Neutron-proton pairing and quartetting in self-conjugate unstable nuclei through transfer reactions

- np pairing in nuclei
- *sd / fp* shell nuclei
- reaction mechanism
- Experimental set-up
- ^{56}Ni(p,d) : one-nucleon transfer
- ^{56}Ni,^{52}Fe (p,^{3}He) : preliminary results

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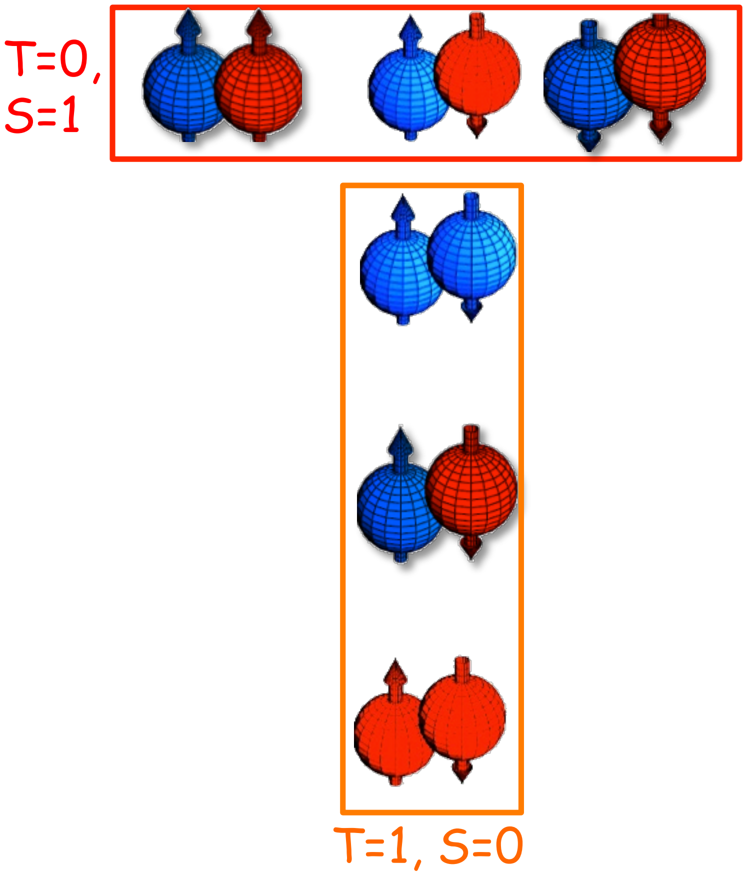
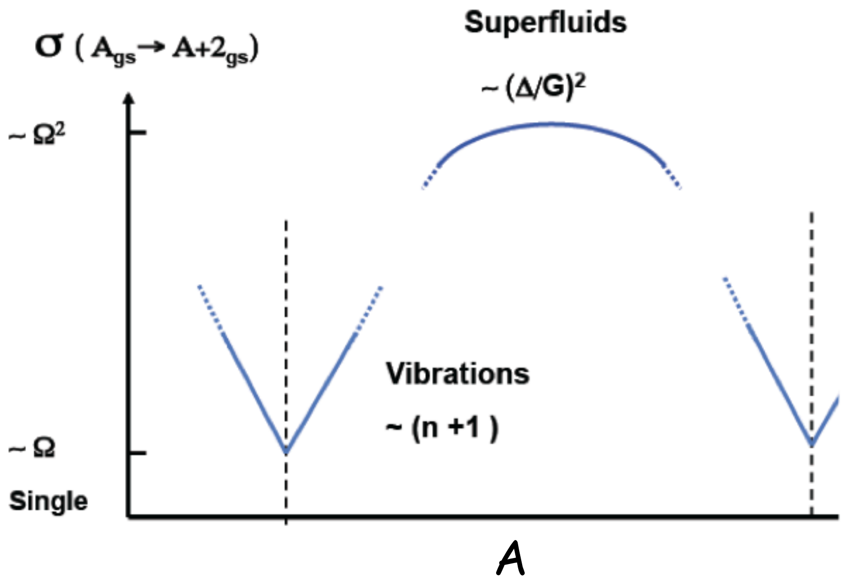
with the help of A.O. Macchiavelli & Y. Ayyad, J. Lee

Generalities about np pairing



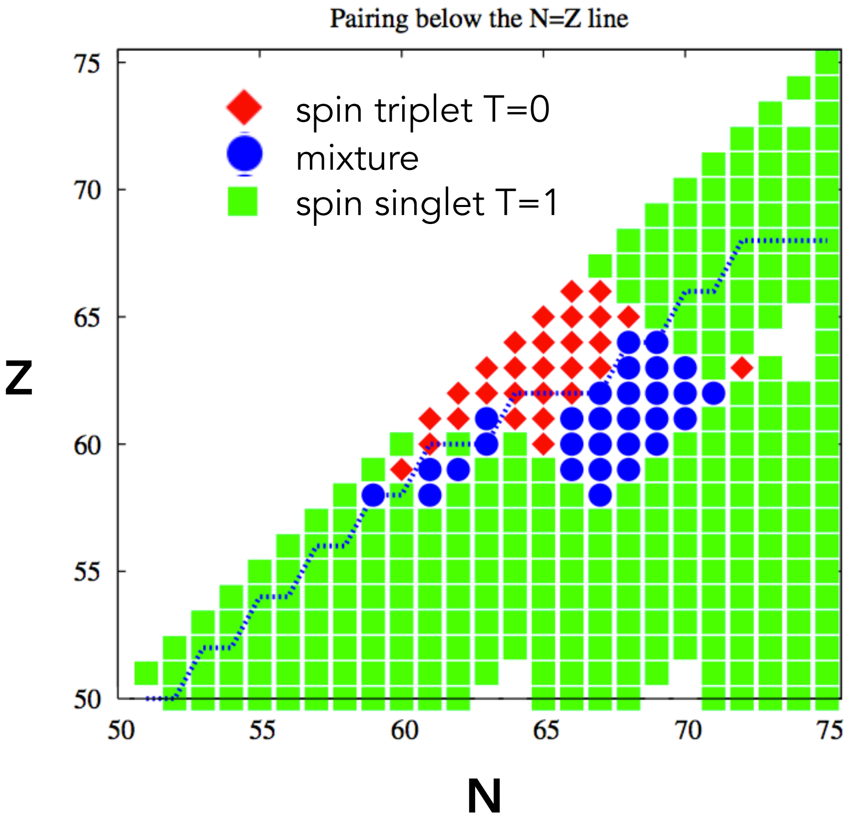
- np pairing :
  - isovector -> defined from isospin symmetry
  - isoscalar -> a lot of uncertainties !
- np pairing mostly (only) in **N=Z nuclei**
- d only bound (J=1+,T=0) A=2 nuclei
  T=0 pairing stronger than T=1 ?
- Correlated state // pair phase of superfluid for T=0?
  --> collective modes ?



