Neutron-proton pairing through transfer reactions : where do we stand ? + Alpha clustering in neutron-rich Be

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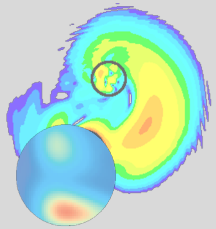
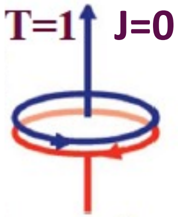
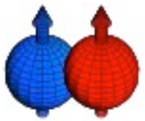


Transfer to study pairing
- **General introduction**
- **stable isotopes : sd-shell**
- **unstable nuclei: *fp* shell**
  - **recent results**
  - **future studies**

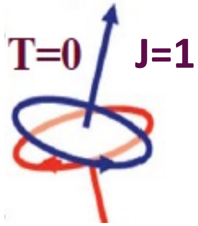
Neutron-proton pairing : generalities

T=1

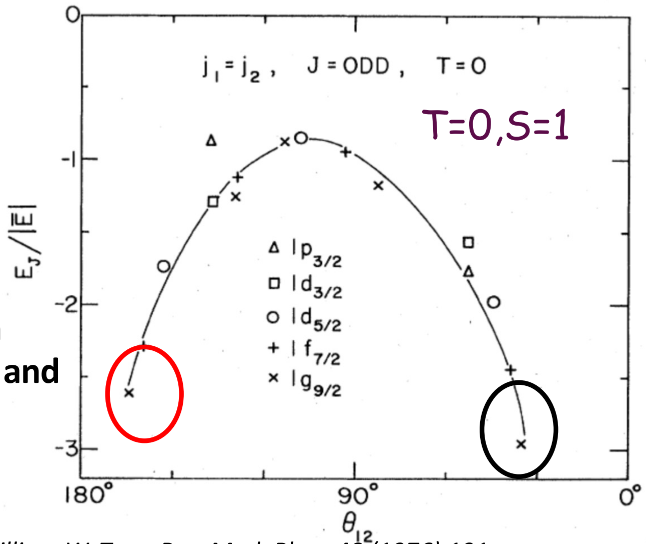




T=0



2 max. attraction for **j** anti-aligned **and aligned**



John P. Schiffer and William W. True, Rev. Mod. Phys. 48 (1976) 191

- np pairing occurs in 2 different states:
  - -**T=0** (isoscalar) <-- unique in np pairs
  - -T=1 (isovector).
- T=0 pairing is stronger than in the T=1 channel

but the question is whether or not the T=0 pairing can create a correlated state in analogy with the BCS superfluid phase.

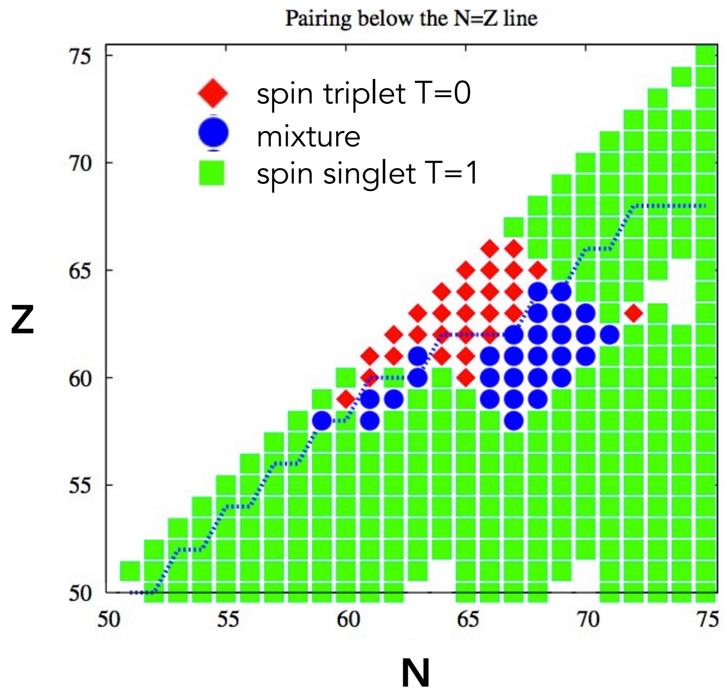
Where to search for np pairing ?

stronger in **high-j orbitals** --> fp shell

2N-transfer reactions were performed initially in the *sd*-shell nuclei and more recently in the *fp*-shell nuclei. A review of these results is presented here.

Where to search for np pairing?

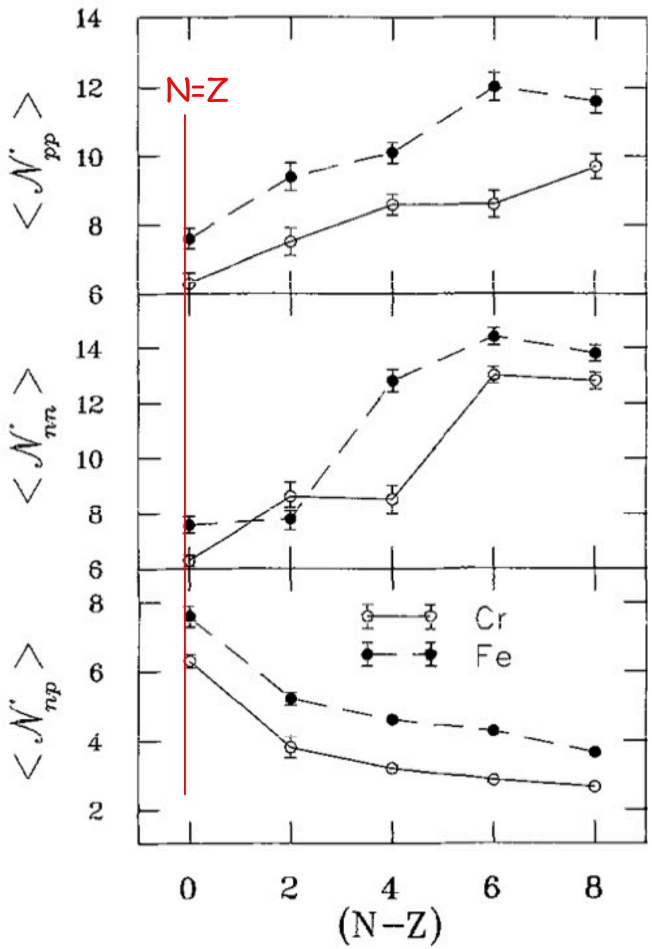
- nn, pp pairing increases when asymmetry increases
- np (T=1) pairing decreases drastically outside N=Z nuclei



Gezerlis et al, PRL (2011)

What about N≠Z nuclei ?
- Mixed state (T=0 and T=1) predicted outside of N=Z

Shell Model Monte Carlo



Engel et al, PLB 389 (1996) 211

Possible experimental probes for pairing

Masses - BE differences

can be described by an appropriate combination of the symmetry energy and the isovector pairing energy.

→ Evidence for full isovector pairing (nn,np,pp) - charge independence.

A.O. Macchiavelli PRC (2000), A.O. Macchiavelli PLB (2000)

➕ Heavy nuclei accessible, "simple" observable

Rotational properties

("delayed alignments") consistent with T=1 cranking model.

Kaneko, Sun, de Angelis, Nuclear Physics A 957 (2017) 144

➕ Heavy nuclei accessible, ➖ model dependent, no clear evidence

Knock-out reactions :

Simpson, Tostevin, 50 years of BCS

What kind of information can we get ? --> not explored experimentally yet

Deuteron transfer reaction : $< A+2|a^{+}a^{+}|A >$

Fröbrich *(Phys. Lett. 1971) -> 2.5 enhancement factor.* *Piet Van Isacker PRL (2005)*

analogous to the transition probabilities BE2's for the quadrupole case.

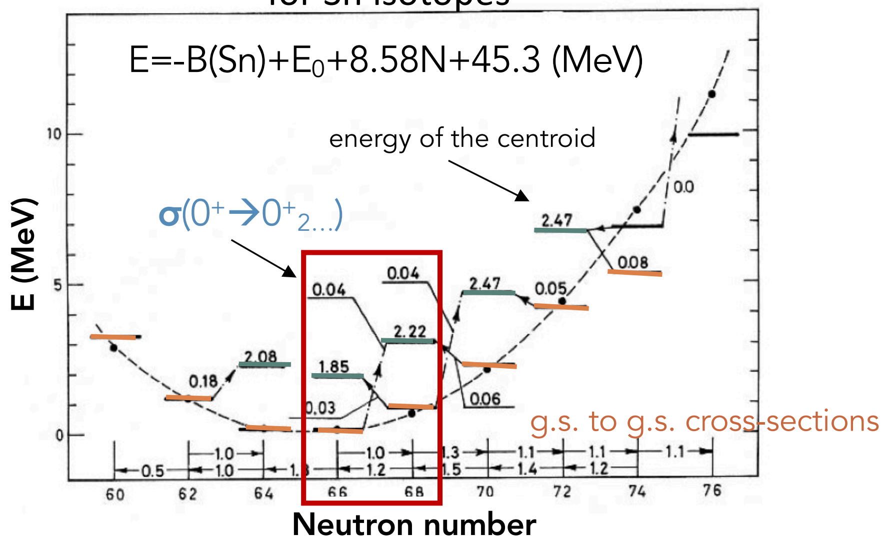
➕ THE "smoking gun"? ➖ beam intensities $>10^4$pps

In this talk

2n-transfer : Rotational vs. vibrational pairing

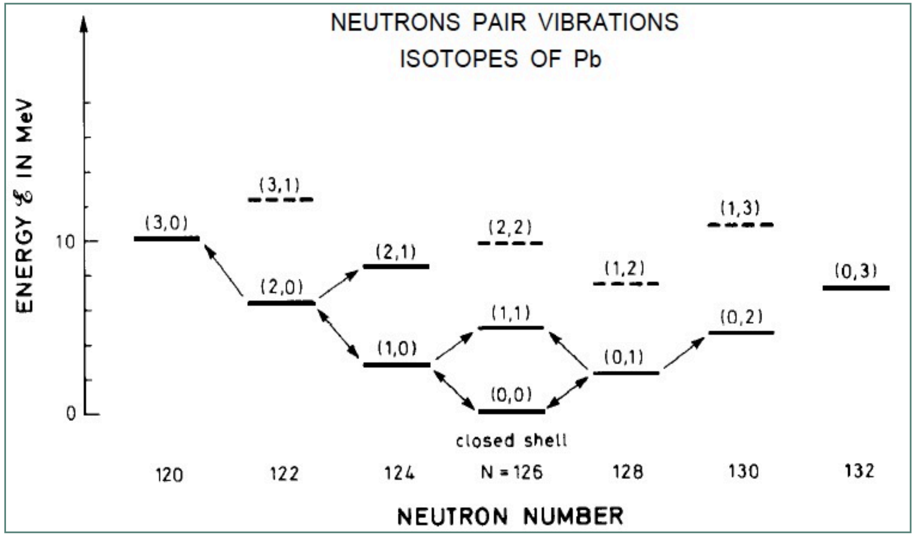
(p,t) & (t,p) : R= σ_{rot}/σ_{qp}~25

for Sn isotopes



- Open shell nuclei -> static deformation of pair field
- "Superfluid" limit
- Rotational-like (parabolic) spectrum for even-N neighbors

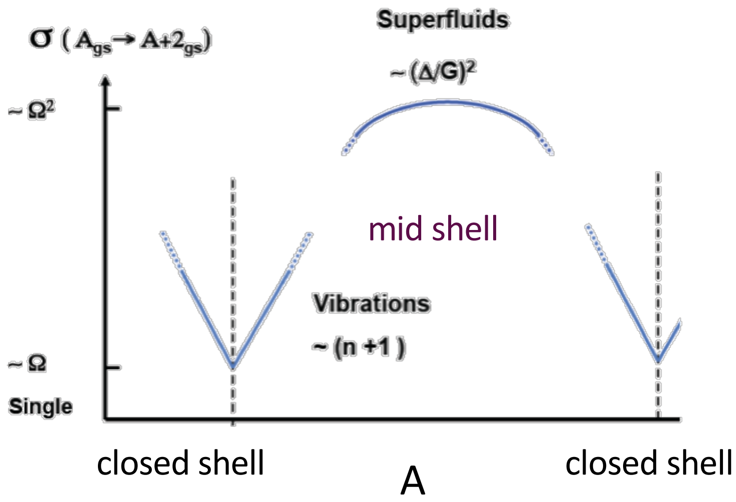
(p,t) and (t,p) : R= σ(gs (A) -> gs(A+2)) ~ Ω



- Closed shell : no static deformation of pair field
- "Normal"nuclei limit
- Vibrational-like spectrum
- Enhancement of pair addition/ pair removal cross section

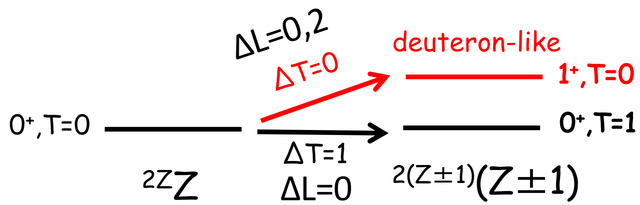
Brink & Broglia, Nuclear superfluidity, Cambridge Press University (2005)

Transposition for np-transfer reactions



If pairing is important, the 2N transfer probability should be enhanced, particularly at mid-shell and will sign the onset of a superfluid phase.

