Meister *et al.*, PRL **88** (2002) 102501 (Ska) Skaza *et al.*, PRC **73** (2006) 044301

Spectroscopy of ^{7}He, summary







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Wurzer *et al.*, PRC **55** (1997) 688
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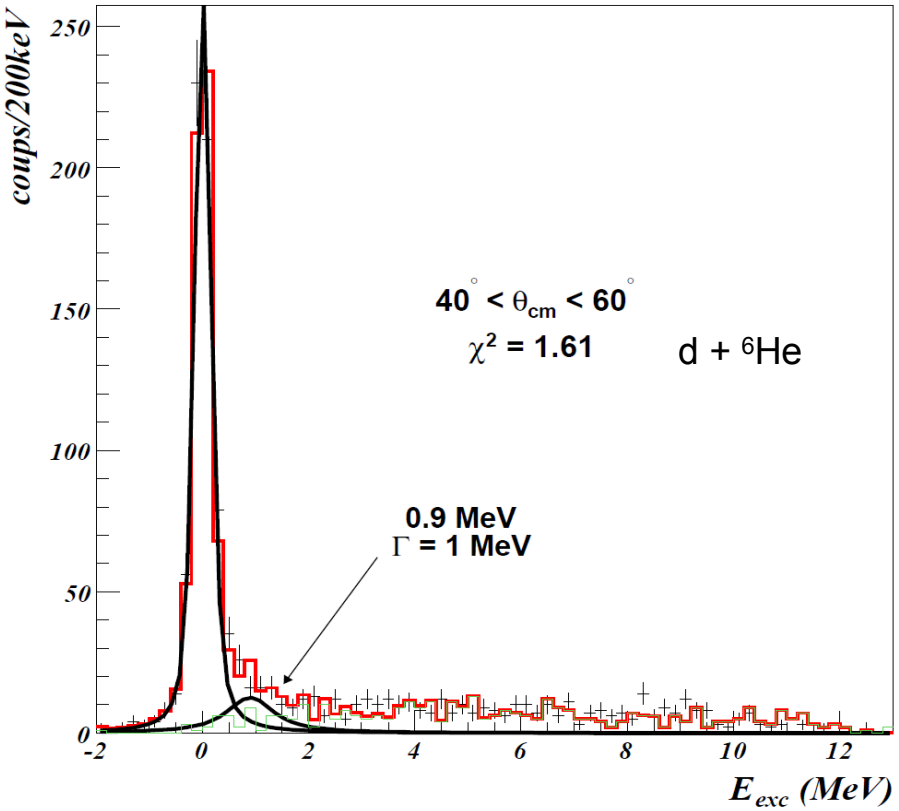
(Mei) Meister *et al.*, PRL **88** (2002) 102501 (Ska) Skaza *et al.*, PRC **73** (2006) 044301