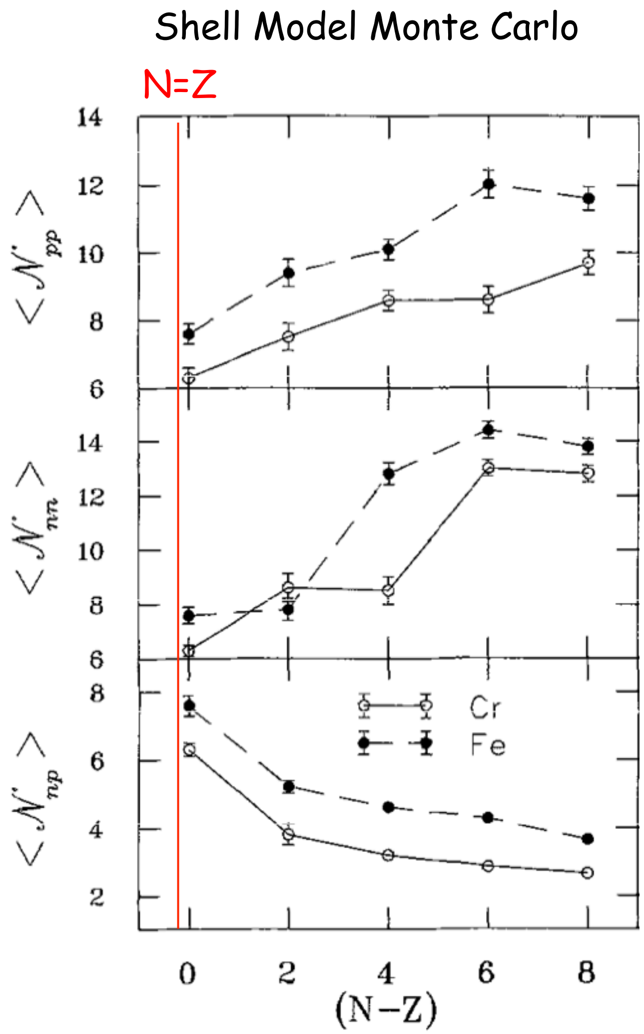
Frauendorf, Macchiavelli, Prog. in Part. Nucl Phys. (2014)

np pairing in N=Z nuclei

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



Gezerlis et al, PRL (2011)



Engel et al, PLB 389 (1996) 211

What about N≠Z nuclei ? Alpha emitters are all n-rich nuclei

np pairing in N=Z nuclei : overlap of w.f.

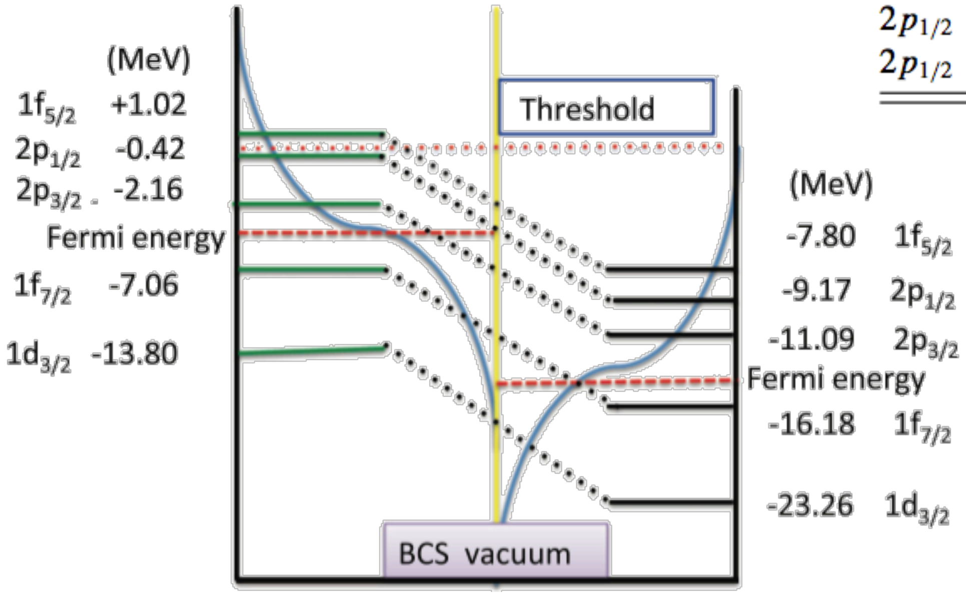
- nn, pp pairing increases when asymmetry increases
- np (T=1) pairing decreases drastically outside N=Z nuclei

Overlap integral of n and p wave functions

Skyrme HF – Sly4

ν	π	^{48}Cr	^{56}Ni	^{64}Ge
$1f_{7/2}$	$1f_{7/2}$	99.9	100.	99.9
$1f_{7/2}$	$1f_{5/2}$	97.7	98.9	99.1
$1f_{5/2}$	$1f_{7/2}$	99.4	99.7	99.8
$1f_{5/2}$	$1f_{5/2}$	99.6	99.8	99.9
$2p_{3/2}$	$2p_{3/2}$	99.6	99.7	99.7
$2p_{3/2}$	$2p_{1/2}$	98.2	99.1	98.9
$2p_{1/2}$	$2p_{3/2}$	99.8	99.6	99.9
$2p_{1/2}$	$2p_{1/2}$	99.1	99.6	99.6

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



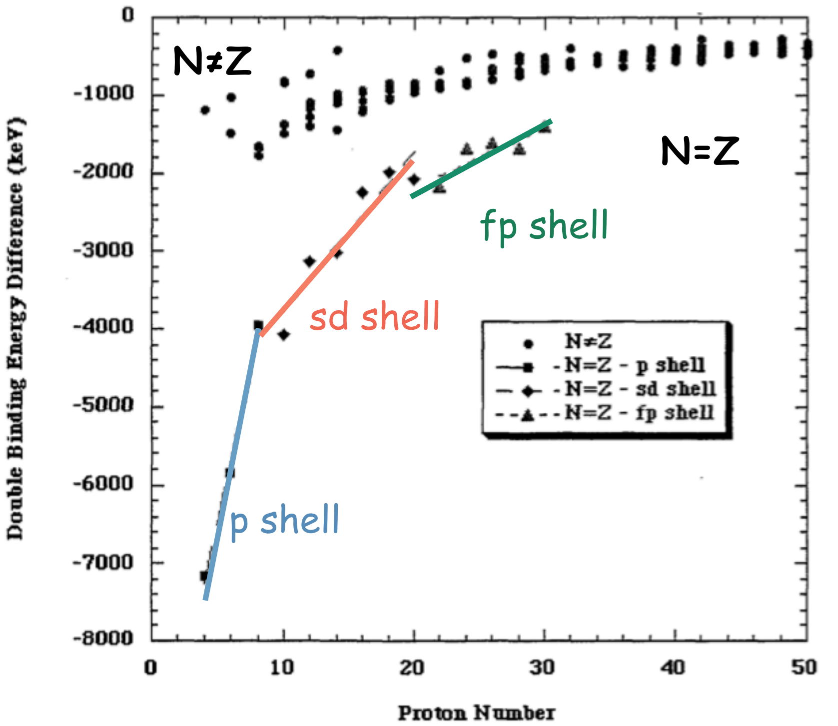
Sagawa, PRC 87 (2013) 034310

- ***fp* shell nuclei**
  Quenching from energy gap difference much lower than that due to the transformation from LS to jj coupling
- ***what about sd* shell nuclei ?**