S. Frauendorf, Prog. in Part. and Nucl. Phys. (2014)
P. van Isäcker, PRL (2005)



reaction	selectivity
$(p,^3He)$	ΔT=0,1
$(^3He,p)$	ΔT=0,1
$(d,\alpha)(\alpha,^6Li)$	ΔT=0
$(\alpha,d)(^6Li,\alpha)$	ΔT=0

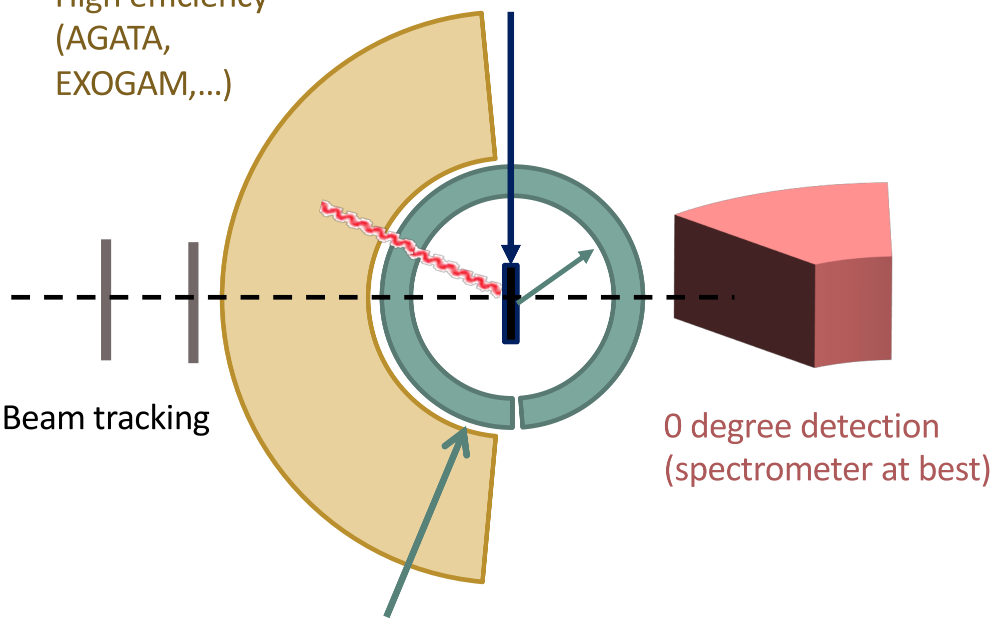
Transfer can take place in

- T=0,J=1 state (deuteron transfer)
- T=1,J=0 state (analog to 2n or 2p transfer)

The $(p,^3He)$ transfer reaction allows both channels ΔT = 0,1 to be studied

The usual observable for np transfer is the ratio $\sigma\ (0^+)/\sigma\ (1^+)$ that gives the relative strength of T=1/T=0 pairing.

Typical experimental set-up for 2N transfer experiment in the unstable N=Z nuclei

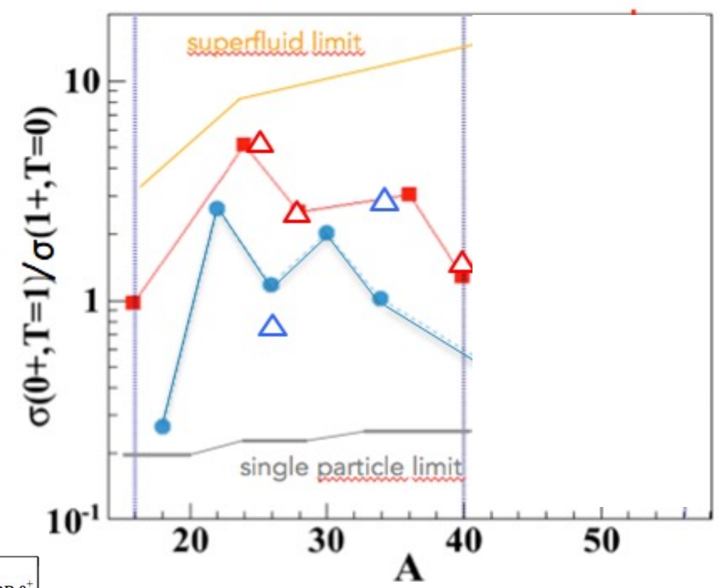


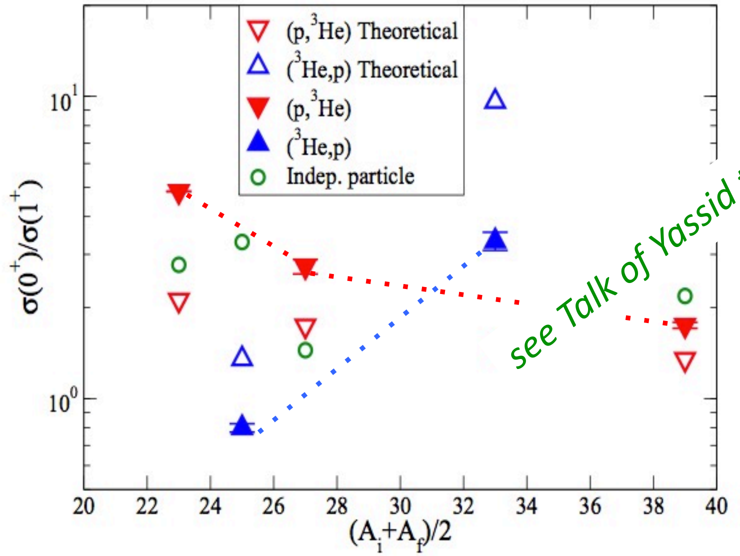
- **Low cross-sections ~100 ub and below**
  --> thick targets
  --> high beam intensities (>10^5 pps)
- **Forward and/or backward particle detection :** depending on stripping or pick-up
  --> high granularity (angular distributions)
  --> good Pid
- **High resolution & high efficiency gamma array :** 2N transfer populate residual odd-odd nuclei with high density of states
- **Integration of ^{3}He cryogenic targets** for (^{3}He,p) measurements
- 0 degree detection to clean the spectra from background contributions

Systematic of dσ(0+)/dσ(1+)

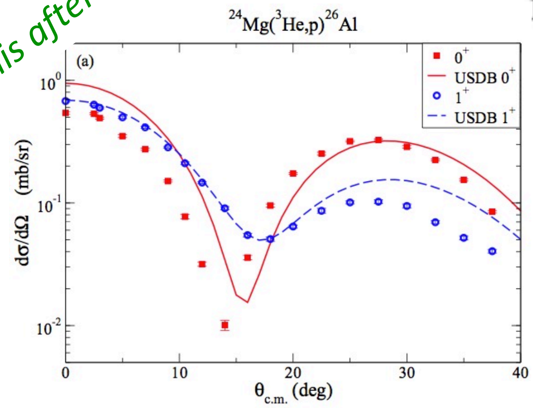
(p,^{3}He)
(^{3}He,p)

- **sd-shell systematic measurement (stable nuclei)**
  - ❑ *From litterature & ENSDF:*
    - max of cross-section (lowest angle measured) + no error bars
    - first 0+ and first 1+ states taken into account (no centroid)
  - ❑ *Recent consistent remeasurement* : *Y. Ayyad et al, PRC96 (2017) (open triangles)*





see Talk of Yassid this afternoon !



Systematic of dσ(0+)/dσ(1+)

- *sd*-shell systematic measurement (stable nuclei)
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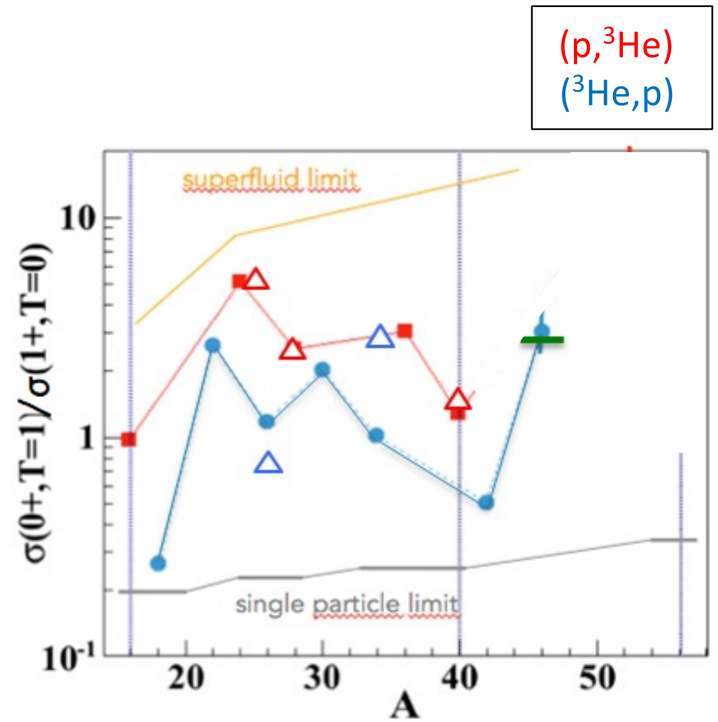
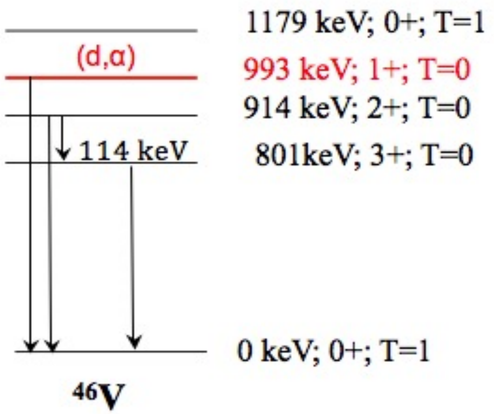
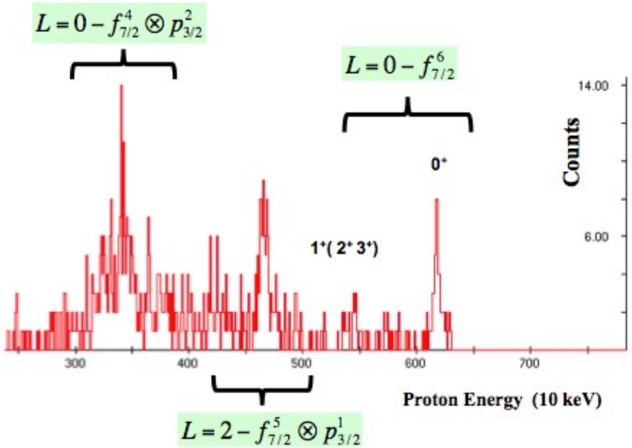


- *fp* shell measurements :
  - $^{44}Ti(^3He,p)^{46}V$
    in inverse kinematics @ Argonne *(A.O. Macchiavelli et al)*





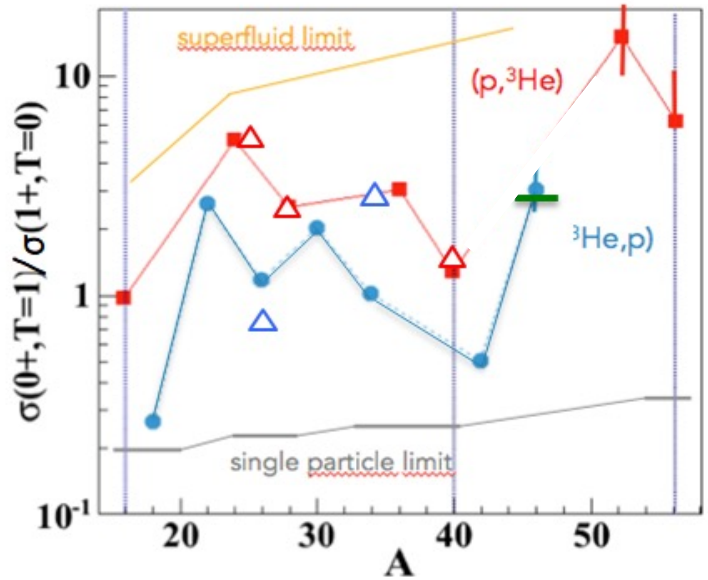
courtesy of A.O. Macchiavelli

Systematic of dσ(0+)/dσ(1+)

- **sd-shell systematic measurement (stable nuclei)**
  - ❑ *From litterature & ENSDF:*
    - max of cross-section (lowest angle measured) + no error bars
    - first 0+ and first 1+ states taken into account (no centroid)
  - ❑ *Recent consistent remeasurement* : *Y. Ayyad et al, PRC96 (2017) (open triangles)*

- **fp shell measurements :**
  - ❑ ^{44}Ti(^{3}He,p)^{46}V in inverse kinematics @ Argonne *(A.O. Macchiavelli et al)*
  - ❑ ^{56}Ni, ^{52}Fe, ^{48}Cr(p,^{3}He)^{54}Co,^{50}Mn : in inverse kinematics @ LISE *(M. Assié et al)*

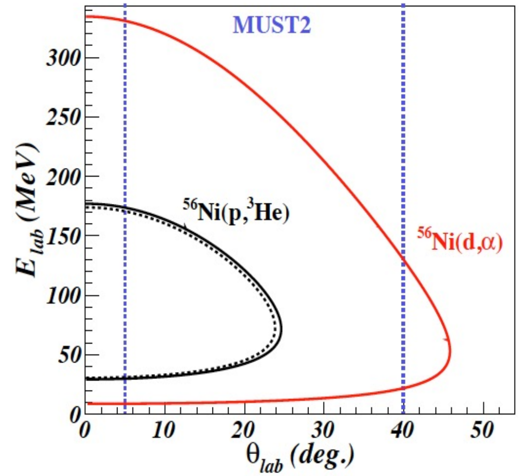
(p,^{3}He)
(^{3}He,p)



❑ Ratios obtained in different experiments and at different energies
--> effect of the reaction mechanism

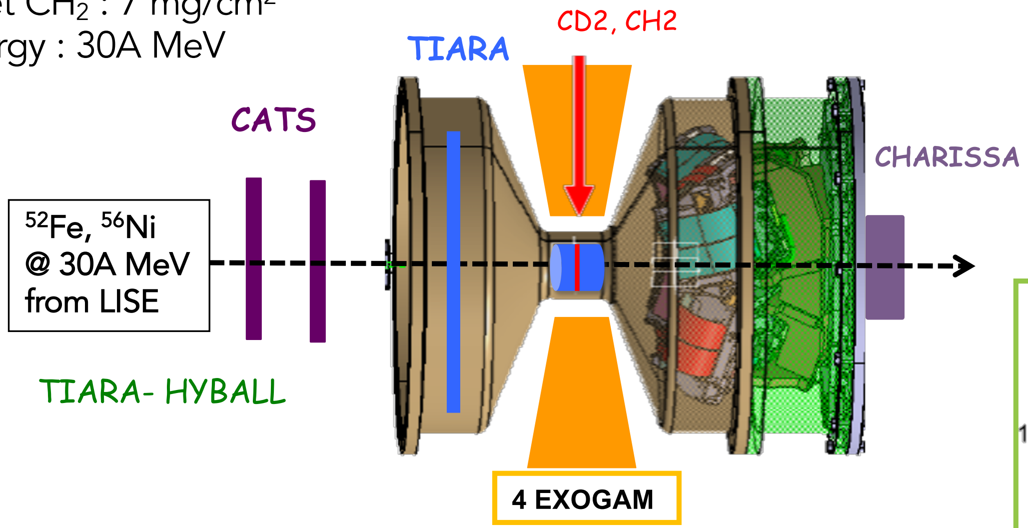
❑ L=0 and L=2 contributions overlaping
--> angular distributions needed