Analysis of the ^{7}He spectra



Symmetric resonances
⇨ compatible with the previous E405S data

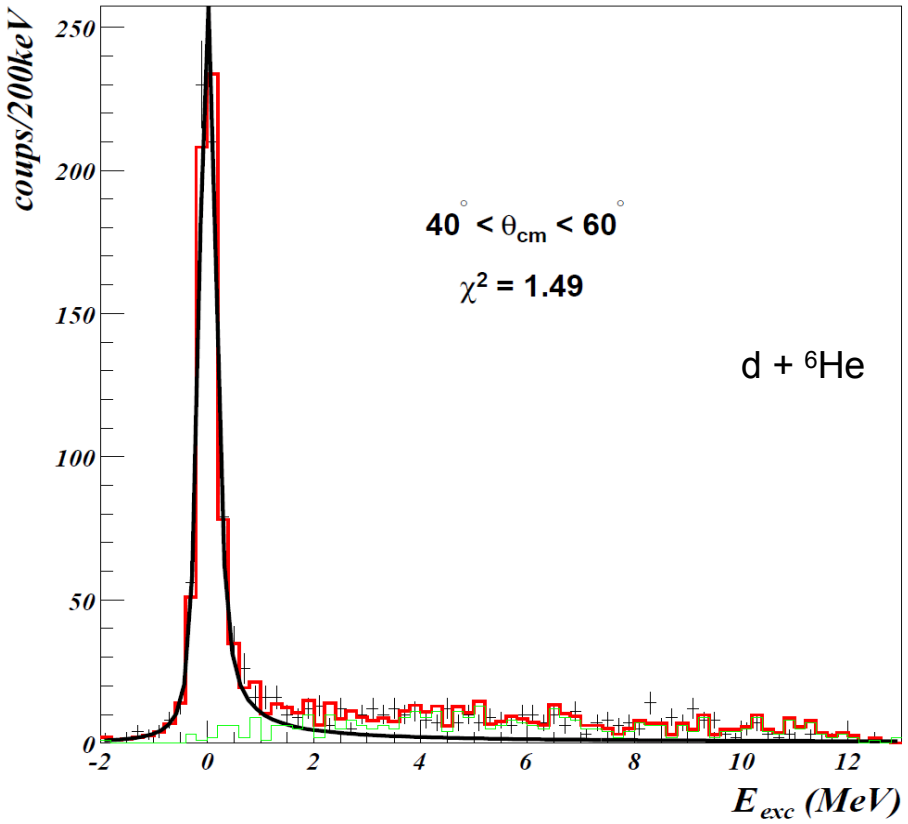
Breit-Wigner

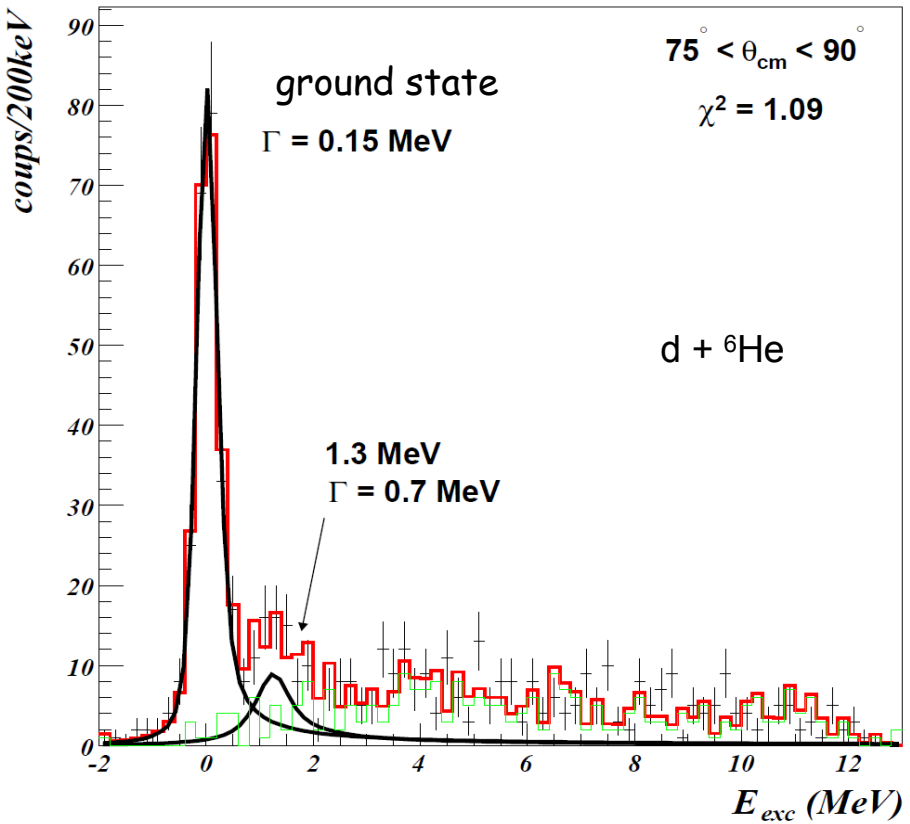
$$f(E) = \frac{1}{\pi} \frac{\Gamma_R/2}{(E - E_R)^2 + (\Gamma_R/2)^2}$$

