Questions about the structure and reaction frameworks

Our goals: structure and spectroscopy

BUT:: the dark side of the experimental techniques
and of the models

How to fight ?
Prototypical example of reactions on proton, elastic scattering and transfer

^{8}He(p,p) (p,d) (p,t) at SPIRAL energy (~15.7 MeV/n)

Illustration of the limitation of the nuclear reaction models.

Flash back to ^{11}Be(p,p)

Questions

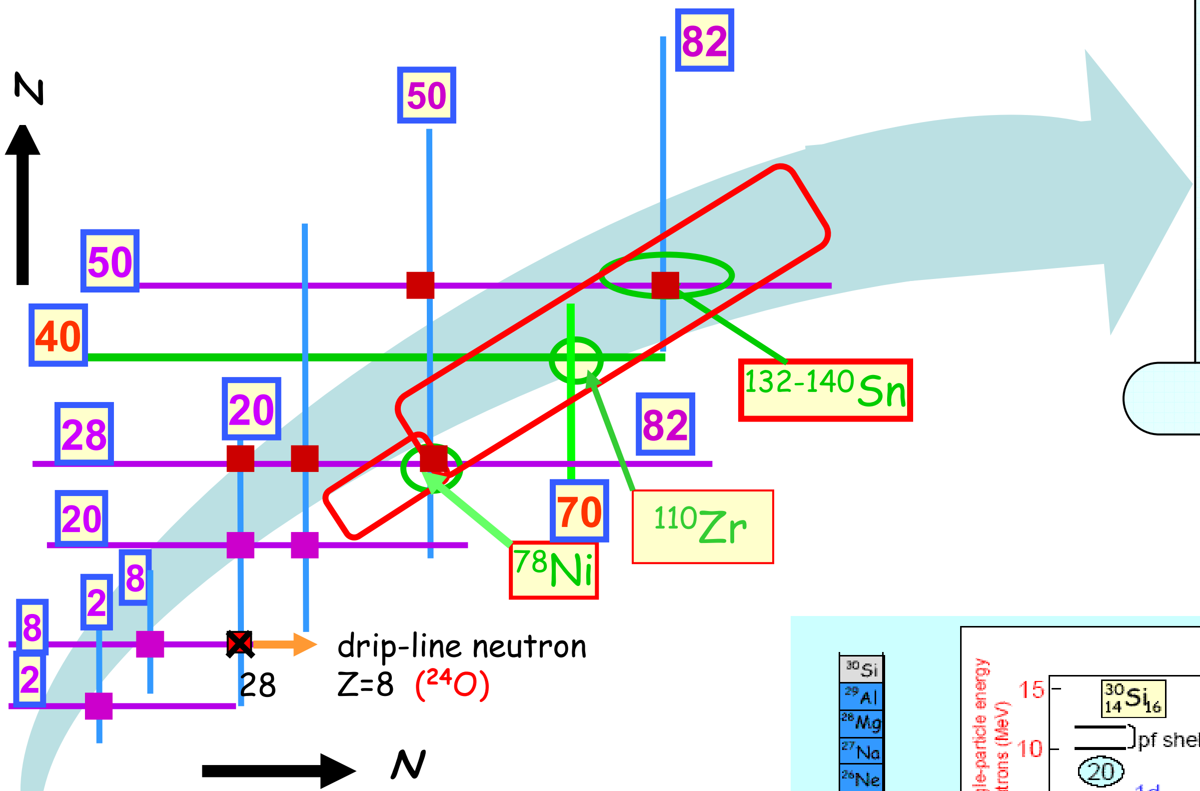
Some hopes

GOALS: exploration and understanding of a new world

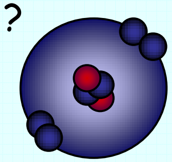
We do REACTIONS to probe the structure and the spectroscopy of the exotic nuclei

stable ^{4}He, ^{16}O, $^{40,48}Ca$, ^{208}Pb

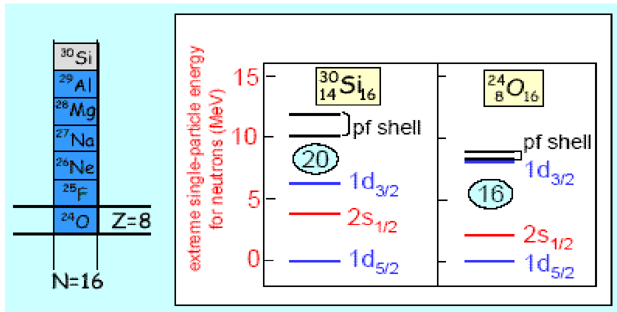
unstable $^{48,56,78}Ni$, $^{100,132}Sn$



Low-lying resonances ?
Neutron excitations ?
soft collective modes ?
Exotic shapes ?
Alpha cluster states ?
Neutron skin ?
Shell evolution ?
New shell effects at
N =16,34, 70 ?
Properties around unstable magic nuclei?



New drip-line nuclei ?



Exotic nuclei
Towards the limit of the nuclear binding

How ? Direct reactions are one way to explore the nuclear landscape with the RIBs

Evolution of the nuclear structure % isospin?
Properties around neutron-rich doubly-magic nuclei ?

