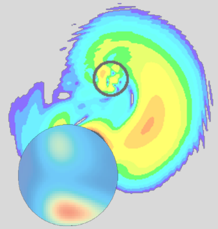
Neutron-proton pairing in the unstable N=Z nuclei of the *f*-shell through two-nucleon transfer reactions

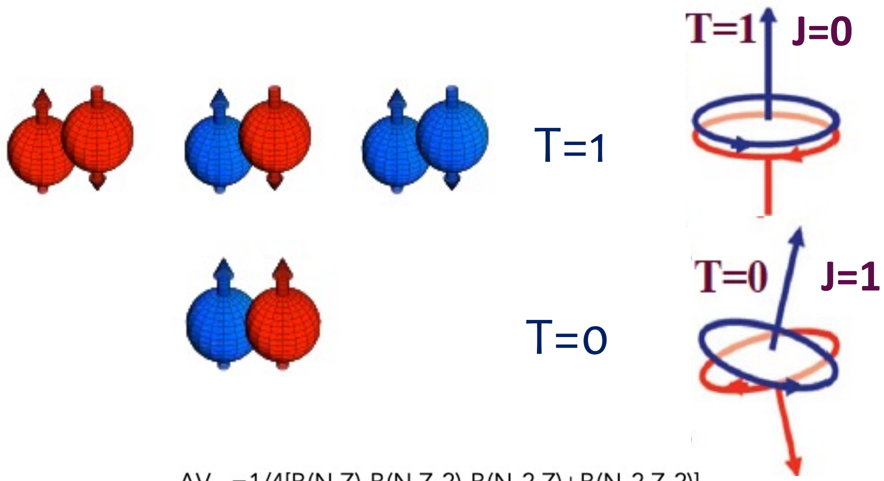
M. Assié, H. Jacob, IJCLab Orsay, assie@ijclab.in2p3.fr

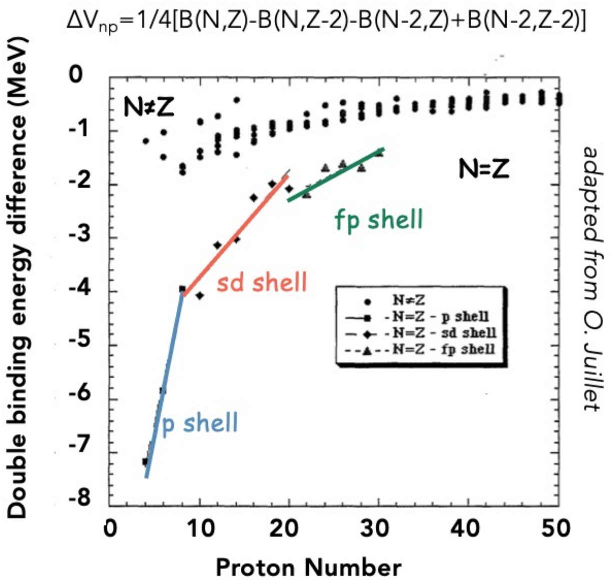


Transfer to study pairing

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

Neutron-proton pairing : generalities





- ► np pairing occurs in 2 different states:
  - -T=1 (isovector)
  - -**T=0** (isoscalar) <-- unique in np pairs

Manifestations of np pairing

- deuteron : only mass-2 nucleus to be bound
- overbinding of N=Z nuclei --> effect of shells

Where to search for np pairing ?

- N=Z nuclei
- stronger in **high-j orbitals** --> fp shell

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

How to probe neutron-proton pairing experimentally ?

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")

recently shown to be compatible with strong T=0 np pairs

B. Cederwall et al, PRL 124, 062501 (2020) /Kaneko et al NPA 957 (2017) 144

- Heavy nuclei accessible
- Model dependence

Knock-out reactions

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

E.C. Simpson, J.A. Tostevin, Fifty years of BCS, 468

- knock-out probes spatial correlations not clear for pairing

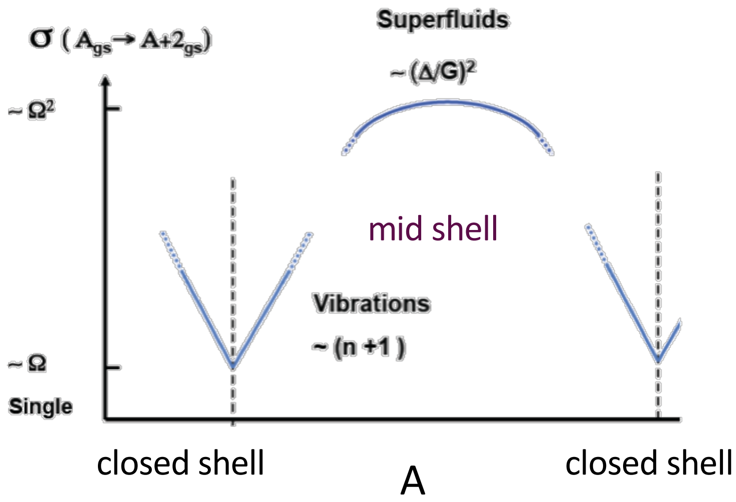
Deuteron transfer reaction

Two-nucleon transfer matrix element for pairing analogous to B(E2)'s for the quadrupole case.

Piet Van Isacker PRL (2005)/ Brink, Broglia Nuclear superfluidity

- smoking-gun ?
- difficult due to beam intensities

np pair transfer reactions



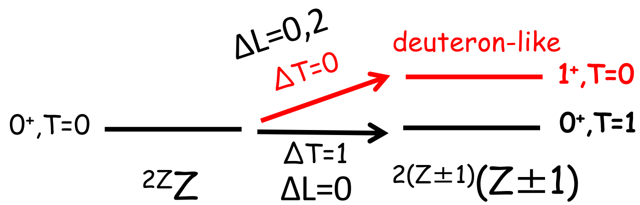
If pairing is important, the 2N transfer probability should be enhanced, particularly at mid-shell and will sign the onset of a superfluid phase.

