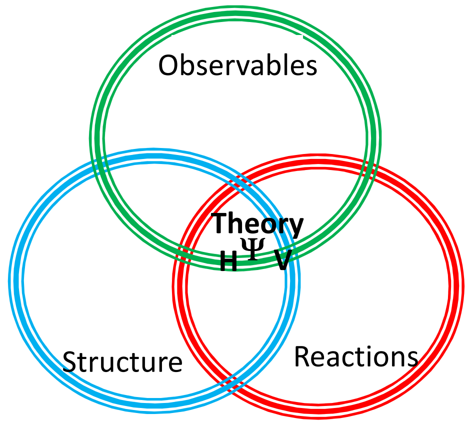
(An experimentalist view) Observables for nuclear reactions

+ Nature exploration & description → **Data set** encoding our (matter) **knowledge**
+ **Parameters** for nuclear interaction potentials, overlaps of wave functions
  →Calculations of (direct) **nuclear reactions**, …
+ Exp-Theory: **constraints** for the modelling of **nuclear interactions**



Reaction Dynamics - Low-energy reactions?
Specific features of colling nuclei? Interaction potentials?

Past present next: https://esnt.cea.fr
Ingredients of nuclear reactions, parameters, models
Objectives: Modelling of nuclear systems and of reaction processes
Better understanding of the nuclear interaction characteristics

2025: https://esnt.cea.fr/Phocea/Page/index.php?id=125
Nuclear pairing; 3D mesh for nuclear dense matter; Symmetry-violating nuclear properties; beta-decay energy spectra; Nuclear distributions ; single-particle energies, …

ESNT 29th June, 2026, Multi-channel reactions of composite nuclei

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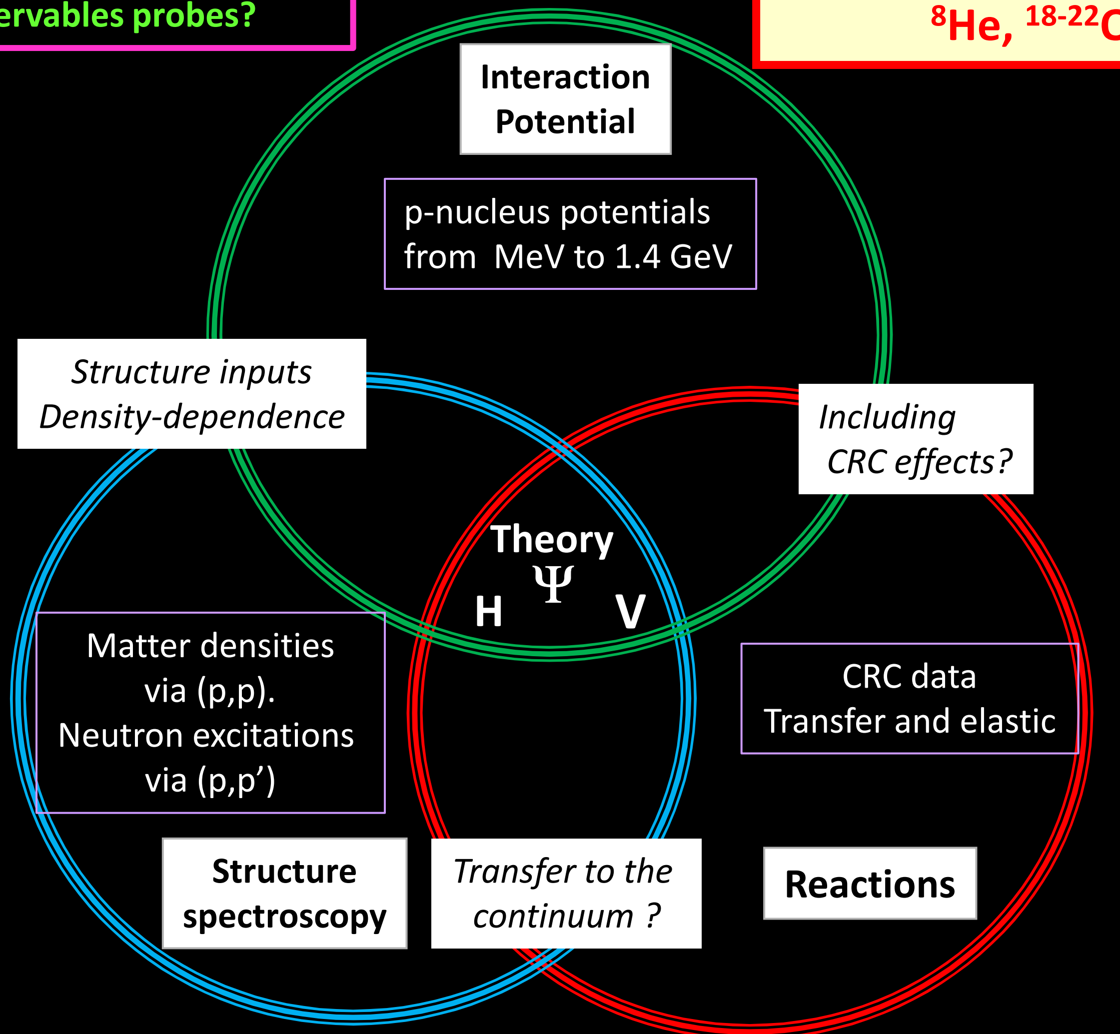
Questions / tools

Motivations
Benchmark of nuclear interactions
How to improve our description?
Relevant observables probes?

Weakly-bound, large asymmetry
→ constraints on the models
Test cases: He and O isotopes
^{8}He, $^{18-22}$O



Relevant observables & probes?

Experiments

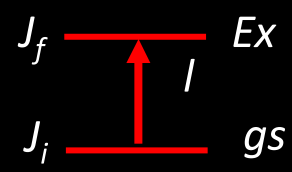
>> combined measurements: nuclear reactions to probe the wave function
>> several energy ranges, basics principle $\lambda = h / p$
>> varying (N,Z) systematics: isotopic/isotonic chains

Transition multipole matrix element M

Interaction field between nucleus and particle probes

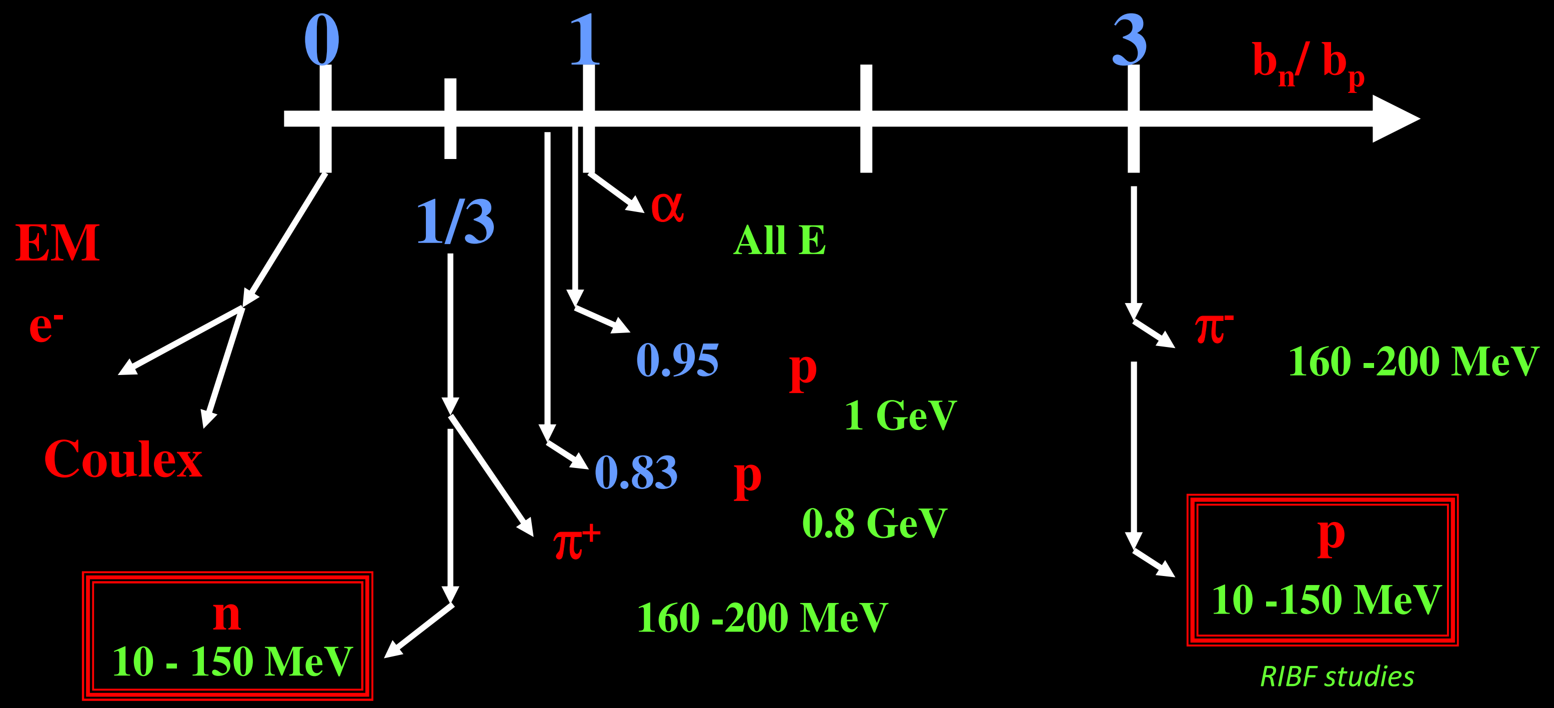
$$M = b_n M_n + b_p M_p$$

$b_{n,p}$ interaction strengths between the external field and n,p of the nucleus*



Phenomenological overview

* bn/bp : A. Bernstein, V. Brown and V. Madsen, PLB 103, 255 (1981)



V.L. EPJA **51**, 91 (2015); *EPJA* **57**, 172 (2021). *Doi: 10.1140/epja/s10050-021-00477-w*

The JLM microscopic nucleon-nucleus optical potential 7Li(p,p)

J.P. **J**eukenne, A. **L**ejeune and C. **M**ahaux,
PRC **16**, 80 (‘77)

Brueckner-Hartree-Fock approximation
and Reid hard core *NN* interaction

$$V(\rho, E) = \sum \alpha_{ij} \rho^i E^{(j-1)}$$

Improved Local Density Approx
(by smearing the potential)

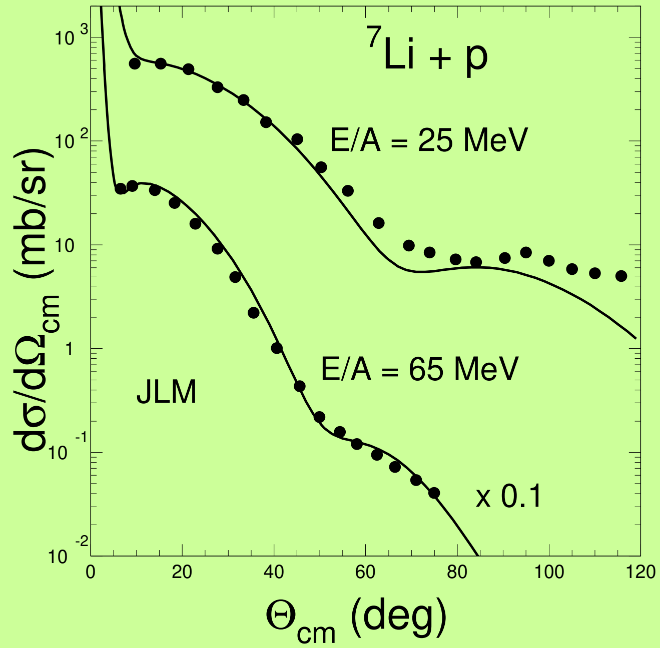
$$U(r, E) = \int V(\rho, E) f(r - \vec{r}\,') d\vec{r}\,'$$

Microscopic complex optical potential
energy and density-dependent
domain of validity : $E_p < 160$ MeV

$$\boxed{U(\rho, E_p) = \lambda_v\, V(\rho, E_p) + i\lambda_w W(\rho, E_p)}$$

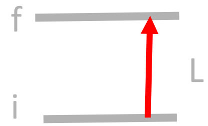
$$\rho : \rho_n\, , \rho_p$$

Light nuclei:
λ_w= **0.8**



JLM calc. for ^{7}Li+p in ref . V. L et al., PLB **517**, 18 (‘01)

The fundamental quantities to be determined experimentally are the multipole transition matrix elements M_p and M_n.



$$M_{p(n)} = < J_f \left\| \sum_{p(n)} r_i^L (\Omega_i) \right\| J_i > \quad \boxed{= \int \rho_{fi}^{p(n)}(r) r^{L+2} dr}$$

$\rho^{p(n)}_{fi} = d\rho_{tr} = <\psi_i \mid \delta \mid \psi_f>$

From Coulex or (e,e ') : B(E2) then Mp

$$\boxed{B(EL; J_i \rightarrow J_f) = (M_p)^2 / (2J_i + 1)}$$

Hadron inelastic scattering measurements are sensitive to M_p and M_n

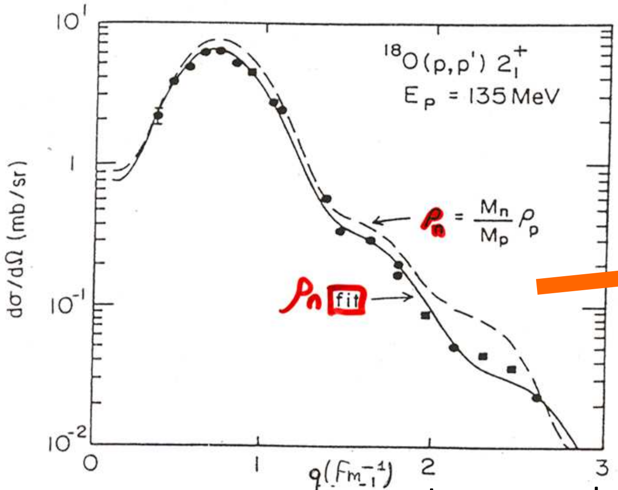
M_n/M_p from (p,p')

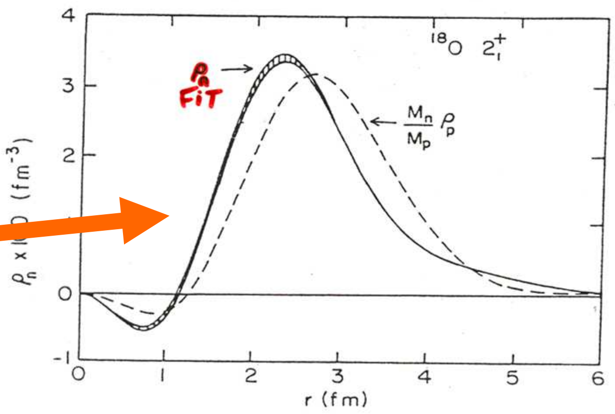
Exp.
Transition density
profiles

$^{18}O(e,e')$

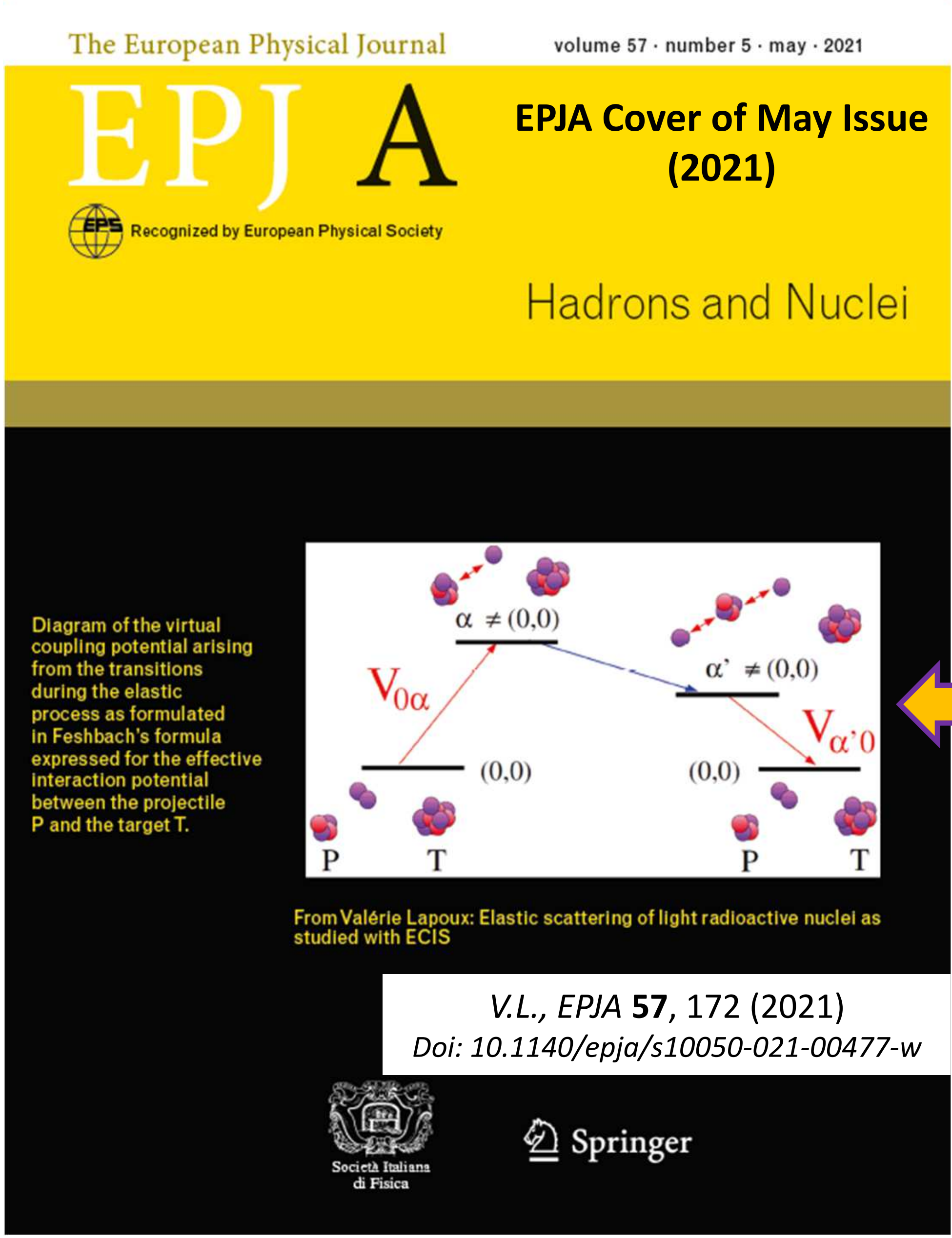
$d\rho^p$

J KELLY PLB 169 (1986) 157





Large angular & transfer momentum domains, statistics



V.L., EPJA **57**, 172 (2021)
Doi: 10.1140/epja/s10050-021-00477-w

Looking back at the textbooks for nuclear reaction theory

→ H. Feshbach, *Ann. Phys.* **5**, *357 (1958)*.
→ *H. Feshbach, Theoretical Nuclear Physics (Wiley, New York, 1992)*