PROPERTIES
Structure and low-lying spectroscopy
Matter density distributions
Shell structure from single-particle states
Excited states J^{π}, shell occupancies (spectroscopic factors SF)

Observables and tools:
excitation spectra and angular distributions **via direct reactions**
>> simple reactions on p and d targets,
study of sp states and of neutron excitation
(p,p'), (p,d) (p,t) & (d,d') (d,p) (d,t)
We need at least I > 10^3 part/s

Incident energy is a key-point: preferably
we should adapt it to momentum matching conditions
(angular momentum window, Qvalue)

Eg : (p,p') 15 to 150 MeV/n
(depending on the modes we want to excite)
(d,p) 5 to 20 A.MeV ; (p,d) 10 to 30 A.MeV
(p,t) Einc between 15 and ~50 MeV/n
(d,^{3}He) Einc>50 A.MeV

THEORY PROBLEMS
Scattering/transfer
to unbound states
Potentials poorly known
Coupling to transfer channels

↑

What is the dark side?

↓

EXP PROBLEMS:
Incident energies are fixed by the production method of the RIB machines
>>not in good matching conditions >> cf (p,t)
Intensities so low that angular distributions are too limited to probe the nuclear densities

Questions

Quantum mechanical object:

Reaction probe selects one aspect of the $|\psi_{nucleus}>$

Our models "project" the nucleus on one specific aspect of the nuclear interaction.

>>model-dependent extraction of gaps and SF

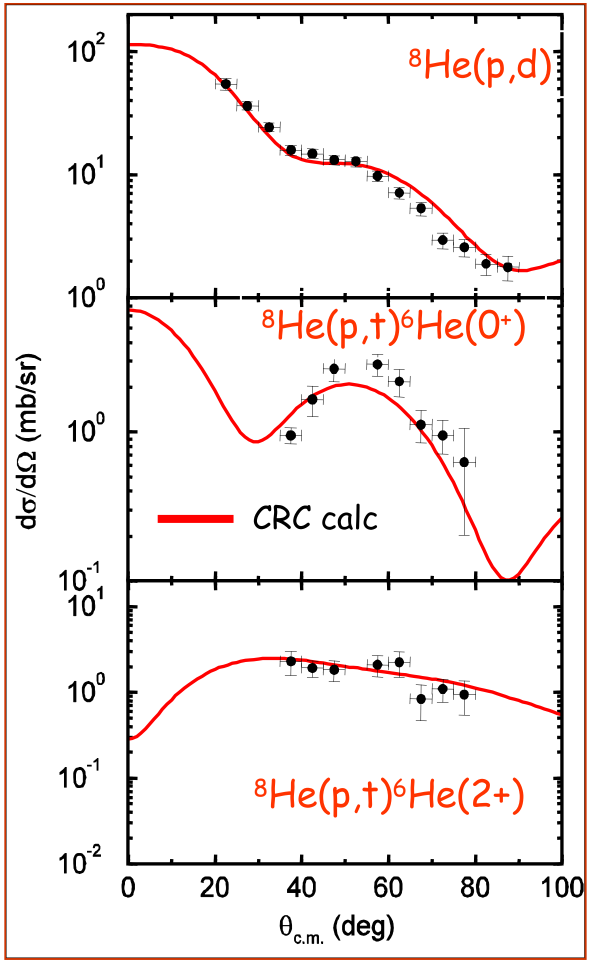
What is the underlying force behind the structure and the spectroscopy?

Form of the tensor force?
Sharing between nn np and pp interactions?
How to treat consistently the interplay between isospin-dependent effect, tensor interaction, Many-body correlations, Coupling to the continuum ?

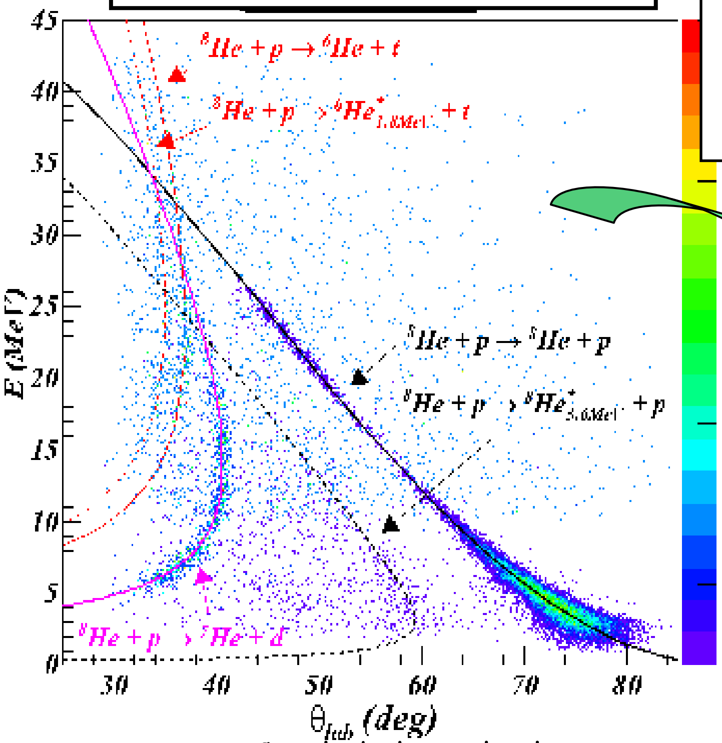
Interaction at play between the interacting nuclei ?