Shell effects on np pairing

▶ Binding Energies

adapted from O. Juillet



Isoscalar pairing affected by shell effects
Spin-orbit effect on np pairing
(particularly in fp shell)

▶ Theoretical predictions : spin orbit

		T=1 $\langle QM\|iv\rangle$	T=0 $\langle QM\|is\rangle$	overlap $\langle iv\|is\rangle$
sd shell	^{20}Ne	0.884	0.953	0.843
	^{24}Mg	0.650	0.911	0.336
	^{28}Si	0.590	0.911	0.343
	^{32}S	0.638	0.973	0.595
fp shell	^{44}Ti	0.901	0.678	0.303
	^{48}Cr	0.906	0.497	0.221
	^{52}Fe	0.927	0.753	0.746
	^{104}Te	0.978	0.489	0.314
	^{108}Xe	0.958	0.354	0.234
	^{112}Ba	0.939	0.375	0.376

Quartet model : Sambatoro, Sandulescu PRC (2015)
id . with Shell model : Gezerlis et al, PRL (2011)

Possible experimental probes

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

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

Fröbrich *(Phys. Lett. 1971) -> 2.5 enhancement factor*

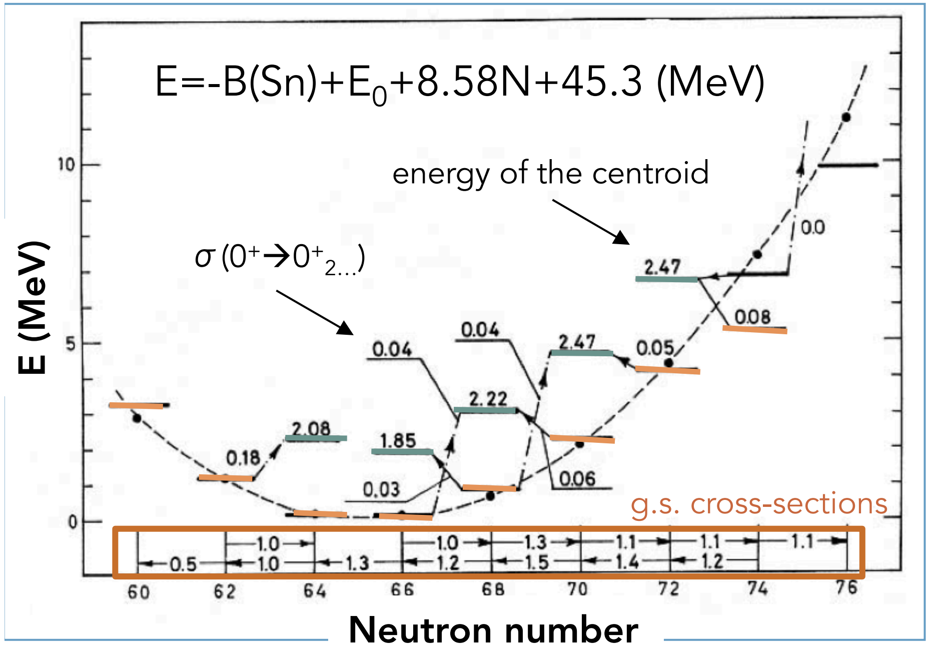
Piet Van Isacker PRL (2005)

analogous to the transition probabilities BE2’s fnr the quadrupole case.

+ The “smoking gun”? – beam intensities >10^4pps

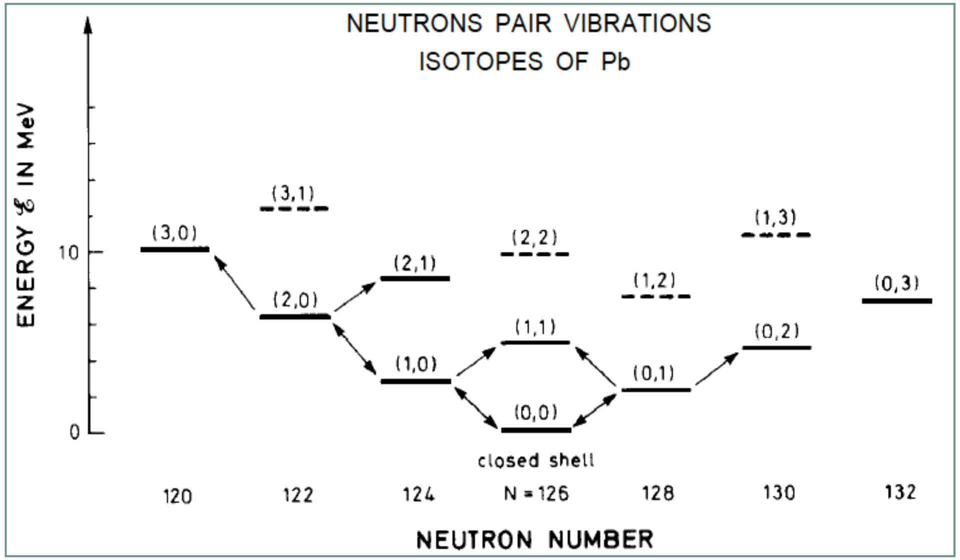
Rotational vs. vibrational pairing

(p,t) & (t,p) : R= σ_{rot}/σ_{qp}~25



- 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

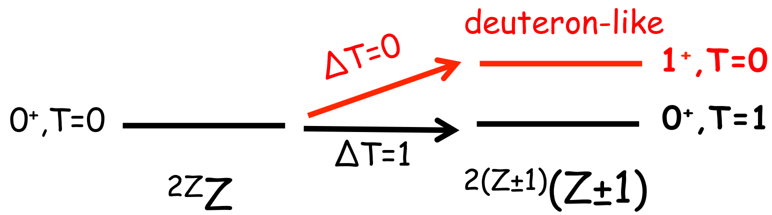
Probing isoscalar pairing through transfer reactions

Deuteron-transfer intensities (IBM model)

Reaction	$C^2_{T=0}$	$C^2_{T=1}$
$EE \rightarrow OO_{T=0}$	3	0
$EE \rightarrow OO_{T=1}$	0	$N_b + 3$
$OO_{T=1} \rightarrow EE$	0	$N_b + 1$