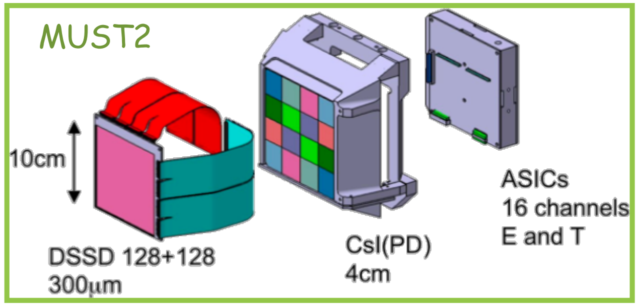
Experimental set-up on LISE



^{56}Ni(p,^{3}He)^{54}Co & ^{52}Fe(p,^{3}He)^{50}Mn

Beams produced by fragmentation of ^{58}Ni primary beam
thick target CH_2 : 7 mg/cm^2
beam energy : 30A MeV

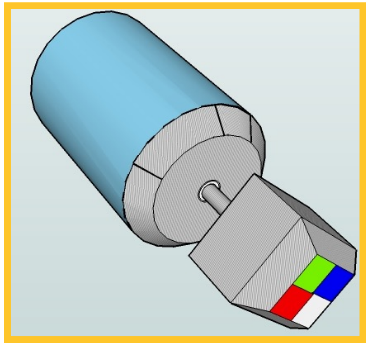


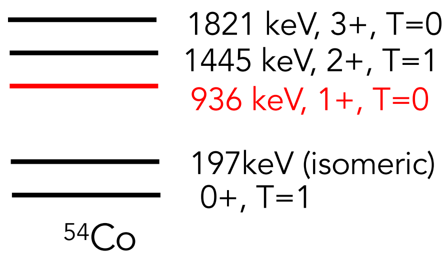


Efficiency ~8%@ 1 MeV

Energy resolution 3 keV

Doppler broadening 80 keV



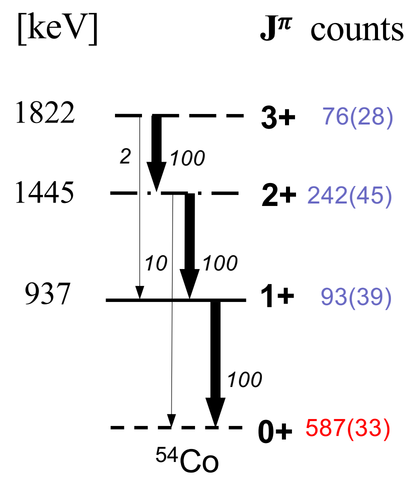


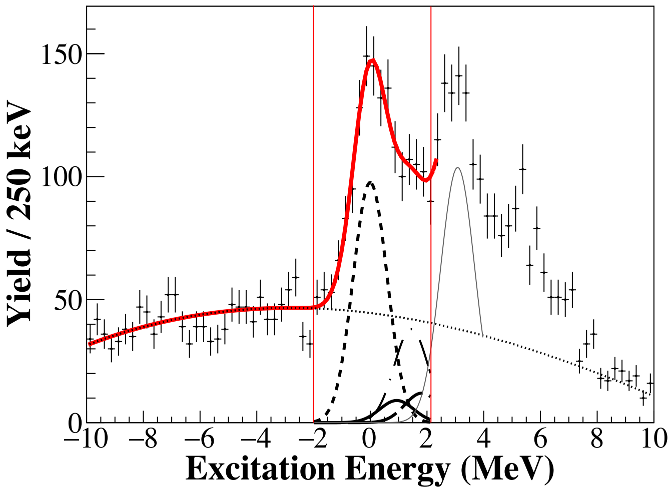
The (p,^{3}He) reaction on ^{56}Ni & ^{52}Fe

B. Le Crom et al, PLB (2022)

closed shell nucleus

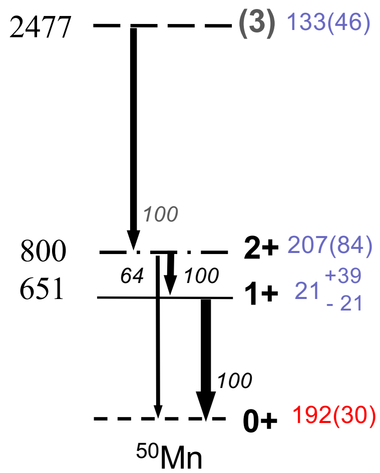
^{56}Ni(p,^{3}He)^{54}Co

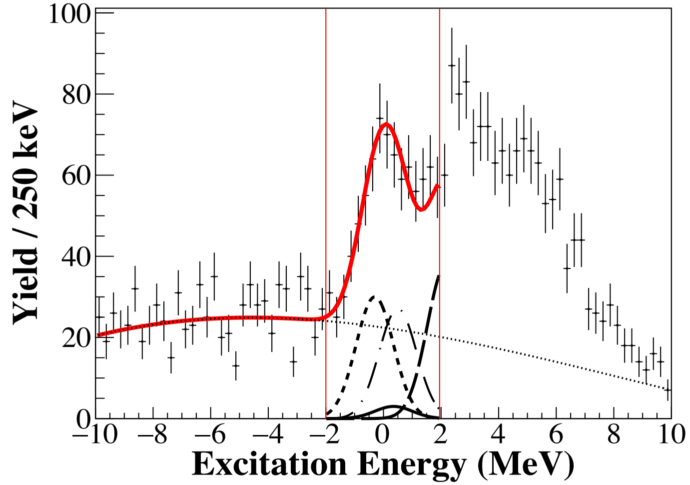




^{52}Fe(p,^{3}He)^{50}Mn

open shell nucleus



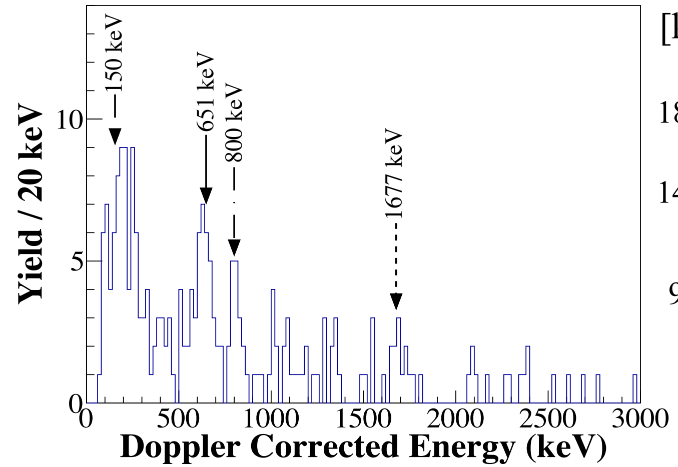


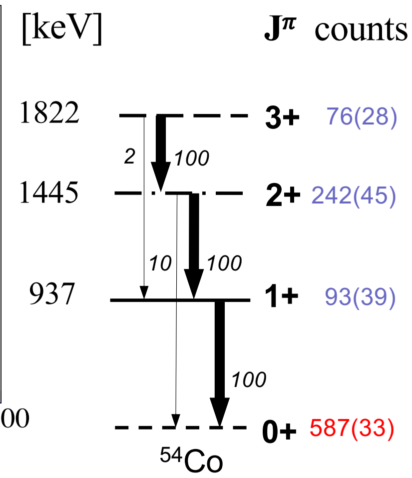
The (p,^{3}He) reaction on ^{56}Ni & ^{52}Fe

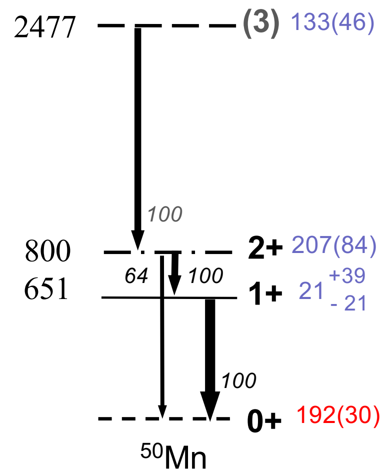
B. Le Crom et al, PLB (2022)

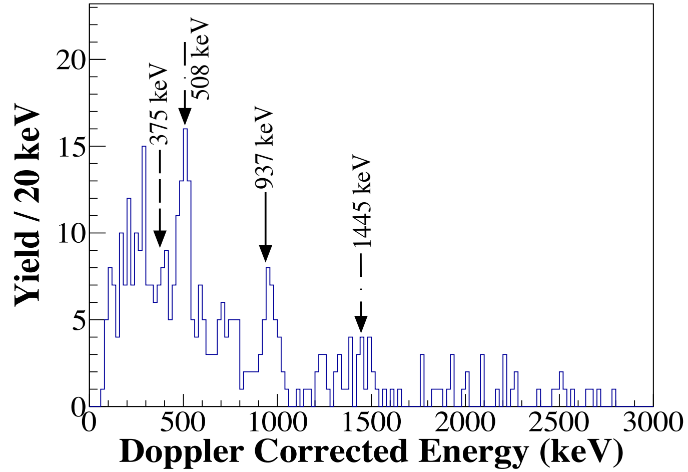
closed shell nucleus — ^{56}Ni(p,^{3}He)^{54}Co

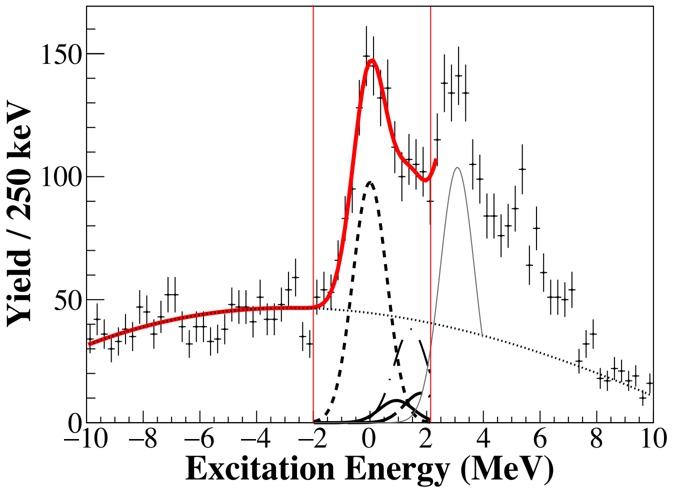
open shell nucleus — ^{52}Fe(p,^{3}He)^{50}Mn



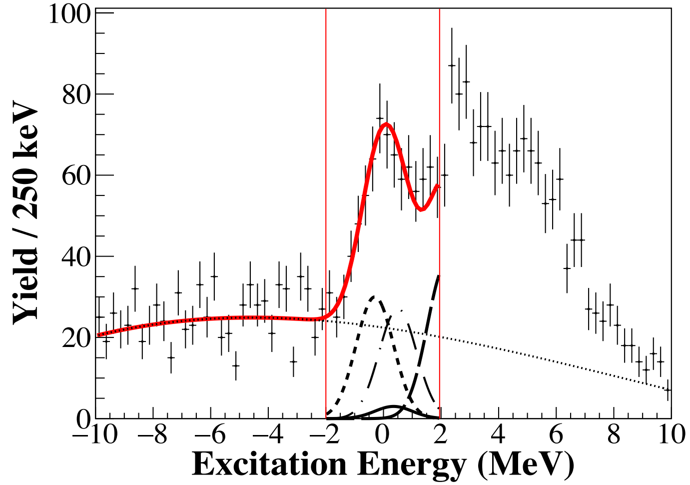








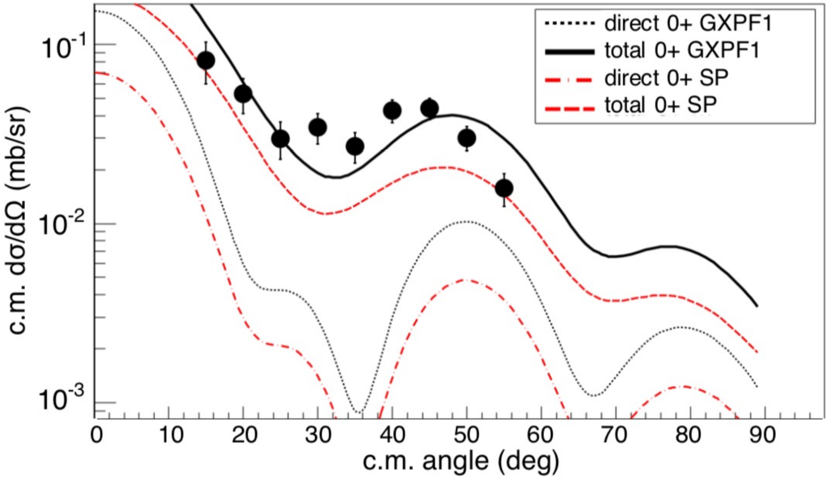
	σ(0+,T=1) (μb)	σ(1+,T=0) (μb)	Ratio
	^{56}Ni(p,^{3}He)^{54}Co		
this work	$109 \overset{stat}{\pm 5} \overset{sys}{\pm 10}$	$17 \overset{stat}{\pm 7} \overset{sys}{\pm 2}$	$6.3^{+3.1}_{-2.1}$
SP	73	19	3.8
GXPF1	136	21	6.4
	^{52}Fe(p,^{3}He)^{50}Mn		
this work	$145 \overset{stat}{\pm 12} \overset{sys}{\pm 15}$	$16^{+29}_{-16} \overset{sys}{\pm 2}$	$9.1^{+\infty}_{-3.7}$
SP	69	16	4.3
GXPF1	257	17	15.1



Comparison with DWBA

B. Le Crom et al, PLB (2022)

Angular distribution for g.s. of ^{54}Co



▸ DWBA calculations

- with form factors from Sagawa-san team including other shells than $f_{7/2}$ (**pairing case**) using GXPF1 interaction
- with single particle form factors (**no pairing case**)

Potentials set from ^{56}Ni(p,d) measurement

▸ Direct vs. sequential ?

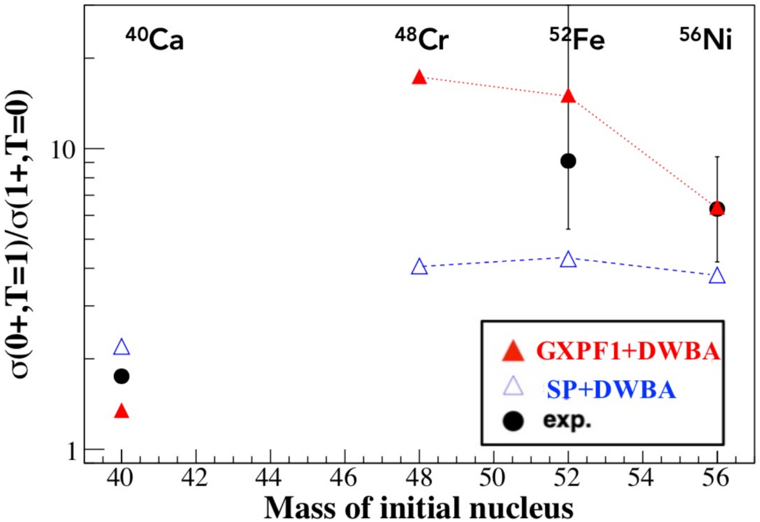
correlations kept in the sequential transfer ?