Shape of the microscopic interaction potentials used for the nuclear reactions ?
How good potentials, frameworks are really good for exotic beams ?
Validity of optical potentials ?
To be checked by measuring carefully the elastic scattering ,
>> Testing ground for the interaction potential and for the reaction models

Structure of ^{8}He extracted from direct reactions on proton target

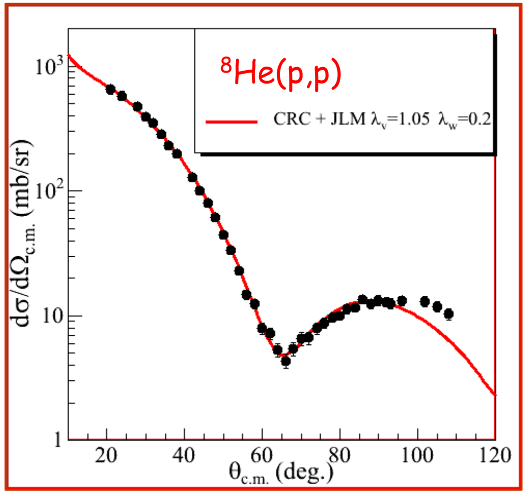


SPIRAL ^{8}He +p @ 15.7A.MeV



Coupled-channel calc.:
N. Keeley (SPhN)

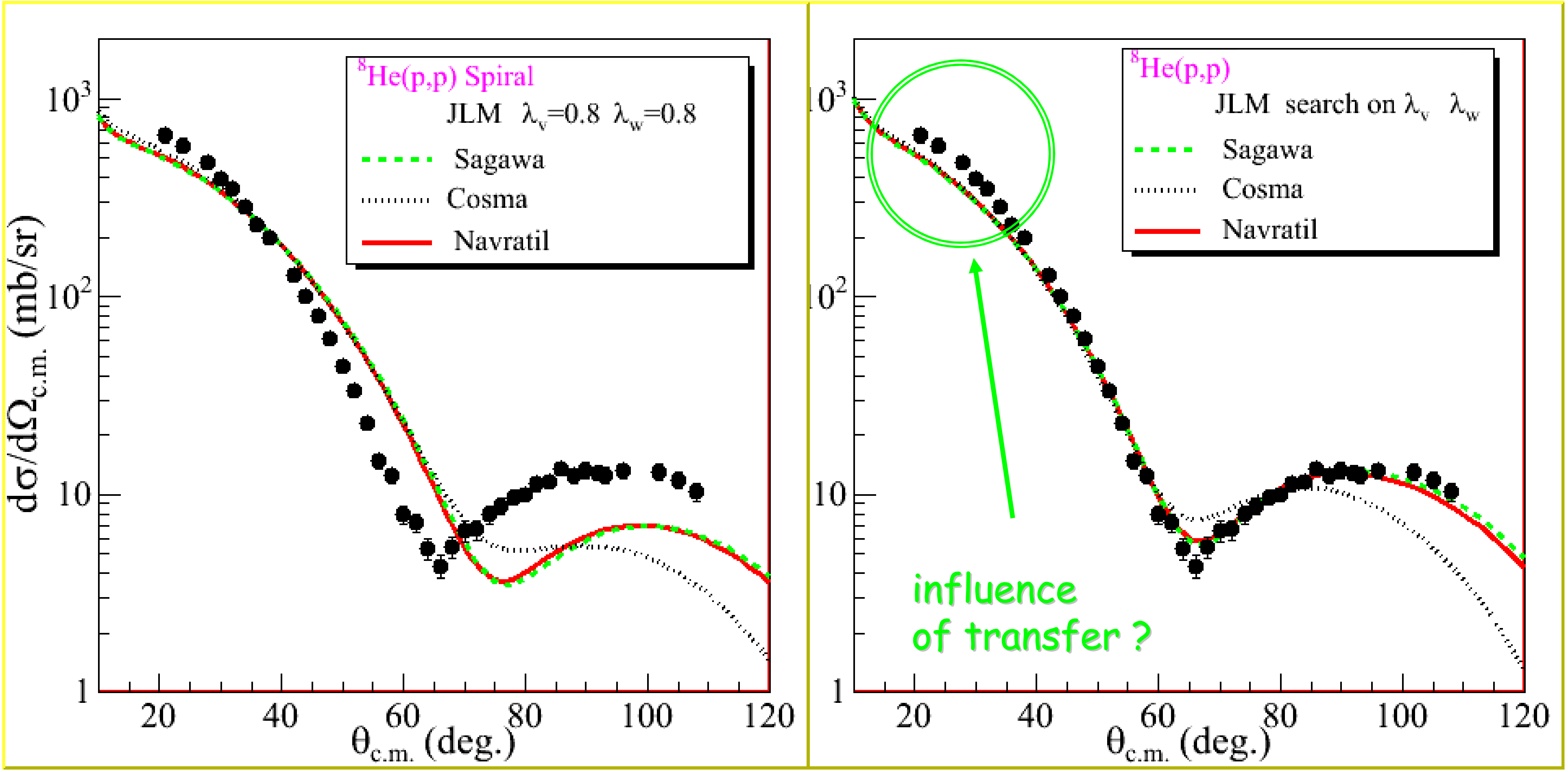
F. Skaza PhD SPhN
F. Skaza, N. Keeley, VL *et al.*,
PLB **619**. 82 ('05)
N. Keeley *et al.*, PLB **646**,222('07)



Structure of ground state & search for unbound excited states

→ spectroscopy of light charged particles p,d,t (MUST)
→ measurements of resonances in ^{8}He NPA 788c, 260 ('07)
→ angular distributions ; analysis in **coupled reaction channels**
PLB **619**. 82 ('05) ; **646**, 222 ('07)