P. van Isäcker, PRL (2005)

- Transfer is proportionnal to the number of pairs
- σ $(0^+)/\sigma$ (1^+)= gives the relative strength of T=0/T=1 pairing



Experimental aspects

reaction	beam E	direction	selectivity
$(p,^3He)$	>20 MeV	forward	ΔT=0,1
$(^3He,p)$	low <5MeV	backward	ΔT=0,1
$(d,\alpha)(\alpha,^6Li)$	>20 MeV	forward	ΔT=0
$(\alpha,d)(^6Li, \alpha)$	low <5MeV	backward	ΔT=0

✧ Best nuclei to study :

. N=Z nuclei with high j orbitals to develop collectivity
$g_{9/2}$ shell like ^{92}Pd ***not accessible experimentally***

. only sd and fp shell nuclei available

Systematics of dσ(0+)/dσ(1+)

- **sd shell systematic**

  from litterature & ENSDF :

  - max of cross-section at the lowest angle measured, no error bars

  - first 0+ and first 1+ states taken into account (no centroid)

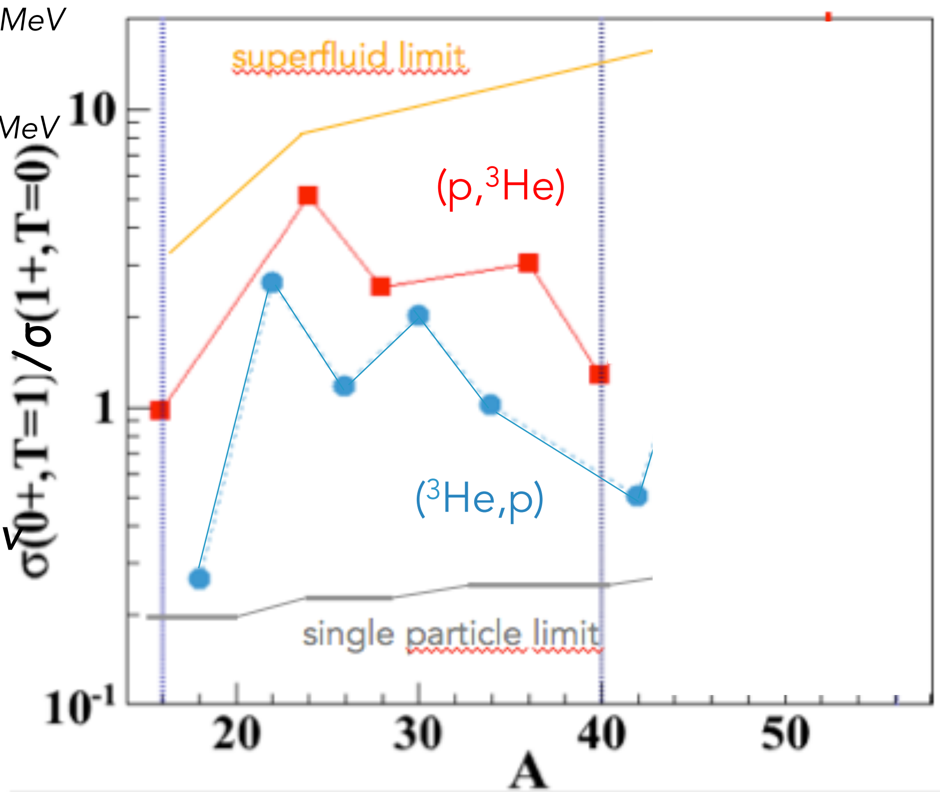
  → *slight difference between (p,^{3}He) and (^{3}He,p)* → **effect of Q-value ? (Brink's conditions)**

  → ^{16}O and ^{40}Ca do not behave as « shell closure »

^{16}O(^{3}He,p)^{18}F	*Sen Gupta, J. Phys. G 12 (1976) 935 18MeV*
^{20}Ne(^{3}He,p)^{22}Na	*Garret, NPA 164 (1971) 449 15 MeV*
^{24}Mg(^{3}He,p)^{26}Al ^{28}Si(^{3}He,p)^{30}P ^{32}S(^{3}He,p)^{34}Cl	*Del Vecchio, NPA 265 (1976) 220 40 MeV* *Nann, NPA 198 (1972)11 24 MeV*
^{40}Ca (^{3}He,p)^{34}Cl	*Pülhhofer, NPA 116 (1968) 516 18 MeV*

very scarce literature for (p,^{3}He)

^{16}O(p,^{3}He)^{14}N	*Fleming NPA 162 (1971) 225* **54 MeV**
^{24}Mg(p,^{3}He)^{22}Na ^{28}Si(p,^{3}He)^{26}Al	*Brown, Ann. Rep. Indiana Univ. (1993)* *89.6 MeV*
^{36}Ar(p,^{3}He)^{34}Cl	*Brunnader, NPA 137 (1969) 487* **45 MeV**
^{40}Ca (p,^{3}He)^{34}Cl	*Sens, NPA 407 (1983) 45* **35 MeV**



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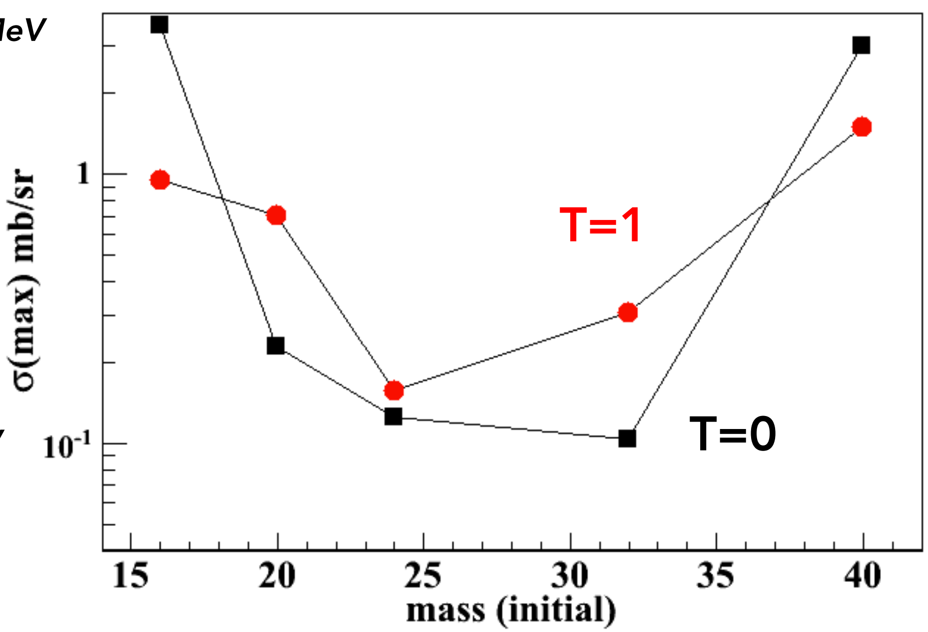
(^{3}He,p) reaction only