General framework of the nuclear reaction theory by H. FESHBACH

Optical model : $U_E = N_r V_{00} + i W$

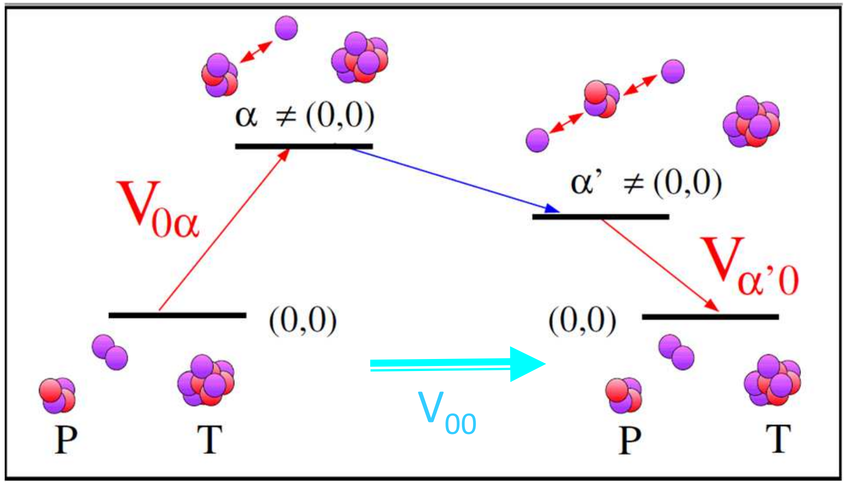
Reproduction of the data with $N_r \sim 1 \Rightarrow$ validity of the model

$N_r < 1 \Rightarrow$ coupling effects

General framework of the nuclear reaction theory by H. FESHBACH

$$U_E = V_{00} + \lim_{\varepsilon \to 0} \sum_{\substack{(\alpha,\alpha') \\ \neq (0,0)}} V_{0\alpha} \left(\frac{1}{E - H + i\varepsilon} \right)_{\alpha\alpha'} V_{\alpha' 0}$$

H. Feshbach, *Ann. Phys.* ***5****, 357 (1958)*. *Theoretical Nuclear Physics (Wiley, New York, 1992)*



Elastic scattering of light radioactive nuclei as studied with ECIS
V.L, EPJA **57**, 172 (2021)

Optical model : $U_E = N_r V_{00} + i W$

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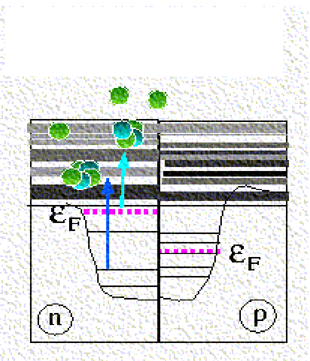
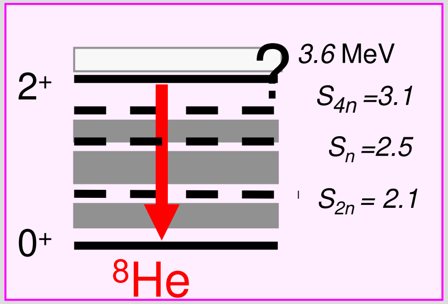
General framework of the nuclear reaction theory by FESHBACH

$$U_E = V_{00} + \lim_{\varepsilon \to 0} \sum_{\substack{(\alpha,\alpha') \\ \neq (0,0)}} V_{0\alpha} \left(\frac{1}{E - H + i\varepsilon} \right)_{\alpha\alpha'} V_{\alpha'0}$$

References +examples: R. Satchler, *Direct reactions* textbook + Y. Sakuragi , PRC 98 ('89) $^{6}Li+^{12}C$, ^{28}Si,...





$^{8}He + p$

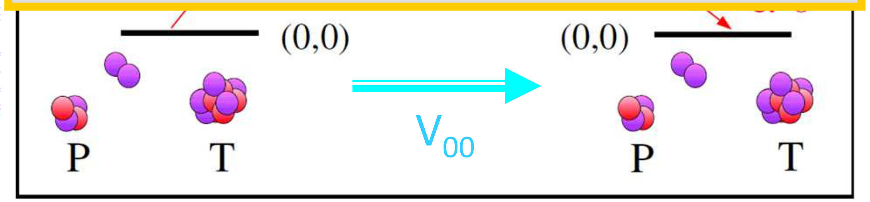
$(p,p)^{8}He$

$(p,p')^{8}He^*$

$(p,d)^{7}He$

(p,t) ...

$U_E = V_{00} + \mathbf{VCP}$



Elastic scattering of light radioactive nuclei

EPJA **57**, 172 (2021)

Previous analysis: coupling effects observed for ^{6,8}He(p,p)

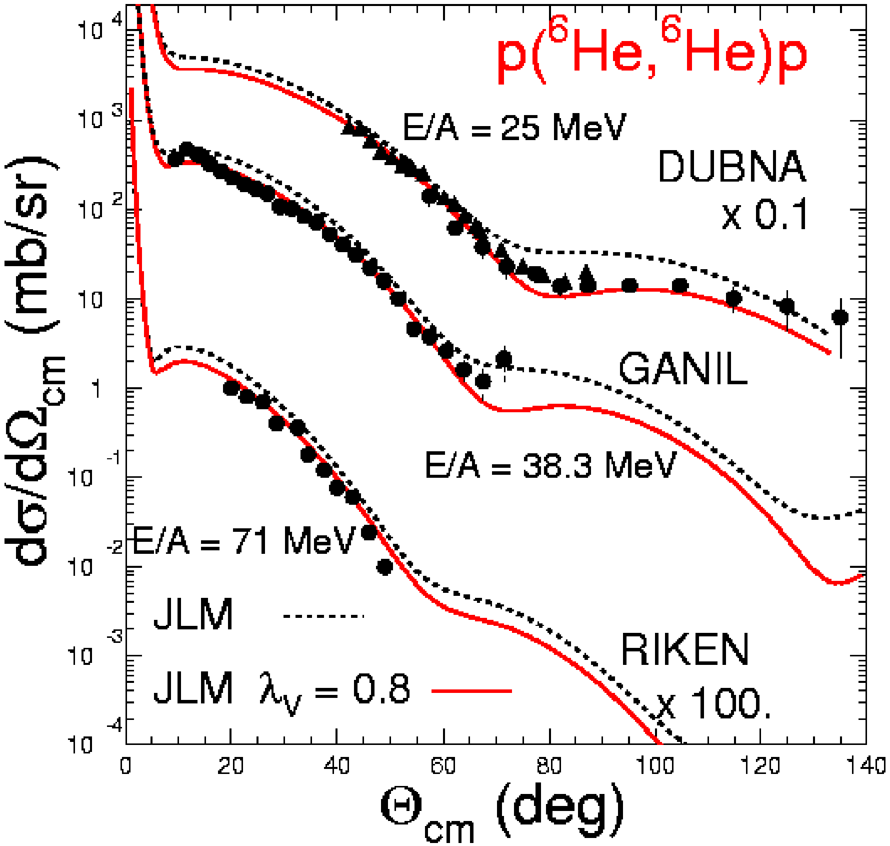
The JLM microscopic nucleon-nucleus optical potential
J.P. Jeukenne, A. Lejeune and C. Mahaux, PRC **16**, 80 ('77)

$$U_{JLM}(^8\mathrm{He+p}) = \lambda_V V + i\,\lambda_W W$$

$\lambda_V = 0.8$; $\lambda_W = 0.8$

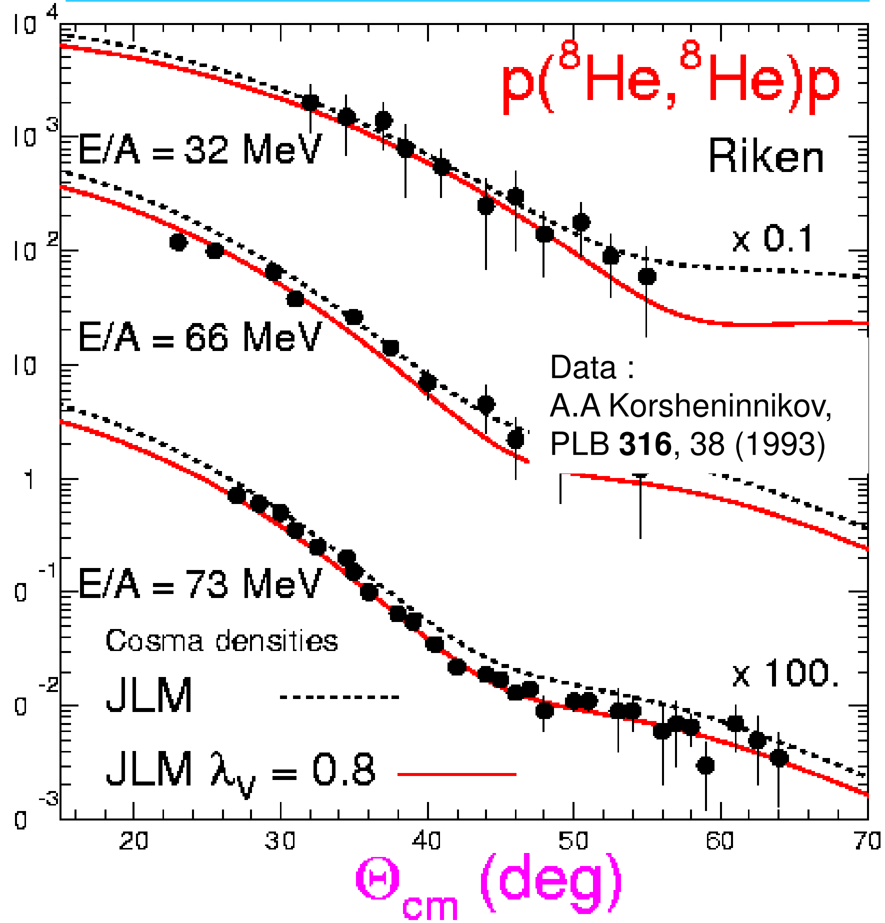
Reduction of the real part: repulsive surface term
(from VCP virtual coupling potential)

GANIL data + JLM analysis:
VLx et al., PLB **517**,18 ('01)



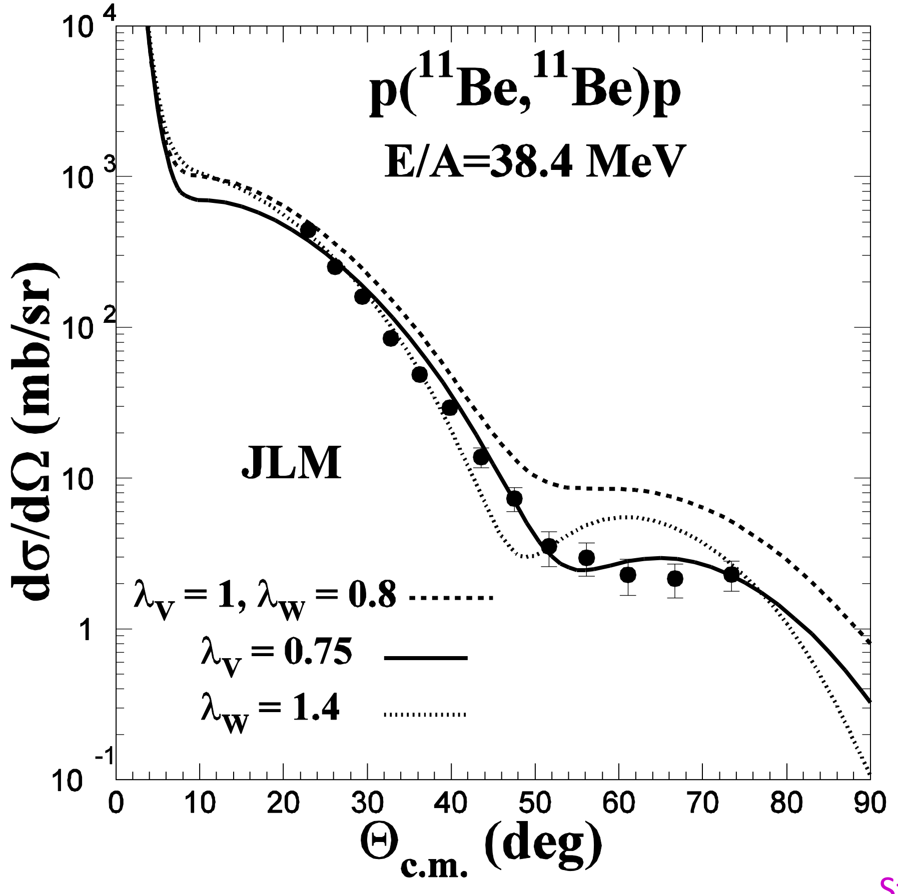
Dubna data :
R. Wolski et al.,
PLB **467**, 8 (1999)

Riken Data : A.A
Korsheninnikov,
NPA**617**, 45 (1997)

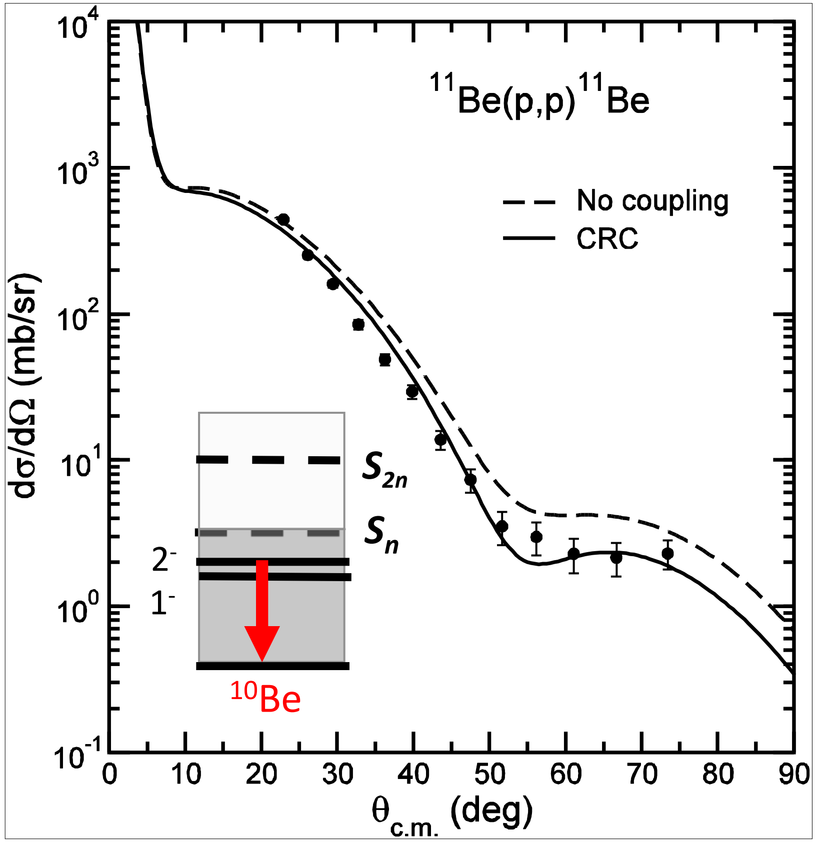


Halo/skin Densities: matter rms 2.5 $\pm$ 0.1 fm

Coupling effects: Due to interplay of different channels? CC to Exc ?
CRC to (p,d)gs? Or (p,d)10Be*?