Potel, Rep. Prog. Phys. 76 (2013) 106301

▸ Comparison of ratios of CS

- Good agreement between exp and DWBA+pairing (although with large error bars)

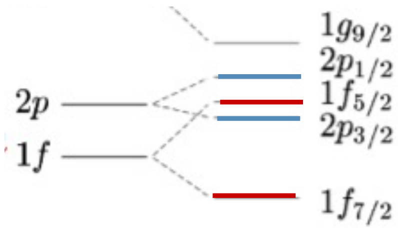
- T=1 ~ superfluid, T=0 very weak due to the effect of spin-orbit that hinders T=0 pairing in the *fp*-shell.



Open questions on np pairing with transfer

1- Effect of the spin-orbit ?

- **Spin-orbit splitting** hinders T=0 pairing in the **f-shell**



T=1 $(1f_{7/2})^2$ & $(1f_{5/2})^2$
T=0 $(1f_{7/2})^2$ & $(1f_{5/2})^2$ &$(1f_{7/2})(1f_{5/2})$

- **What would be the effect for the 2p shell ?** (smaller spin-orbit splitting)
  --> case of ^{58}Cu
  --> ^{58}Cu only odd-odd nucleus in fp-shell with g.s. T=0

- **Is there any effect of spin-orbit in the sd-shell ?**
  $d_{3/2}$ and $d_{5/2}$ spin-orbit splitting of the same order of magnitude as for $f_{7/2}$ and $f_{5/2}$ and even stronger in the *g*-shell

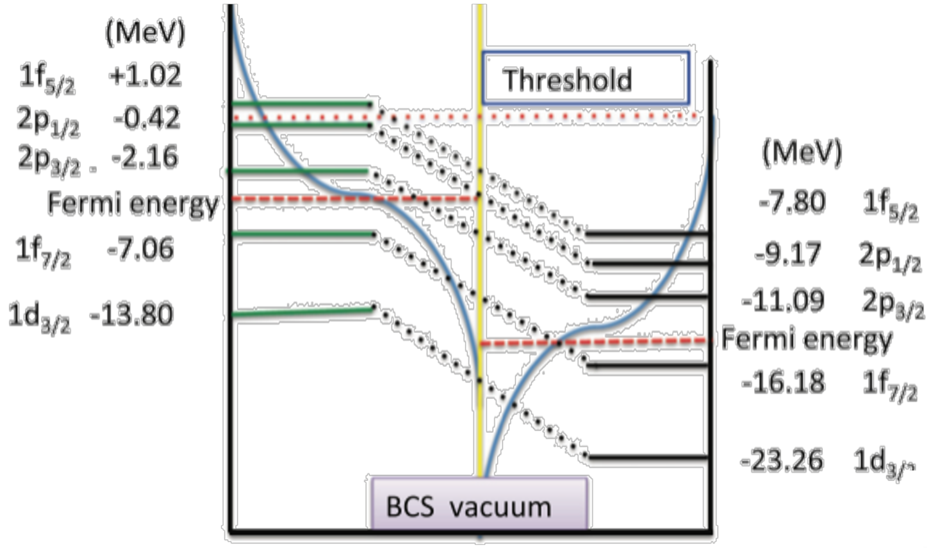
2- Effect of other (repulsive) channels ?

- **Baroni et al PRC 2010 :** T=0 pairing weakened by the contributions of $^1P_1$ and D-wave (repulsive)

Open questions on np pairing with transfer

3- Coulomb effect ?

8.8 MeV gap between $f_{7/2}$ n and p in ^{56}Ni



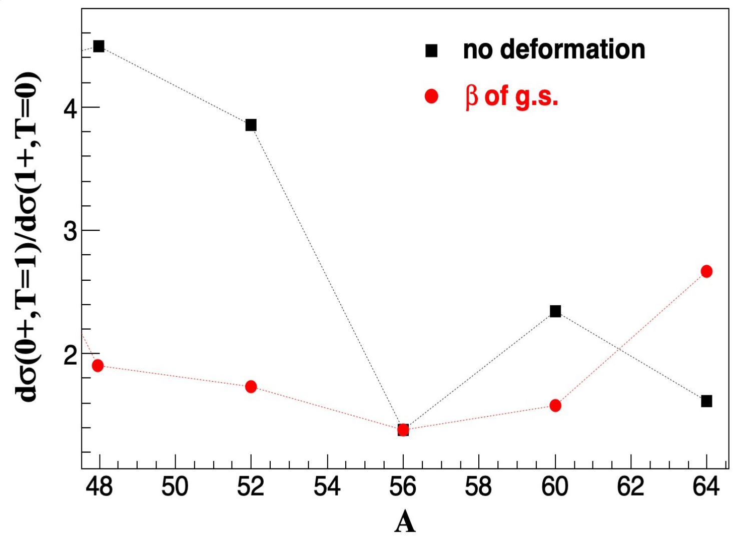
4- Effect of deformation ?

- **The case of ^{48}Cr**

Deformation affects strongly the ratios of the CS in particular in ^{48}Cr

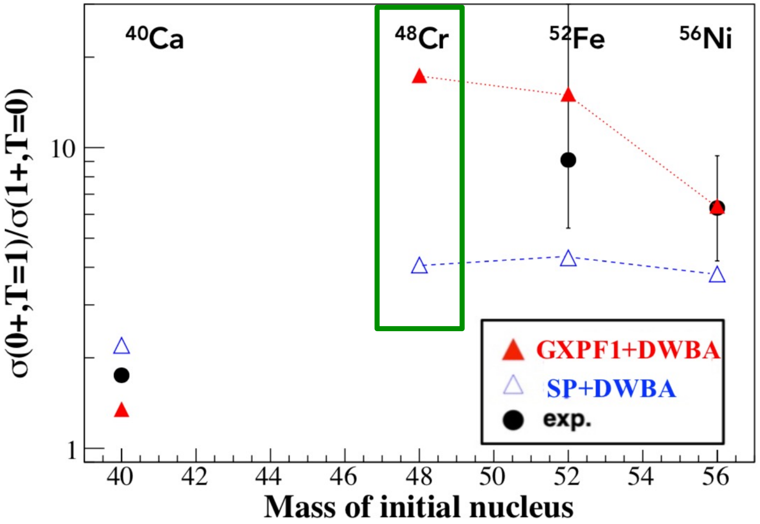
→ **experiment performed at GANIL : ^{48}Cr(p,^{3}He) run in 2023**

PhD thesis of Hugo Jacob



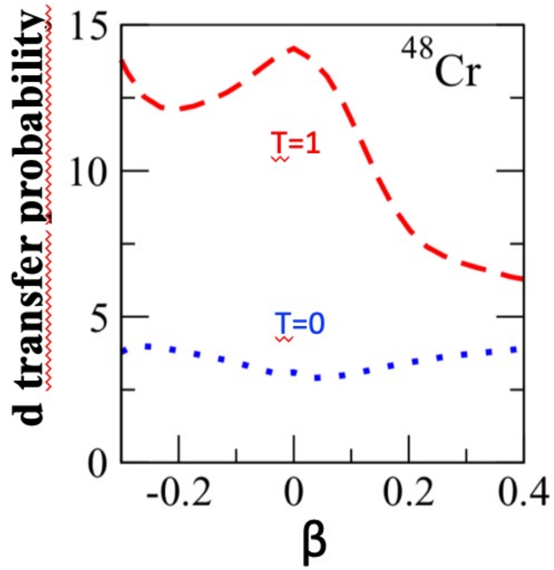
. Gambacurta, D. Lacroix, Phys. Rev. C 91 (2015)

Interplay between pairing and deformation



- Case of ^{48}Cr : comparison with ratios predicted by DWBA calculations for 2 cases:
  - single particle case (no pairing)
  - np pairing through TNA from Shell Model + GXPF1 calculations (pairing)

^{48}Cr	ENSDF	GXPF1
B(E2, 2+->0+) w.u.	31 (4)	20.5
β_2	0.368	



- Recent calculations combining deformation and pairing

  D. Gambacurta, D. Lacroix, Phys. Rev. C 91 (2015)

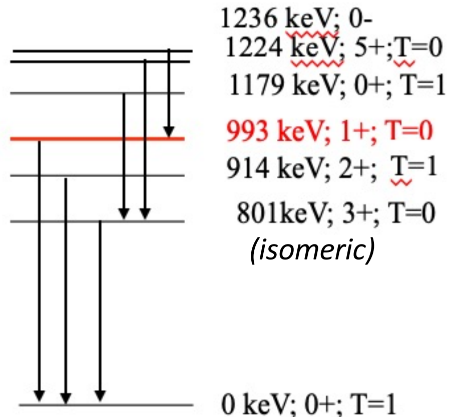
  --> It affects mainly the T=1 component

  --> The ratio could be lowered by a factor of about 3

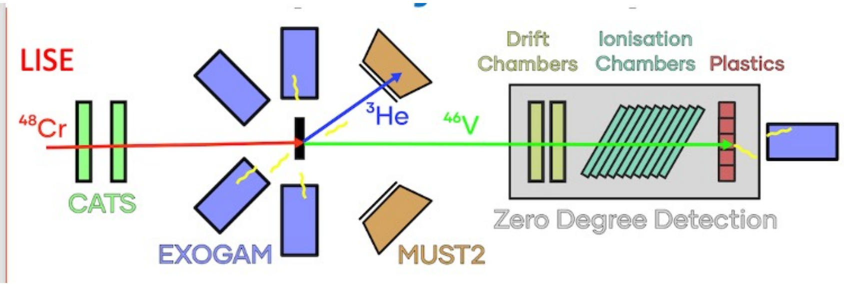
The main goal of the experiment is to measure the ratio $\sigma(0^+)/\sigma(1^+)$ for $^{48}Cr(p,^3He)^{46}V$ to compare with theoretical predictions.

Experimental method for $^{48}Cr(p,^{3}He)^{46}V$

<u>Beam production</u>:
Fragmentation of $^{50}Cr^{23+}$ at 72 MeV/u on 1 mm thick ^{9}Be target to produce ^{48}Cr at 30 MeV/u with 10^{6}pps and 90% purity.
<u>Target</u>: CH_2 target 5 mg/cm^2
<u>Experimental set-up:</u>
Given the high density of states in ^{46}V, particle-gamma coincidence needed.

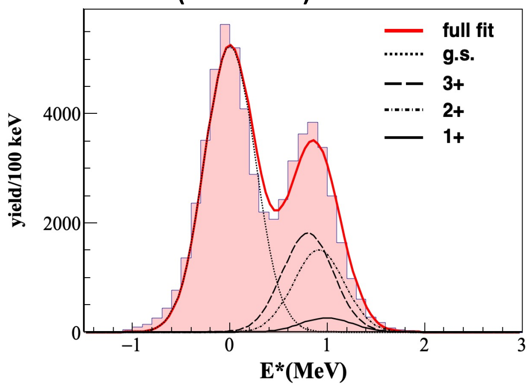


Level scheme of ^{46}V

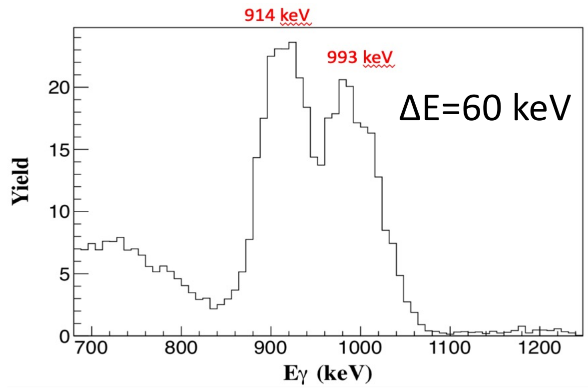


Excitation energy (from particle)

ΔE (FWHM)=611 keV



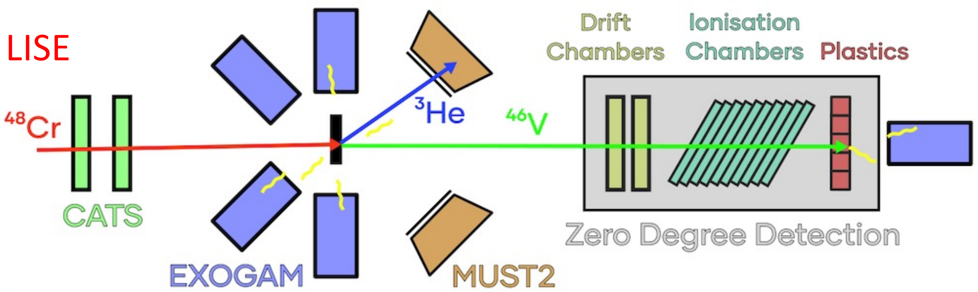
EXOGAM response to 1+ & 2+ decay

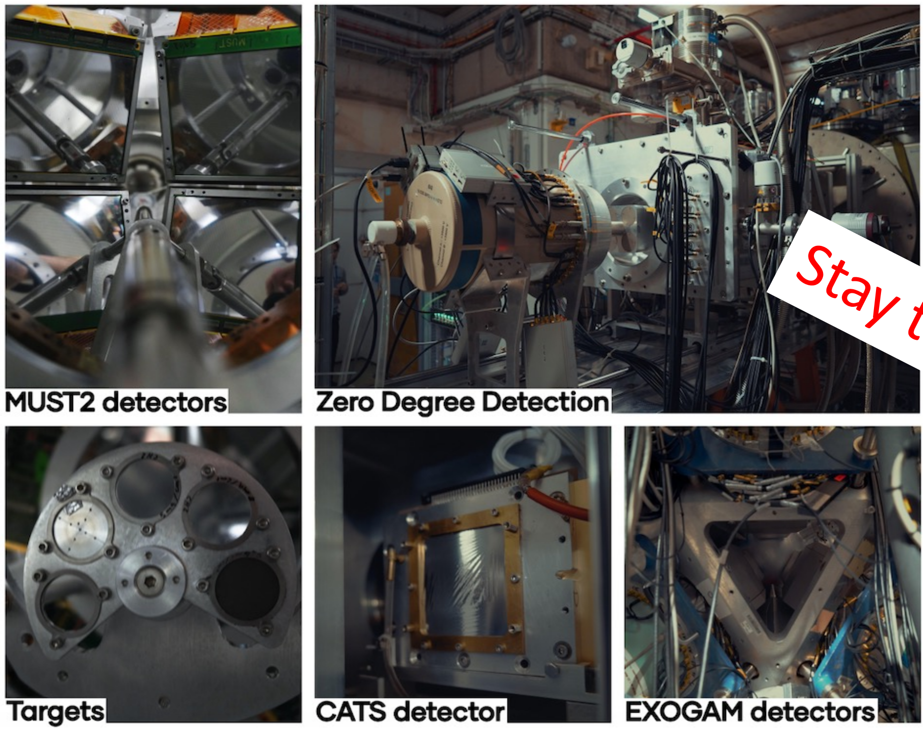


--> For the 0+,T=1 (g.s.) : σ (0$^+$) & angular distribution can be deduced from E* measurement
--> For the 1+,T=0 (993 keV) : particle-gamma coincidence to determine σ (1$^+$)
angular distribution from gamma gated E* spectrum (if enough statistics)