Deformed resonance,
by assuming energy-dependent width,
for E > Er

$$\Gamma_R = \Gamma_R(1 + K(E - E_R))$$

Analysis of the ^{7}He spectra

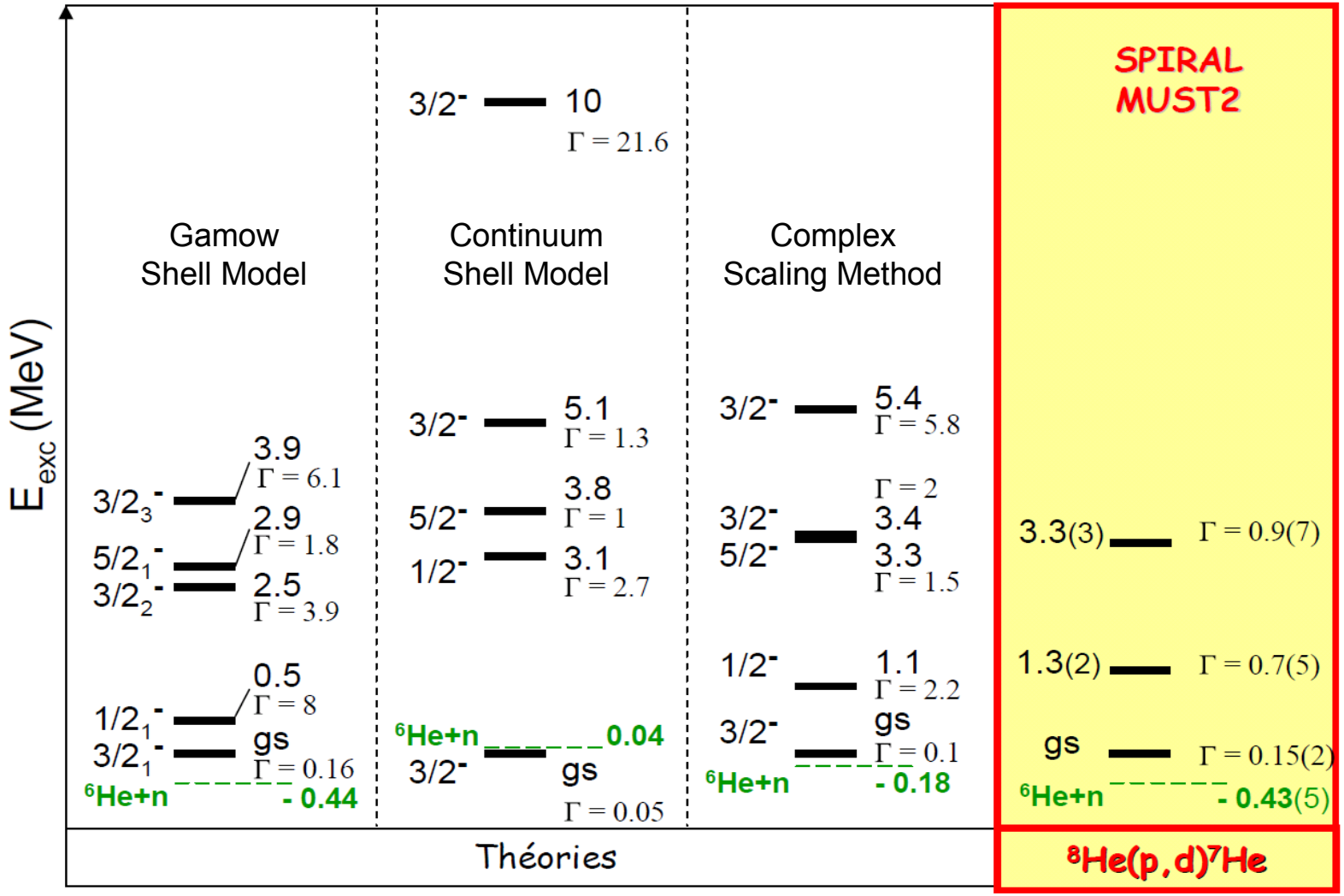




Asymmetric resonances
⇨ Ground state only

conservation between 60°$_{cm}$ et 120°$_{cm}$

Spectroscopy of ^{7}He: data vs Theories

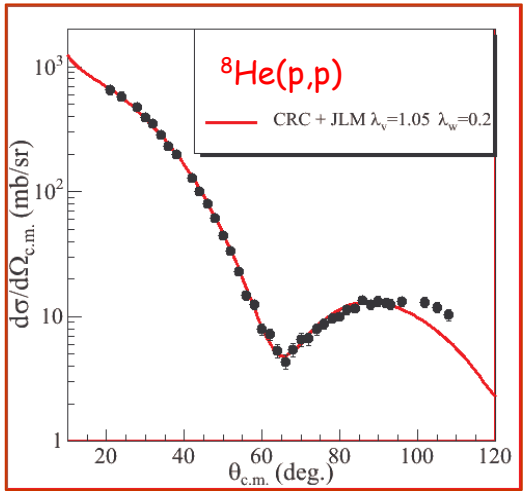


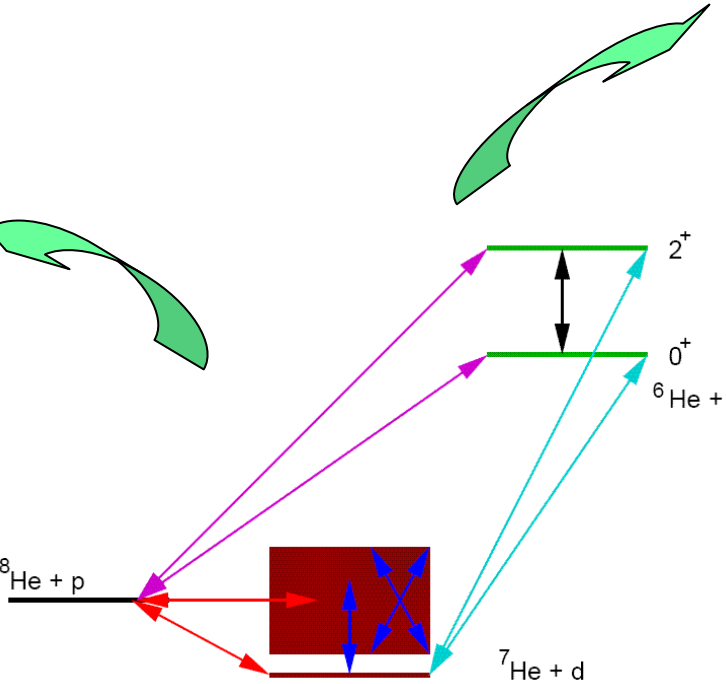
Hagen *et al.*, PRC **71** (2005) 044314	Volya *et al.*, PRL **94** (2005) 052501	Myo *et al.*, PRC **76**(2007) 054309

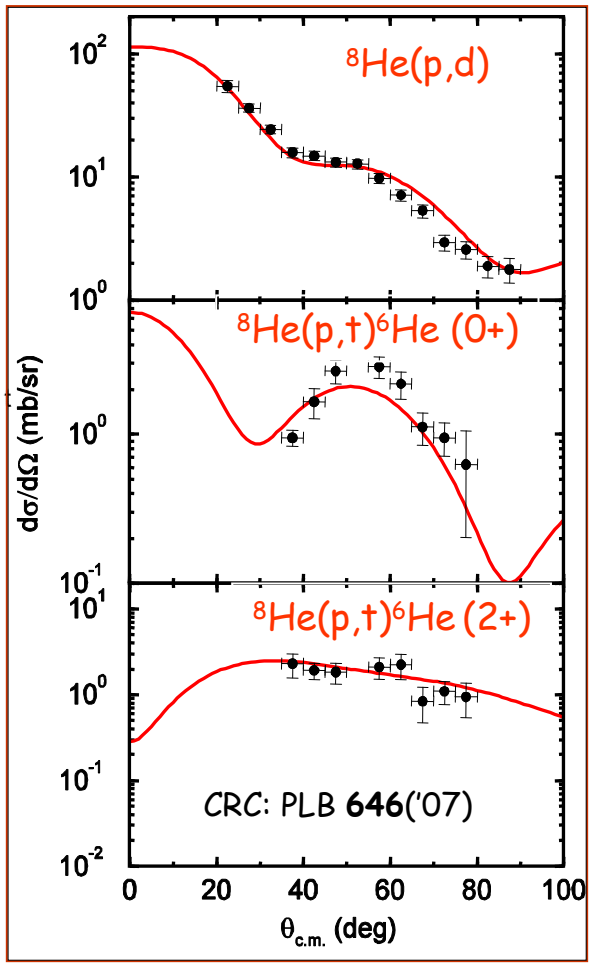
Interpretation of direct reactions: ex of ^{8}He+p @ 15.7 A.MeV