Data+ Virtual coupling potential
for elastic scattering of ^{10,11}Be on p
in V. Lx *et al.*, PLB **658**, 198 ('08)



Strong pickup-coupling effect on p+^{11}Be elastic scattering
N. Keeley and V. Lx PRC **77**, 014605 ('08)

CRC calc : elastic ^{11}Be+p coupled to the ^{11}Be(p,d)^{10}Be*
pickup to the 5.960 1- & 6.263 MeV 2- doublet in ^{10}Be

Observables of nuclear densities & reactions (via ESNT)

Confrontation experiment-theory *Structure & Reaction dynamics*

Light nuclei / Nuclear structure, spectroscopy, resonances, direct reactions

Complex processes: Fusion /Fission

Reaction Dynamics for low-energy reactions? Fusion?
Complex mechanisms (fusion, fission…) would require understanding of:

+ The specific features of colliding nuclei (impacting interaction potentials) *e.g. halo nuclei*

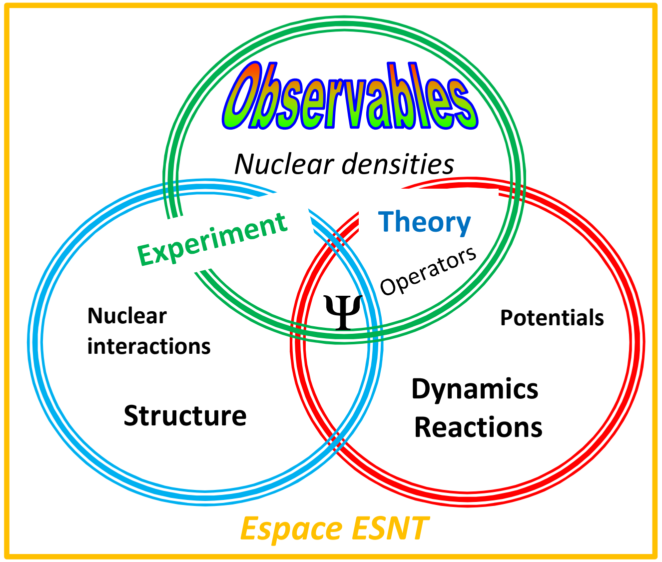
→ *impact on the fusion cross sections due to breakup and transfer channels, possibly enhanced by the halo structure*

→ ***Needs for Nuclear densities, nuclear spectroscopy***

+ Interaction potential (projectile-target) of the entrance channel → ***via the elastic scattering***

+ Coupled reaction channel effects, inelastic, transfer…

→ ***Needs for proton, deuteron, alpha,… scattering off stable and unstable nuclei***



Espace de Structure et de réactions Nucléaires Théorique
ESNT projects (past, present, next) : ***https://esnt.cea.fr***

Observables for nuclear reactions

Examples of low-energy nuclear reaction studies for light halo nuclei: **^{6}He(p,t)^{8}He**

Without entering into the (metallic) details of the experimental detection setup

Experimental observables

Raw data energies, trajectories, incoming/outgoing particle identification
number of interacting particles/produced particles
Relativistic KINEMATICS → missing mass method
→ E(gs), Excitation spectra, cross sections

^{8}He (p,p) ^{8}He -- ^{8}He(p,d) ^{7}He -- **^{8}He(p,t)^{6}He** Coupled Reaction Channel analysis

Benchmark observables for nuclear models from direct reactions of the exotic 6,8He on proton

ESNT workshop 3-6 December 2024 ***https://esnt.cea.fr/Phocea/Page/index.php?id=123***

Light nuclei between single-particle and clustering features

OMP approaches using JLM potential for ^{6,8}He(p,p)

See: ***Nuclear densities combining electron and proton scattering probes***

In ESNT workshop Oct 2025 ***https://esnt.cea.fr/Phocea/Page/index.php?id=131***

Charge and matter distributions in nuclei

V.L. *Elastic scattering of light radioactive nuclei as studied with ECIS*.
Eur. Phys. J. A **57**, 172 (2021). https://doi.org/10.1140/epja/s10050-021-00477-w
V.L *Weakly-bound Borromean structures of the exotic 6,8He nuclei through direct reactions on proton* EPJA **51**, 91 (2015) Doi: *10.1140/epja/i2015-15091-2*

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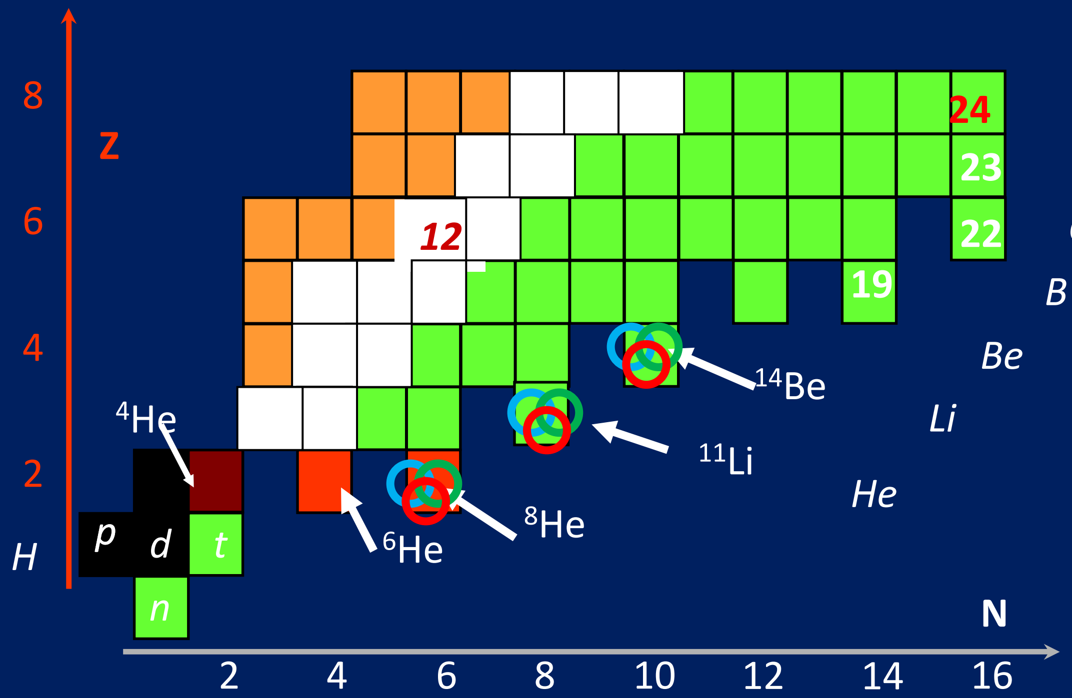
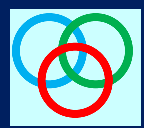
Exotic nuclei: questions & probes



Motivations
Benchmark of nuclear interactions
How to improve our description?
Observables & Relevant probes?



borromean nucleus

Exotic nuclei

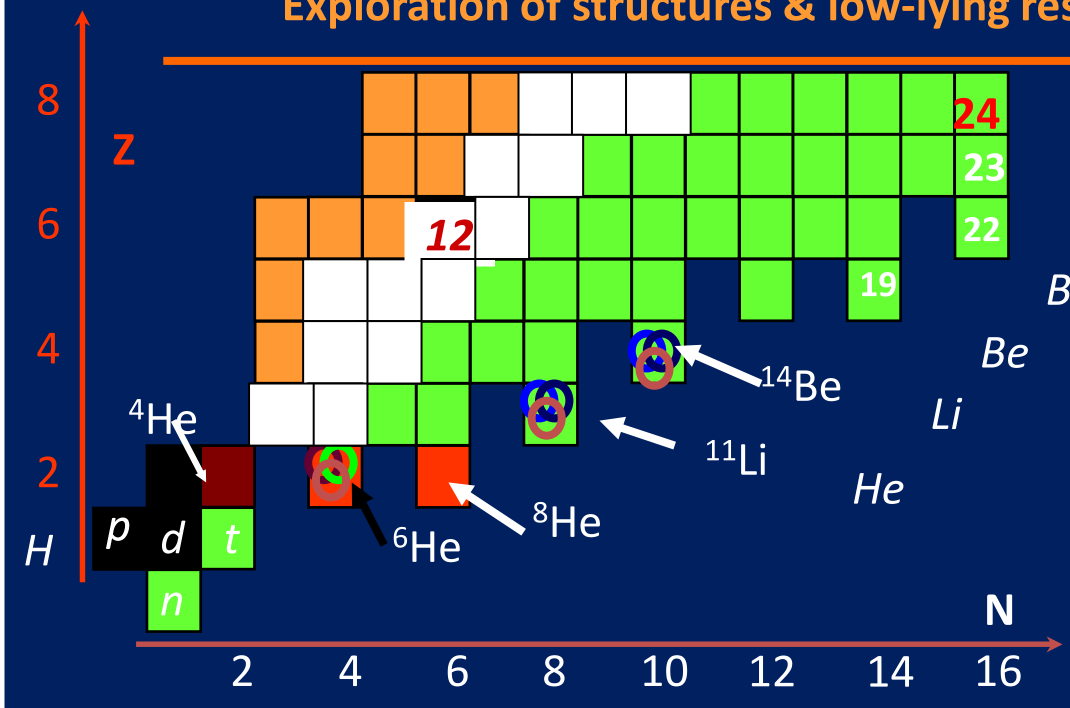
+ Exploration of new phenomena
→ Constraints on nuclear models
+ Evolution of properties with isospin
→ Constraints on interactions

+ Properties in neutron-rich nuclei towards the dripline,
Three-body forces *& continuum:*
binding energy, radii, low-lying (2^{+}) states in even-even

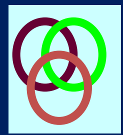
Weakly-bound, large asymmetry
→ Test cases: ^{6,8}**He**

Spectroscopy & Nuclear matter radii
via elastic scattering on proton target

Exploration of structures & low-lying resonances of weakly-bound nuclei



Beyond dripline: nuclei as resonances ~10^{-21}s → n decay



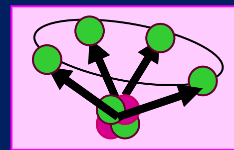
borromean nucleus

Evolution of structure spectroscopy at large isospin?
→ unbound excited states

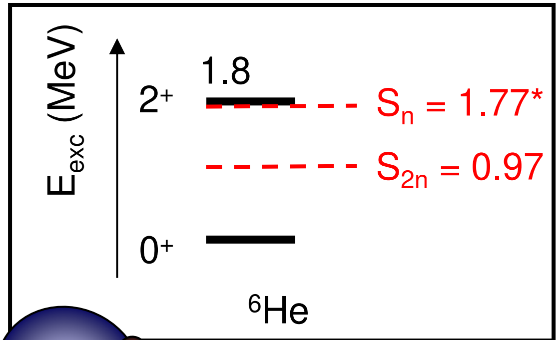
VIA DIRECT REACTIONS
→ simple mechanism & models

BUT …check interplay between coupled (reaction) channel effects

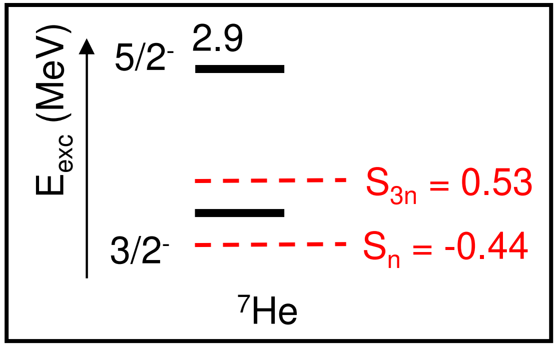
^{8}He N/Z =3
drip-line nucleus



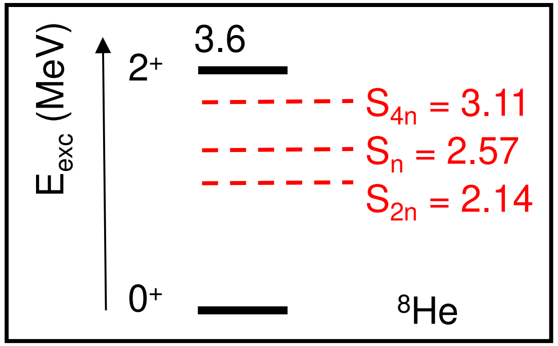
***AME03, 1.8 : AME12**



$T_{1/2}$ =805 ms



unbound



$T_{1/2}$ =119 ms

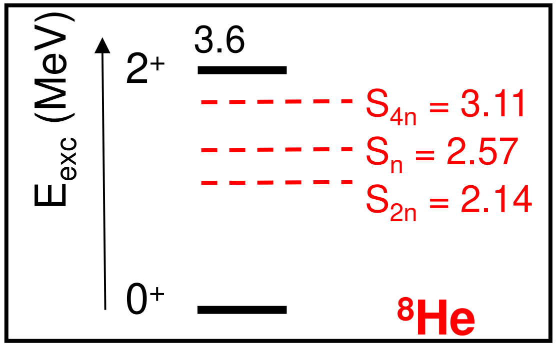
Low-lying resonant states of ^{6}He via the 2 neutron-transfer reaction of ^{8}He on proton

GOALS

Study of weakly-bound nuclei at large asymmetry (N-Z)/A
→ constraints on the nuclear structure models

TEST reaction models, extract new resonant states, Ex, J^{π}, overlap of wf (Spectro.Factors)

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



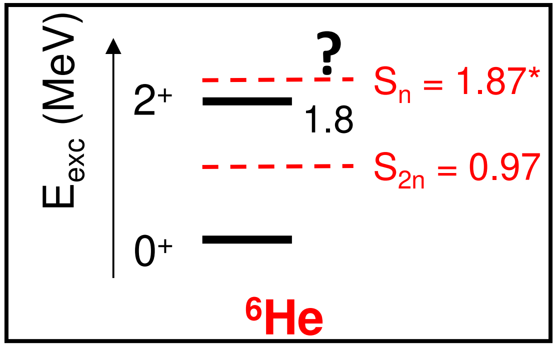
$T_{1/2}$ =119 ms

2 neutron-transfer

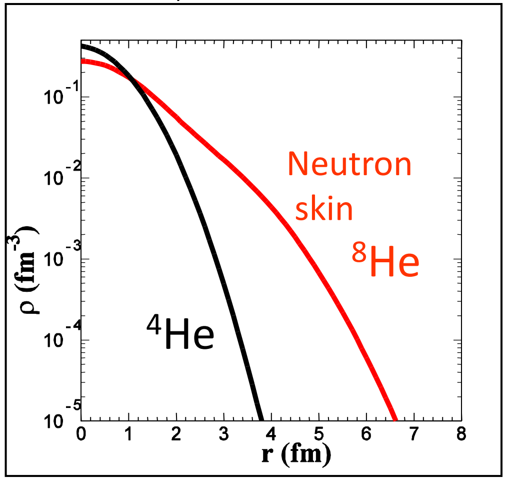
$^{8}He+p \rightarrow {}^{6}He$+triton

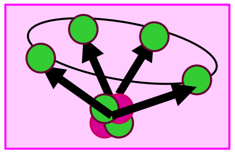
$^{8}He+p \rightarrow {}^{6}He^{*}$+triton
$\rightarrow {}^{4}He+2n+t$

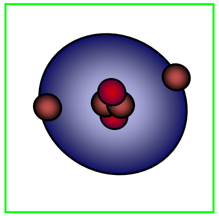
***AME12**

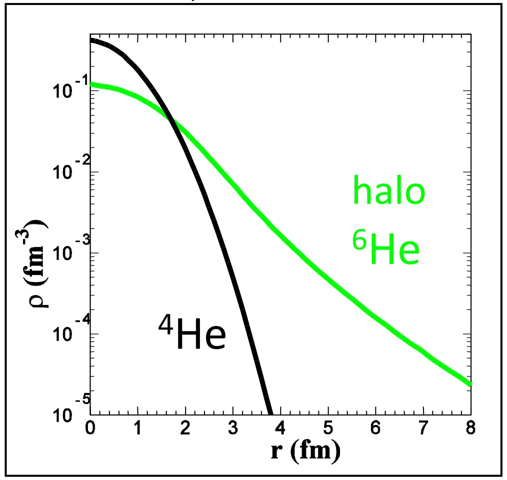


$T_{1/2}$ =805 ms

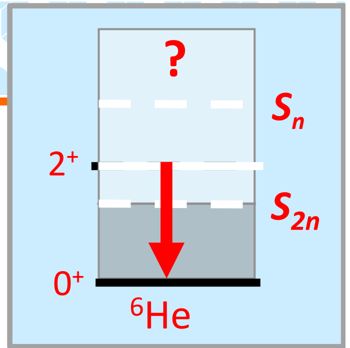








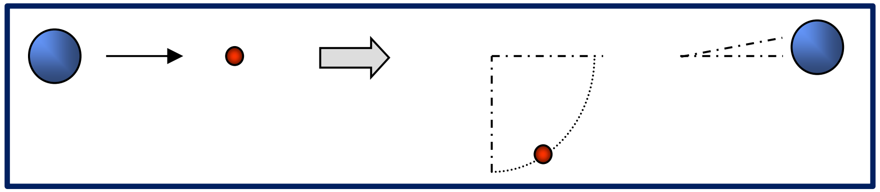
Observables from kinematical reconstruction of direct reactions on proton



Direct reactions with exotic beams: principle and technique

$^8\mathrm{He} + p \rightarrow {}^6\mathrm{He} + t$

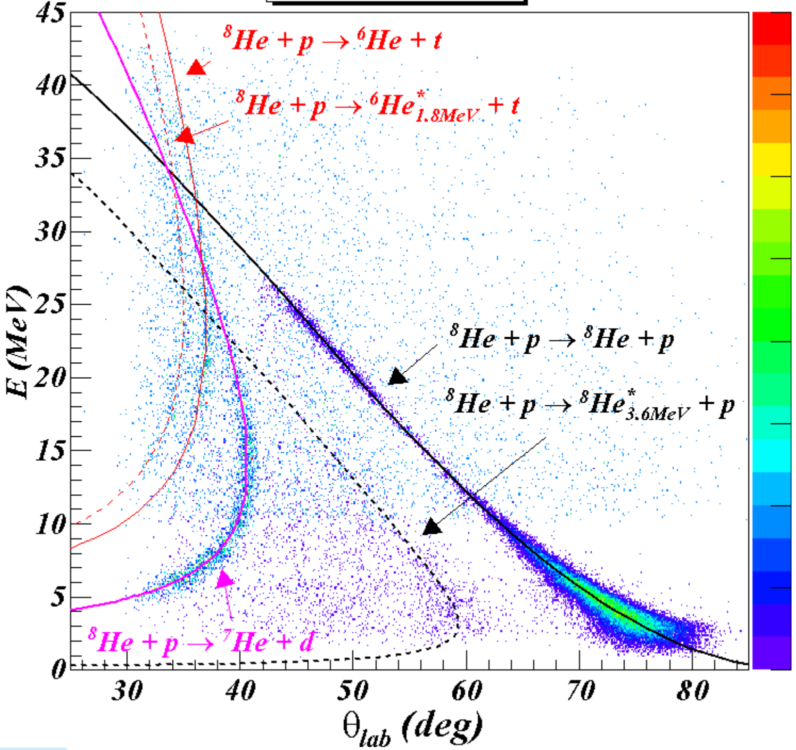
$^8\mathrm{He} + p \rightarrow {}^6\mathrm{He}^* + t$
$\rightarrow {}^4\mathrm{He} + n + n + t$