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

Transfer can take place in

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

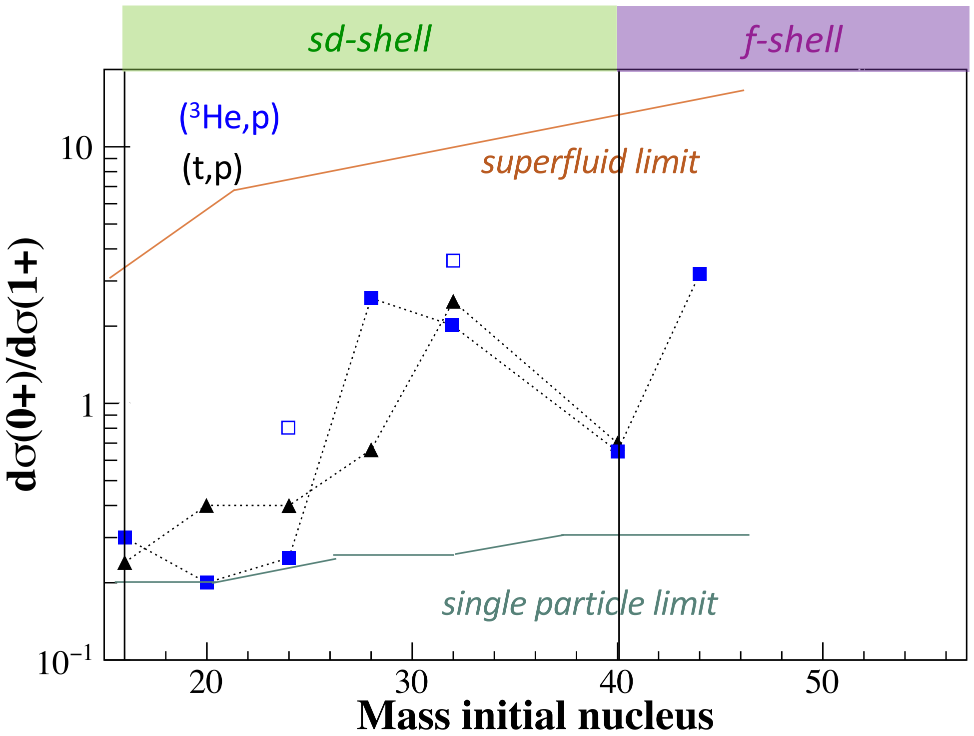
The (p,^{3}He) transfer reaction allows both channels $\Delta T = 0,1$ to be studied



reaction	selectivity
(p,^{3}He)	$\Delta T=0,1$
(^{3}He,p)	$\Delta T=0,1$
(d,α)(α,^{6}Li)	$\Delta T=0$
(α,d)(^{6}Li, α)	$\Delta T=0$

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

State-of-the-art for two-nucleon addition modes

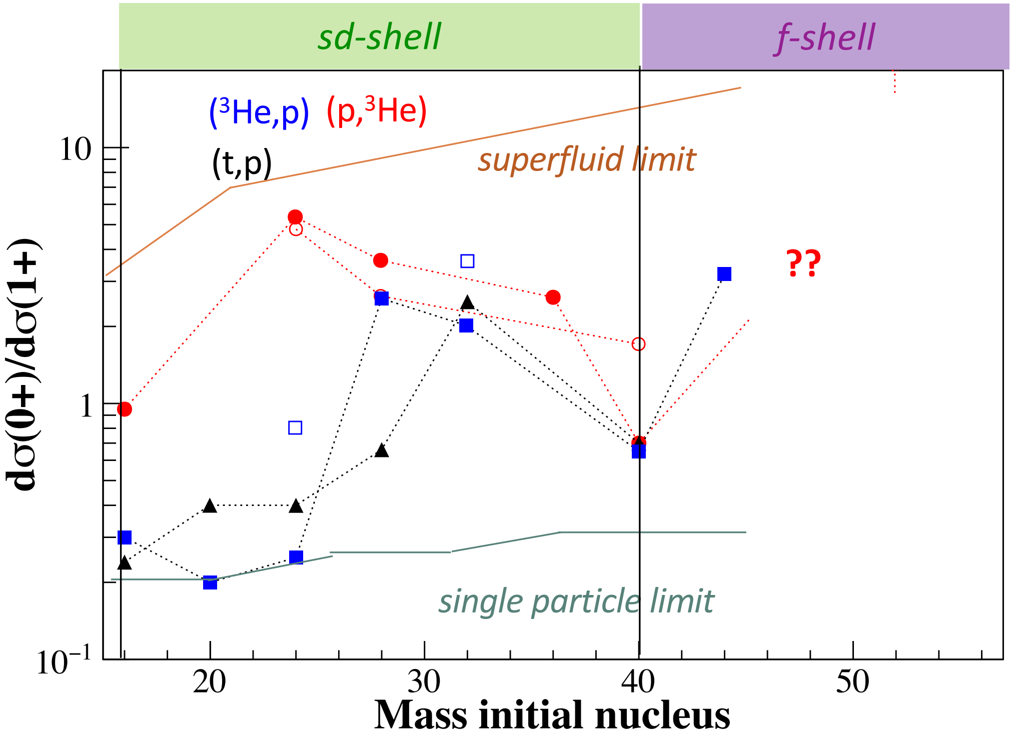


Adapted from Frauendorf, Macchiavelli, Prog. Part. Nucl. Phys. 78(2014)

- **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 (no centroid)
  - *Recent consistent remeasurement for (^3He,p)*: *Y. Ayyad et al, PRC96 (2017) (open squares)*

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

State-of-the-art of two-nucleon transfer (adding & removing)



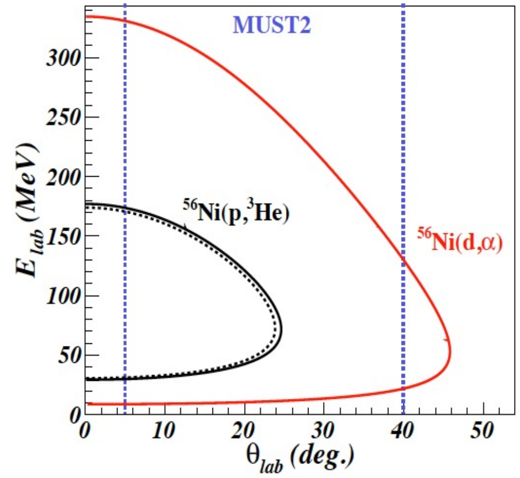
Disclaimer :

- Ratios from different experiments and at different energies
- L=0 and L=2 contributions mixed --> angular distributions needed

- **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 (no centroid)
  - *Recent consistent remeasurement for (^{3}He,p) and (p,^{3}He): Y. Ayyad et al, PRC96 (2017) (open symbols)*

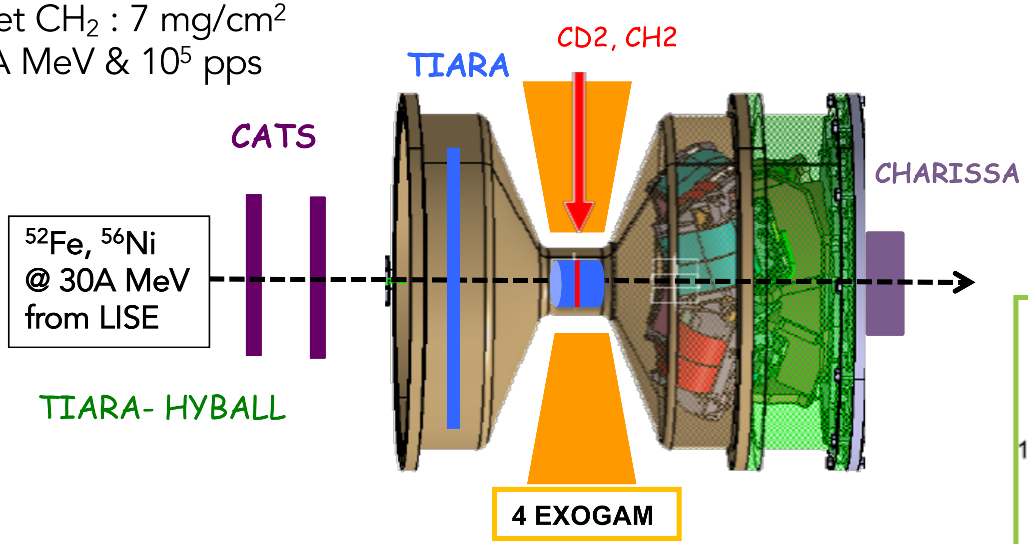
- **fp shell measurements :**
  - $^{44}Ti(^{3}He,p)^{46}V$ in inverse kinematics @ Argonne *(A.O. Macchiavelli et al)*
  - ^{56}Ni, ^{52}Fe, $^{48}Cr(p,^{3}He)^{54}Co$, ^{50}Mn, ^{46}V : in inverse kinematics @ GANIL *(H. Jacob ,M. Assié, B. Le Crom et al)*