Analysis of elastic $^8He(p,p)$ within optical model framework



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

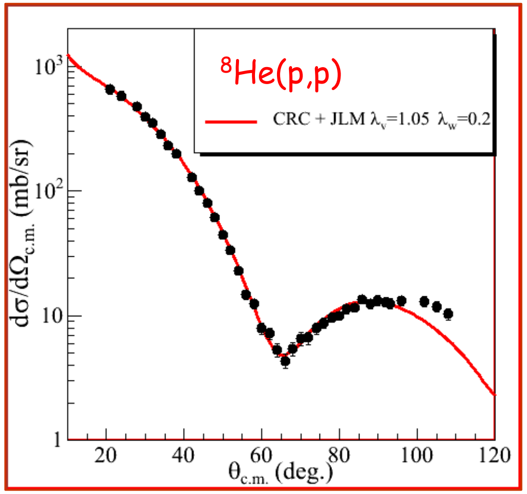
	λ_v	λ_w
COSMA	1.04	1.16
SAGAWA	1.13	1.07
Navrátil	1.11	1.06

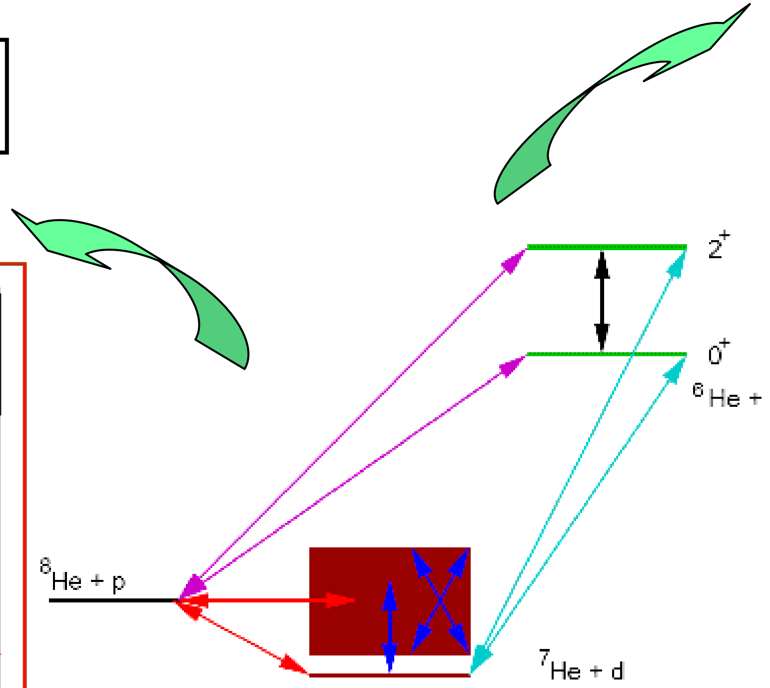
Repulsive surface terme generated by the coupling
→ Complex Virtual Coupling Potential PCV

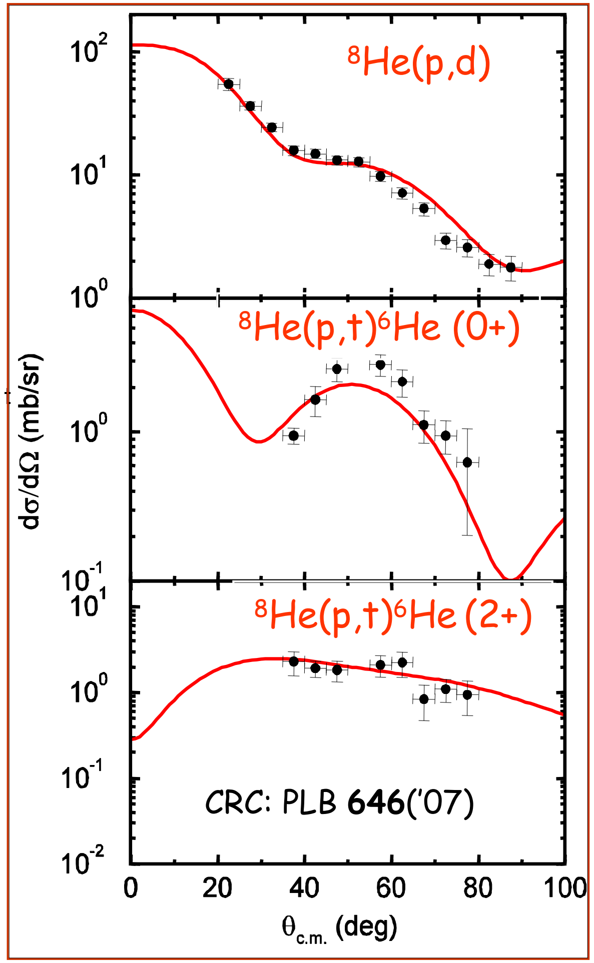
At low energy not only the reduction of V_r
change of the shape of the complex potential due to the coupling

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 factors C^2S from
$(d\sigma/d\Omega)_{theo}$ % $(d\sigma/d\Omega)_{exp}$

The transferred angular momentum L_t indicates J^{π}

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 →

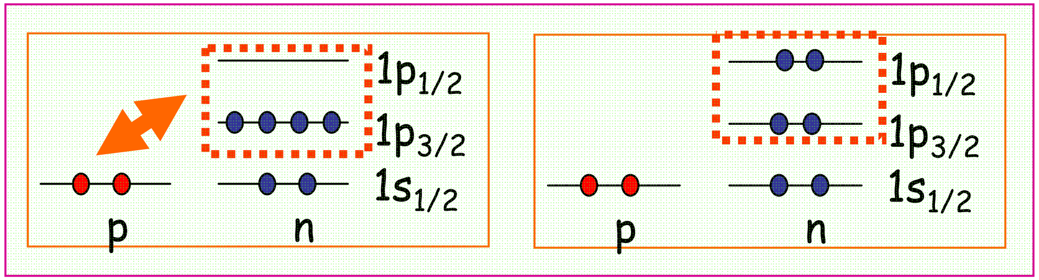
N. Keeley et al. : PLB **646**, 222('07)