Study of the two-nucleon transfer reaction $^{48}Cr(p,^{3}He)^{46}V$

MUGAST spokesperson : V. Girard-Alcindor

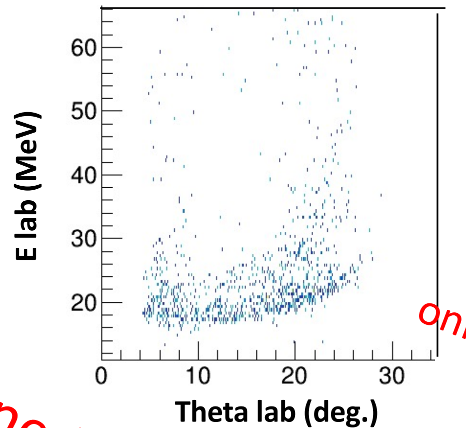


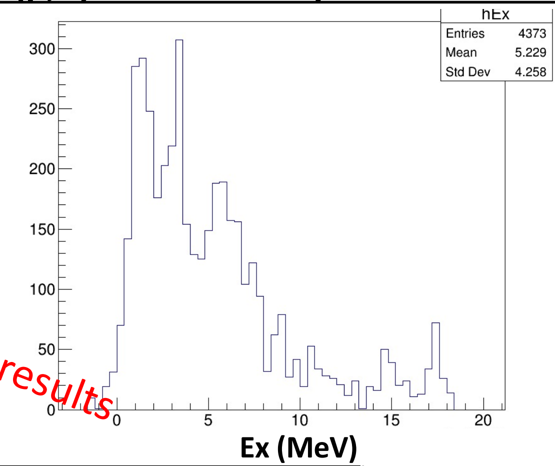


Stay tuned ...

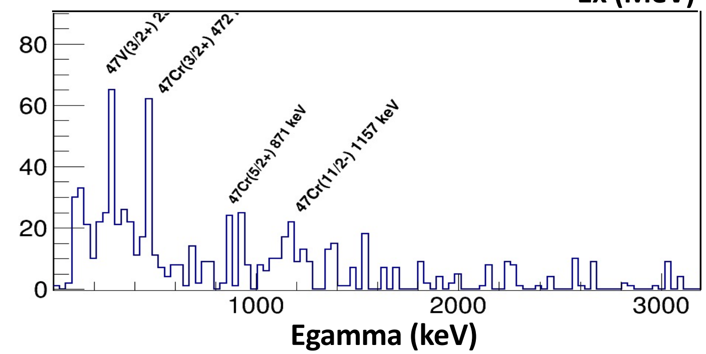
- ^{48}Cr : 2.5 10^5 pps, 97% purity
- CH_2 target

Preliminary results from $^{48}Cr(p,d)$ with a small part of statistics





online results



Thank you for your attention and thank you to

V. Girard-Alcindor, H. Jacob (IJCLab)

B. Le Crom[a], M. Assié[a,*], Y. Blumenfeld[a], J. Guillot[a], H. Sagawa[b], T. Suzuki[c], M. Honma[b], N.L. Achouri[d], M. Aouadi[d], B. Bastin[e], R. Borcea[f], W.N. Catford[g], E. Clément[e], L. Cáceres[e], M. Caamaño[h], A. Corsi[i], G. De France[e], M-C. Delattre[a], F. Delaunay[d], N. De Séréville[a], Q. Deshayes[d], B. Fernandez-Dominguez[h], M. Fisichella[j], S. Franchoo[a], A. Georgiadou[a], J. Gibelin[d], A. Gillibert[i], F. Hammache[a], O. Kamalou[e], A. Knapton[g], V. Lapoux[i], S. Leblond[d], A.O. Macchiavelli[k], F.M. Marqués[d], A. Matta[g,1], L. Ménager[e], P. Morfouace [a,2], N.A. Orr[d], J. Pancin[e], X. Pereira-Lopez[d,h], L. Perrot[a], J. Piot[e], E. Pollacco[i], D. Ramos [h,3], T. Roger[e], F. Rotaru[f], A. M. Sánchez-Benítez[l,4], M. Sénoville[i], O. Sorlin[e], M. Stanoiu[f], I. Stefan[a], C. Stodel[e], D. Suzuki[a,5], J-C Thomas[e], M. Vandebrouck[e,6]

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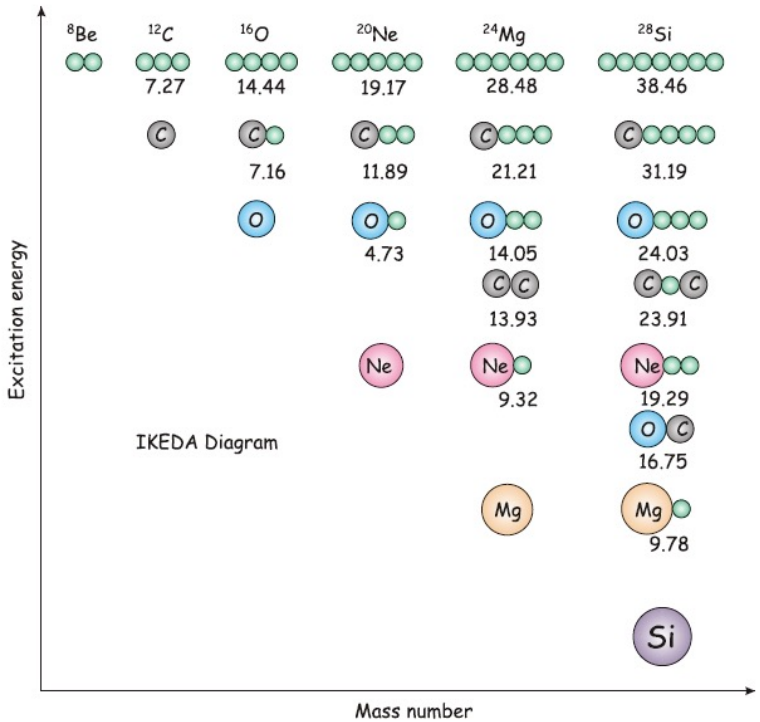
Alpha clusters in the neutron-rich Be isotopes

courtesy of D. Beaumel, IJCLab

Clustering in light nuclei

The Ikeda diagram

For N=Z=2n "alpha-conjugate" nuclei



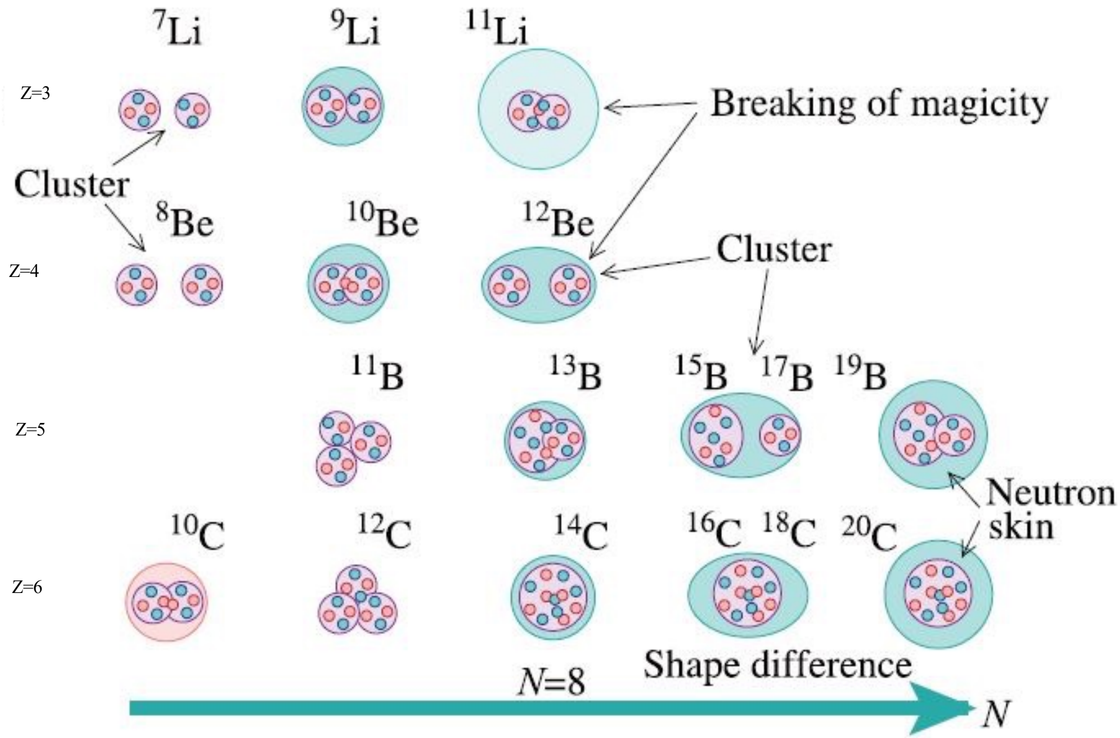
K.Ikeda, N.Takigawa, H.Horiuchi, **PTP (1968)**

- Cluster structure typically occurs close to cluster decay thresholds
- Based on properties of some near threshold states
  - ✓ Rotational bands with molecule-like structure
    Very large moment of inertia
  - ✓ Large alpha-decay widths

⇒ Unified picture of clustering

Clustering in light neutron-rich nuclei

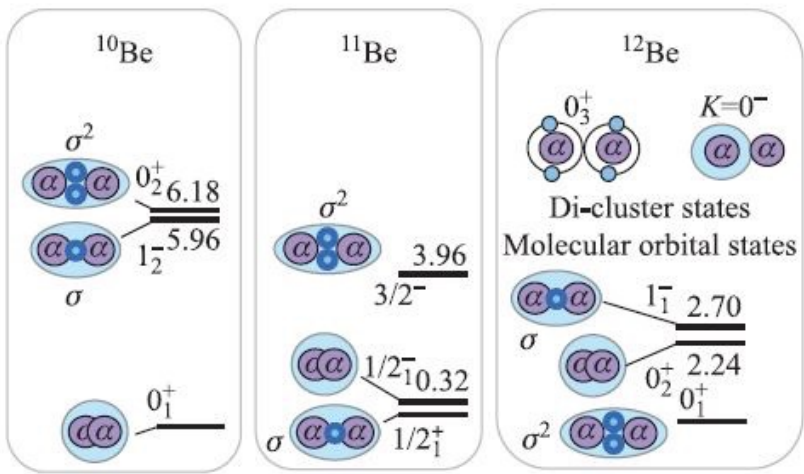
GROUND-STATES !



Antisymmetrized Molecular Dynamics (AMD)
Y.Kanada-En'yo, H.Horiuchi, Front. Phys. 13 (2018)

When Adding neutrons to N=Z nuclei:
Various Molecular structures
Neutron orbiting around the core of clusters
for low-lying states including the ground-state

Case of neutron rich Be



p orbit ↔ p-orbit in SM limit – reduce clustering
s orbit ↔ sd intruder configuration –enhance clustering

Calls for direct evidence of Molecular structure !

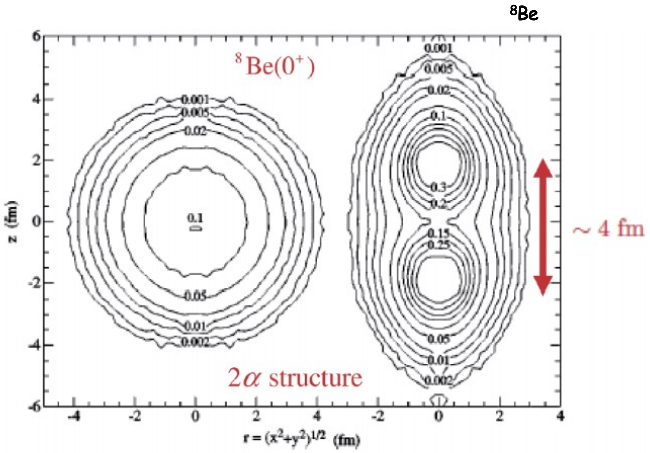
Calculations from first principles for Be isotopes

QMC calculation for ^{8}Be

R.B. Wiringa, S.C.Pieper, J.Carlsson, V.R. Pandharipande, Phys. Rev. C 62 (2000)