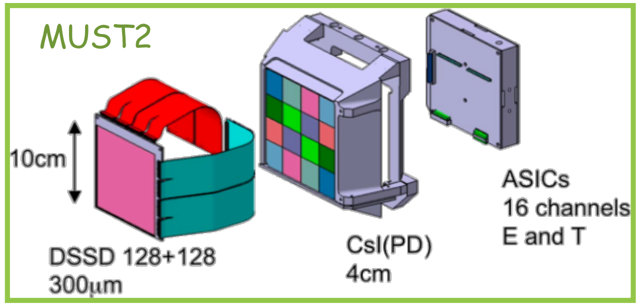
Experimental set-up on LISE @ GANIL



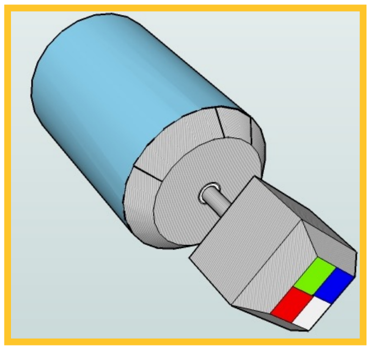
^{56}Ni(p,^{3}He)^{54}Co & ^{52}Fe(p,^{3}He)^{50}Mn

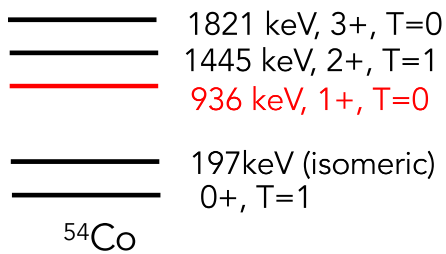
Beams produced by fragmentation of ^{58}Ni primary beam
thick target CH_2 : 7 mg/cm^2
beam: 30A MeV & 10^5 pps





Efficiency ~8%@ 1 MeV
Energy resolution 3 keV
Doppler broadening 80 keV

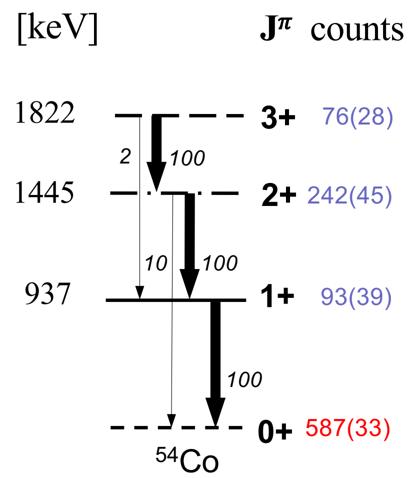


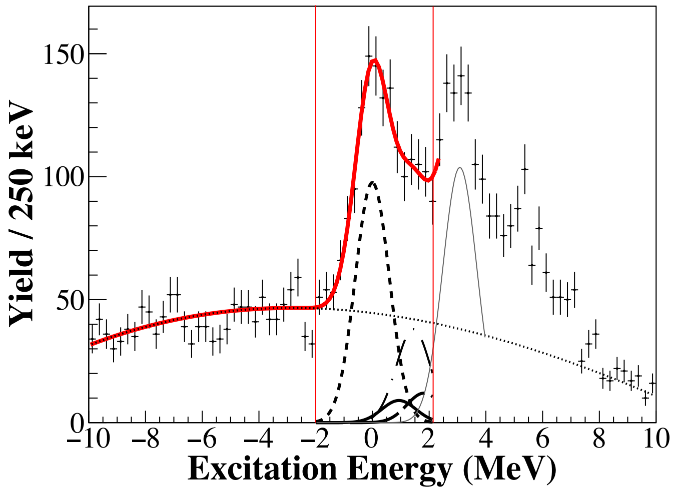


The (p,^{3}He) reaction on ^{56}Ni & ^{52}Fe

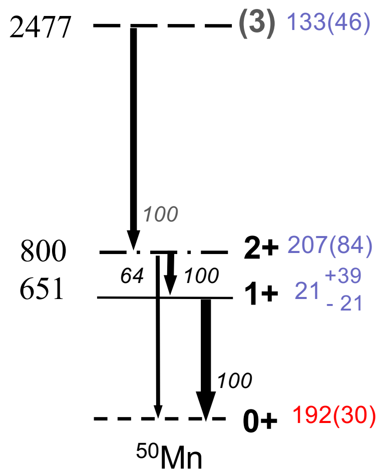
B. Le Crom et al, PLB (2022)

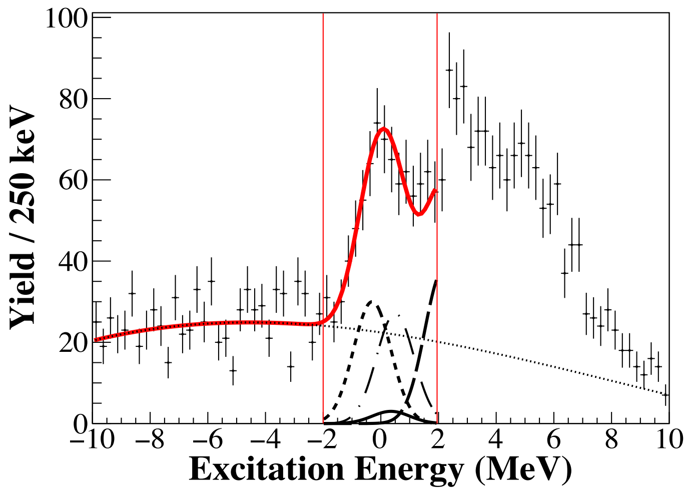
closed shell nucleus **$^{56}Ni(p,^3He)^{54}Co$**





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





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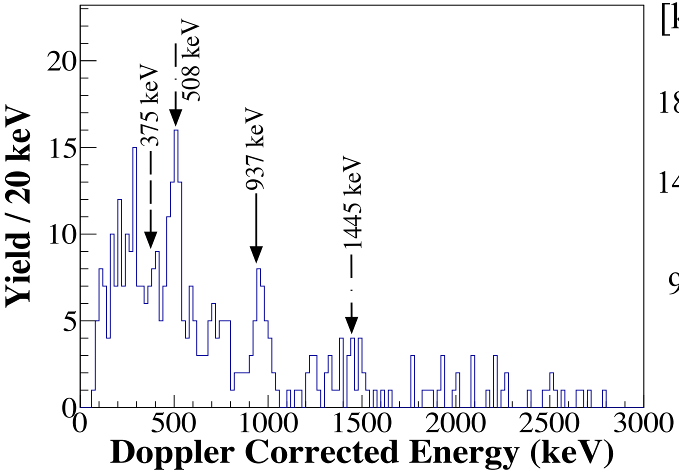