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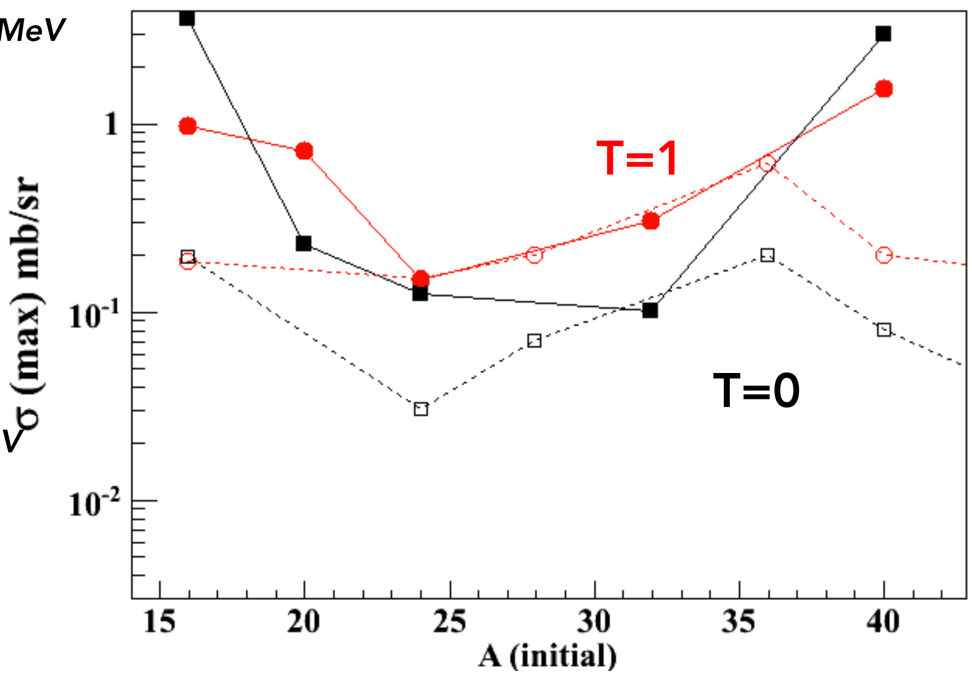
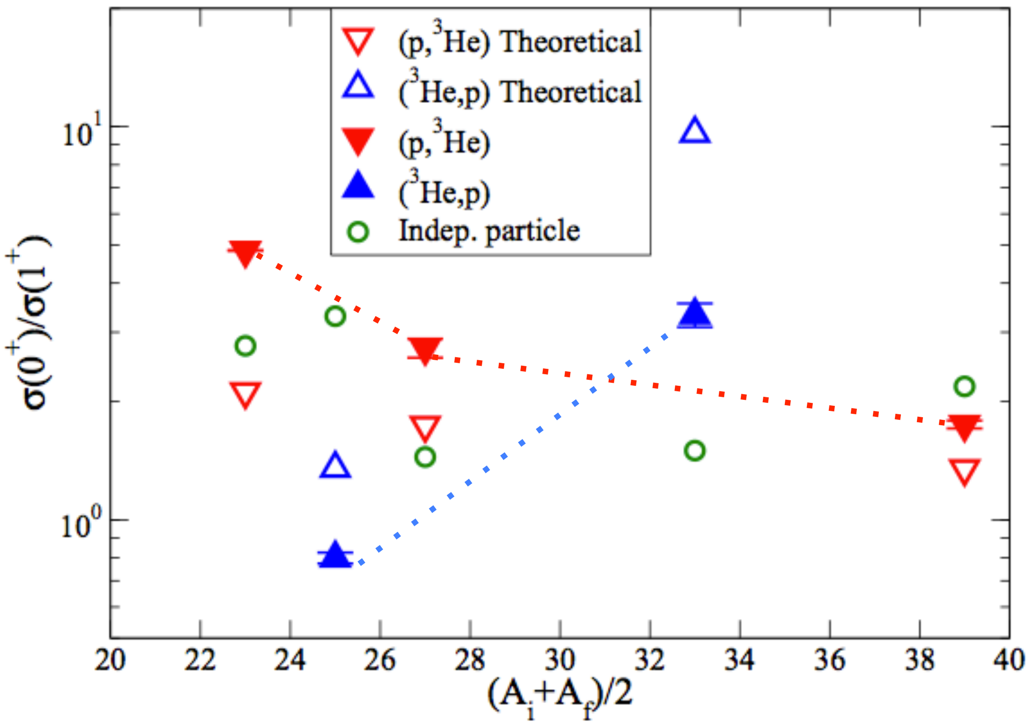
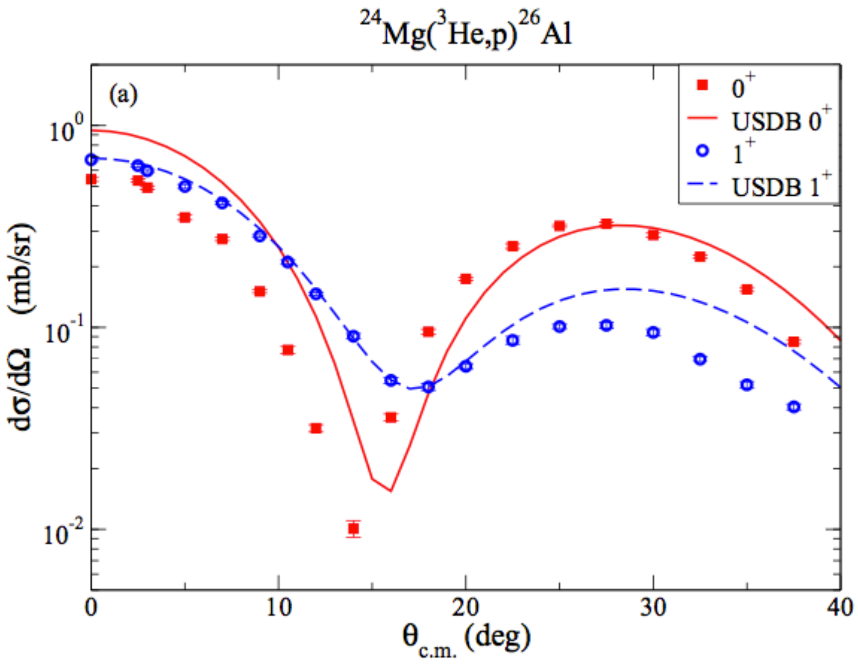
(^{3}He,p) & (p,3He) (dashed) **reaction**



Systematics of dσ

- sd shell systematic remeasurement





Angular distribution for $^{24}Mg(^{3}He,p)$

△△ **remeasurement J. Lee @ Osaka RCNP @ 25 MeV**
-> Y. Ayyad *et al*, PRC96 (2017)
Theory : J. Lay (INFN-Padova) 2nd order DWBA