Coupled reaction channel (CRC) calculations needed:
Cf ^{8}He+p Analysis → N. Keeley, SPhN [now: univ of Varsaw]
F. Skaza *et al.*, PLB **619**. 82 ('05) ; PRC **73**, 044301 ('06)
N. Keeley *et al.*, PLB **646**, 222('07)

E405s -GANIL-MUST
^{8}He +p @ 15.6 MeV/n







Spectroscopic factor
$C^2S\ (d\sigma/d\Omega)_{théo} = (d\sigma/d\Omega)_{exp}$

The transferred angular momentum L_t indicates J^{π}

CRC analysis: structure of ^{8}He

PREVIOUS INTERPRETATION

Data ^{8}He(p,t) @ 61.3 A.MeV - RIKEN
A.A.Korsheninnikov et al, PRL **90**, 082501 ('03)
DWBA analysis : [^{8}He/^{6}He(0+)] = [^{8}He/^{6}He(2+)] = 1
(only (p,t) no elastic data)

CRC ANALYSIS INTERPRETATION OF SPIRAL DATA

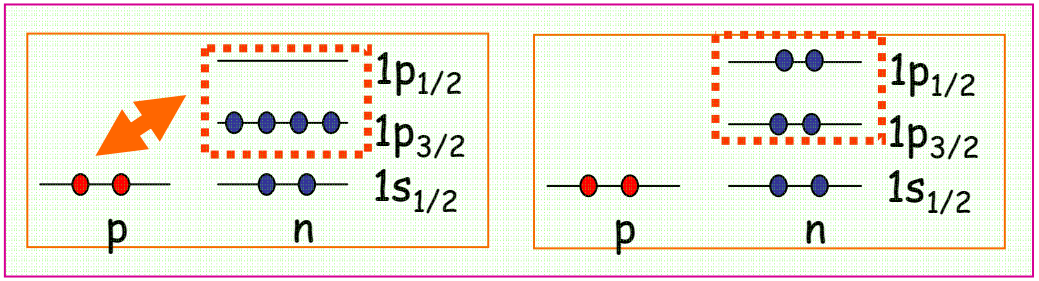
N. Keeley et al. : PLB **646**, 222('07)

^{8}He(p,d)^{7}He $C^2S = 3.4 \pm 1.3$

complete set:
(p,p), (p,d) and (p,t)
@ 15.6 MeV/n

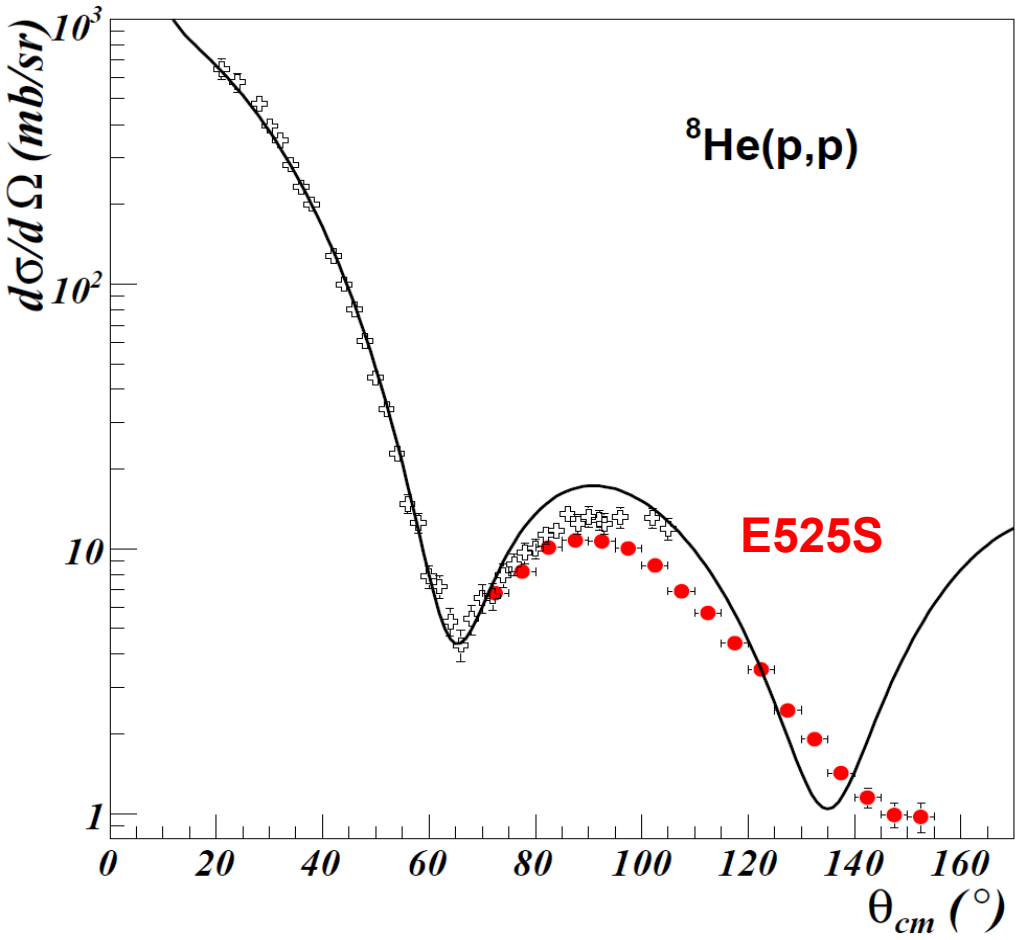
(p,t) → wave function ^{8}He % ^{6}He
[^{8}He/^{6}He(0+)] =1 ;
[^{8}He/^{6}He(2+)] =0.014
Mixing: $(p3/2)^4$ and $(p3/2)^2\ (p1/2)^2$