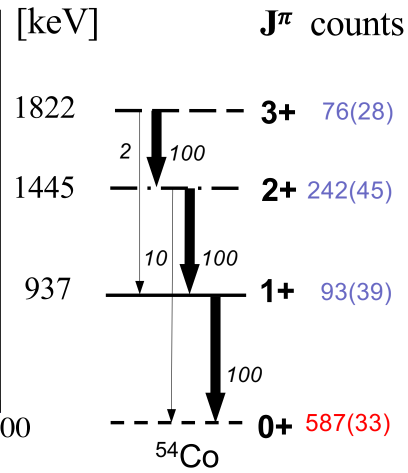

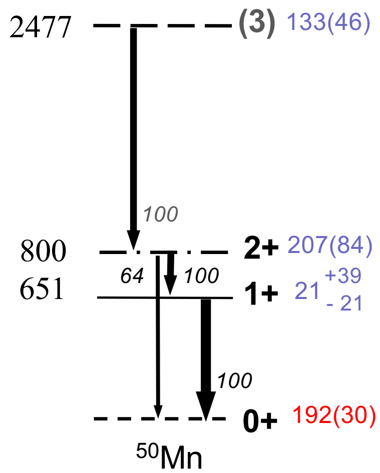

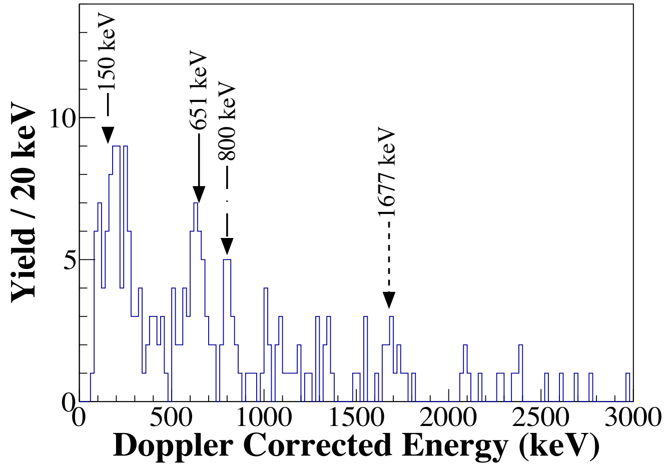

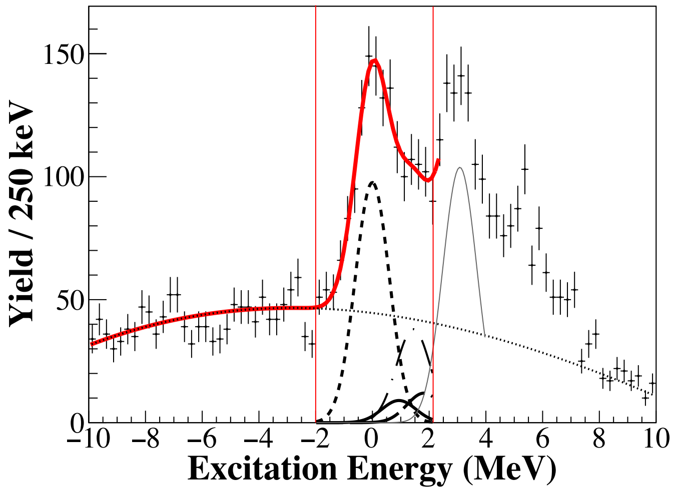

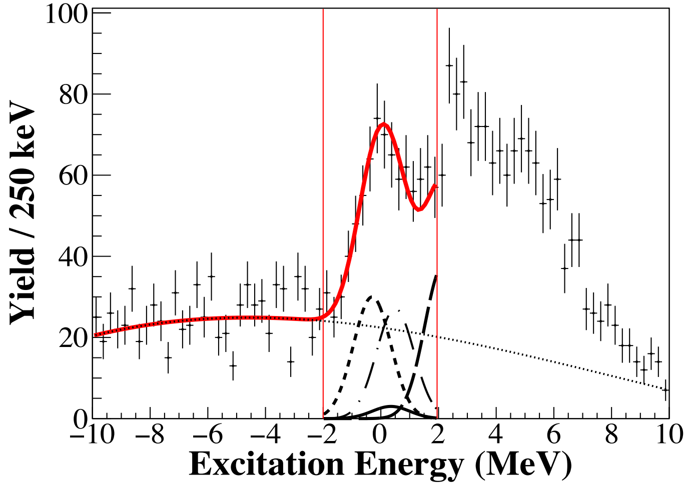

Comparison with DWBA

B. Le Crom et al, PLB (2022)

▸ Experimental and theoretical cross-sections

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

- Cross-sections for 1+ state very small and well reproduced with DWBA+GXPF1
- Large cross-sections for the g.s. but overestimated by the calculation (particularly for ^{52}Fe)

▸ 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

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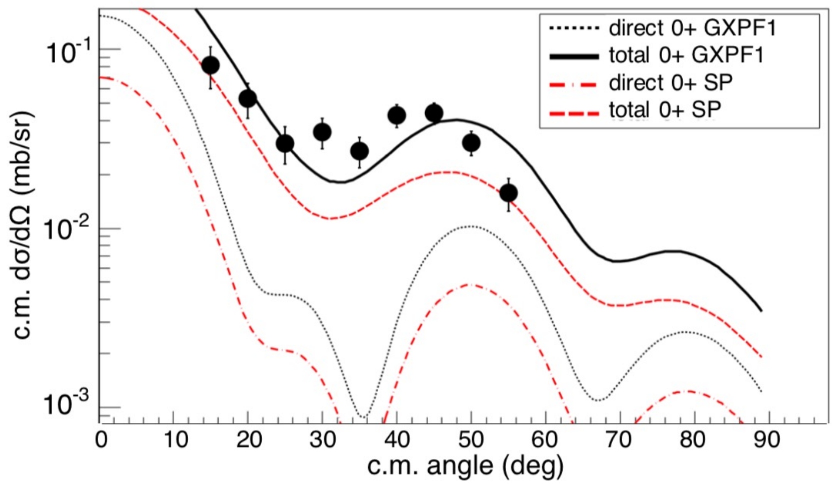
Angular distribution for g.s. of ^{54}Co



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

▶ Direct vs. sequential ?