Systematics of dσ(0+)/dσ(1+)

- **sd shell systematic remeasurement**

  consistent measurement by J. Lee & Y. Ayyad-Limonge at RCNP Osaka in direct kinematics

  np transfer reactions

  ^{3}He beam at 25 MeV: ^{24}Mg(^{3}He,p), ^{32}S(^{3}He,p)

  Proton beam at 65 MeV: ^{24}Mg(p,^{3}He), ^{28}Si(p,^{3}He),^{40}Ca(p,^{3}He)

  2n transfer reactions (comparison to np transfer) ^{24}Mg(p,t), ^{28}Si(p,t)

^{16}O(^{3}He,p)^{18}F	*Sen Gupta, J. Phys. G 12 (1976) 935*
^{20}Ne(^{3}He,p)^{22}Na	*Garret, NPA 164 (1971) 449*
^{24}Mg(^{3}He,p)^{26}Al, ^{28}Si(^{3}He,p)^{30}P, ^{32}S(^{3}He,p)^{34}Cl	*Del Vecchio, NPA 265 (1976) 220*; *Nann, NPA 198 (1972)11*
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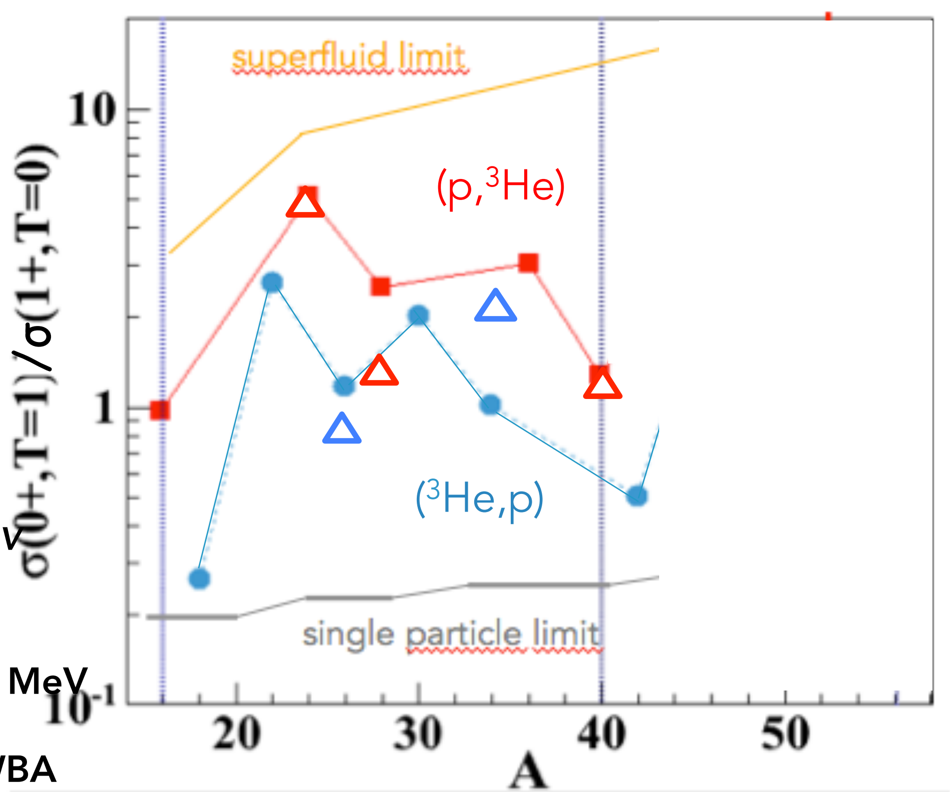

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Reaction mechanism effect : some aspects

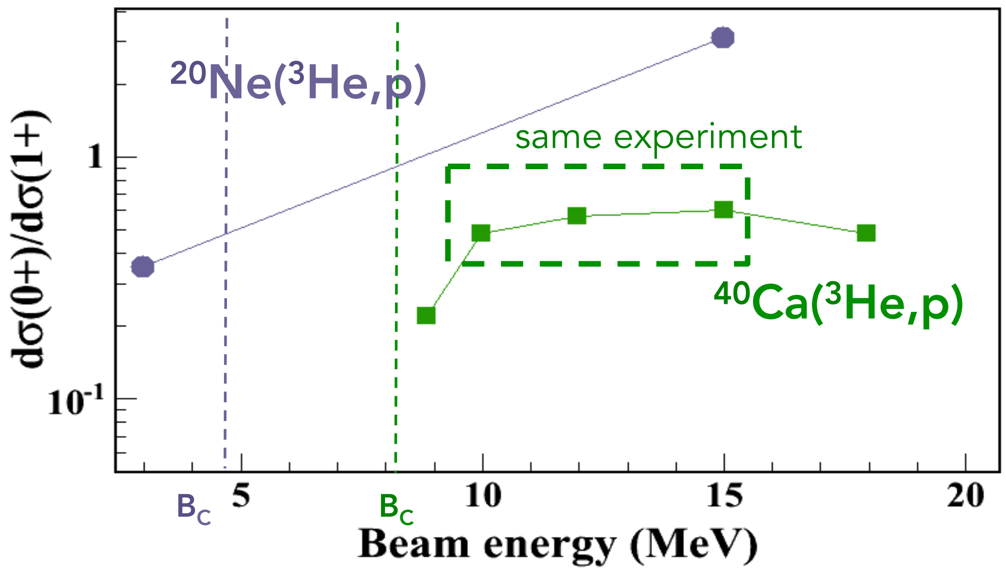
- **Beam energy**

$^{40}Ca(^3He,p)$

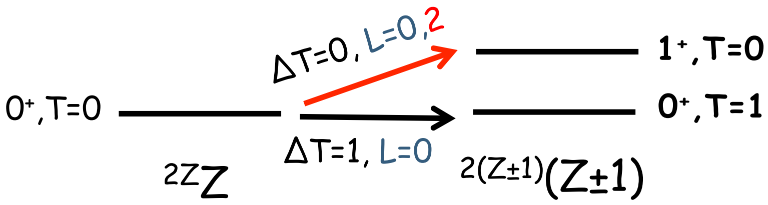
Sherr, Ann. Phys. 66 (1971) 548 → **8.9 - 26 MeV**
Pülhhofer, NPA 116 (1968) 516 → **18 MeV**
Zurmulhe Nucl. Phys. 80 (1966) 259 → **10-12-15 MeV**