and re-analysis of RIKEN data



Consistent with the results from quasi-elastic scattering of ^{8}He at GSI,
LV Chulkov et al, NP***A759***, 43('05) [^{8}He/^{6}He(0+)] : 1.3 ± 0.1
And recent theoretical calculations: Hagino, Takahashi, Sagawa PRC **77**, 054317 ('08)
Neutron configurations % ^{8}He (gs.) : $(1p_{3/2})^4$: 34.9 % ; $[(1p_{3/2})^2(p_{1/2})^2]$: 23.7 %

Elastic scattering data for ^{8}He(p,p)



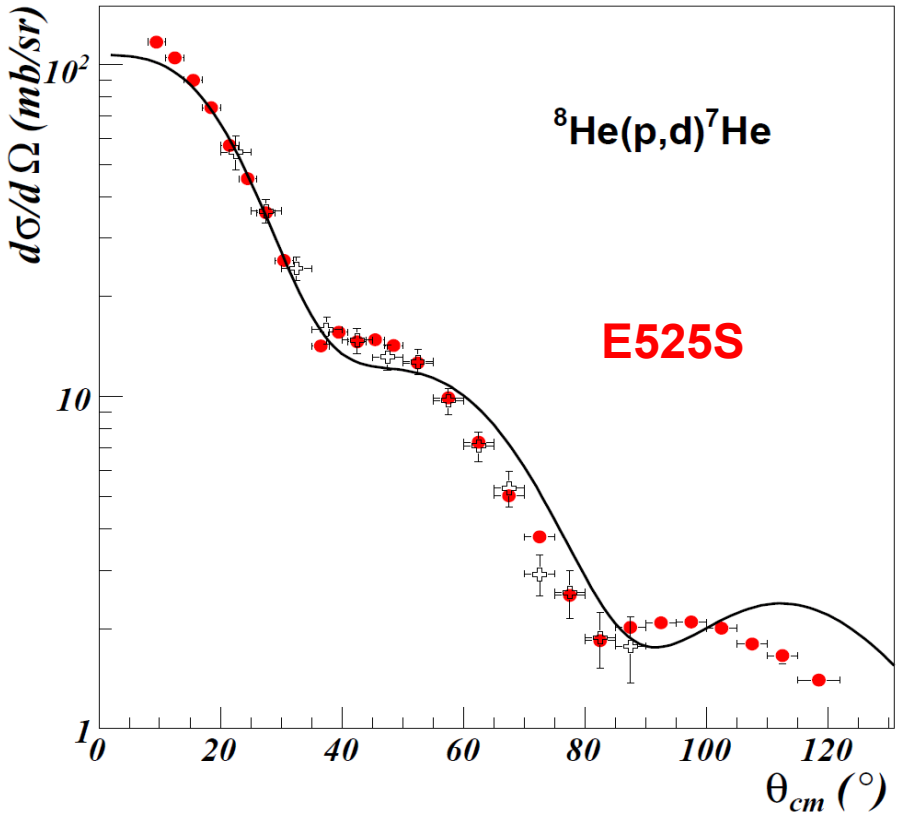
E405S data:
F. Skaza *et al.*, PLB **619**, 82 (2005)

Coupled channel reactions :
Keeley *et al.*, PLB **646**, 222 (2007)

Systematical Errors ~11%

Transfer cross sections to ^{7}He

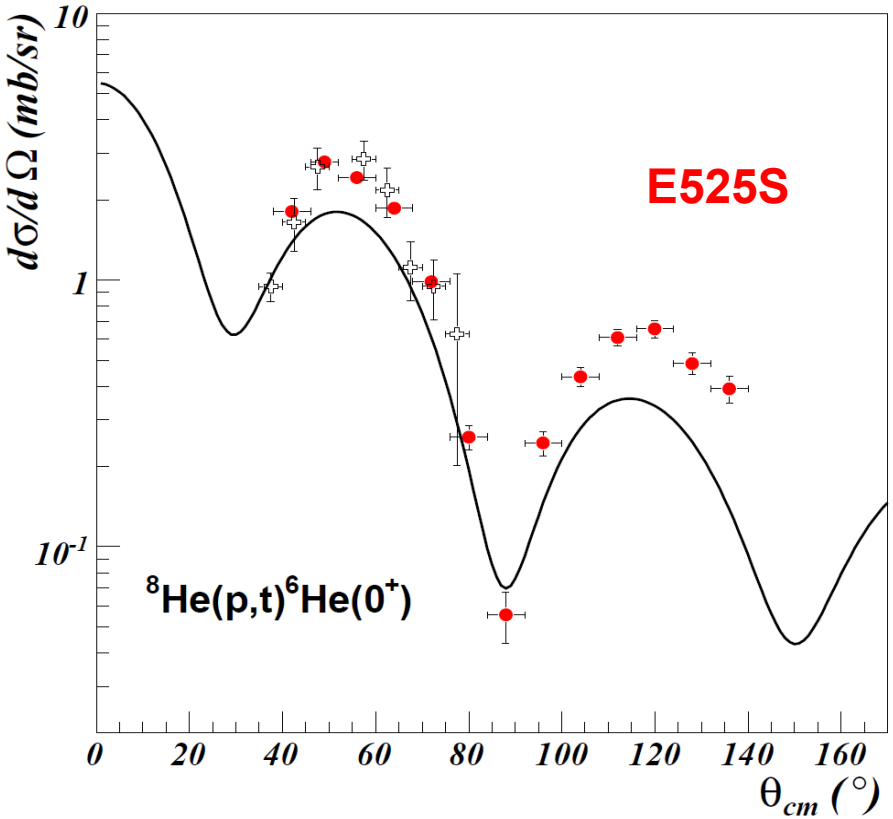
(asymmetric gs resonance)