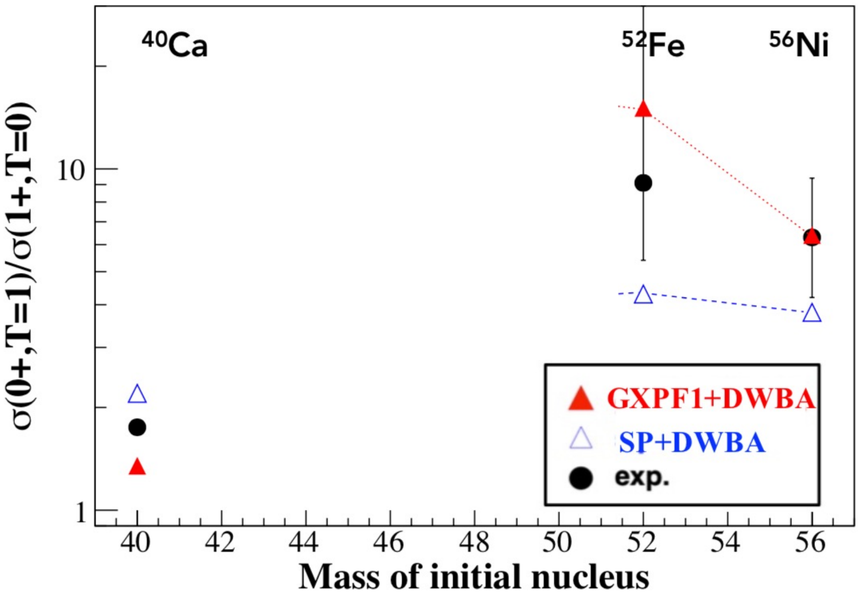
correlations kept in the sequential transfer

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

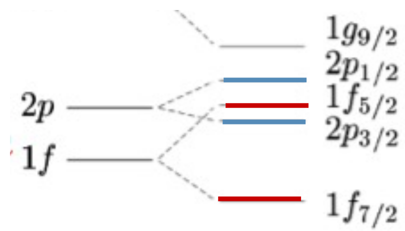
Comparison with DWBA

B. Le Crom et al, PLB (2022)

- Systematic 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.

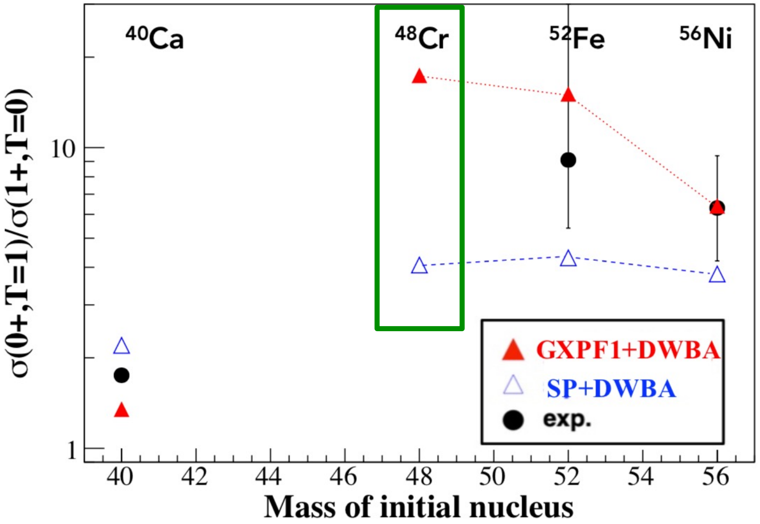


T=1 $(1f_{7/2})^2$ & $(1f_{5/2})^2$
T=0 $(1f_{7/2})^2$ & $(1f_{5/2})^2$ &$(1f_{7/2})(1f_{5/2})$

- Effect of other channels ?

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

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)

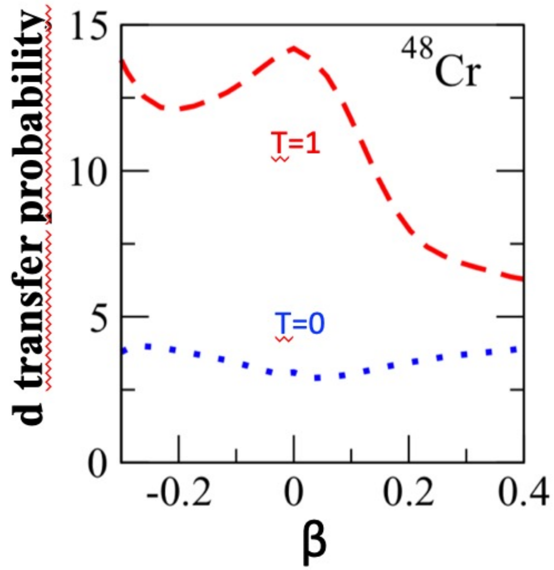
^{48}Cr	ENSDF	GXPF1
B(E2, 2+->0+) w.u.	31 (4)	20.5
β_2	0.368	

- 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

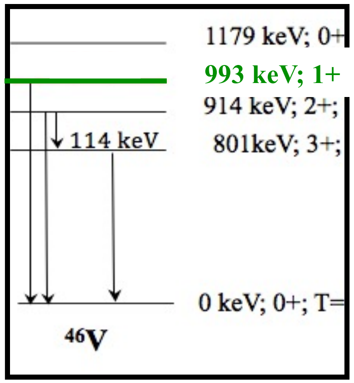


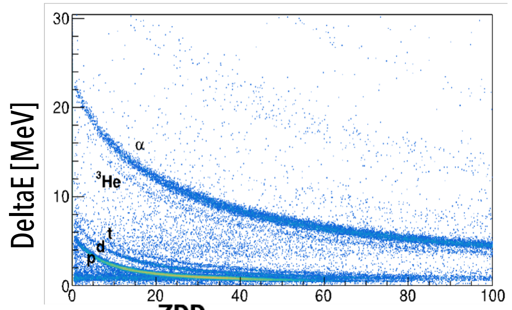
The main goal of the experiment is to measure the ratio σ (0$^+$)/σ (1$^+$) for ^{48}Cr(p,^{3}He)^{46}V to compare with theoretical predictions.

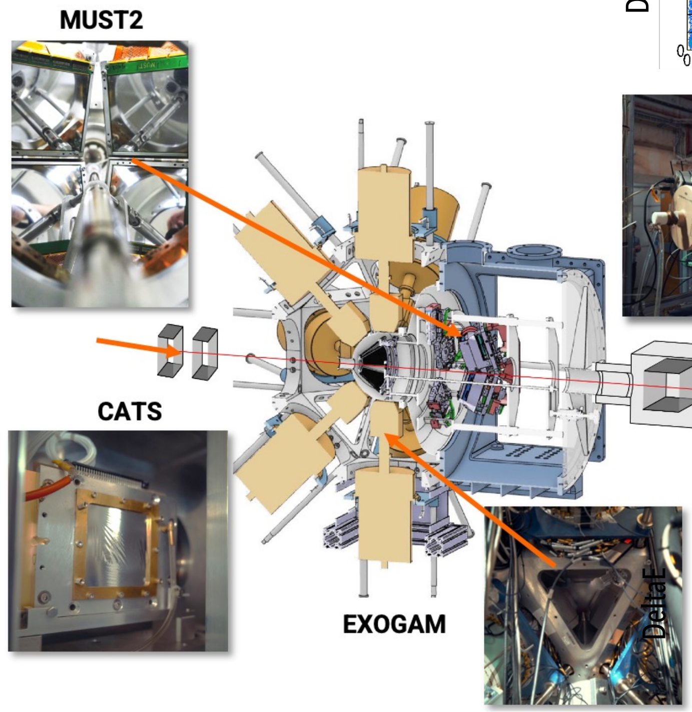
MUGAST@LISE at GANIL

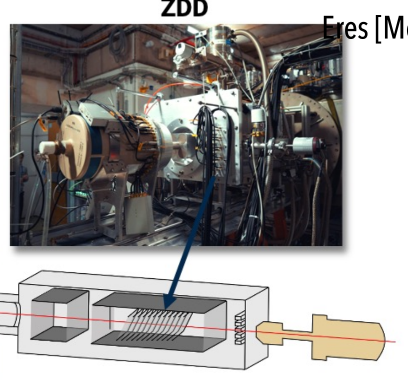
H. Jacob, IJCLab (PhD)