Kinematics

Reaction energy conservation ; Ex from (Ep, ***p***)
$M_{recoil}\, c^2 = E_0 + 2(p_{inc}\, c^2)(p_p\, c^2)(\cos \Theta_p) - 2T_p(E_{inc} + m_p c^2)$
$E_{ex} = M_{recoil}\, c^2 - E_0$

$^8He + p$



Kinematical reconstruction ^{8}He(p,t)^{6}He*

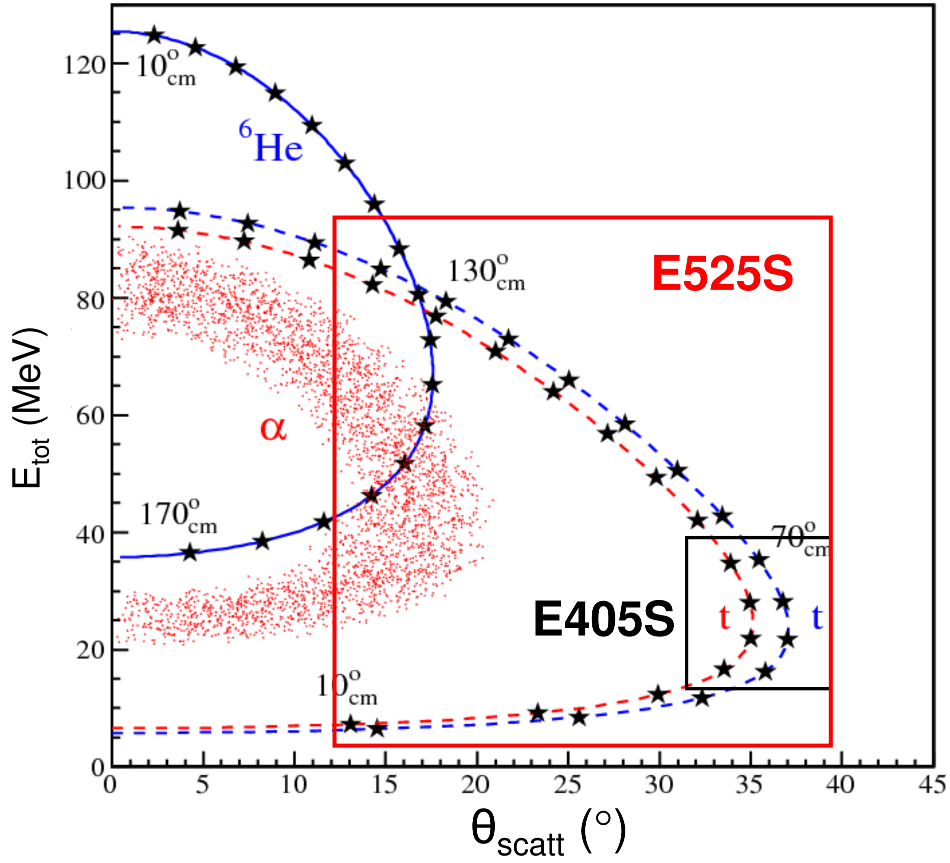
Spectra E_x +dσ/dΩ

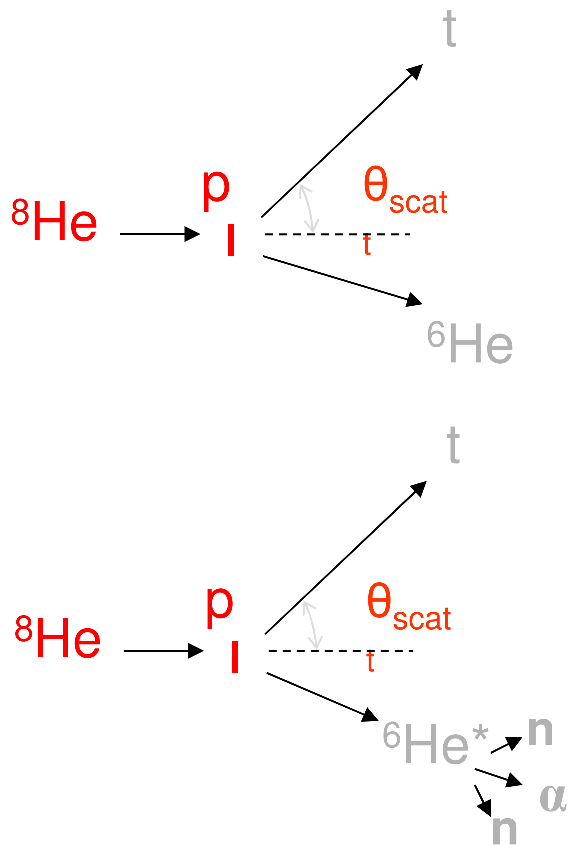
Missing mass method
Coincidence (ejectile +p) >> Signature of reaction
Ex (^{6}He) from (***p***, E) of proton

MUST2
X,Y, E,TOF
identification
E_{tot}, θ

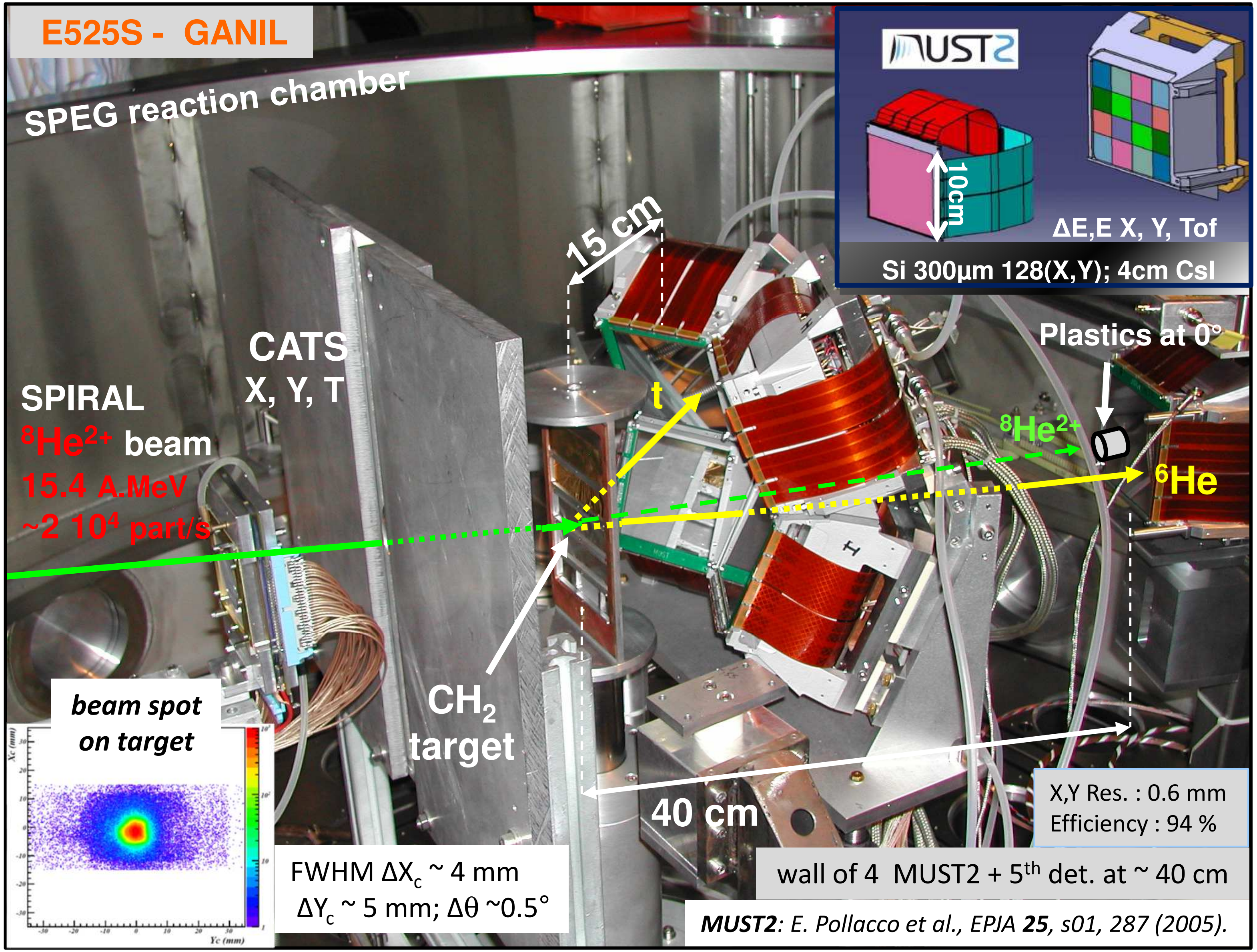
Beam tracking **CATS**
impact on target; θ_{inc}

Experimental method-kinematics





(E,x,y,t) + identification of all particles ⇨ Kinematics (E_{tot},θ_{scatt}) $\underset{\text{mass}}{\overset{\text{missing}}{⇨}}$ Spectra E_{exc} + $d\sigma/d\Omega$

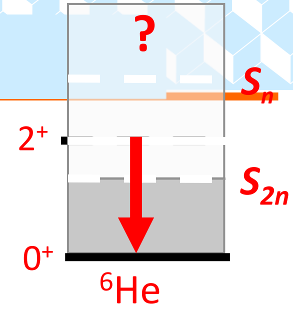


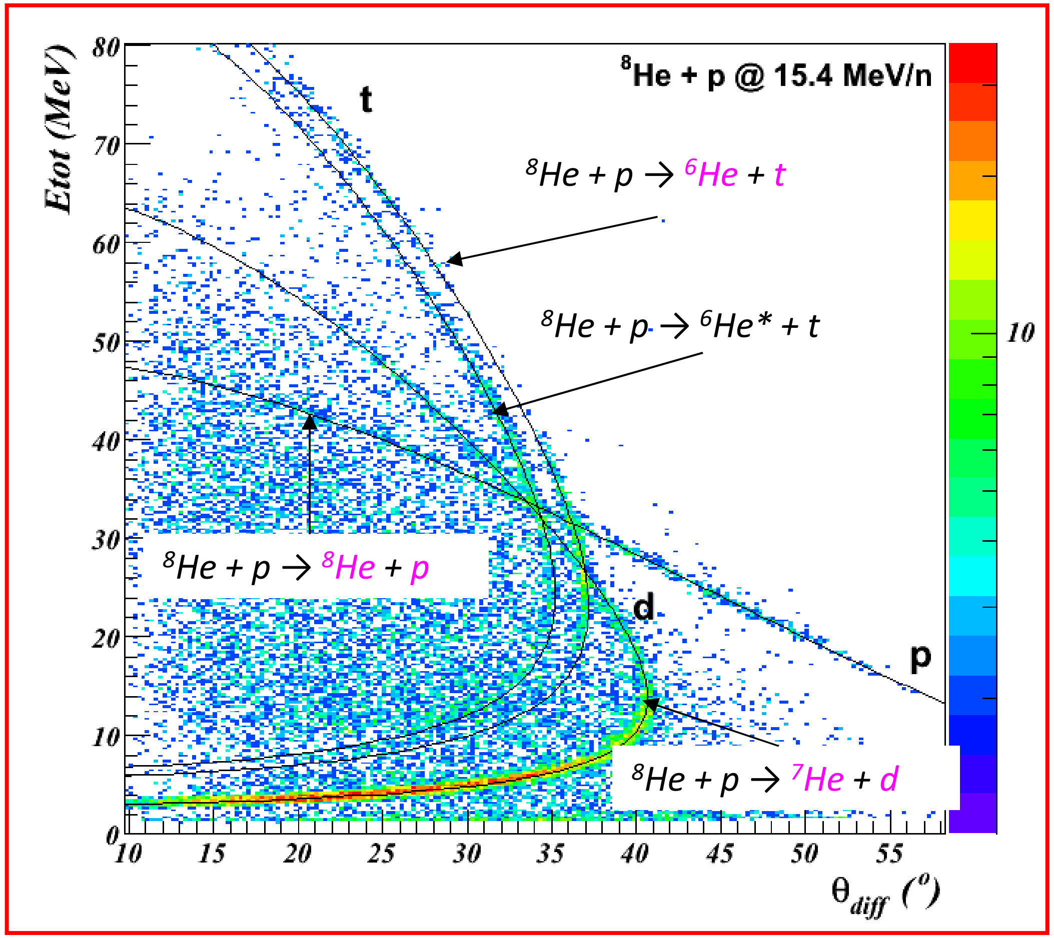
MUST2: E. Pollacco et al., EPJA ***25****, s01, 287 (2005).*

Observables from kinematical reconstruction of direct reactions on proton

Reactions, Ex Kinematics

$^{8}He(p,t)^{6}He^{*}$





$^{8}He + p \rightarrow {}^{6}He + t$

$^{8}He + p \rightarrow {}^{6}He^{*} + t$
$\rightarrow {}^{4}He + n + n + t$

6He

$^{8}He + p \rightarrow {}^{7}He + d$

$^{8}He + p \rightarrow {}^{6}He + n + d$
$\rightarrow {}^{4}He + 3n + d$

7He

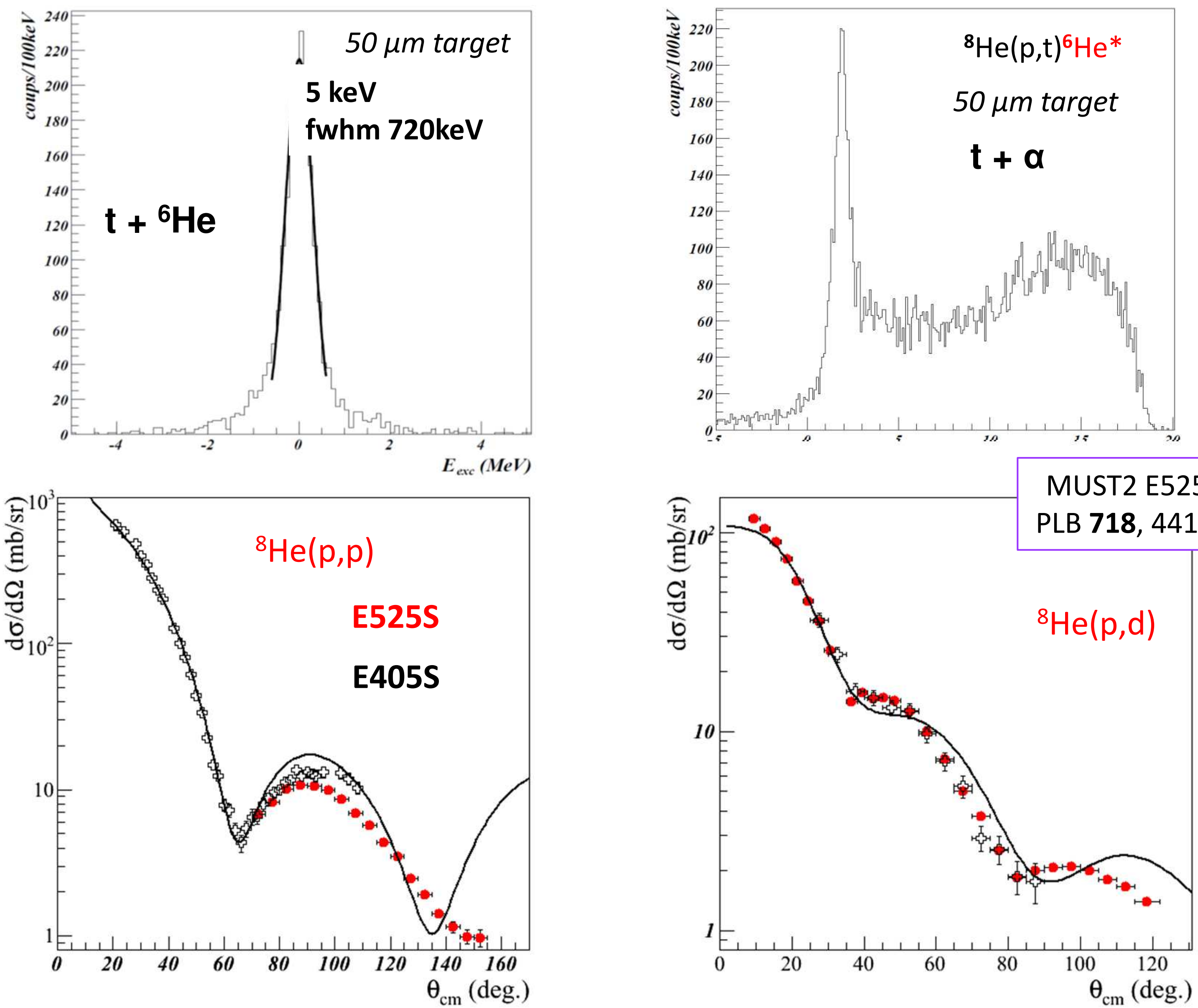
Missing mass method
Signature of reaction
Coincidence (ejectile +p)
Eexc (^{6}He) from (***p***, E) of proton