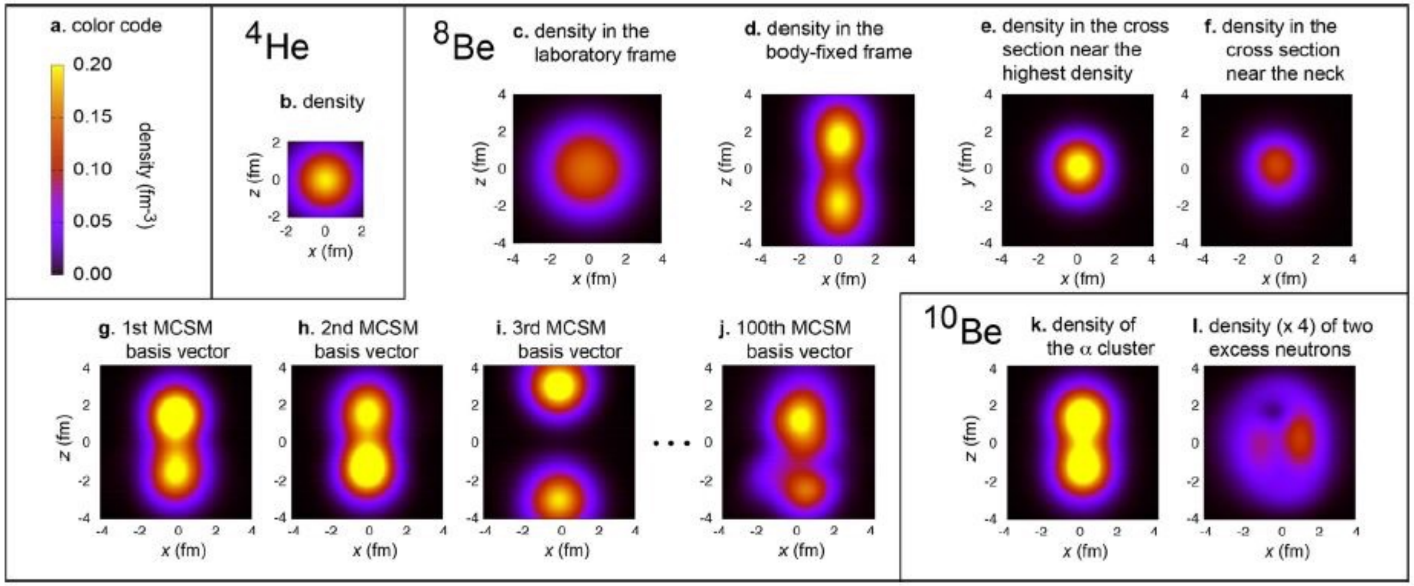
Quantum Monte-Carlo

AV18 + Urbana IX



Rotational band well reproduced

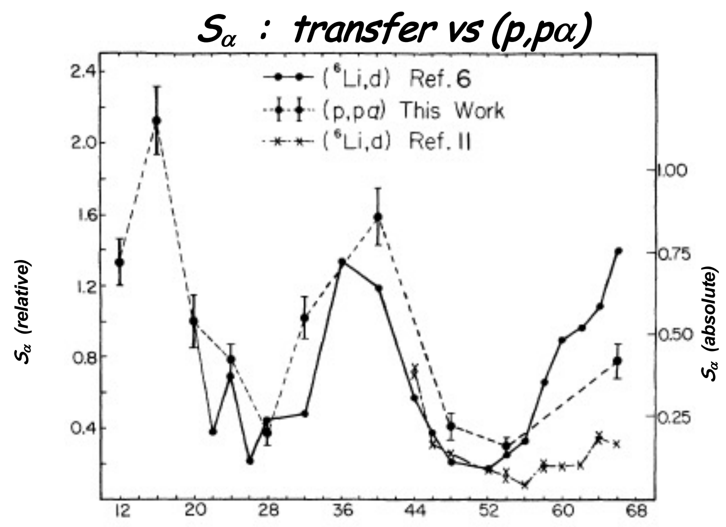
Be isotopes in no-core Monte-Carlo Shell Model



T.Otsuka, T.Abe et al., Nature comm. 2022

Cluster knockout reactions

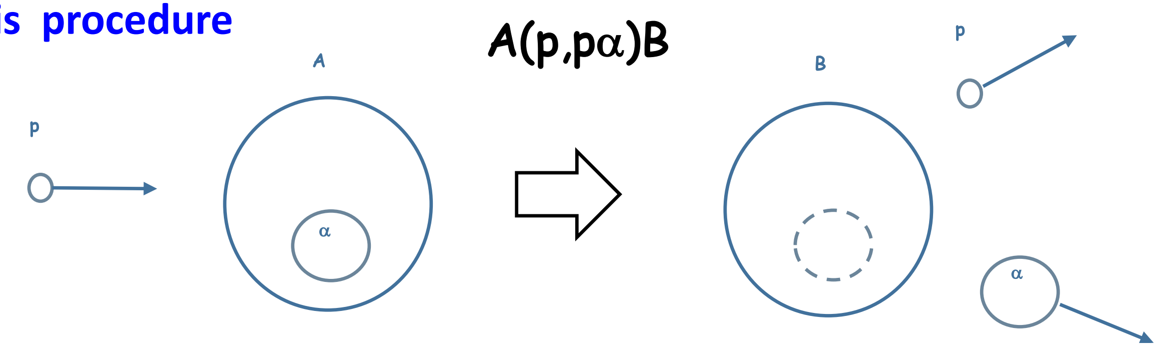
- Direct reaction
  - ✓ short reaction time (~10^{-22}s)
  - ✓ one-step dominant
- (e,e'p), (p,2p) and (p,pn) for nucleons
  (p,pa), (a,2a) for alpha cluster
- Well-studied since the 70's with proton and alpha beams on stable targets
- Incident p energy : 100~400 MeV
  (l ~ 0.5-0.25fm)
- *Peripheral* reaction
- Extraction of spectroscopic factors S_a



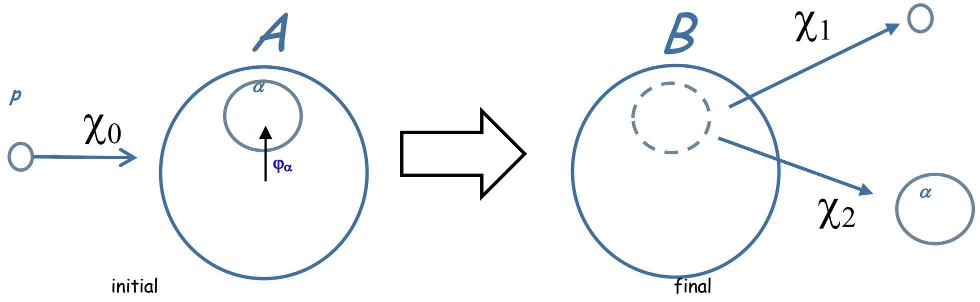
(T. Carey et al., PRC (1984)) ***Target mass No.***

- **Recently: new analysis procedure**

A(p,pα)B



Amplitude and cross-section in Distorted Wave Impulse Approximation (DWIA)



DWIA

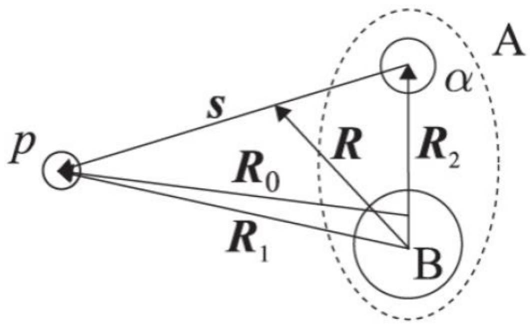
$$\frac{d^3\sigma}{dE_1^L d\Omega_1^L d\Omega_2^L} = F_{\text{kin}} C_0 \frac{d\sigma_{p\alpha}}{d\Omega_{p\alpha}} (\theta_{p\alpha}, E_{p\alpha}) \left| \bar{T}_{P_0 P_1 P_2} \right|^2$$

Kinematical factor

Constant

2-body p–α Xsection

Transition amplitud



$$T_{P_0P_1P_2} = \left\langle \chi_{1,P_1}^{(-)}(R_1)\, \chi_{2,P_2}^{(-)}(R_2) \left| t_{p\alpha}(s) \right| \chi_{0,P_0}^{(+)}(R_0)\, \varphi_\alpha(R_2) \right\rangle$$

$\chi_{0,P_0}^{(+)}(R_0)$ $\chi_{1,P_1}^{(-)}(R_1)$ $\chi_{2,P_2}^{(-)}(R_2)$ distorted waves for p-A, p-B and α-B
Obtained from elastic scattering dat

$t_{p\alpha}(s)$ Transition interaction

$\varphi_\alpha(R_2)$ **Cluster Wave function**

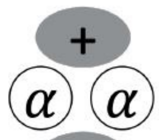
- Phenomenological
- **Microscopic (AMD, ab initio …)**

THSR-based calculations for ^{10}Be(p,pα) ^{6}He$^{(GS)}$ at 250 MeV/u

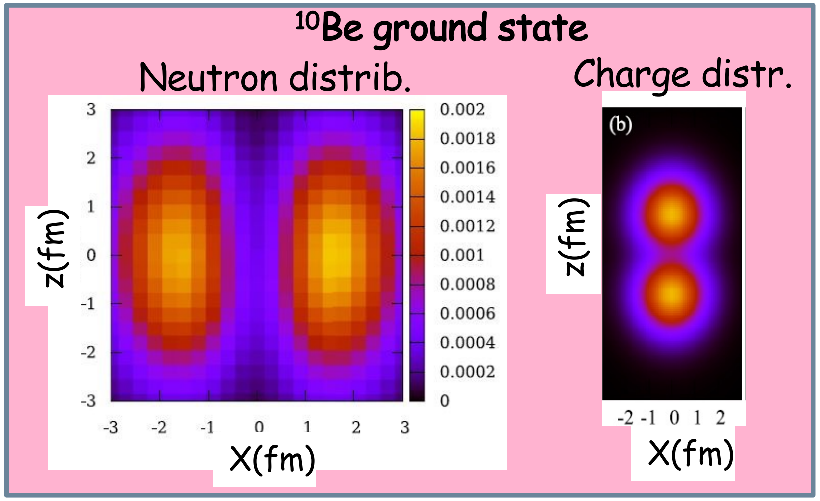
M.Lyu et al., PRC 97 (20.

Tohsaki, Horiuchi, Schuck, Röpke (THSR) wave-function
Well adapted to discuss cluster states in light nuclei
→ Cluster wave-function
  overlap of ^{10}Be and ^{6}He
→ Optical potentials
  folding of calculated density

^{10}Be: 2a + 2n(p)



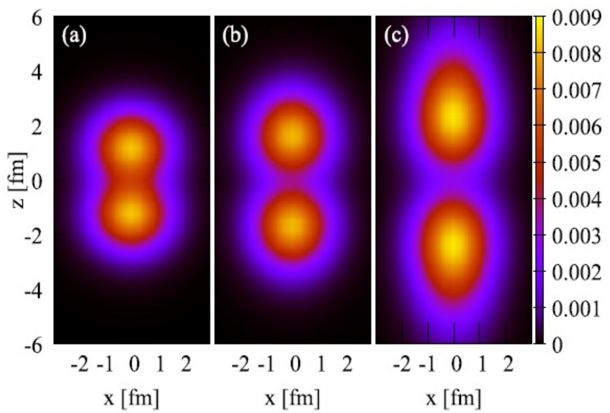
π-orbit



Good reproduction of :

- ^{10}Be GS energy
- Charge radius 2.31fm (exp=2.36fm)

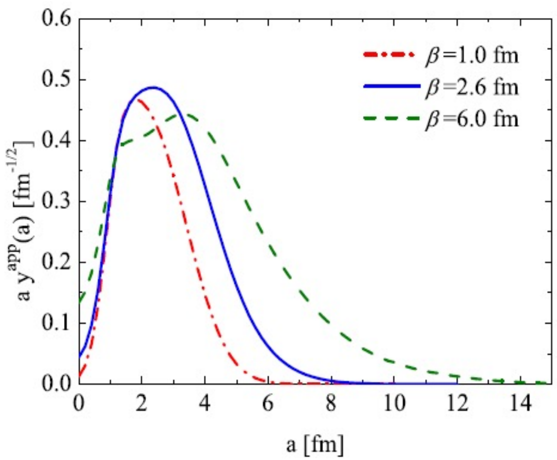
^{10}Be charge distribution



↑ **Variational result**

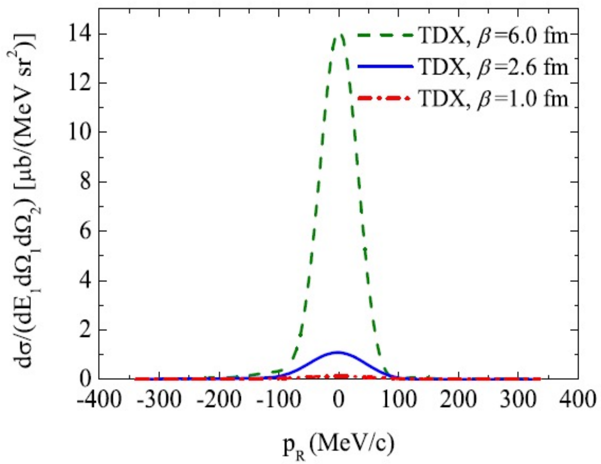
RWA

Cluster wave-function



DWIA calc.