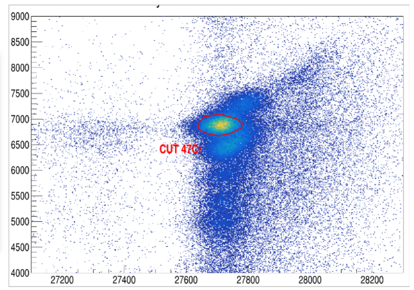
- Goal of the experiment : measure cross-section for removing a neutron-proton pair (T=0 or T=1) from ^{48}Cr (β=0.35) via the reaction ^{48}Cr(p,^{3}Heγ)^{46}V







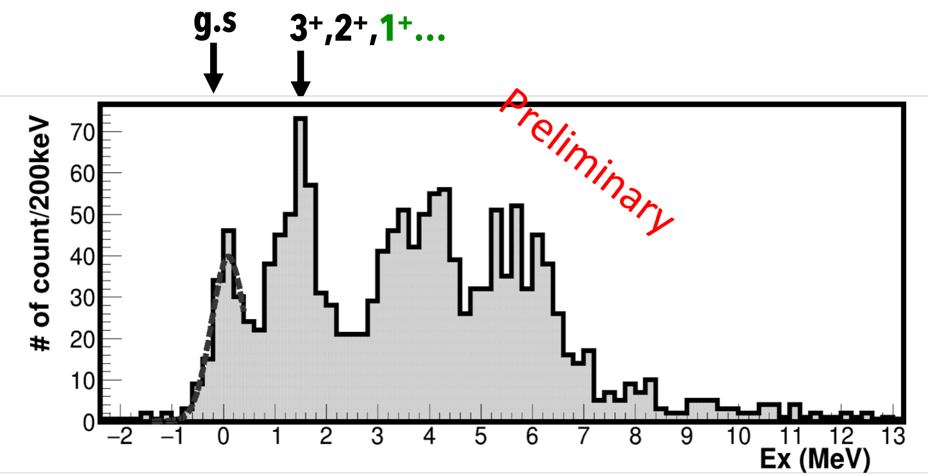


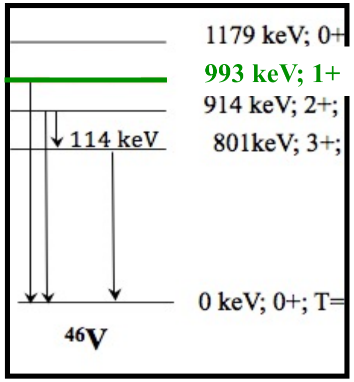


ToF CATS-ZDD

Preliminary results

H. Jacob, IJCLab (PhD)





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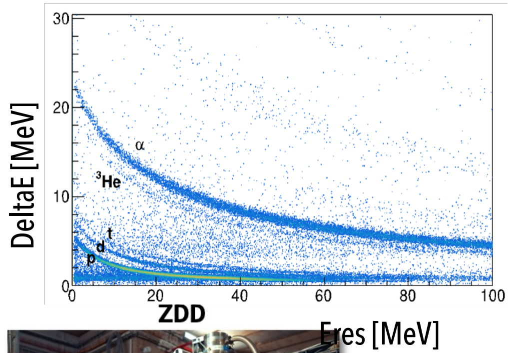

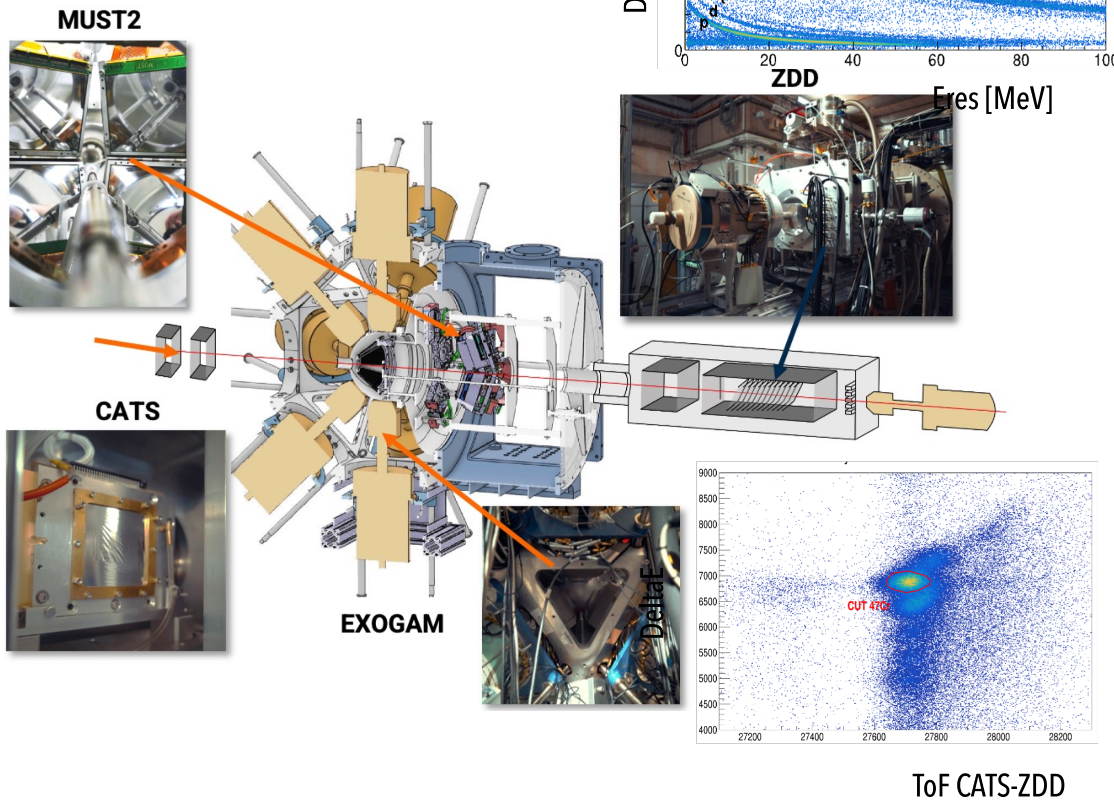

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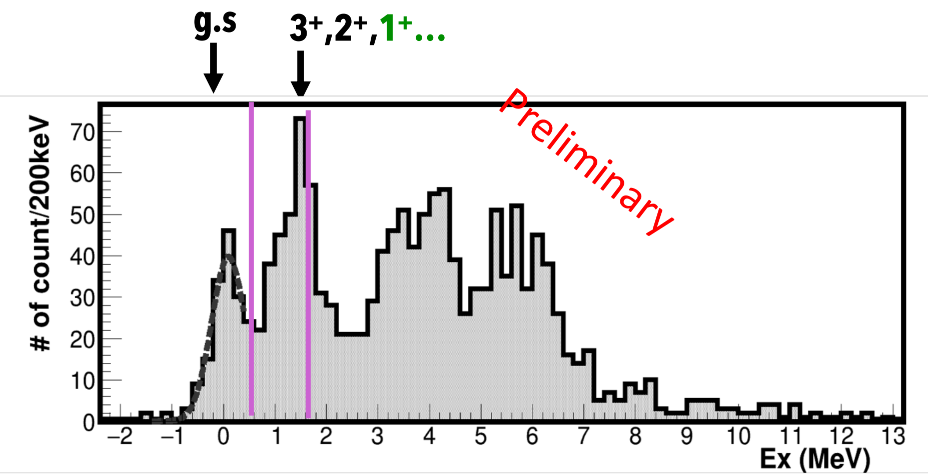