Spectra $E_x + d\sigma/d\Omega$

$\Delta E^{*} \sim$ 400-750 keV

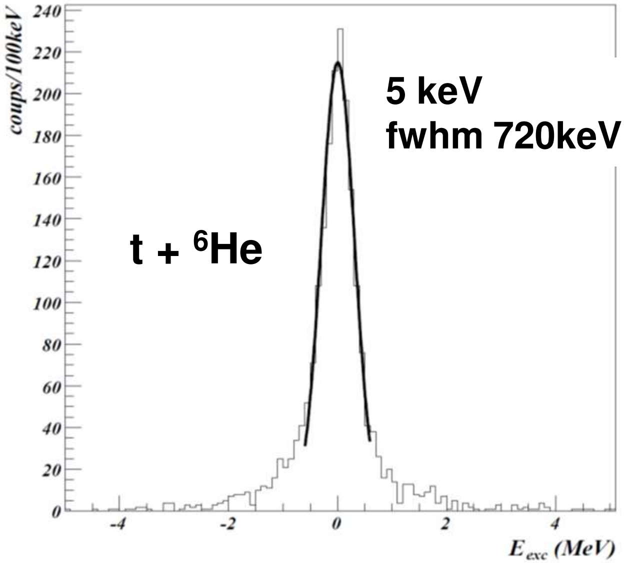
Precision on the ^{6}He gs position: 5-10 keV
Energy resolution: 720 keV with a 50 µm (4.48mg/cm²) CH_2 target

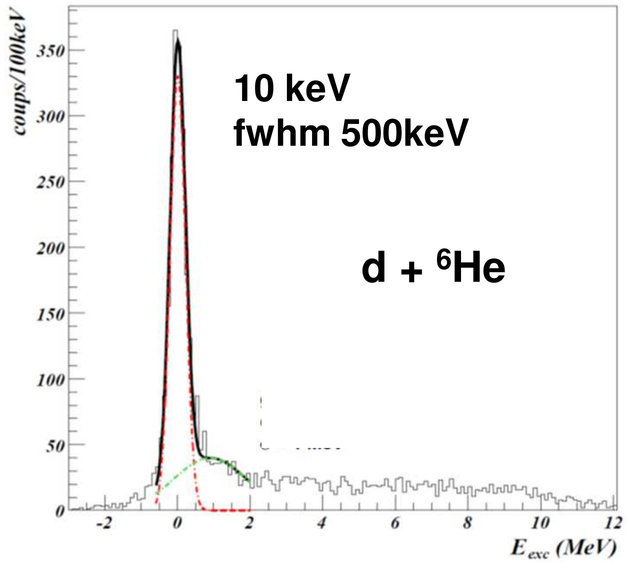
Excitation energy spectra with particle coincidences

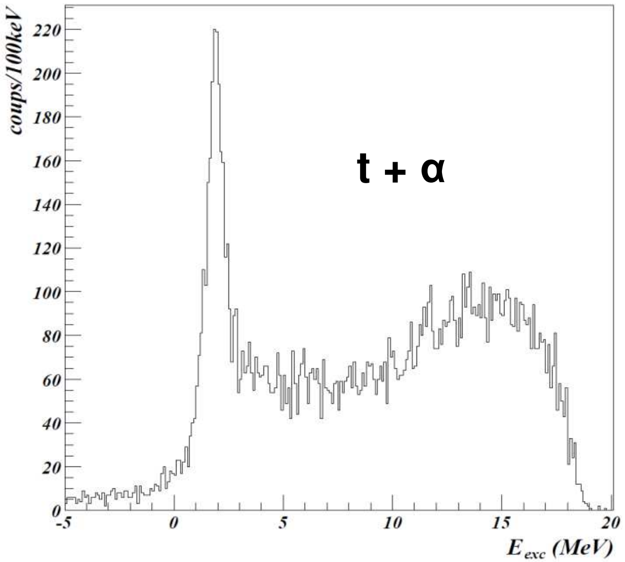


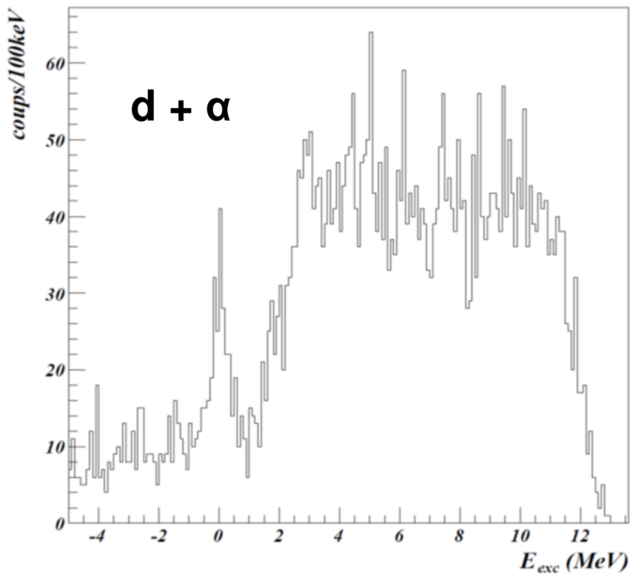
MUST2 E525S data
PLB **718**, 441 (2012).

Excitation energy spectra with particle coincidences



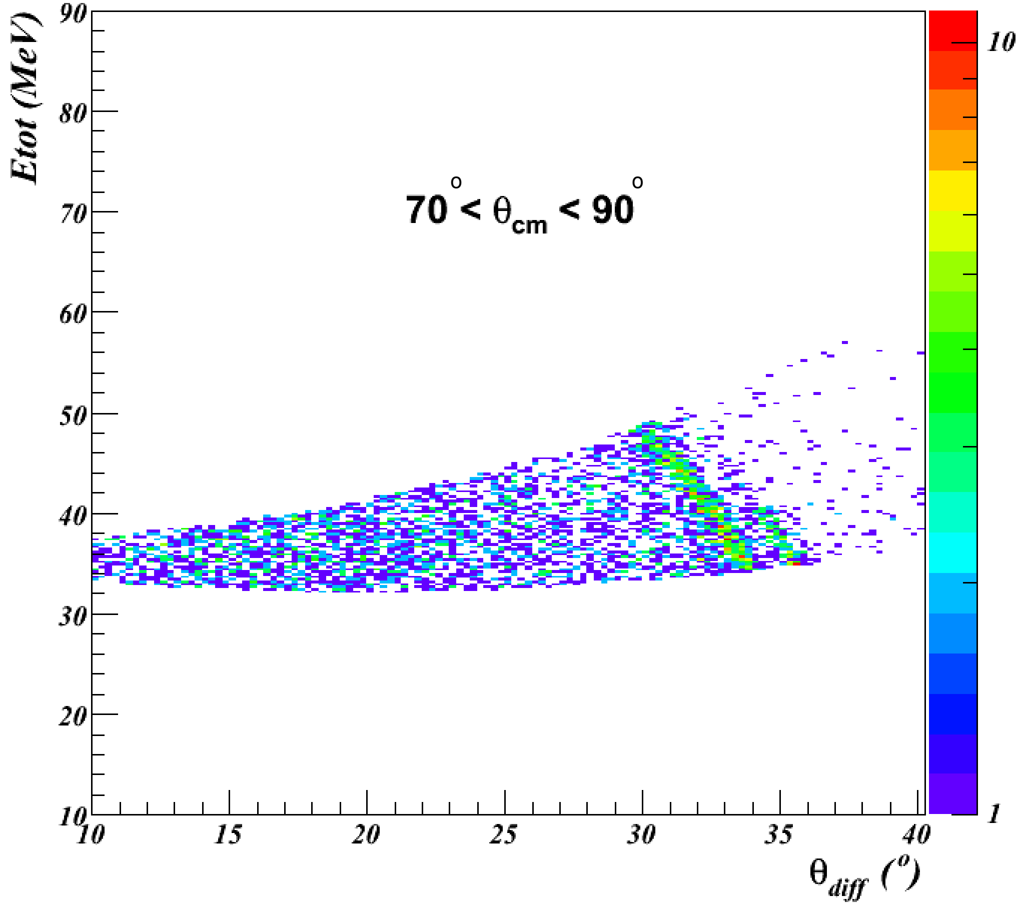


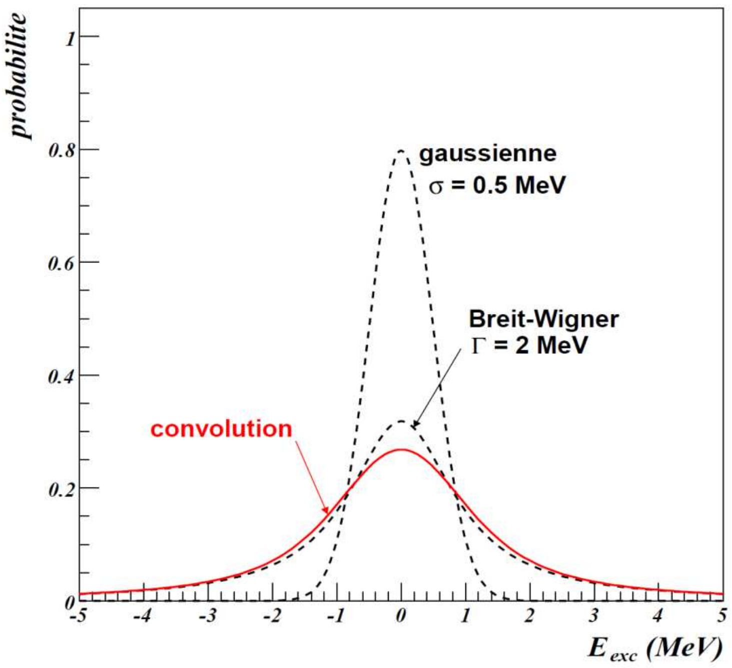




All data on the 50 µm target

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 excitation spectra of ^{6}He: searching for resonances

1st step: estimation of the physical background:

few-body kinematics in exit channel, alpha+n+n background ; reactions producing alpha +triton coincidences (due to the Carbon content of the target)

2nd step: subtraction of the physical background to locate the possible resonances

modeling including the effect of the experimental resolution:

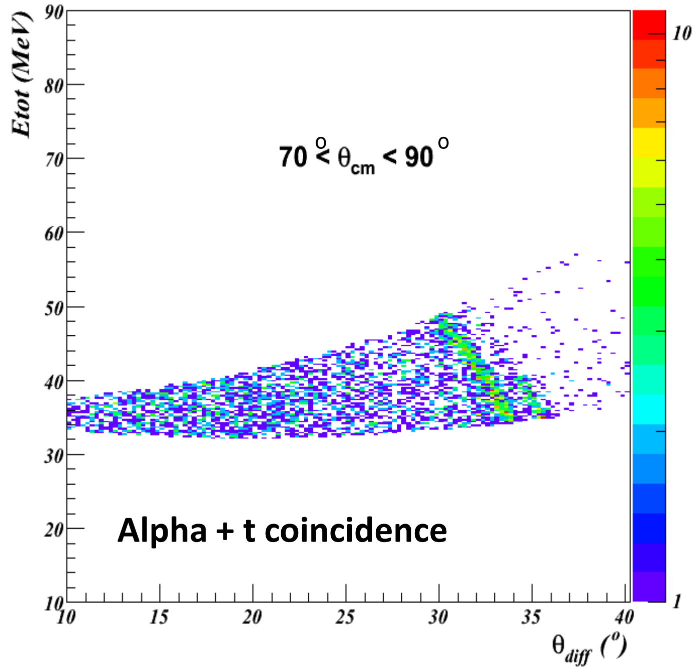
Breit-Wigner folded with a Gaussian function

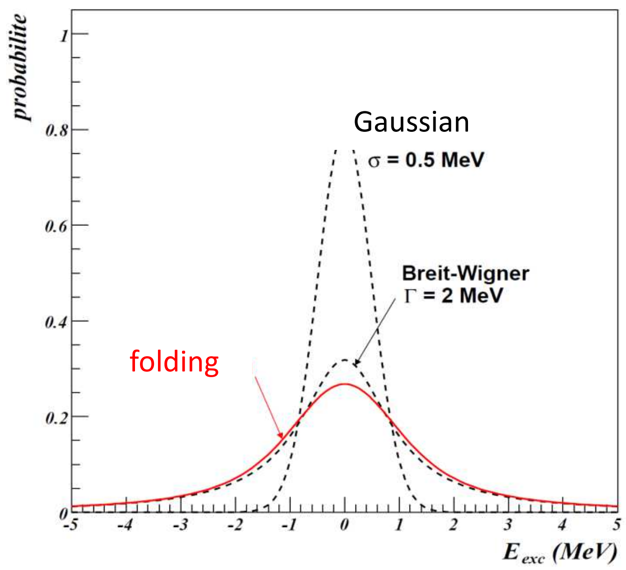
→ resonance fixed 2+ at 1.8 MeV (width Γ = 113keV) + 2 structures fixed at 15 MeV

→ 3 structures (possible resonances) are observed

3rd step: existence of the res. is checked on the total spectra for a series of slices in c.m. angles: 2.65 (Γ = 1.6) ; 5.3 (Γ = 2) MeV conserved ;

8.55 (Γ = 0.8) MeV structure not conserved



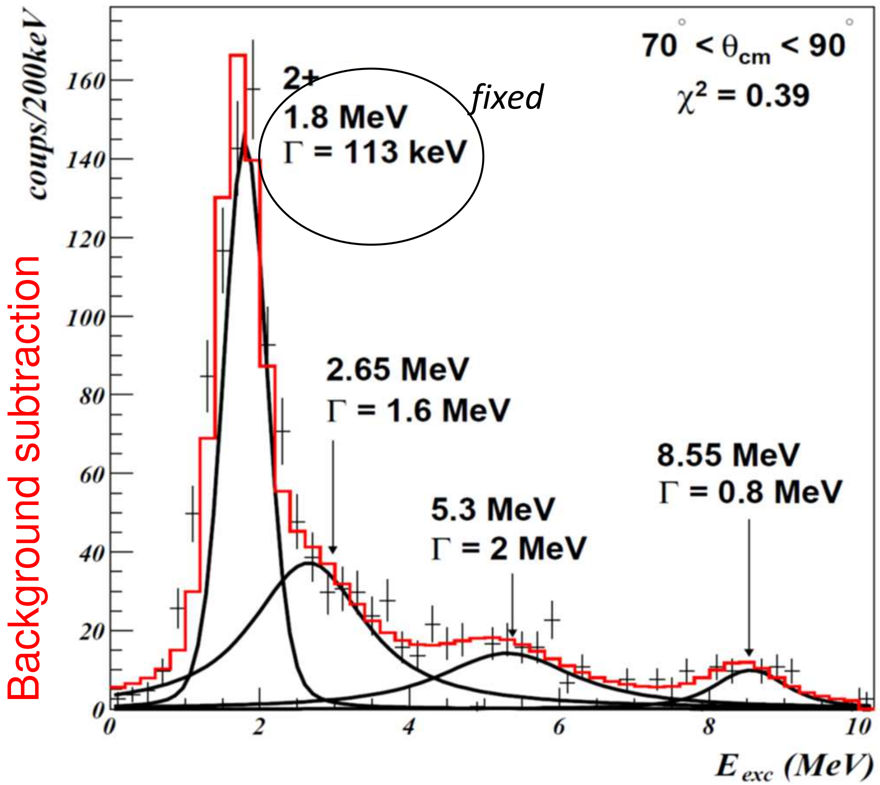


Analysis of the ^{6}He spectra: resonances

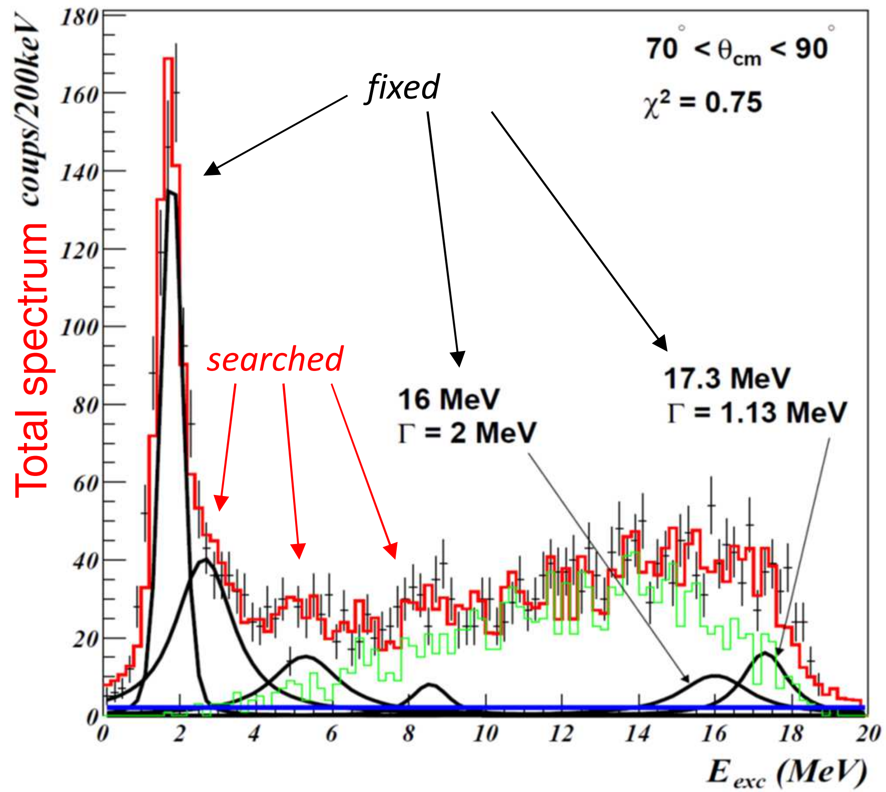
Sources of physical background
Few-body kinematics in exit channel → Alpha+n+n background
C content in target → possible reactions producing alpha in coinc with t