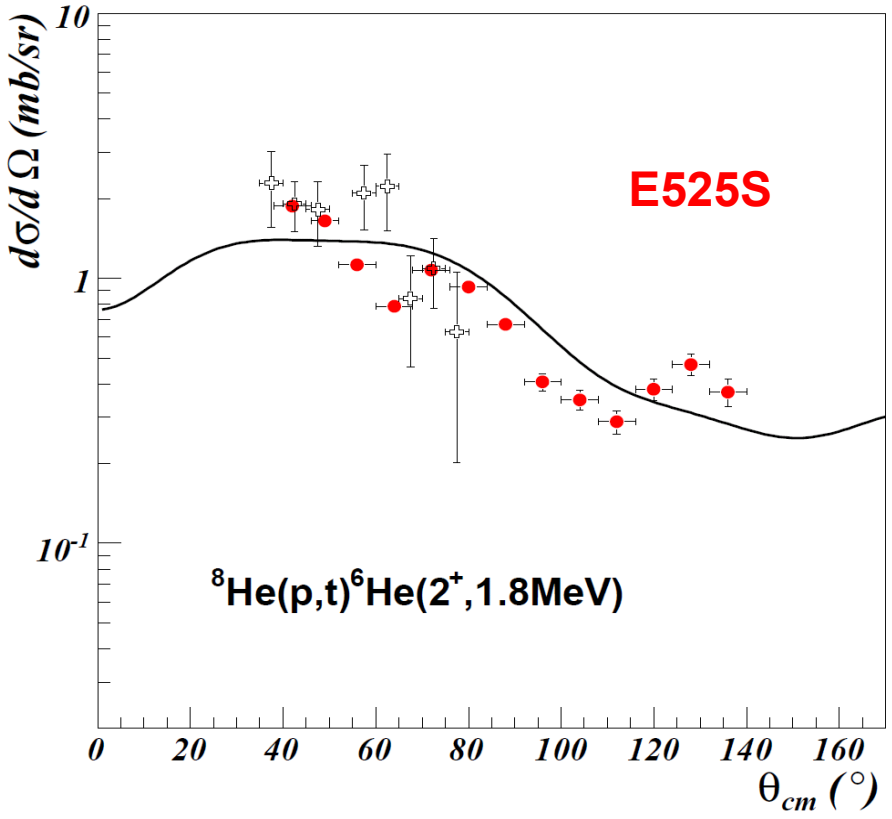


E405S data:
Skaza *et al.*, PRC **73**, 044301 (2006)

Coupled reaction channel analysis :
Keeley *et al.*, PLB **646**, 222 (2007)