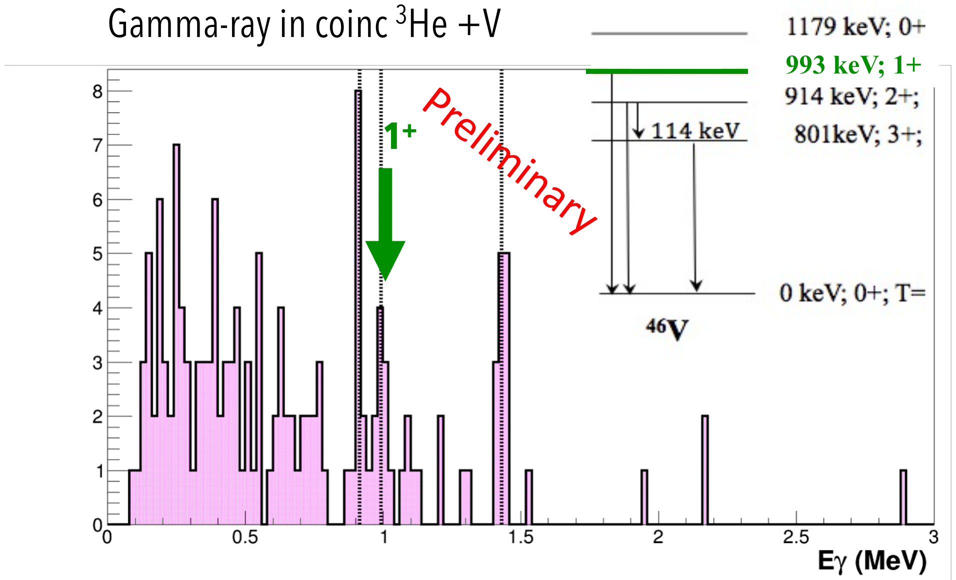

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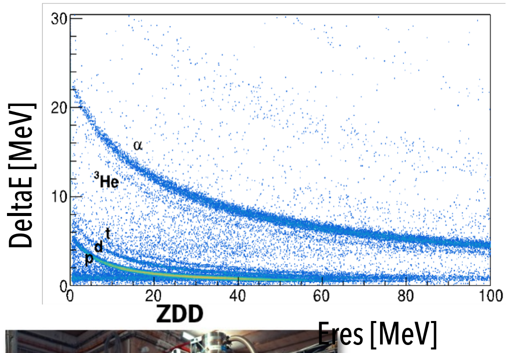

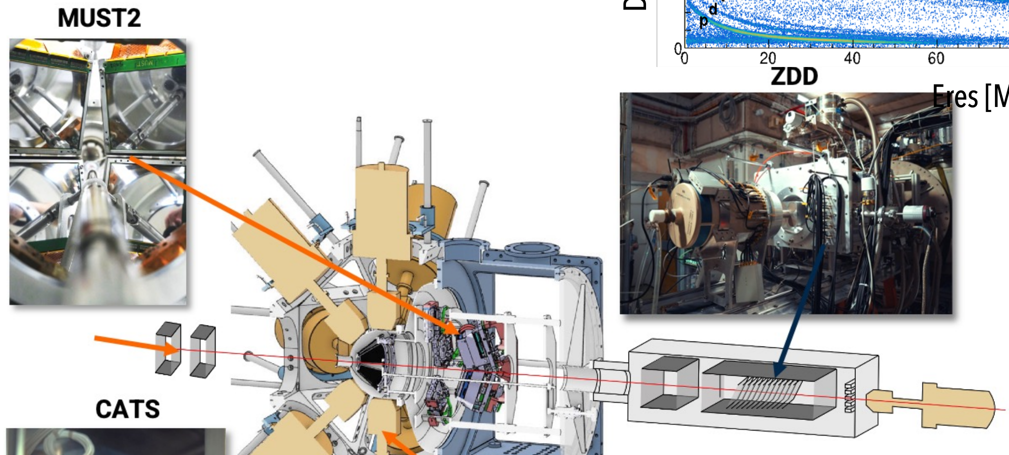

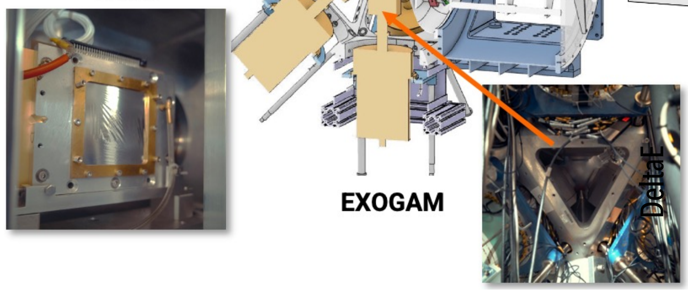

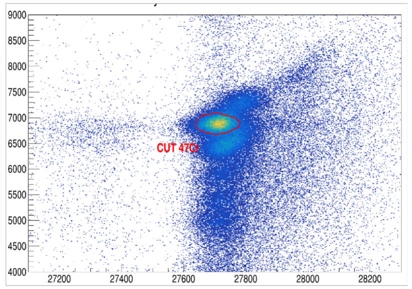

ToF CATS-ZDD

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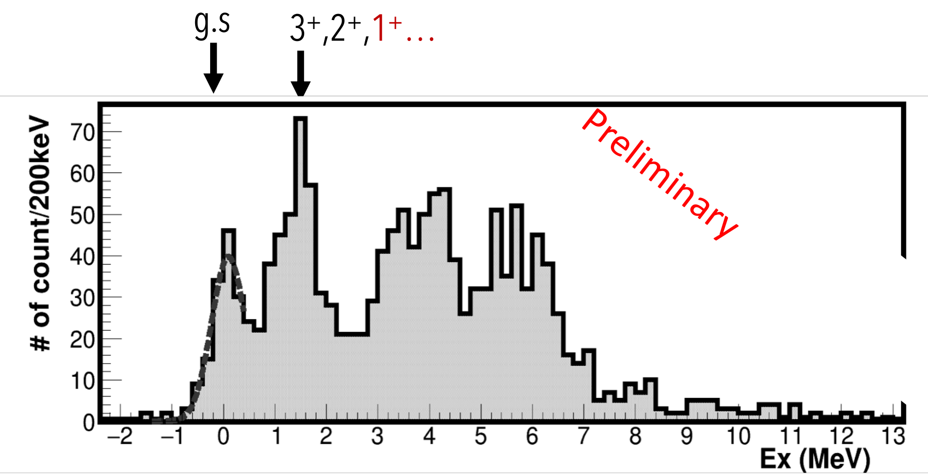