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

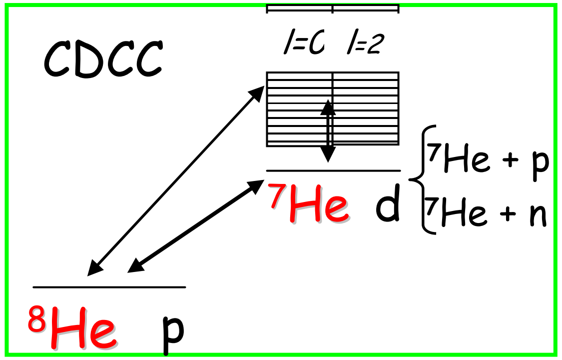
and re-analysis
of RIKEN data

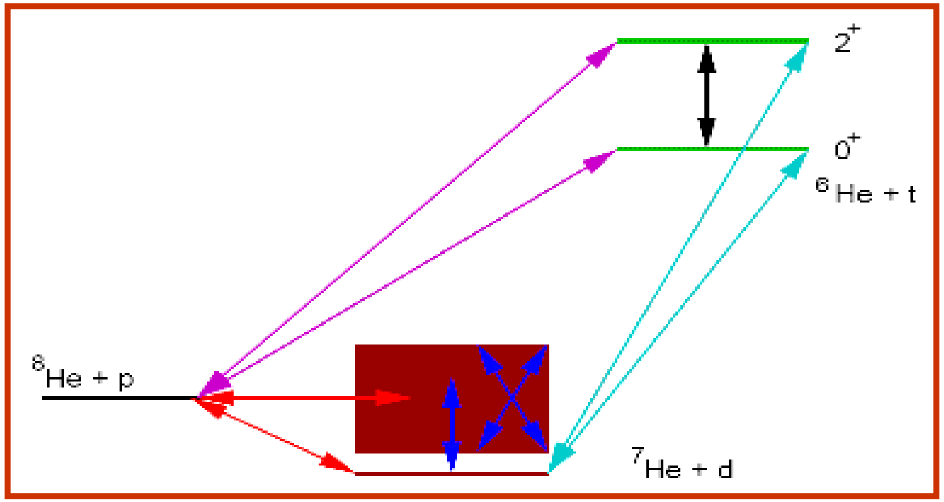
^{8}He(p,d)^{7}He C^2S = 3.4 ± 1.3

(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 $(p3/2)^2$ $(p1/2)^2$



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 %





Case of ^{8}He(p,p) – ^{8}He(p,d)^{7}He - ^{8}He(p,t)

>> within CDCC the deuteron continuum is correctly taken into account

BUT what about the unbound ^{7}He ? Only a WS form factor is used.

How to treat the nuclear form factor for d+7He all in the continuum?

>>within CDCC and CRC we can adopt microscopic potentials for 8He+p

(eg JLM density dependent complex potential using proton and neutron density distributions)

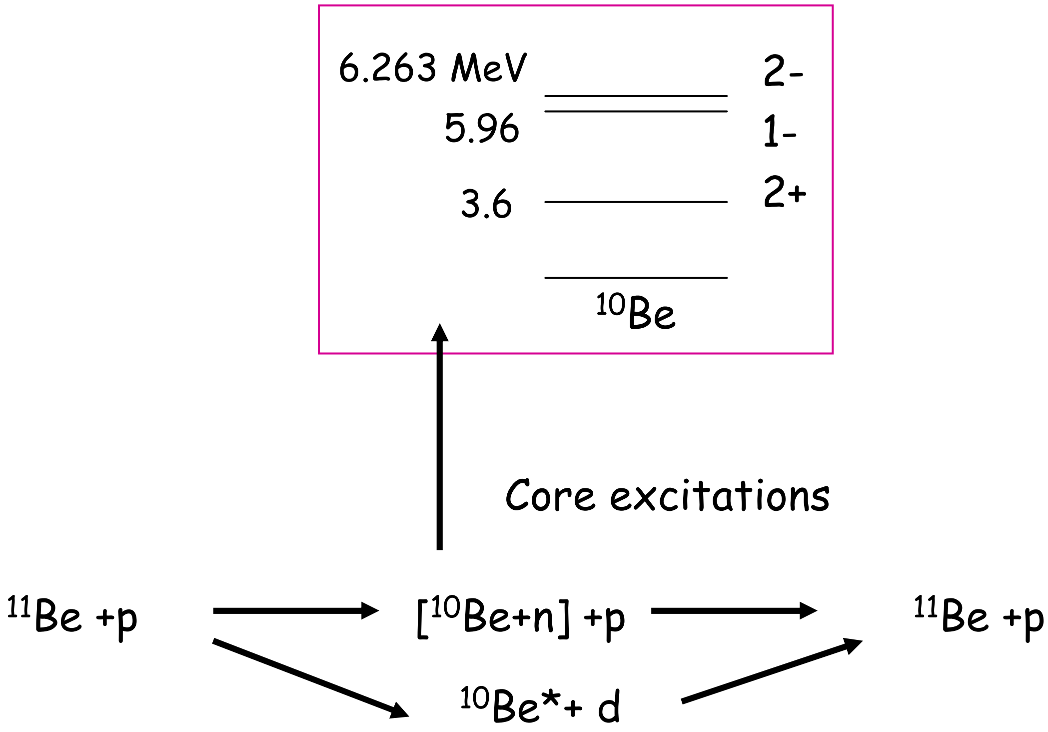
But what about d+^{7}He potential, t+^{6}He? >>We rely on **phenomenological potentials**

Binding potentials for the nuclei >>taken as WS

We adopt prescription for the WS paramters (eg ro=1.25fm) >>> reliability ?