Transfer cross sections to ^{6}He

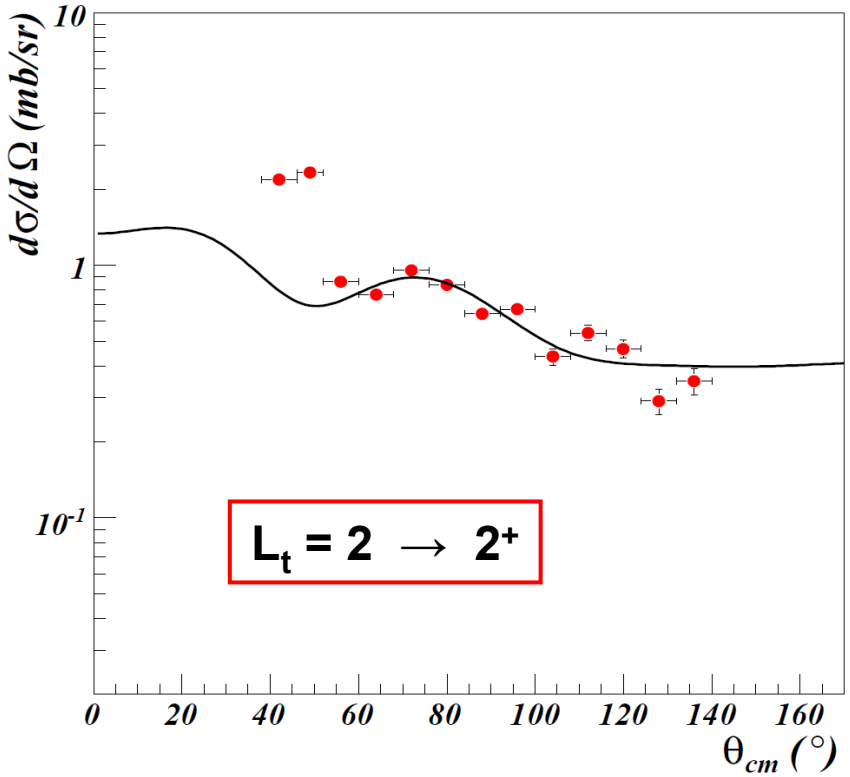




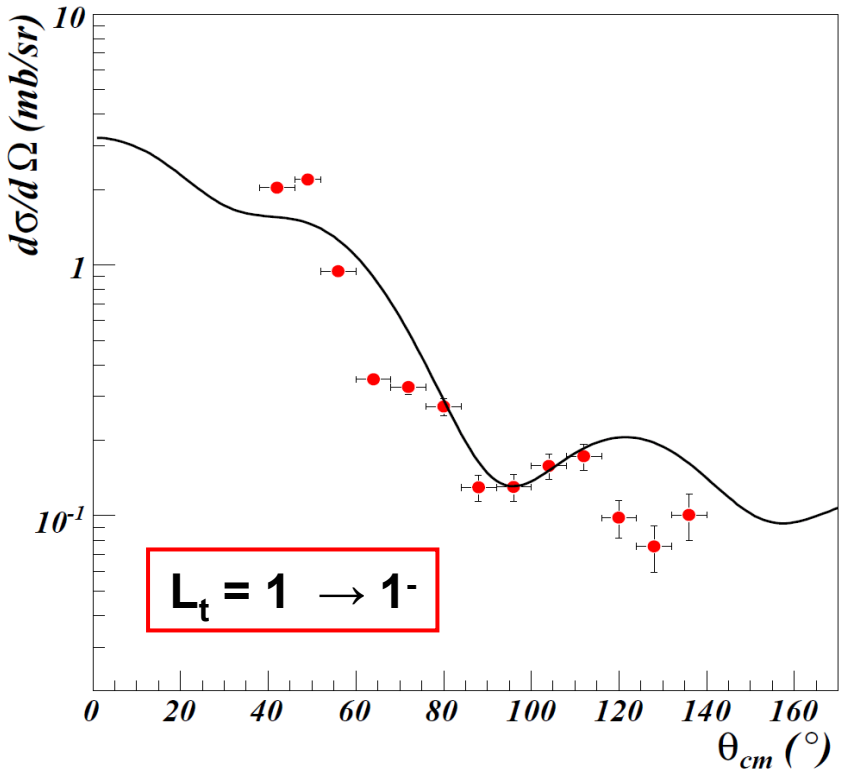
Couled reaction channel analysis and E405S data
in Keeley *et al.*, PLB 646 (2007) 222