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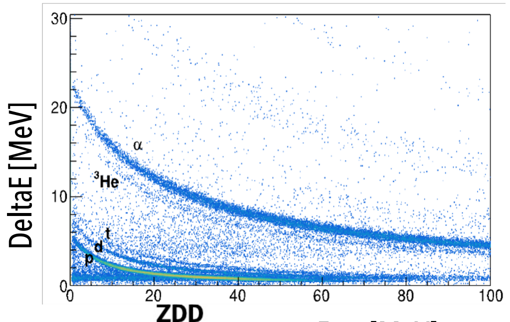
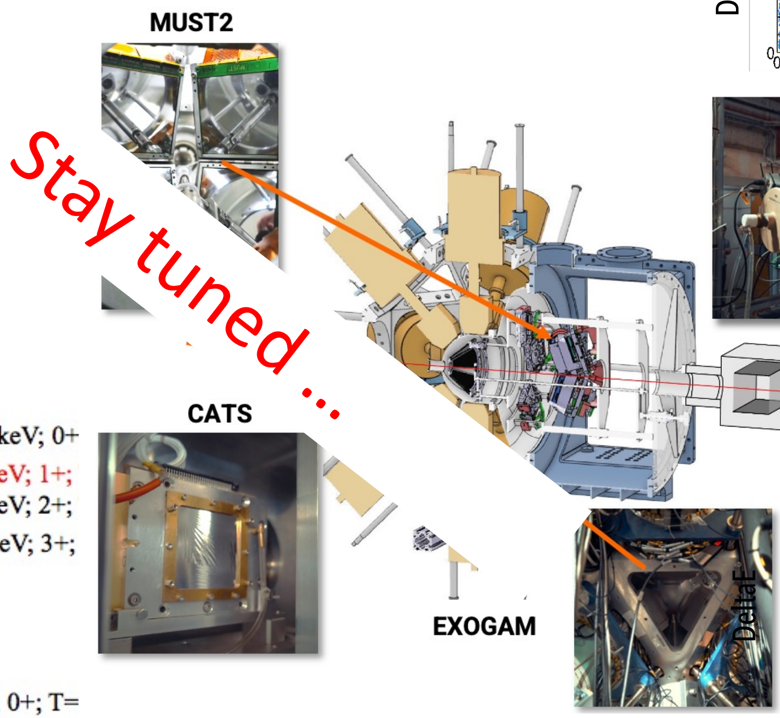
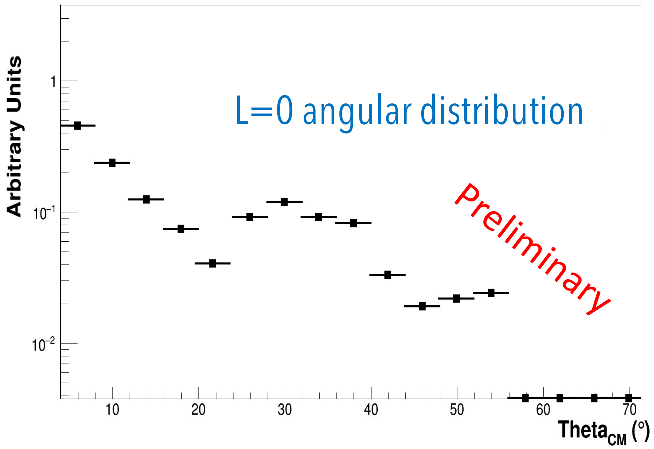
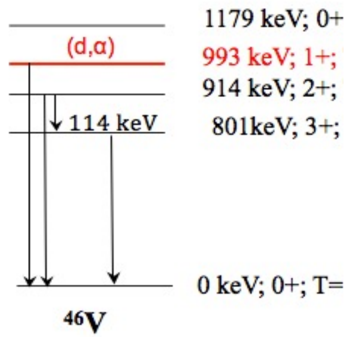
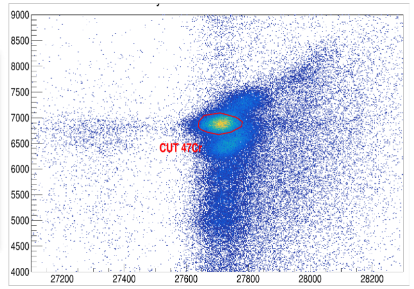




Angular distribution for ^{46}V g.s







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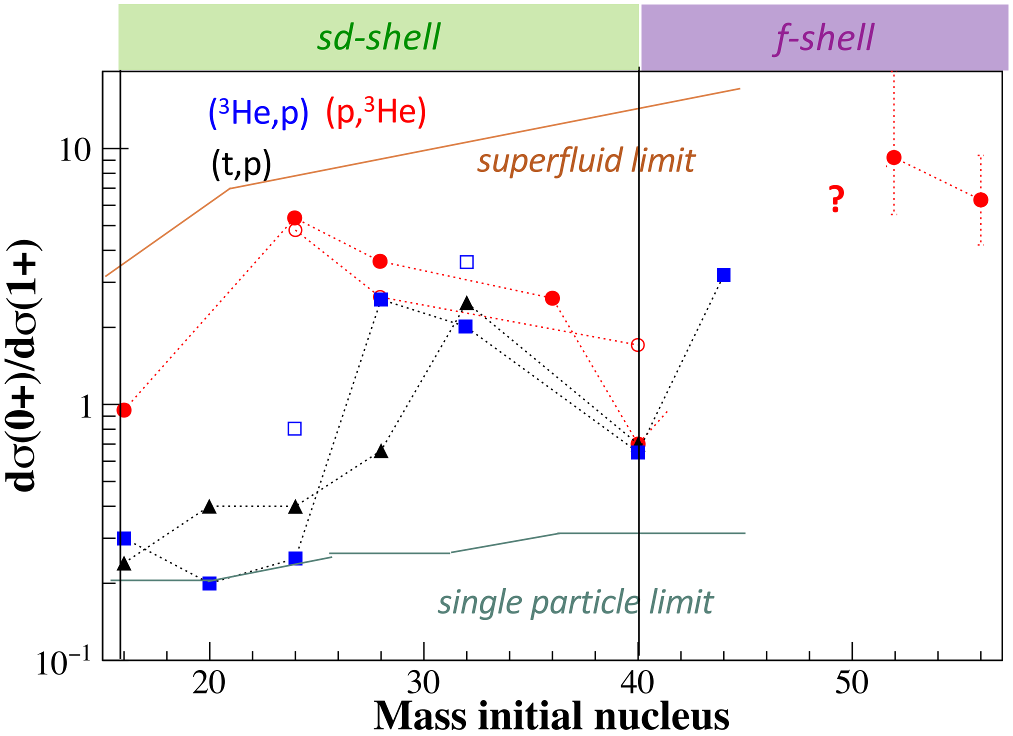
Conclusion and perspectives



Overview of np pairing investigation through 2N-transfer (adding and removing)

- *sd*-shell and *fp*-shell --> consistent with T=1 superfluid pairing,
- *fp*-shell : clear hindrance of T=0 pairing (very weak cross-sections)
- *Challenge for the next coming years :* reach higher-*j* nuclei !

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