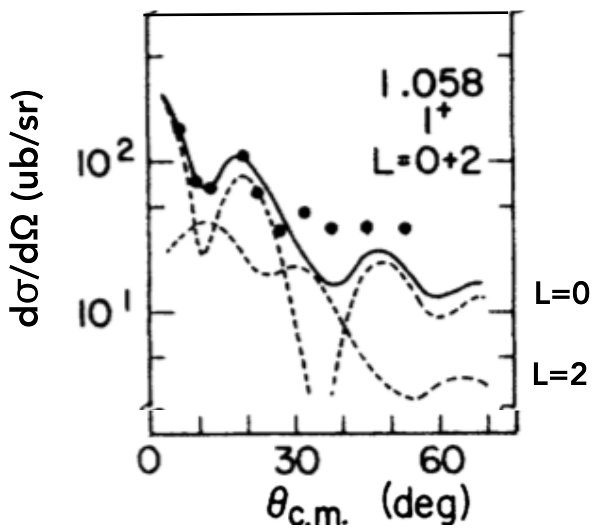
$^{20}Ne(^3He,p)$

Meynadier, NPA 161 (1971) 305 → **3 MeV**
Garett, NPA 164 (1971) 449 → **15 MeV**



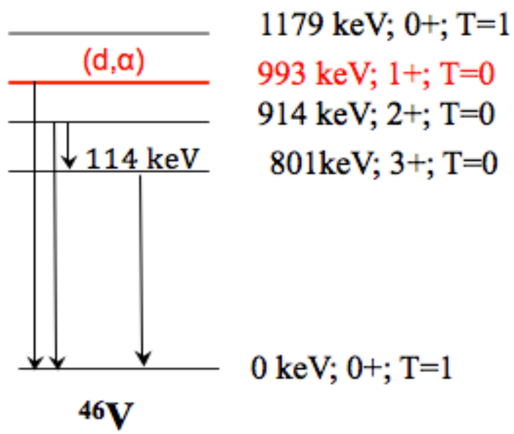
- **L transfer : 0 and 2 contributions**

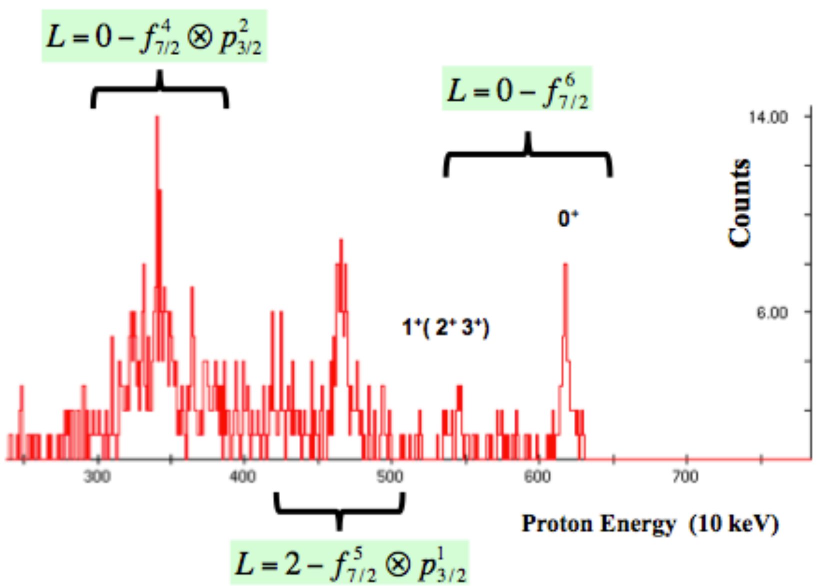


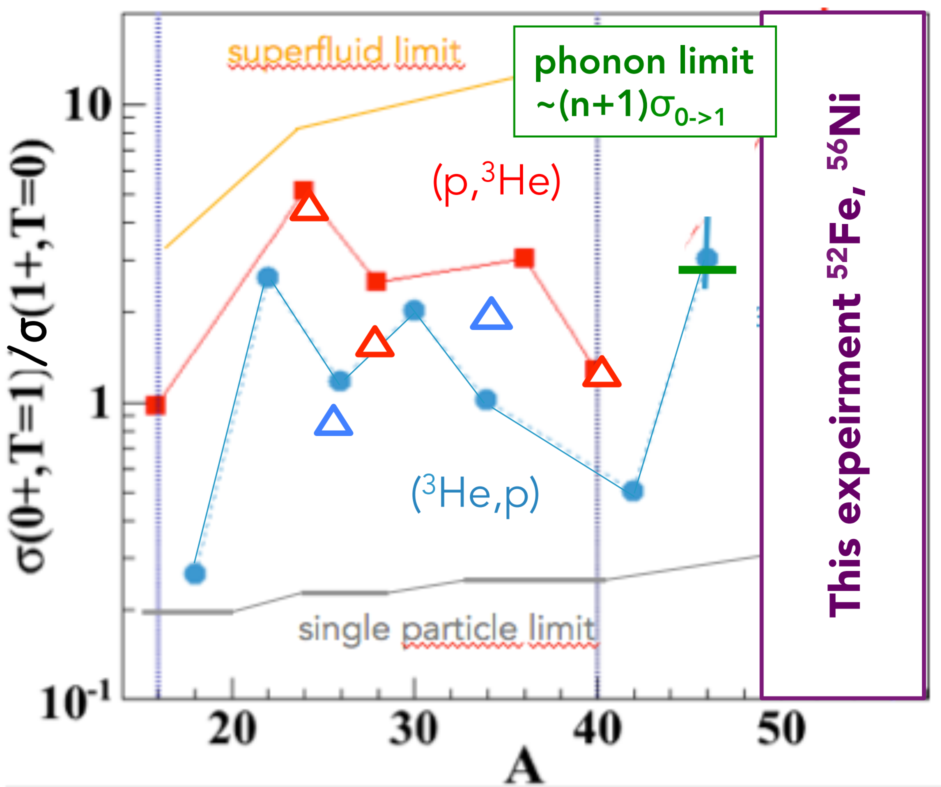


Case of ^{44}Ti

- **sd shell systematic**
  remeasured consistently by J. Lee & Y. Ayyad-Limonge
- **One measurement in fp shell : ^{44}Ti**
  A.O. Macchiavelli et al, in preparation
  @ ATLAS facility at Argonne National lab







courtesy of A.O. Macchiavelli

Experiment at GANIL : ^{56}Ni, ^{52}Fe (p,^{3}He)

- Beam produced by fragmentation with the LISE spectrometer

  ^{56}Ni, ^{52}Fe @ 30A MeV

- Reactions measured :