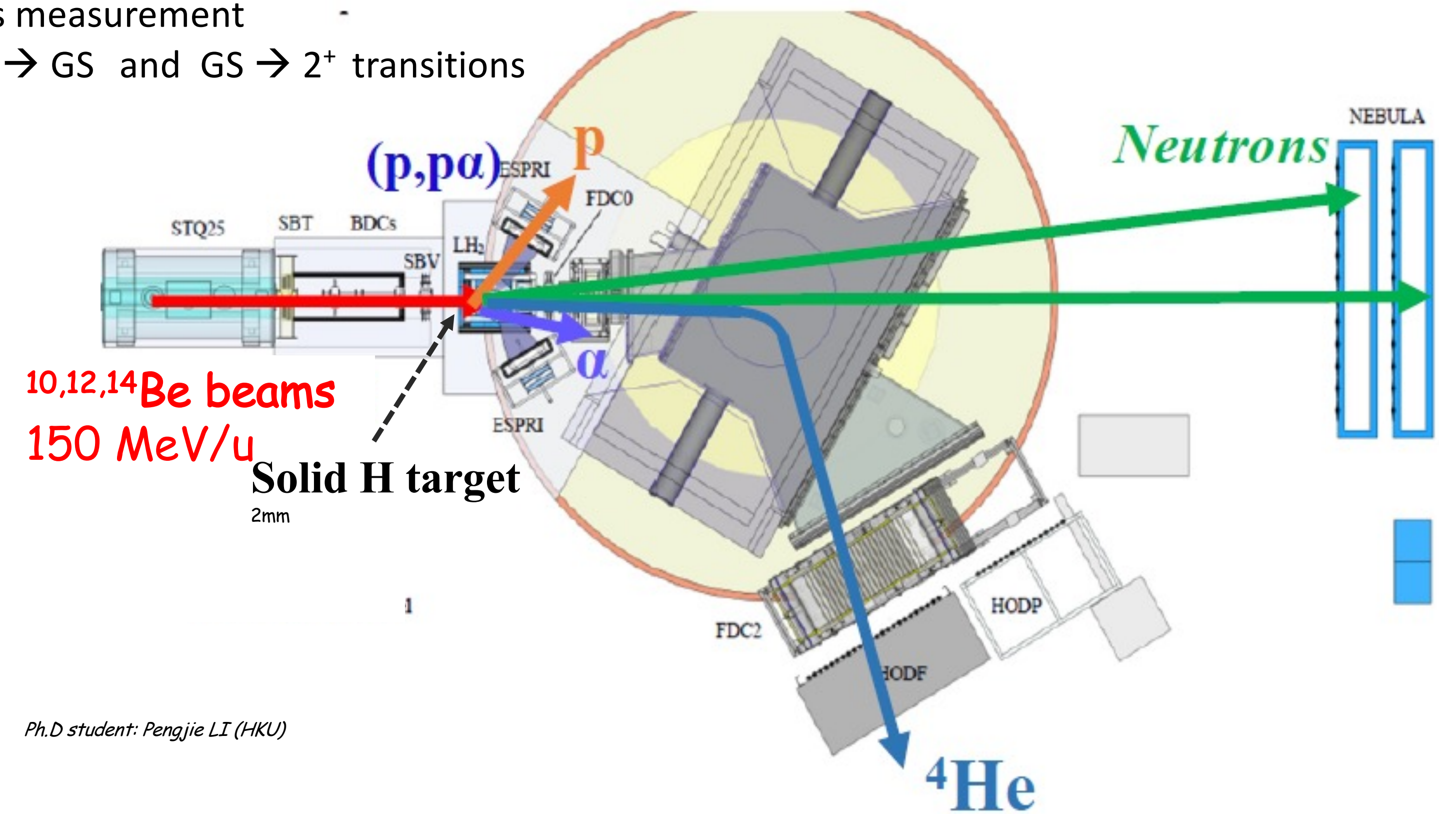
^{10}Be(p,pa) cross-section



Study $^{10,12,14}Be(p,pa)$ at 150 MeV/u

- Clustering in n-rich Be
- First spectrum for the 6n system

- Missing-mass measurement
- measure: GS → GS and GS → 2^+ transitions



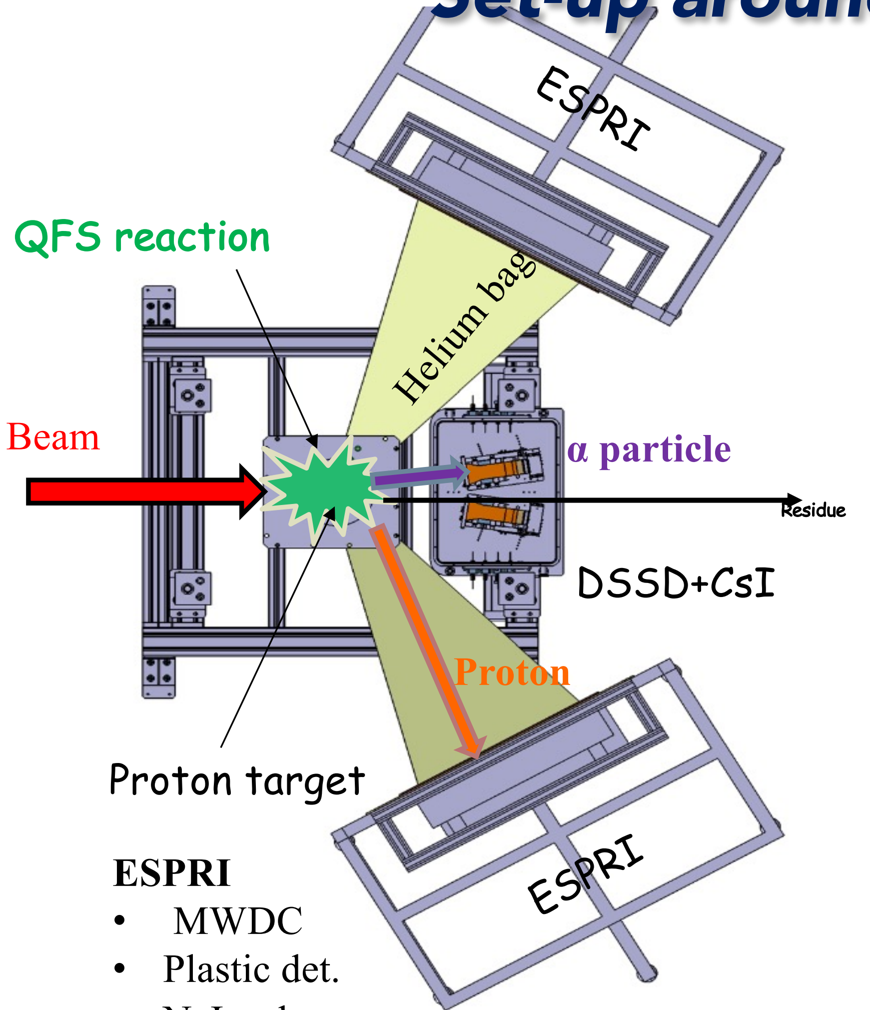
Ph.D student: Pengjie LI (HKU)

<u>Collaboration</u>: **IJCLab, Hong Kong U., RIKEN**, TI Tech, LPC Caen, Tohoku U., RCNP Osaka, CEA Saclay, Kyoto U., TU Darmstadt, NIPNE Bucharest, Kyushu U.

Samurai12 collaboration

HKU: S.D. Chen, J. Lee, P.F. Liang, T. Lokotko, X. X. Xu , **Pengjie Li**
IJC Lab: M. Assié, D. Beaumel, S. Franchoo, F. Hammache, E. Rindel, I. Stefan
RIKEN: H. Baba, T. Harada, T. Isobe, N.Kitamura, Y. Kubota, H. Otsu, V. Panin, M. Sasano, D. Suzuki, T. Uesaka, Z. H. Yang, J. Zenihiro
TU Darmstadt: A. Frotscher, H.N. Liu, Y.L. Sun, J. Tanaka, A. Obertelli
LPC Caen: L. Achouri, J. Gibelin, F. M. Marqués, N. Orr
TiTech: Y. Kondo, A. Kurihara, H. Miki, T. Tomai, H. Yamada, M. Yasuda
Tohoku Univ.: Y. Matsuda
RCNP Osaka: , M.J. Lyu, K. Ogata
CEA Saclay: , A. Corsi, A. Gillibert

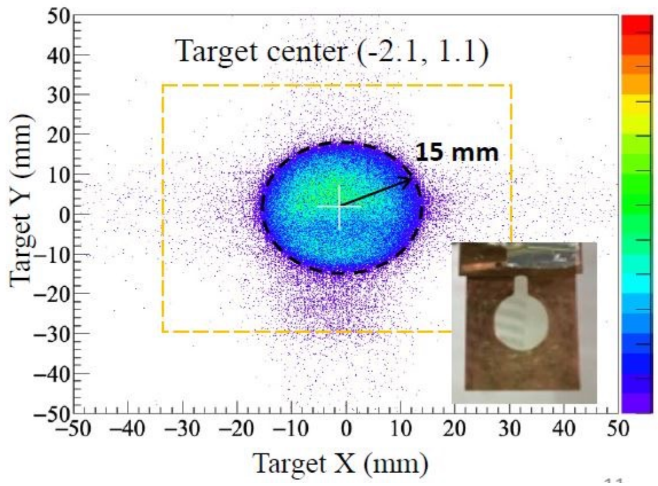
Set-up around target



ESPRI
- MWDC
- Plastic det.
- NaI rods

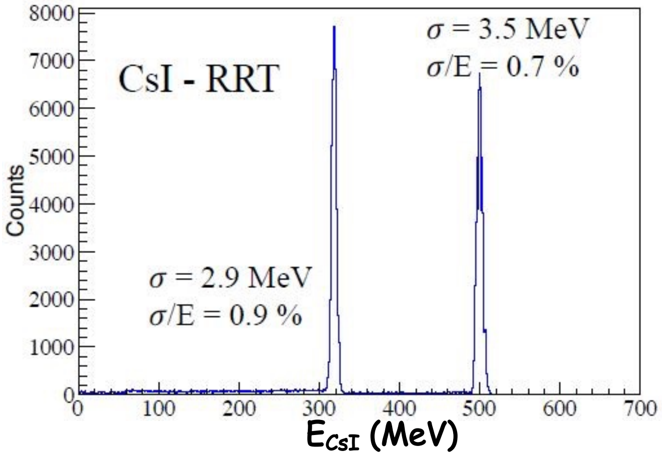
Target : 2mm-thick solid H

Y.Matsuda et al., NIMA 643 (2011)