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

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

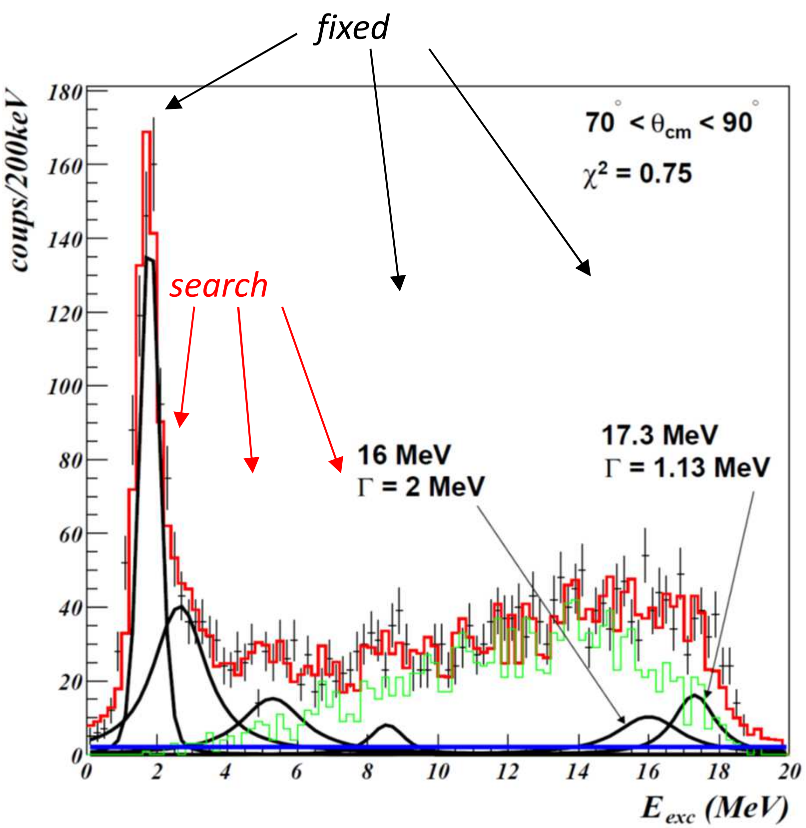


χ^2 between 0 and 10 MeV

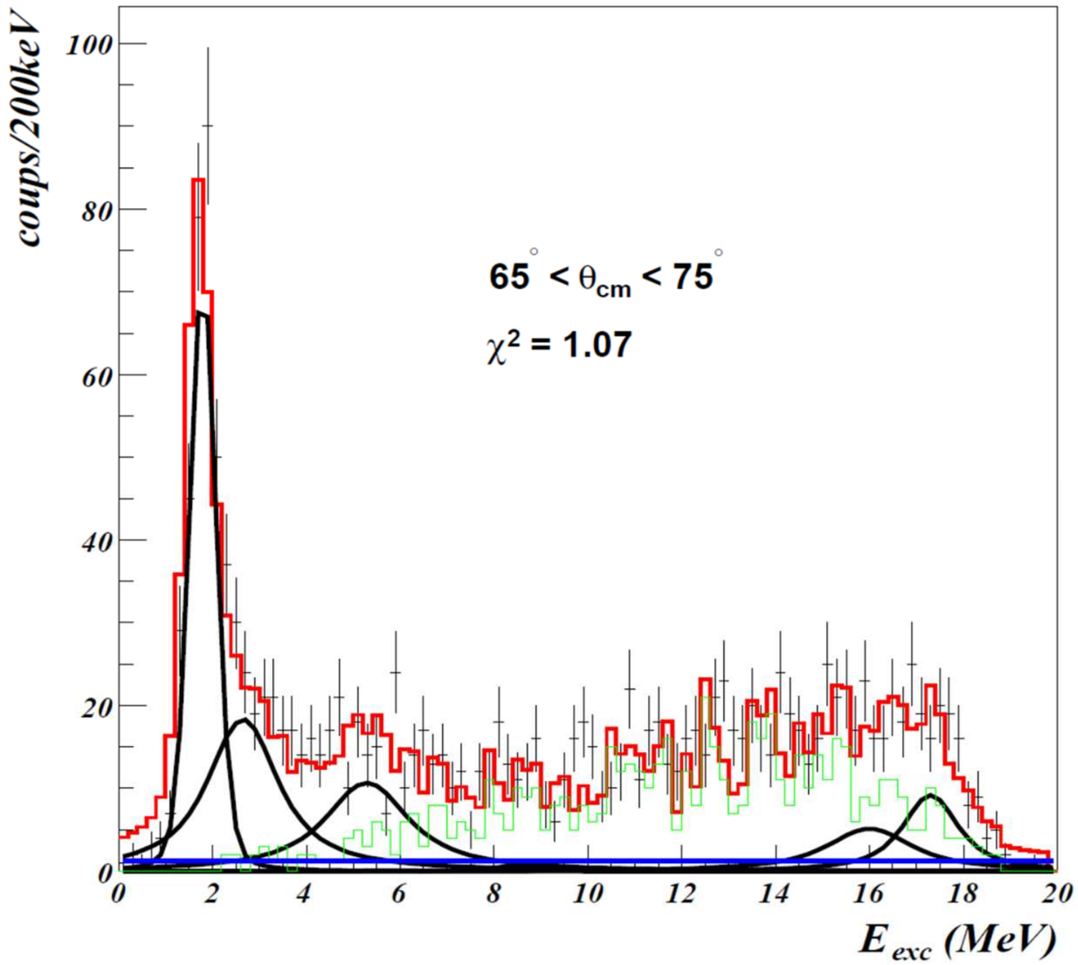


χ^2 between 0 and 20 MeV

→*Operations done for all Ex spectra [for various slices/gates on c.m. angles in the kinematics]*

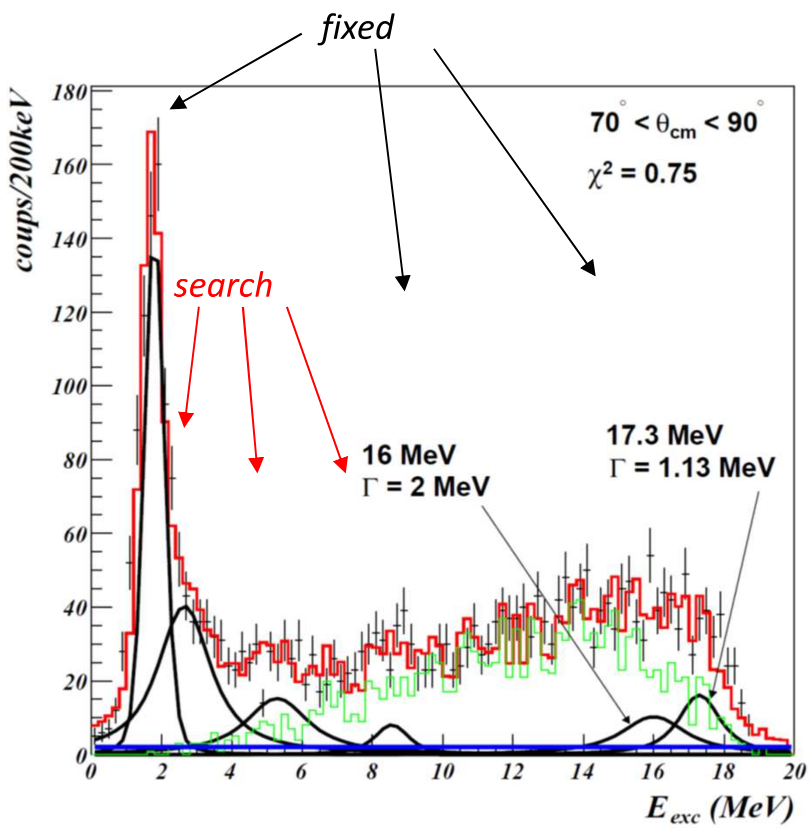


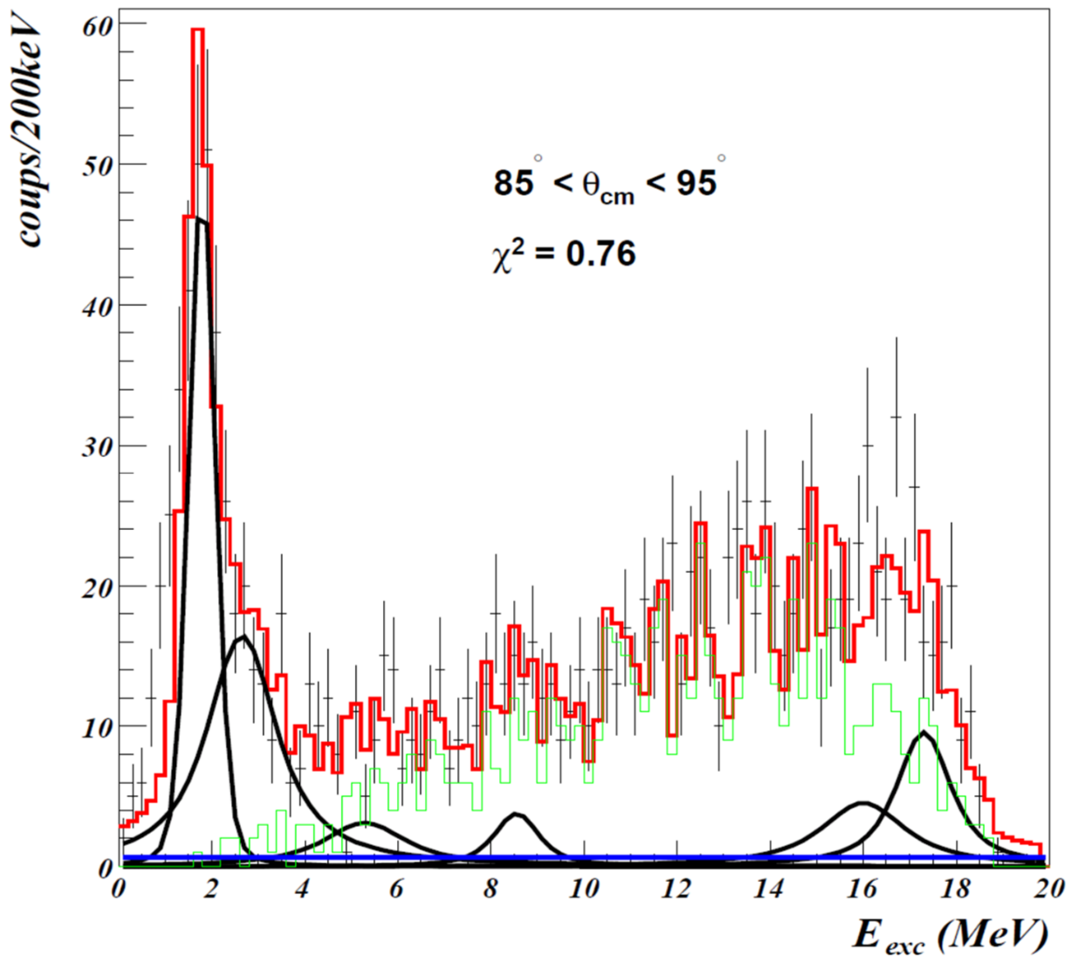
3rd step : checking,
the resonance parameters must be the same within error bars for the various gates on the c.m angles



→ *Operations done for all Ex spectra [for various slices/gates on c.m. angles in the kinematics]*

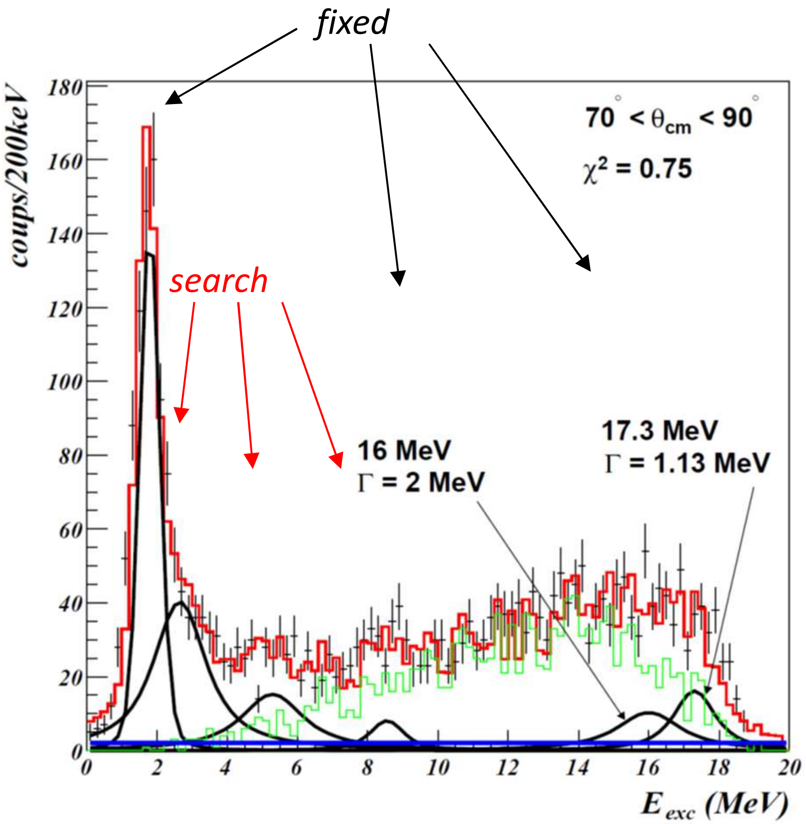
3rd step : checking,
the resonance parameters must be the same within error bars for the various gates on the c.m angles



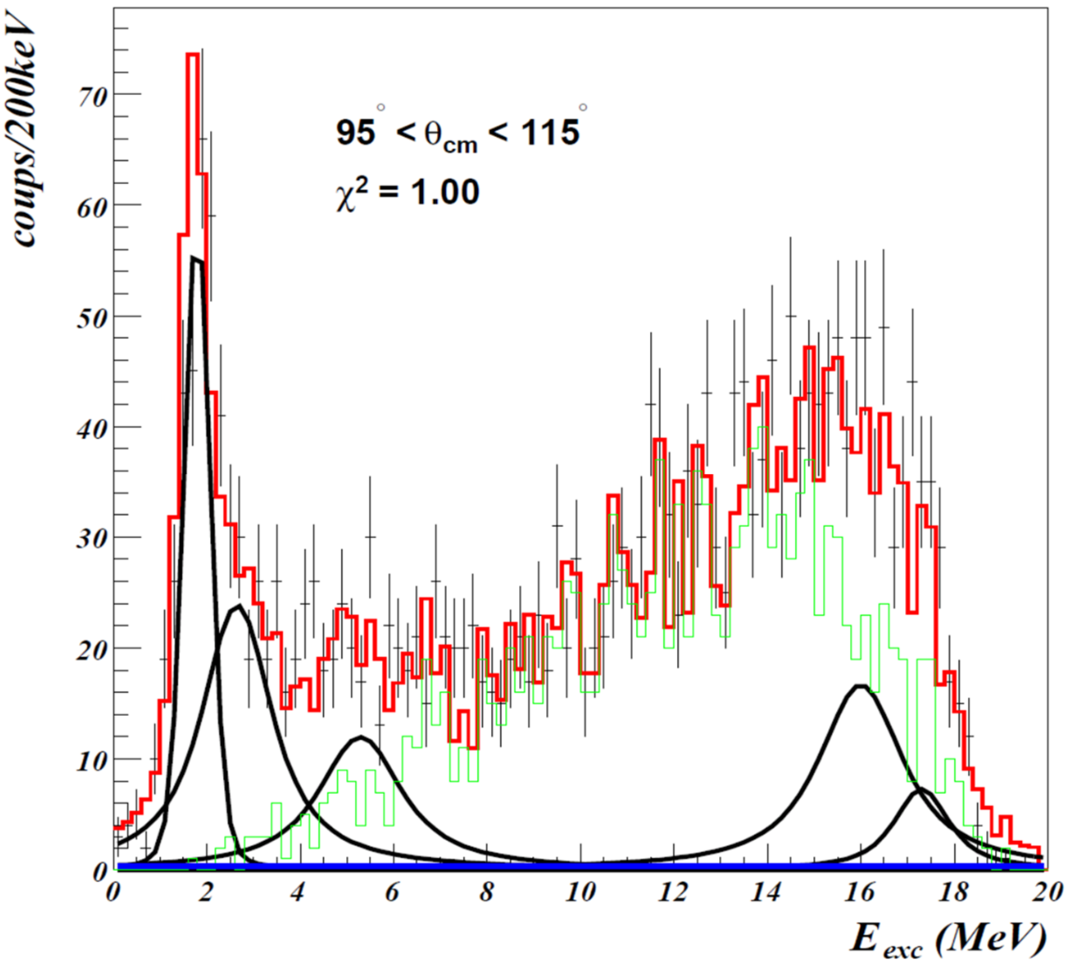


Analysis of ^{6}He spectra: resonances

→*Operations done for all Ex spectra [for various slices/gates on c.m. angles in the kinematics]*