Transfer cross sections to ^{6}He

E_{exc} = 2.65 MeV Γ = 1.6 MeV



E_{exc} = 5.3 MeV Γ = 2 MeV



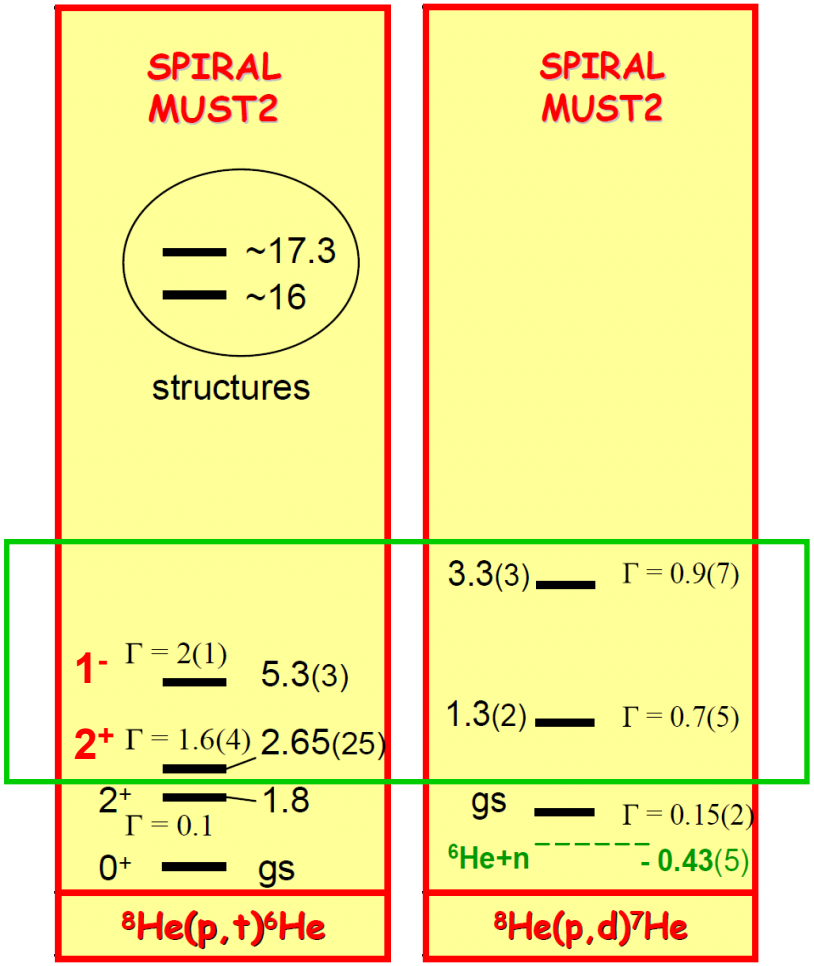
^{8}He + p → t + ^{6}He*

0^+ 0^+ J^π

Calculations : N. Keeley,
A. Soltan Inst. Varsaw

Shape of $d\sigma/d\Omega$ (θ_{cm}) gives L_t

Conclusions

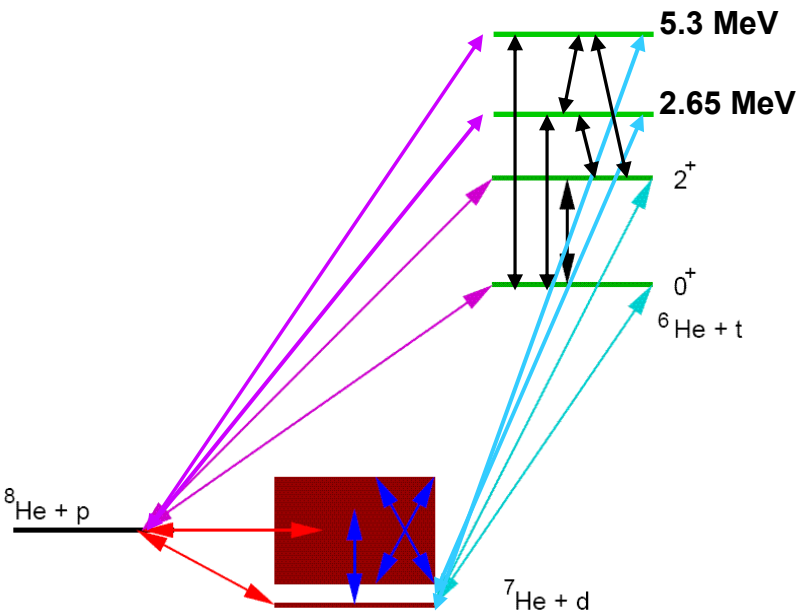


In agreement with recent theories
Effective interaction technics for the Gamow shell model
PRC **71**, 044314 ('05),
G.Hagen, M.Hjorth-Jensen, J.S.Vaagen

→ essential ingredients to explain the spectroscopy: couplings to continuum + effective interactions [ab initio 3 body]

- **Identification of TWO NEW STATES IN ^{6}He**
- **State ~ 1 MeV CONFIRMED IN ^{7}He**

Perspectives



Future: complete CRC analysis of dσ/dΩ data

N. Keeley (Varsaw).et al.
→FRESCO code,
→Using 2 particle form factors

Tools for the spectroscopy of low-lying resonances

via direct nuclear reactions

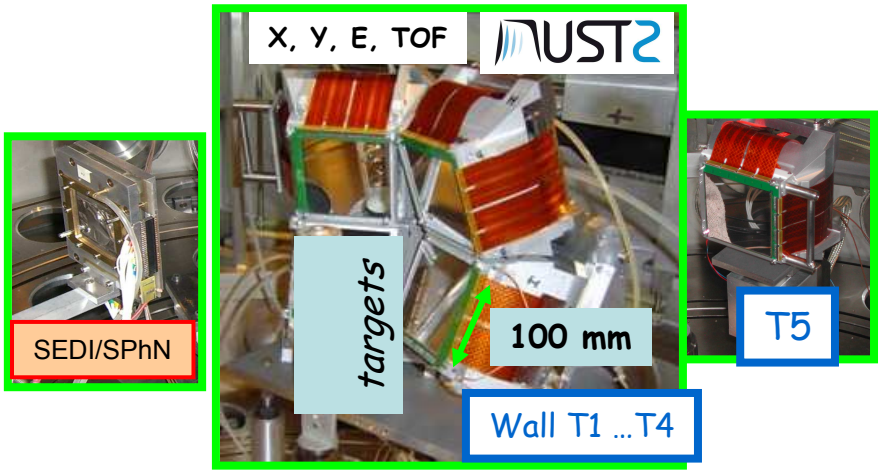
Improved devices for the
light charged particle spectroscopy
Complete measurement of main reaction channels
Access to bound & unbound states

Prototypical experiment for the search of unbound excited states: ^{8}He(p,p) (p,d), (p,t)

POWERFUL TOOLS

SPIRAL beam + MUST2

+ BTD-CATS



Next

Improved reaction framework for the interpretation of the observables:
More realistic form factors in coupled Reaction Channel Analysis ?
coupling to the continuum : unbound states in the exit channel in CDCC ?

Unbound states

Controversy/debate: existence of low-lying states
Ex: ^{7}He

Crucial questions

→ related to how we succeed in understanding the true nature of the resonant states
It challenges our description of the unbound nuclei, our modelling of the nuclear correlations

It deals with: Structure and reactions embedded in the continuum
How to disentangle structure information from reactions effects ?
Sensitivity of the reactions to the resonances ?

How to model the resonances ?
Phase space (few-body kinematics) effects ?
Deformation of the resonances ?

We need to go further :

To develop our knowledge of the transition form factors to resonant states (criteria ?)
To Know how the resonant states are deformed with the continuum coupling
Energy -dependence ? L-dependence ?

E525S collaboration

IRFU - SPhN : N. Alamanos, F. Auger, B. Avez, R. Dayras, A. Drouart, A. Gillibert, V. Lapoux, X. Mougeot (PhD 05-08), L. Nalpas, E. Pollacco, C. Simenel

IPN - Orsay : D. Beaumel, Y. Blumenfeld, J. Guillot, J-A. Scarpaci H. Iwasaki (*Univ Koln*), D. Suzuki (*Univ. of Tokyo*)

GANIL : C. Force, L. Gaudefroy, T. Al Kalanee, W. Mittig, T. Roger, P. Roussel-Chomaz

A. Soltan - Warsaw : N. Keeley, K. Rusek, I. Strojek

FLNR - Dubna : R. Wolski

University of Ioannina : A. Pakou, T. Mermizedakis

Florida State University : K. W. Kemper