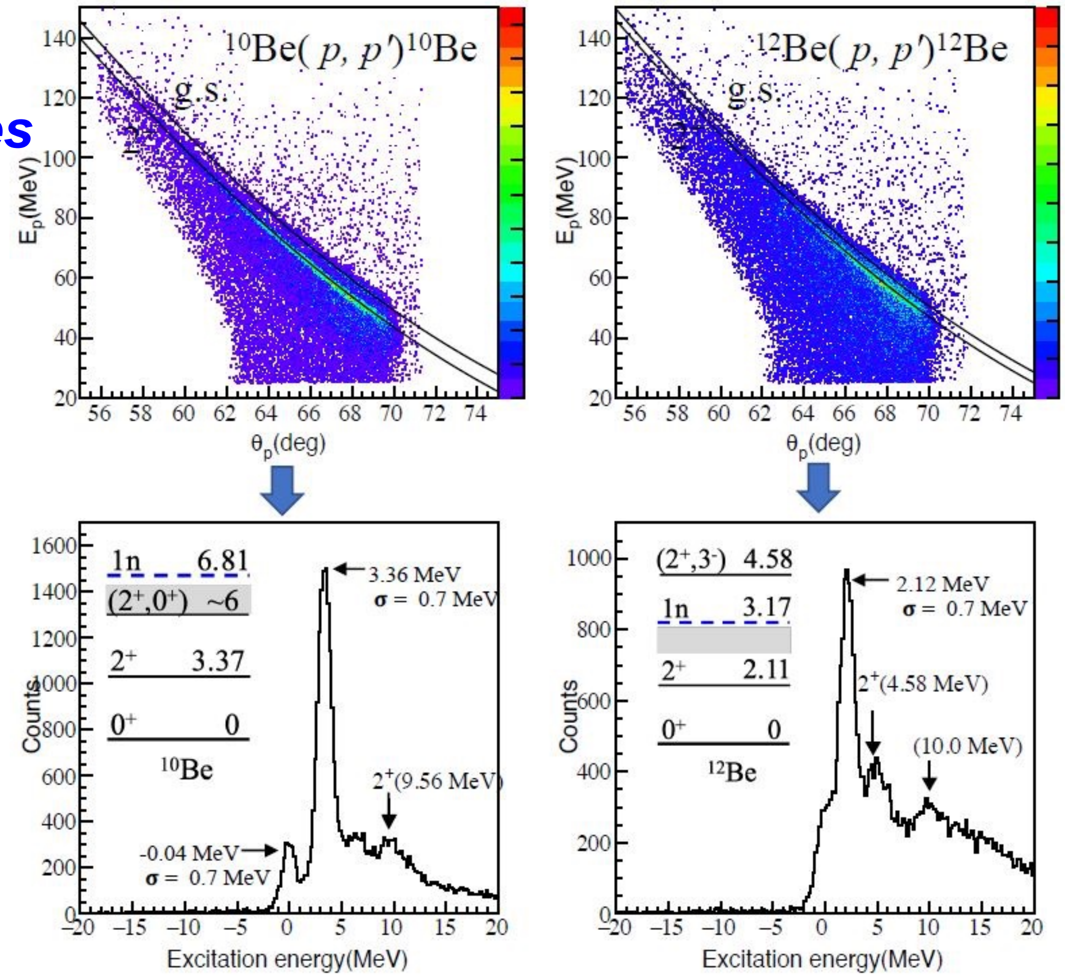


Energy calibrations of Telescopes

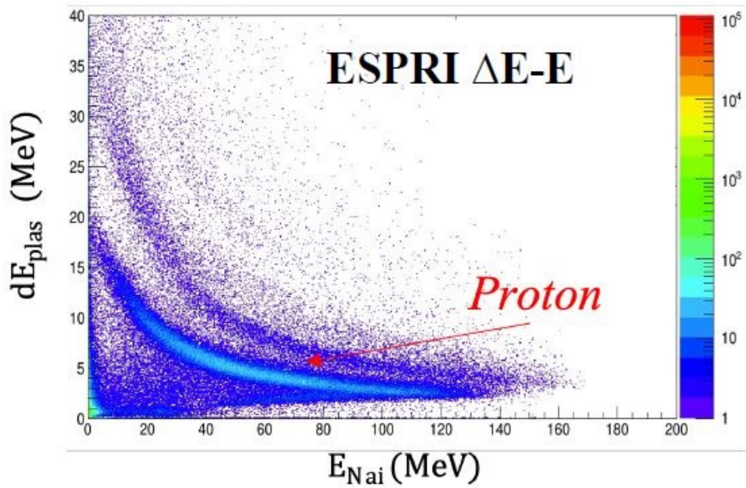
α beams at 120 and 150 MeV/u

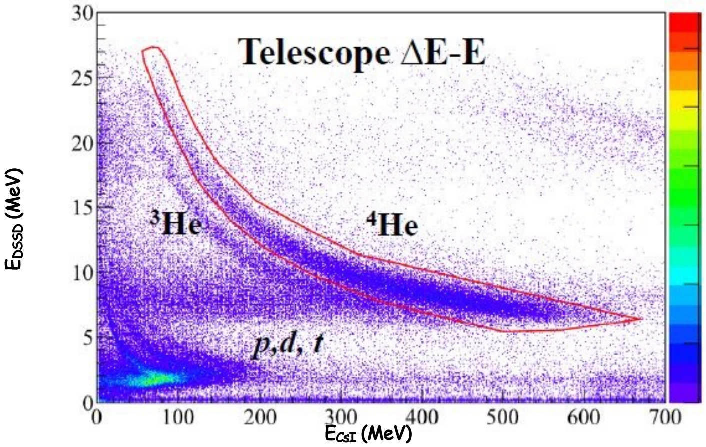


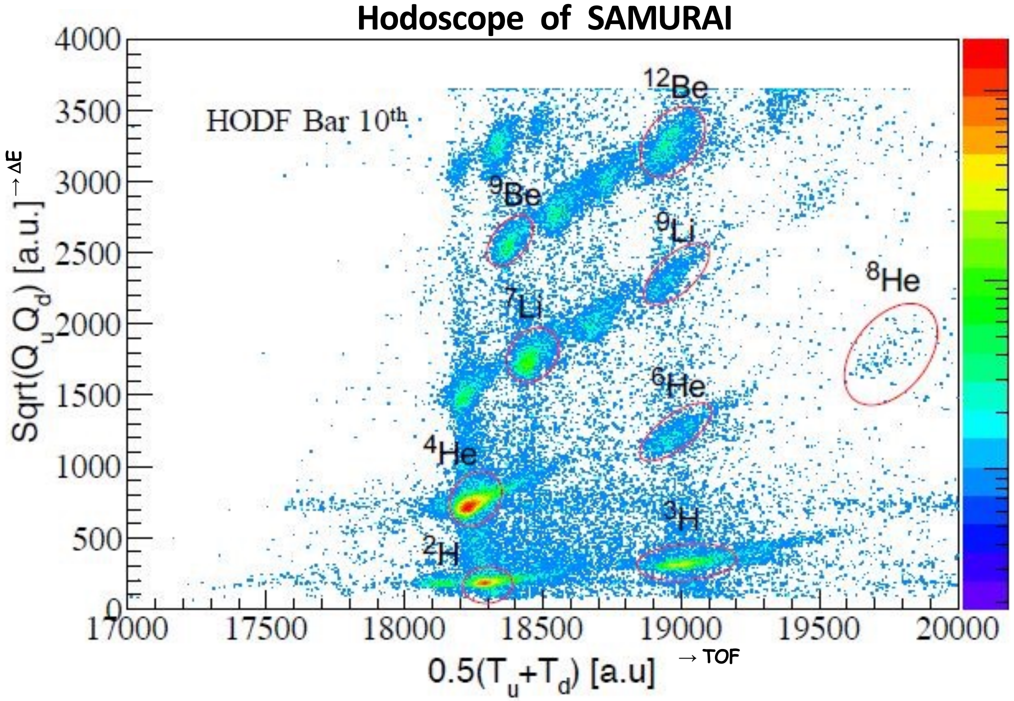
Energy calibrations of ESPRI



Particle identification – channel selection

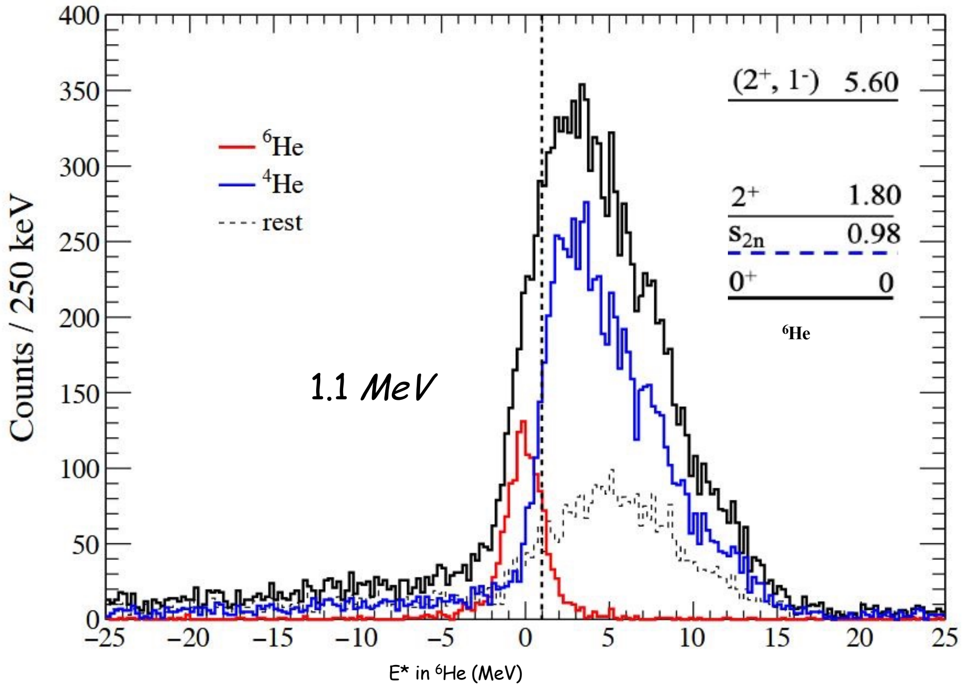






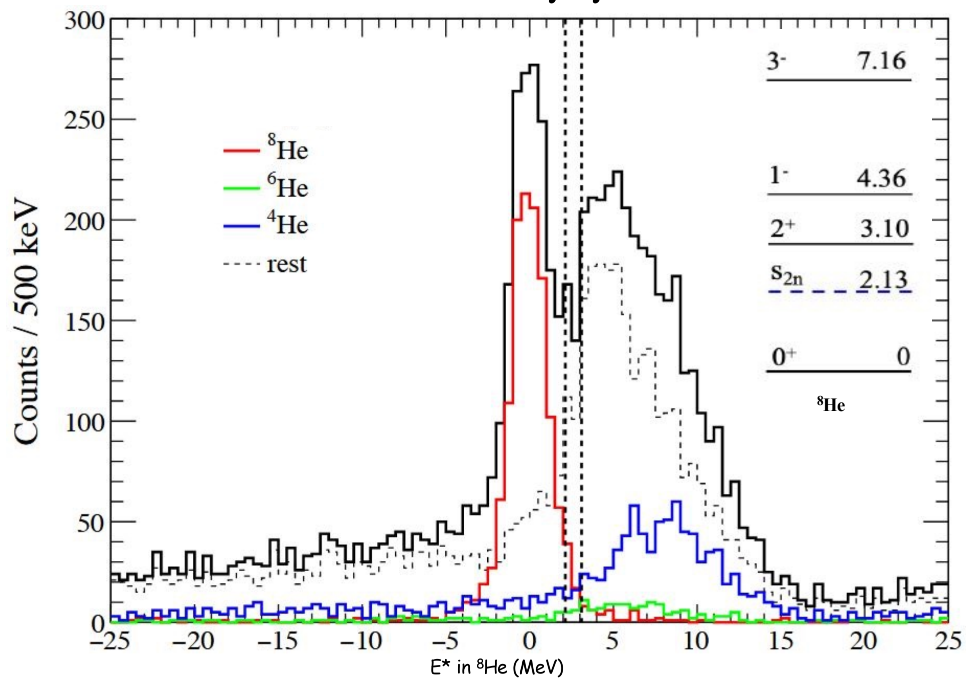
Excitation energy spectra

$^{10}Be(p,p\alpha)$



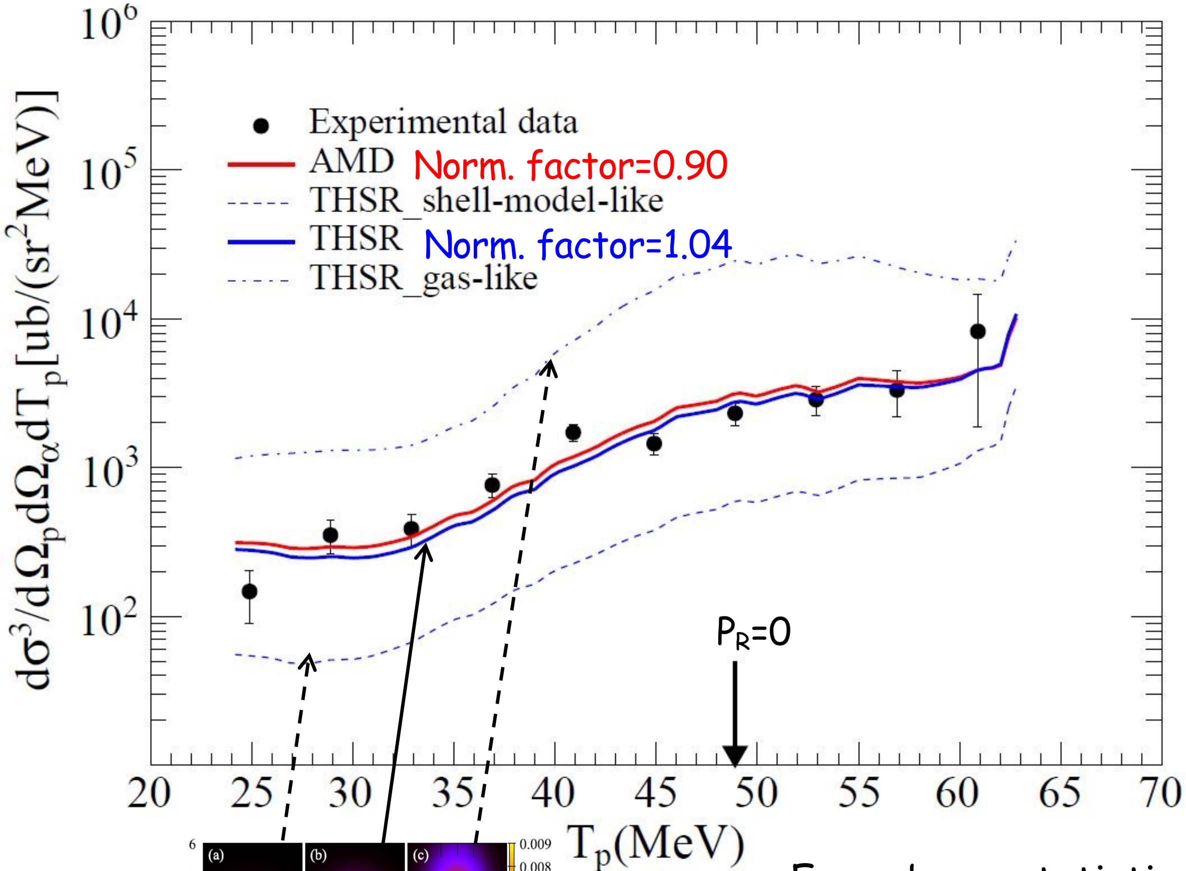
σ ($^6He^{GS}$) = 1.1 MeV

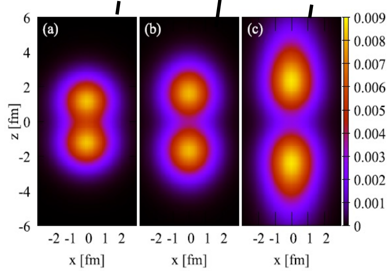
$^{12}Be(p,p\alpha)$



σ ($^8He^{GS}$) = 1.1 MeV

TDX for $^{10}Be(p,p\alpha)^6He^{(GS)}$





Error bars: statistical + error on PV

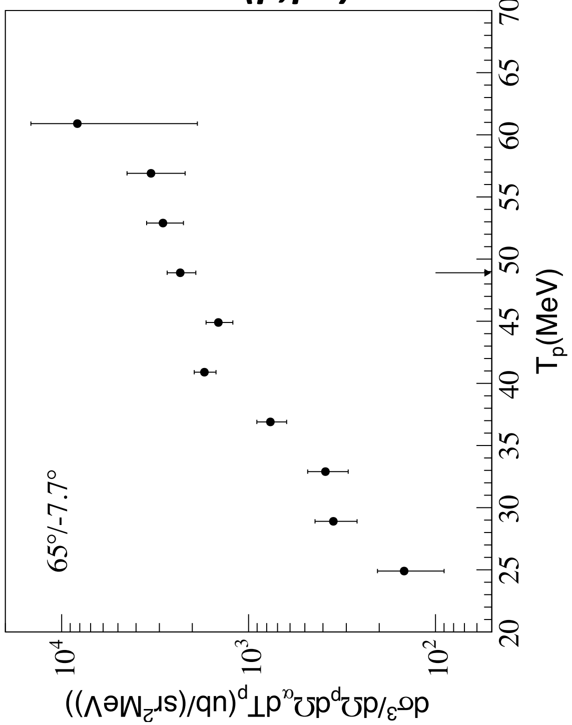
Optical potentials : from Dirac phenomenology

Molecular structure of the ^{10}Be GS is validated

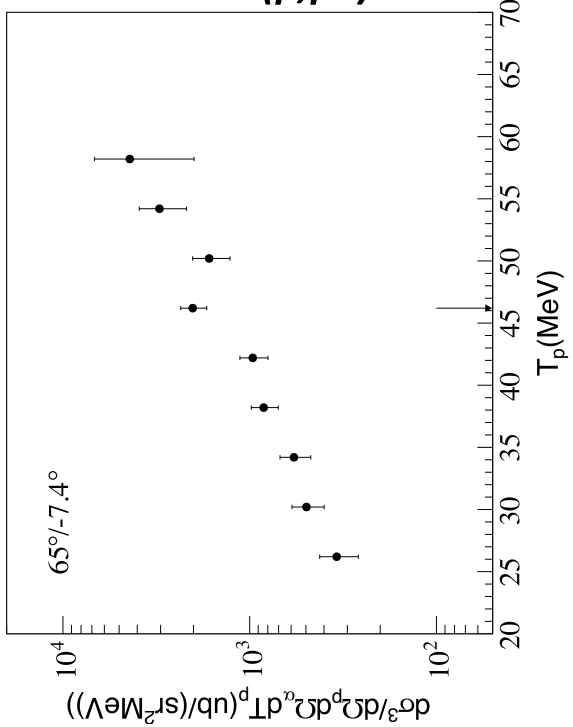
Submitted for publication

Experimental TDX for $^{10\sim14}Be(p,p\alpha)$

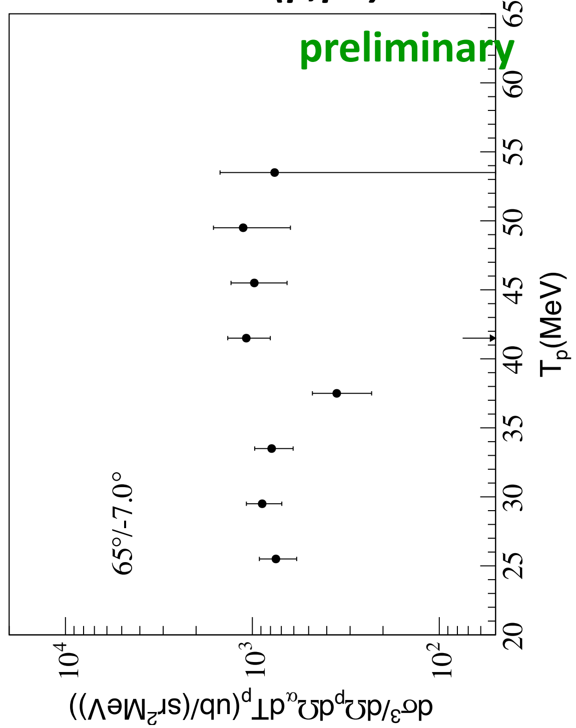
$^{10}Be(p,pa)^{6}He$



$^{12}Be(p,pa)^{8}He$



$^{14}Be(p,pa)^{8}He$



Gated by ^{8}He residue

Clustering evolution with N

Conclusions/Prospects

- First measurement of (p,pa) in inverse kinematics with RIB with proper kinematical conditions
  → direct evidence of the Molecular structure of the ^{10}Be GS

- First steps to quantitatively probe cluster evolution in GS towards the dripline
  Preliminary results show large triton K.O. Xsec for the halo nucleus ^{14}Be

  Complementary program using transfer reaction at LISE/GANIL with the MUGAST array
  E870 experiment accepted at last GANIL PAC meeting
  (p,a) and (d,^{6}Li) pickup reactions in inverse kinematics

- Planned study of (p,pa) on n-rich Carbon isotopes at RIKEN/Samurai (accepted expt)
  (spokesperson: Zaihong Yang)