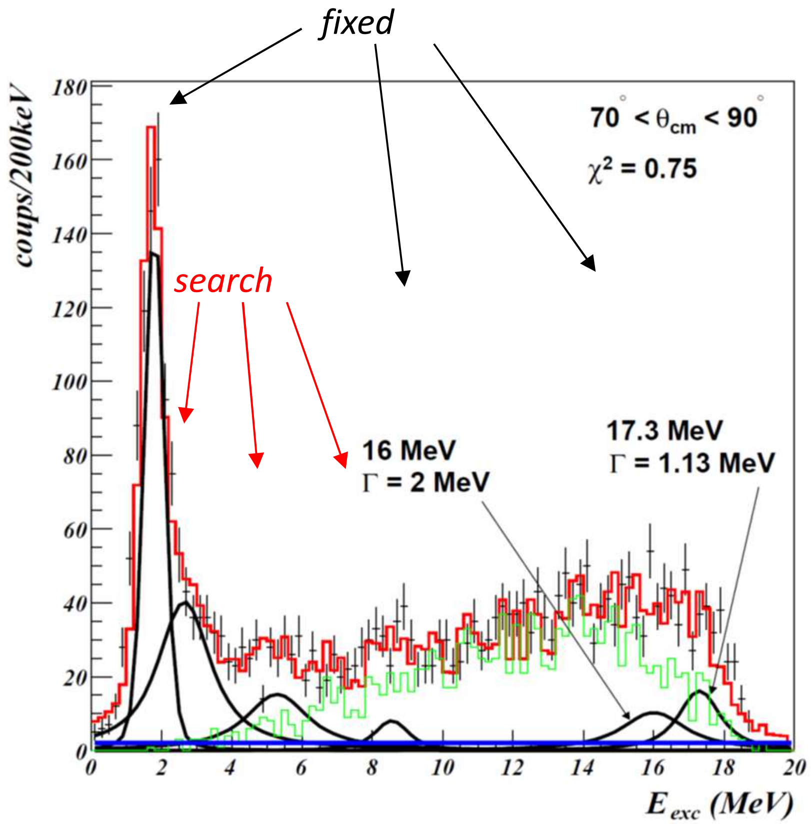


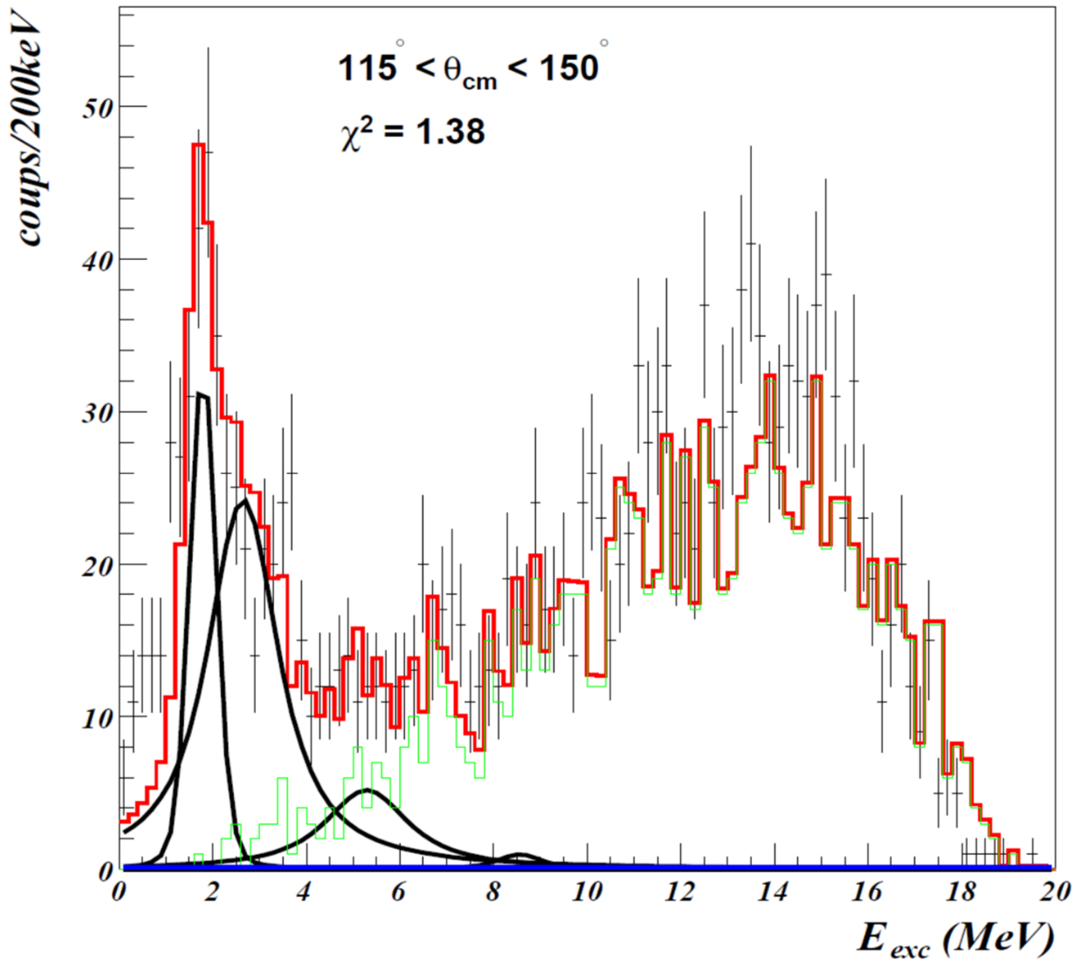
3rd step : checking,
the resonance parameters must be the same within error bars for the various gates on the c.m angles



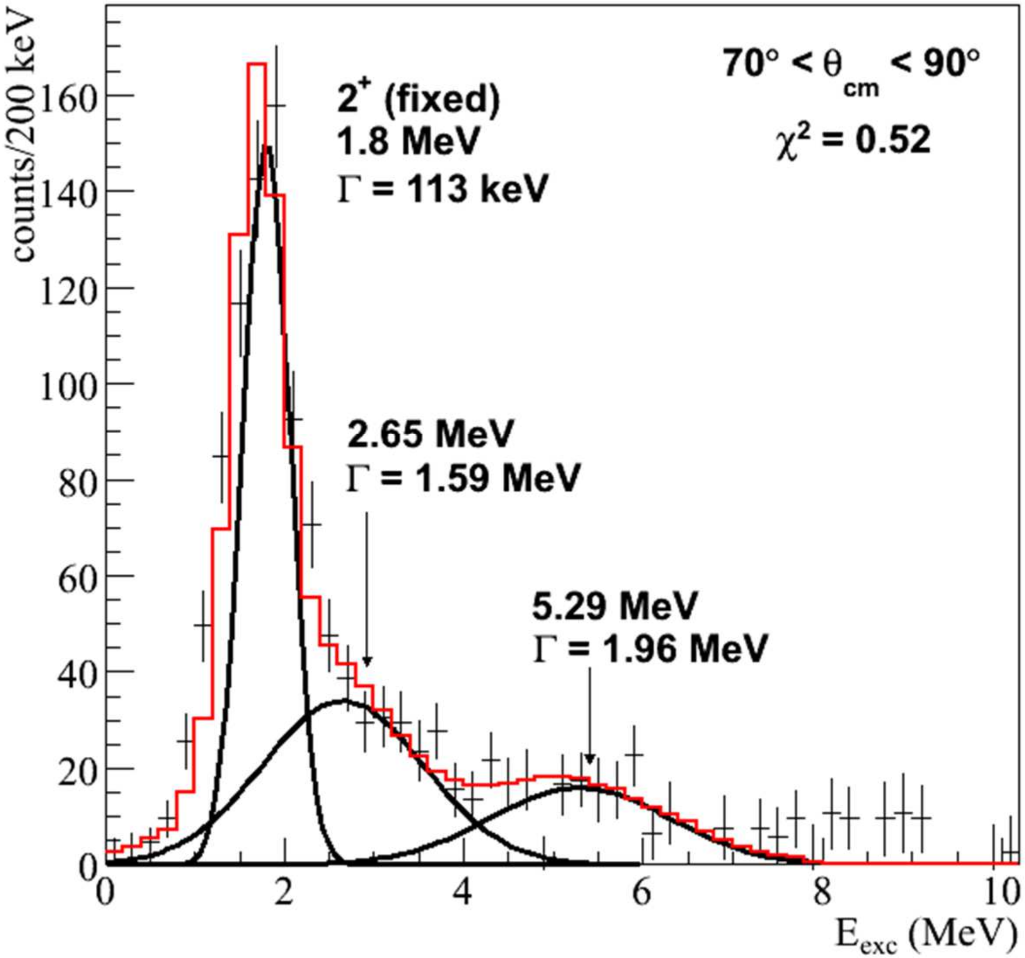
→*Operations done for all Ex spectra [for various slices/gates on c.m. angles in the kinematics]*

3rd step : checking,
the resonance parameters must be the same within error bars for the various gates on the c.m angles





Observables - ^{6}He excitation energy spectrum (with background subtraction)



MUST2 E525S data at GANIL

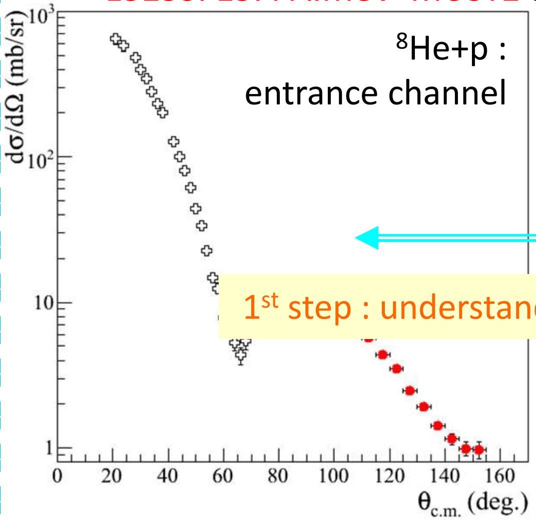
X. Mougeot , V.L. *et al.,* PLB **718**, 441 (2012). PhD work: X. Mougeot (CEA)

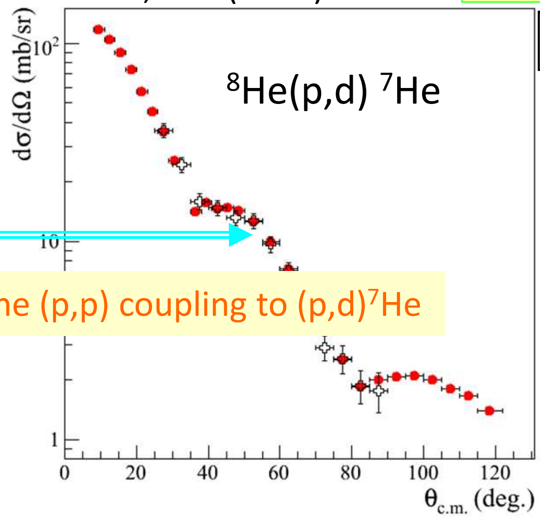
Observables: Elastic &transfer data of ^{8}He +p

E405S: 15.7 A.MeV; MUST data
E525S: 15.4 A.MeV MUST2 data PLB **718**, 441 (2012).

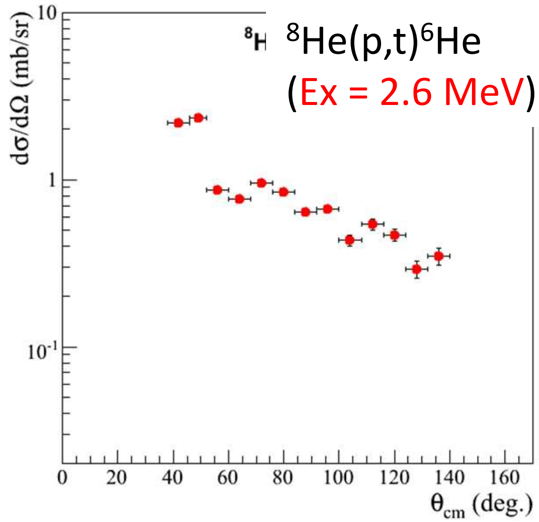
→ extract structure information (densities, SF)
→ check the consistency of the calculations on the data set for the various reaction channels

all direct reactions at the same incident energy

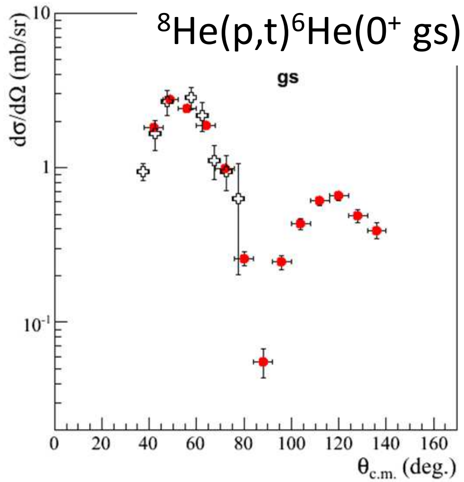


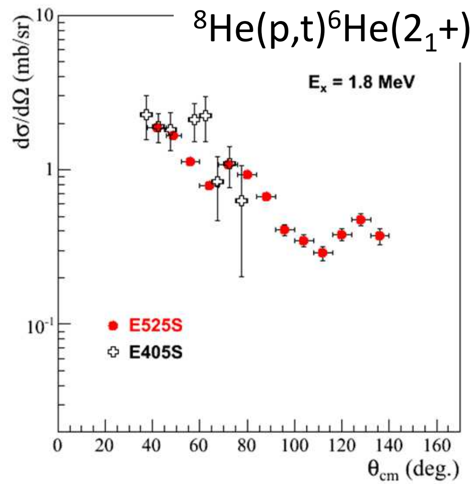


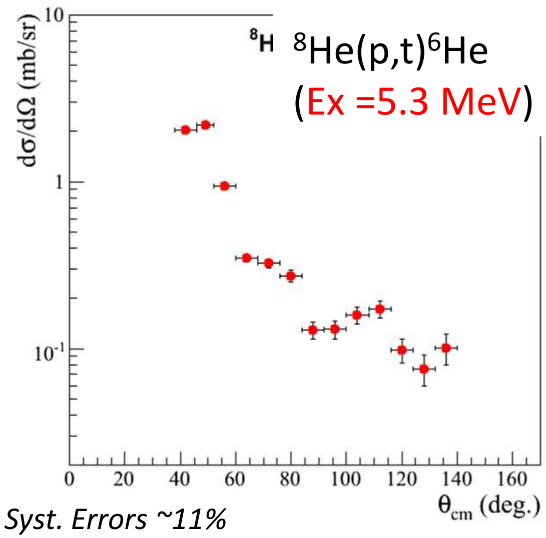
1st step : understand the (p,p) coupling to (p,d)^{7}He



* Large (p,d), (p,t) cross sections compared to (p,p) → DWBA not valid
GENERAL framework : Coupled Reactions Channel model





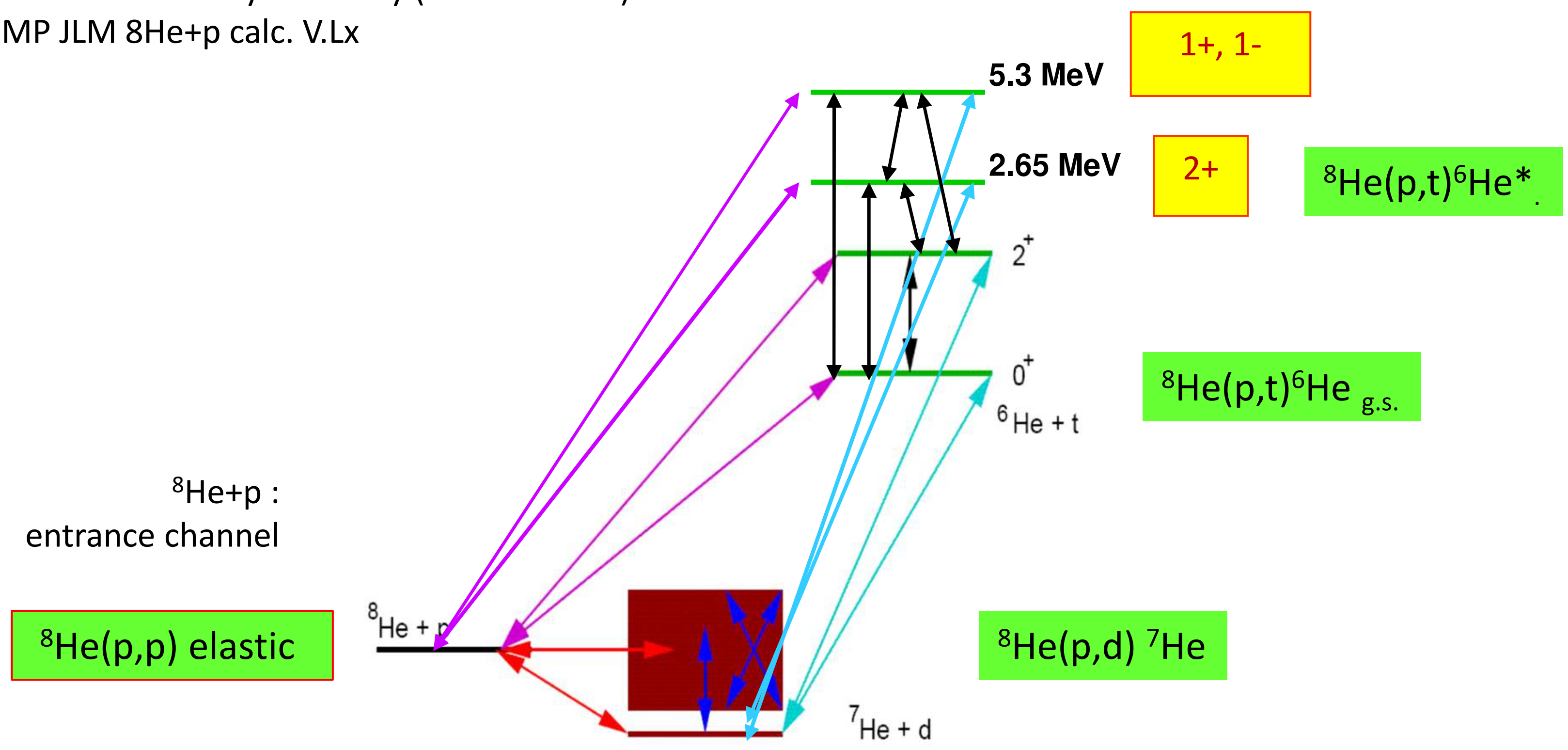


NB: Total Syst. Errors ~11%

Calculations: Elastic &transfer data of ^{8}He +p

DATA E405S: 15.7 A.MeV; MUST data
E525S: 15.4 A.MeV MUST2 data PLB **718**, 441 (2012).
CRC calculations by N. Keeley (Warsaw univ.)
OMP JLM 8He+p calc. V.Lx

all direct reactions at the same incident energy



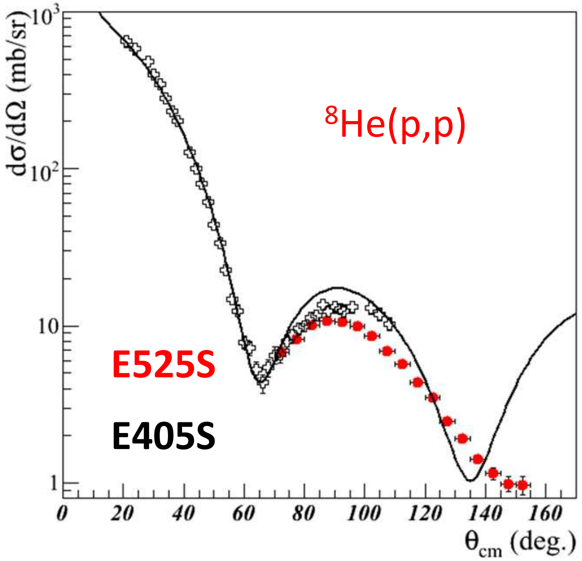
→ extract structure information (densities, overlap of wave functions?)
→ check the consistency of the calculations
on the data set for the various reaction channels