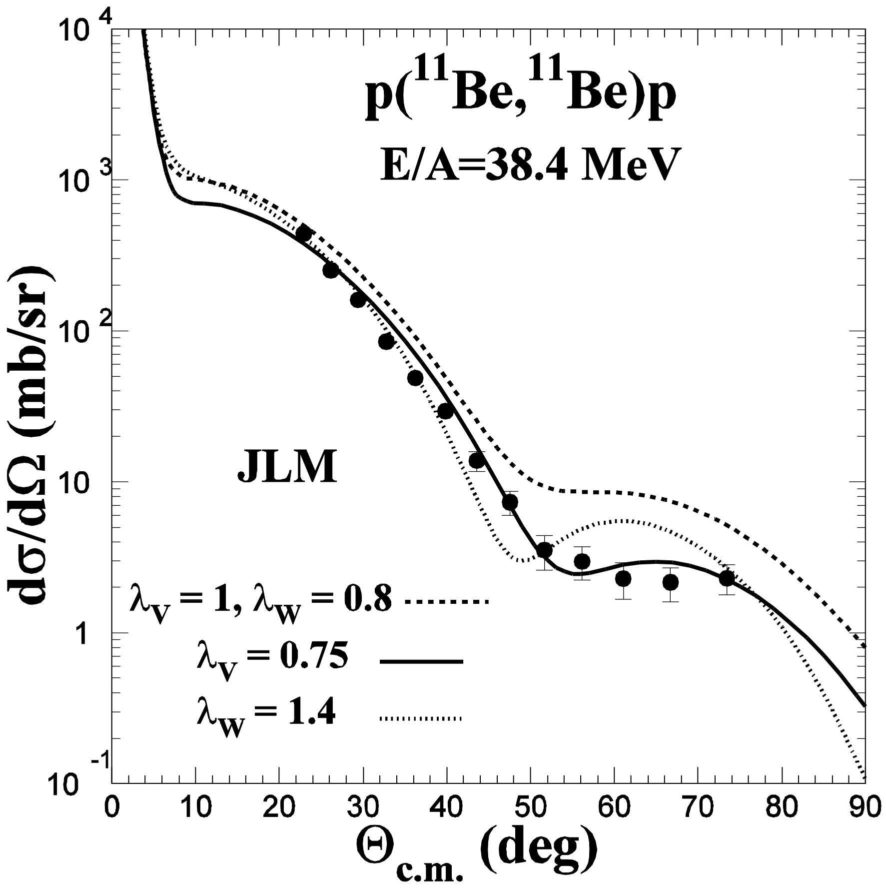
Sophisticated models are developed to treat the core excitation effects.
Cf Core excitation in ^{11}Be A Moro's talk 25th Oct

But what about the coupling to transfer channels?



(p,d) transfer to gs and to excited states of ^{10}Be

Looking at p+^{11}Be elastic scattering



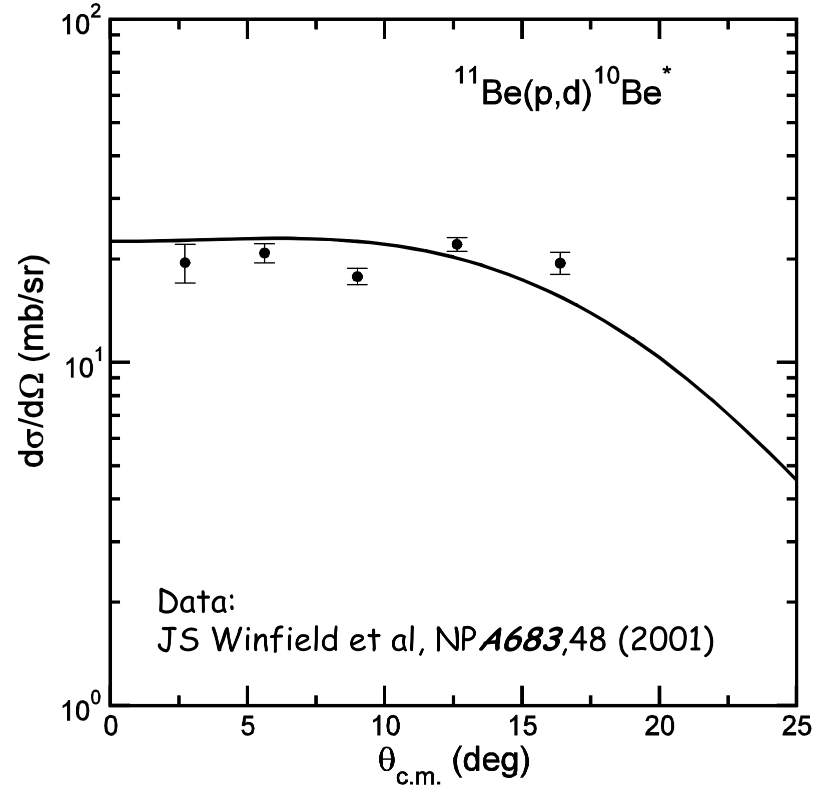
local microscopic complex potential JLM,
J.P. Jeukenne, A. Lejeune & C. Mahaux,
PRC 16 ('77) 80
valid for Ep, En up to 160 MeV