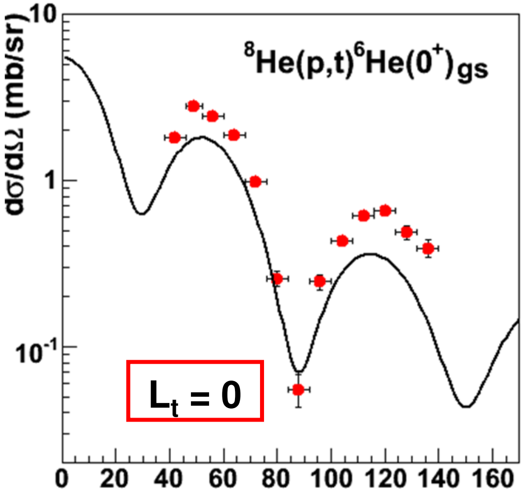
Questions

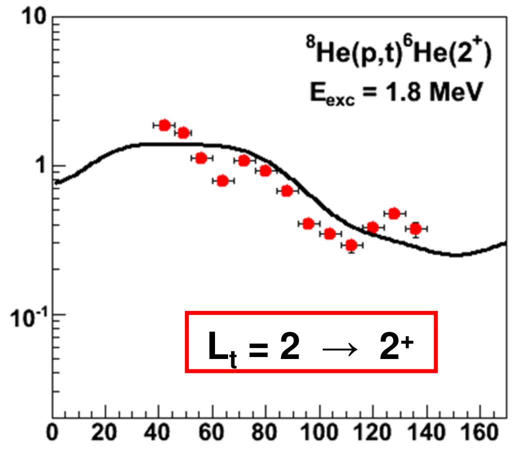
Paths improving the structure-reaction frameworks

Comparisons EXP-theory for all the data sets of ^{8}He+p

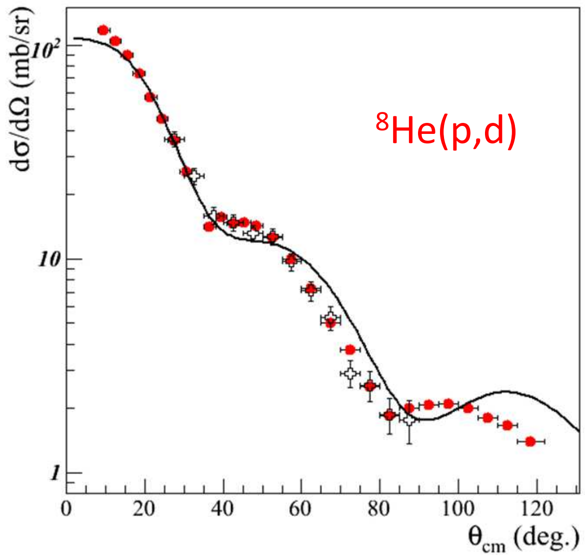
E525S data PLB **718,** 441 ('12)
CRC calc. N Keeley (Warsaw)



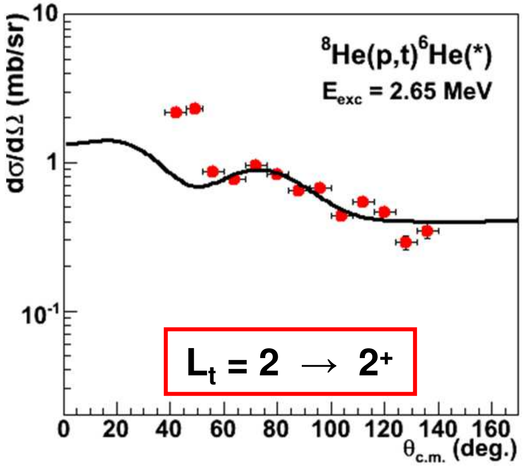




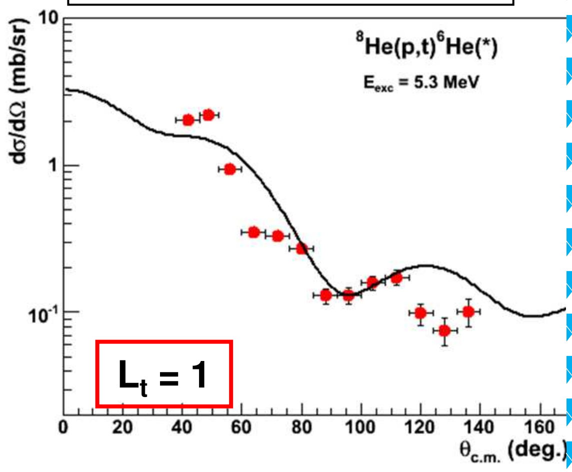
Shape of $d\sigma/d\Omega$ (θ_{cm}) gives L_t



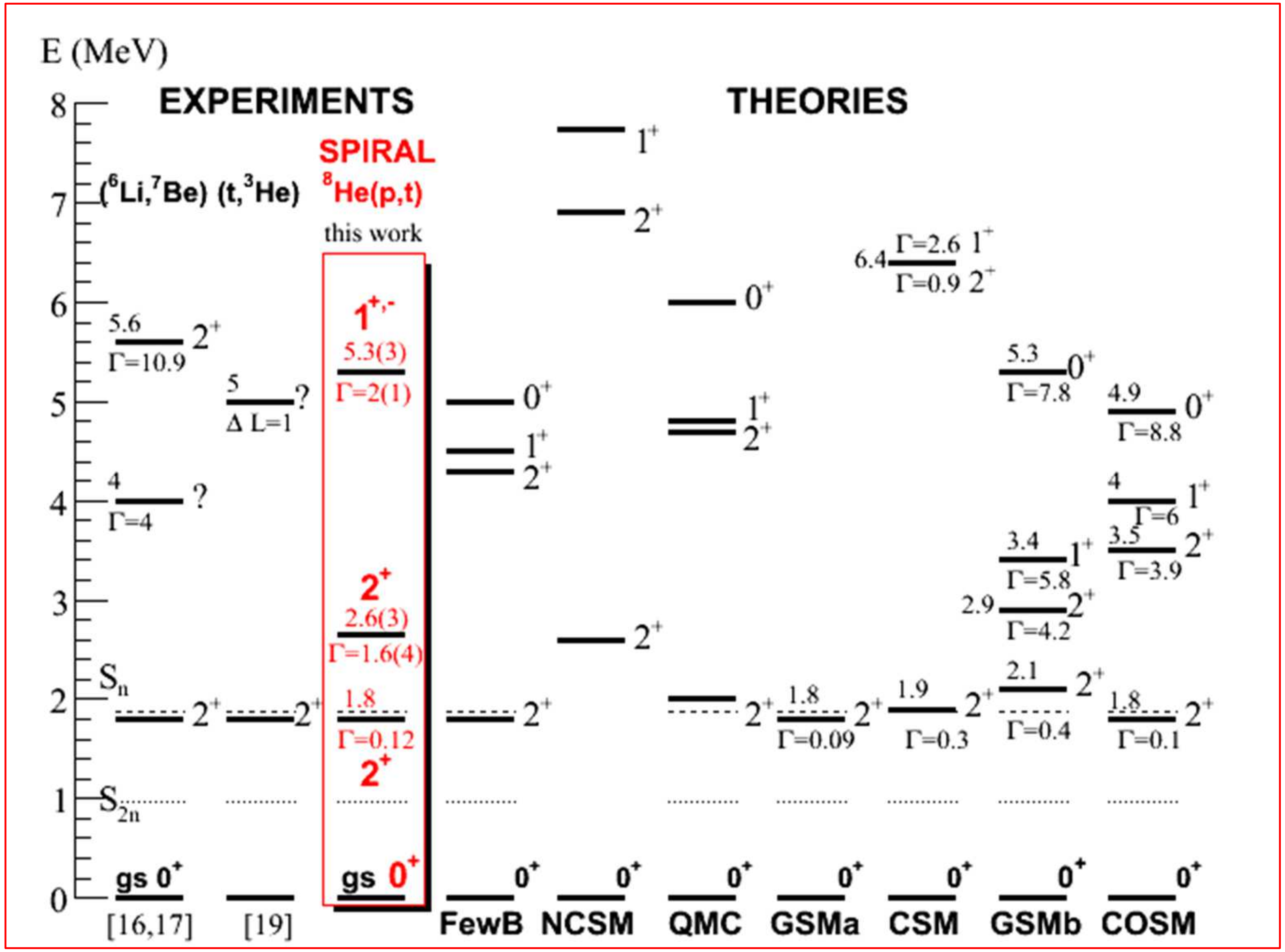
E_{exc} = 2.6 MeV Γ = 1.6 MeV



E_{exc} = 5.3 MeV Γ = 2 MeV



Observables - , spectroscopy of ^{6}He from ^{8}He(p,t)



QMC
Pieper *et al.*
PRC **70**,054325 (‘04)

NCSM
No Core Shell Model
Navratil, Barrett *et al.*

FewB Danilin *et al.*
PRC **55**, 577 (‘97).

CSM
Volya, Zelevinsky,
PRL**94,** 052501 (‘05).
GSMa Ploszajczak
GSMb Hagen,
Hjorth-Jensen, Vaagen,
PRC**71**, 044314 (‘05).
COSM Myo, Kato, Ikeda,
PRC 76 (2007) 054309.

[16] J. Jänecke *et al.*, PRC **54**, 1070 (1996).
[17] S. Nakayama *et al.*, PRL **85**, 262 (2000).
[19] T. Nakamura *et al.*, PLB **493**, 209 (2000); EPJA**13**, 33 (2002).

Fig - E525S results
PLB **718**, 441 (2012).
N.B. AME2003 Sn =1.86 MeV
2015: AME2012 1.71 MeV

Conclusions   Perspectives

We need "**coupled-reaction-channel**" type measurements -frameworks:
- To check the consistency of the structure/potential inputs on the various channel calculations
- To finally extract structure & spectroscopy

Cf EPJA 51:91 (2015) *Weakly-bound structures of the exotic ^{6,8}He via direct reactions*
Review: set-up, reactions, analysis - results on He radii

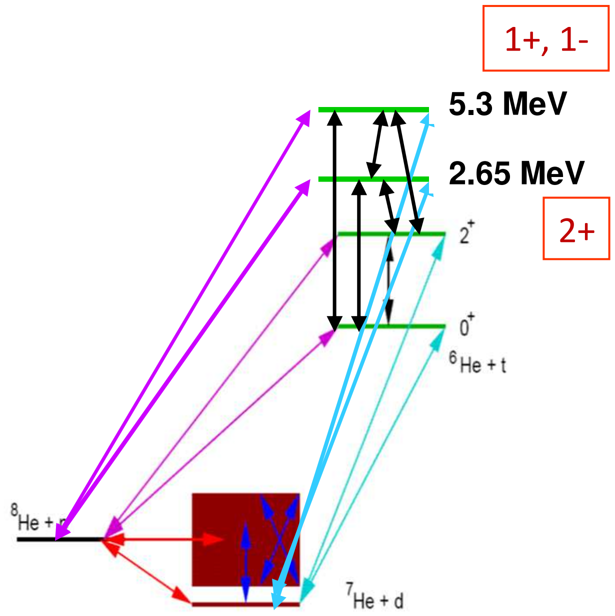
Questions

Paths improving the structure-reaction frameworks?

+ How to model the continuum states in the intermediate or exit channels?

+ Progress in using the same nuclear interaction to calculate structure wf, spectroscopy and reactions ?

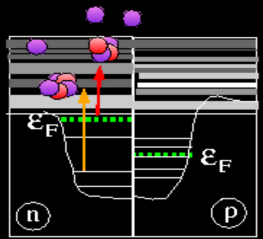
+ More realistic nucleon or overlap form factors in CRC analysis ? From ab -initio calc (2NF+3NF)?

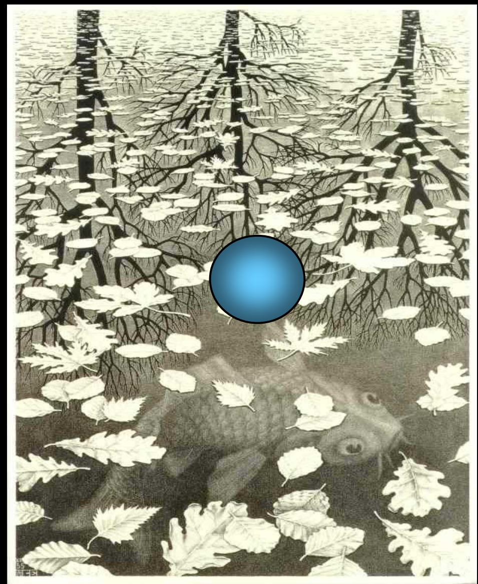


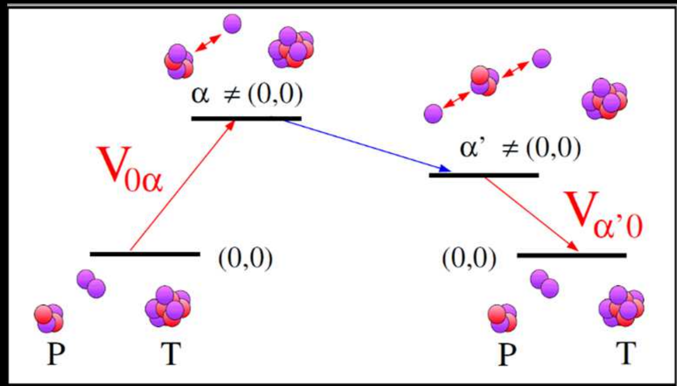
Next   REQUEST TO THEORISTS: use/check ^{8}He+p system !

Goals for structure-reaction theories: from fish to bird

Scattering states







Reaction studies for states close to the continuum?

Bound states

We need theories with:

- structure and reactions on the same footing
- Treatment of states embedded in the continuum
- Treatment of reaction coupling between nucleon transfer & elastic entrance channels
- possibly taking into account realistic ab-initio nuclear forces

$\boxed{\psi}$ ***Observables***

Theories for E_{gs}, E_x , r_{ch}, r_m … ρ_{ch}, ρ_m
\+ direct access to (p,p), (e,e) reactions

→ **Egs, Ex, nucleon density observables**
→ **(rp, rm)**

→ **benchmarks for theories**
Evolution of interactions

→ **necessary step to build an unified model for structure & reactions**

Experiment- theory *ab-initio* calculations of matter radii r_m

Summary

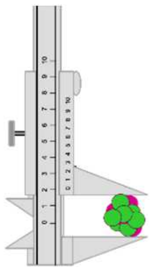
State-of-the-art *ab-initio* calculations
Various technics, 2 interactions : EM, $NNLO_{sat}$
→E_B **and matter radii**

(p,p) microscopic OMP analysis →r_m
- from (e,e) & (p,p) *data for stable nuclei*
- exotic from (p,p) MUST-GANIL data

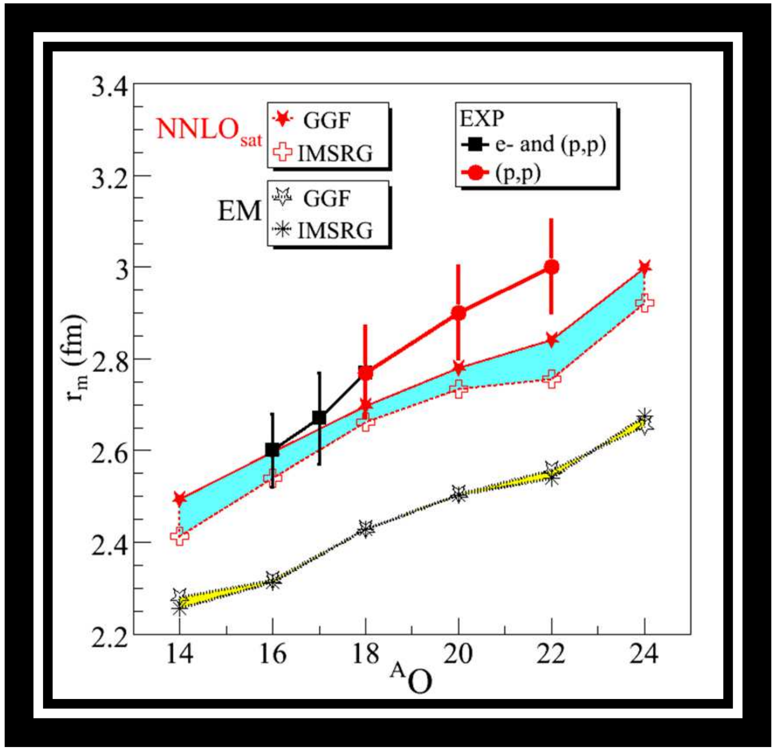
Conclusions

→ Crucial role played by the r_m observable for the test of the interaction is underlined

Using matter radii as benchmarks for theories
Evolution of the choices of interactions?



PRL **117**, 052501 (2016)



Perspectives

→Improvements of the reliability of *ab initio* calculations for properties towards driplines, beyond Z = 8, selecting fundamental **observables like radii.**

More reliable calculations of radii also needed

→To have quantitative evaluation of the properties of very-neutron nuclei, today not accessible experimentally nor in far future

→ To reach quantitative estimate of reaction rates with microscopic structure inputs

→ key benchmark-necessary step to build an unified model for structure & reactions.