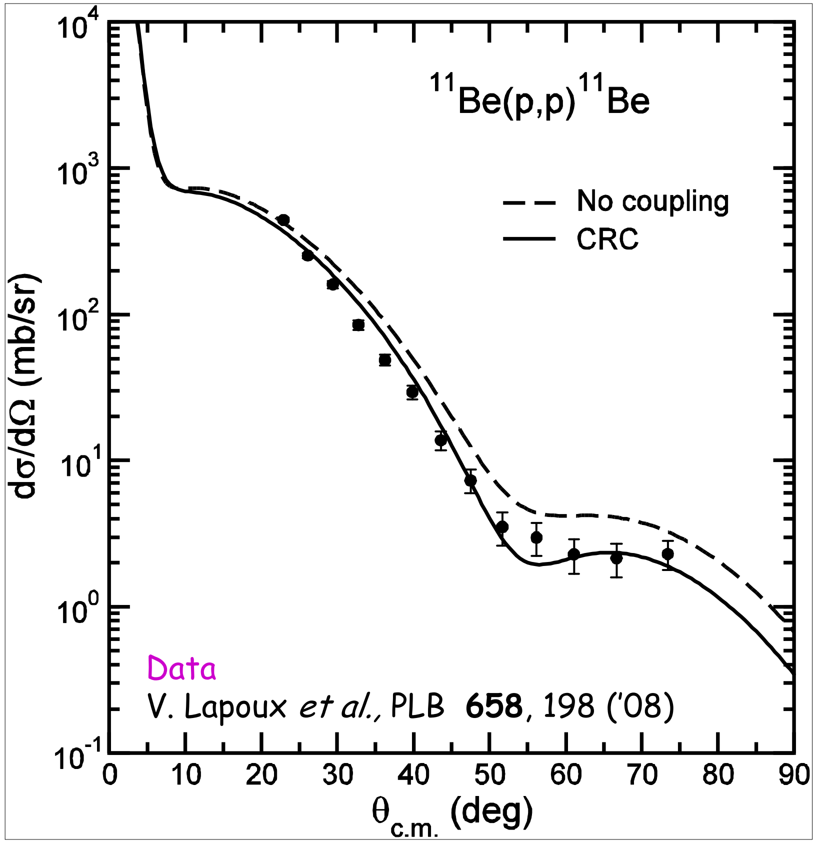
$$U(\rho,E) = \lambda_V V(\rho,E) + i\,\lambda_W W(\rho,E)$$

Using HF+correlations densities
for ^{11}Be from H.Sagawa PLB (1992)

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

Strong pickup-coupling effect on p+^{11}Be elastic scattering





N. Keeley and V. L PRC ***77***, 014605 ('08)

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

Hopes definition of the appropriate scattering theory and standard nuclear model

>> we can identify the best we can do using the present nuclear models

what are the paths of improvement?

Model Side:
Use of microscopic densities to generate the nuclear interaction potentials
>>Theory needs to work on transition densities, form factors, spectroscopic amplitudes
to incorporate the effects enhanced in the case of exotic weakly-bound nuclei:
coupling to the continuum, many-body correlations, shell structure embedded in the continuum,
3-body nuclear force, >> correlations & interactions $V_{NN}(Tz)+V_{NNN}(Tz)$

microscopic complex density-dependent potentials
Cf JLM nucleon-nucleus potential Jeukenne, Lejeune, Mahaux PRC (1977)
CEG 07 –complex nucleus-nucleus potential Y. Sakuragi's talk, TFurumoto et al. PRC 78 ('08).
In reaction models (CRC, CDCC)
developments are needed for instance in case of unbound nuclei in the intermediate step
or to incorporate on the same footing structure and reactions

The best we can do:

- MICROSCOPIC COMPLEX POTENTIALS
  → To test the validity of the nuclear densities
- COUPLED CHANNEL REACTION FRAMEWORK
  → To include coupling to excitations and reaction channels

Experimental side in a "CRC approach"

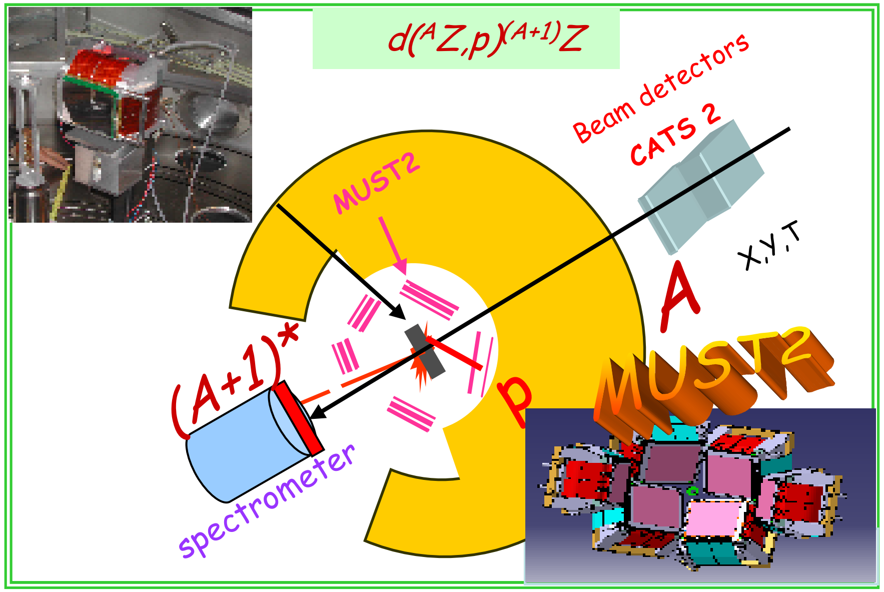
>> collect the data for the main reaction channels not only the reactions of interest

→ helpful to understand to reaction coupling effects.

>> systematic measurement of (p,p') and (d,d') along isotopic chains for neutron-rich nuclei

→to probe the validity of microscopic potentials

→ to understand the role of core excitation and of the coupling between reaction channels like (p,p) (p,d), and (d,d) (d,p).



WORKS

- **Collect accurate data covering a large angular domain**
- **Elastic: entrance OM potential under control (p,p) (d,d)**
- Check role of continuum coupling
- Sensitivity to the detailed structure of exotic nuclei,
- Test unusual shape +unbound states
- Compare to models (SM, HFB, BCS+QRPA, AMD, GSM etc…)

When moving towards the drip-lines, the continued validity of the standard models may be questioned:

-- first we deal with very weakly-bound nuclei which may excite, break-up easily or couple to transfer channels during reactions.
>> the reaction framework should be improved to take into account these effects as accurately as possible and to treat on the same footing the bound discrete states, the unbound states, the states embedded in the continuum and the scattering states.

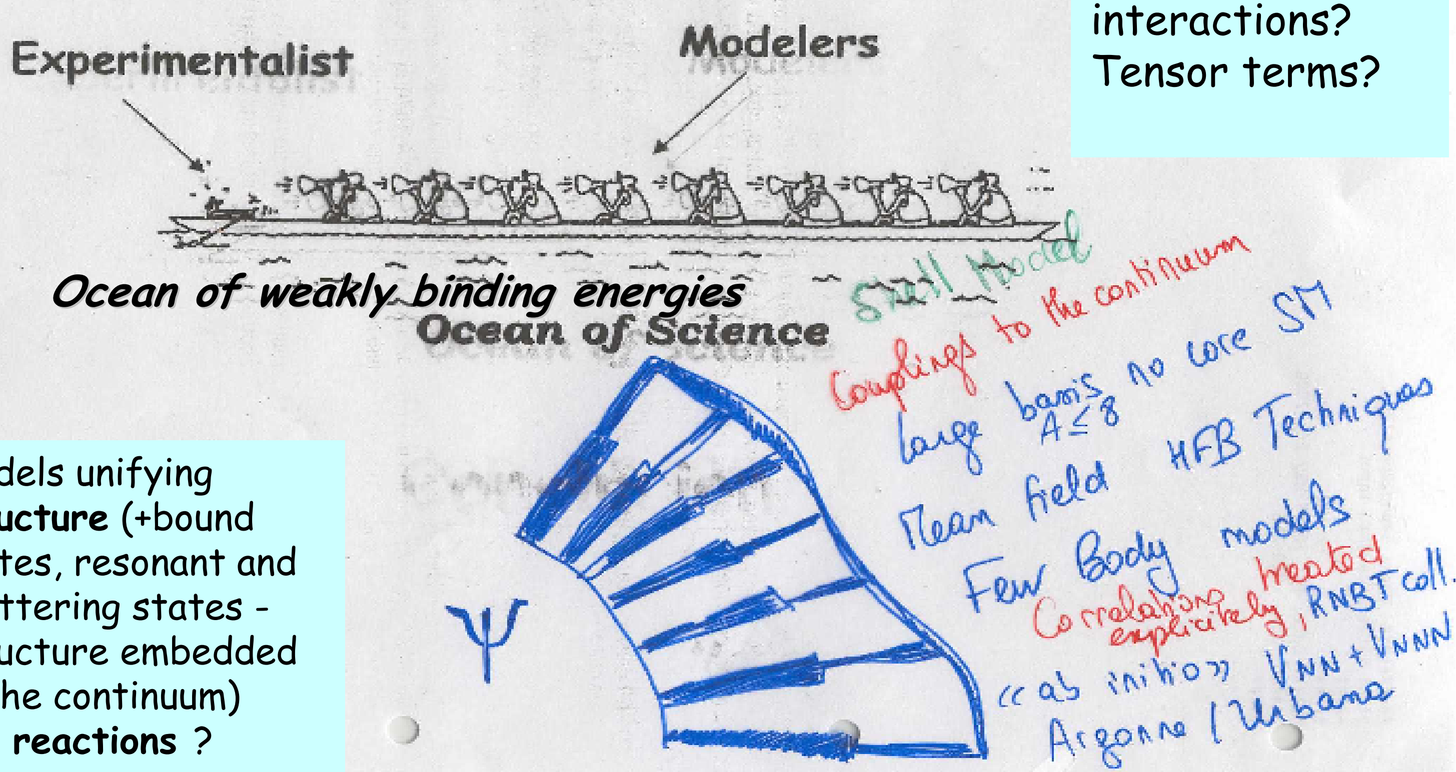
-- the other source of uncertainty comes from the validity of the nuclear interaction potential which is used to describe the interaction between projectile and target.
--also questions are on the validity of the few-body methods versus methods based upon G-matrix interaction potentials

>> also we need to check the validity of all the models in terms of energy domain.

We need to define an appropriate unified reaction framework treating:
-the interplay between structure and reactions;
-the coupling between reaction channels,
and between reactions and the transition to the continuum.

conclusions ... prospectives

Which *NN+NNN* interactions?
Tensor terms?



Models unifying **structure** (+bound states, resonant and scattering states - structure embedded in the continuum) and **reactions** ?