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

  ^{56}Ni (d,^{4}He) ^{54}Co

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

- **thick targets** : 7 mg/cm^2

- Odd-Odd nucleus level Scheme

1821 keV, 3+, T=0

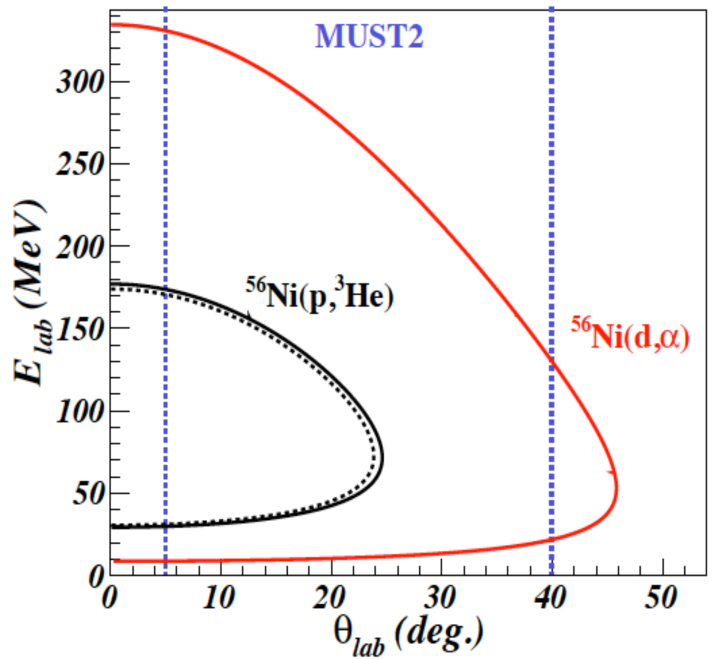
1445 keV, 2+, T=1

936 keV, 1+, T=0

197keV, 7+, T=0 (isomeric)

0+, T=1

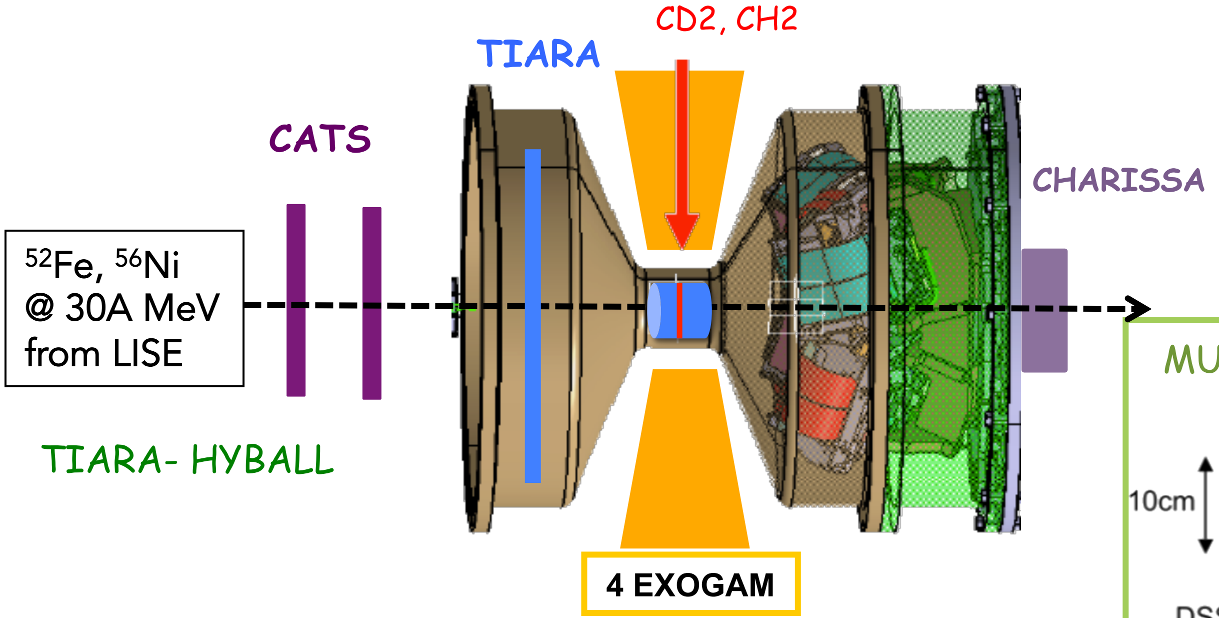
^{54}Co

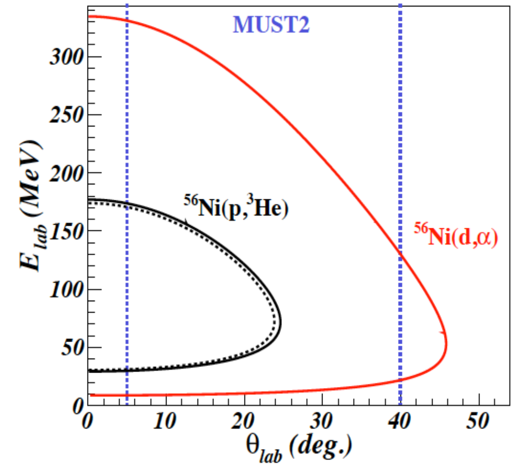


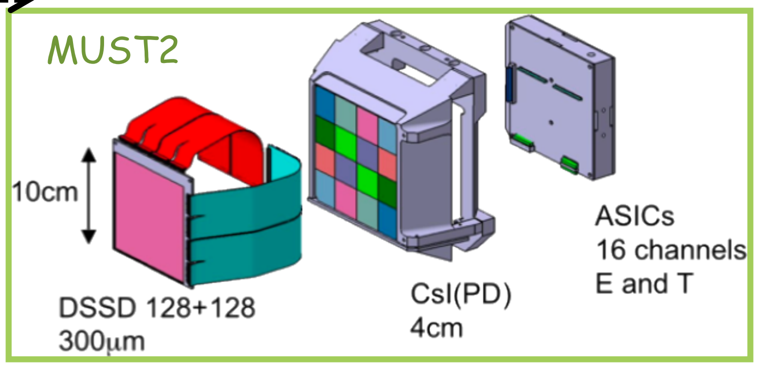
Experimental set-up

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

thick target CH_2 : 7 mg/cm^2
beam energy : 30A MeV



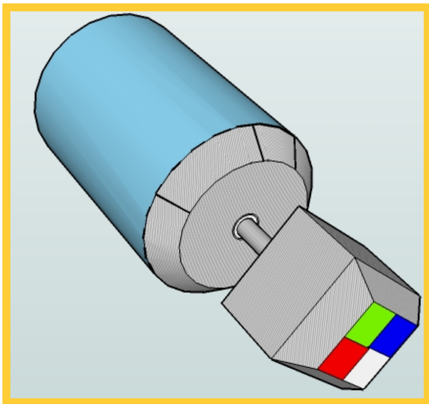


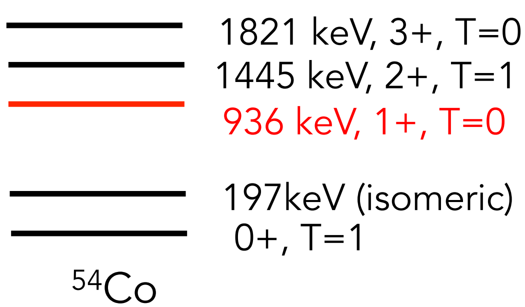


Efficiency ~8%@ 1 MeV

Energy resolution 3 keV

Doppler broadening 80 keV

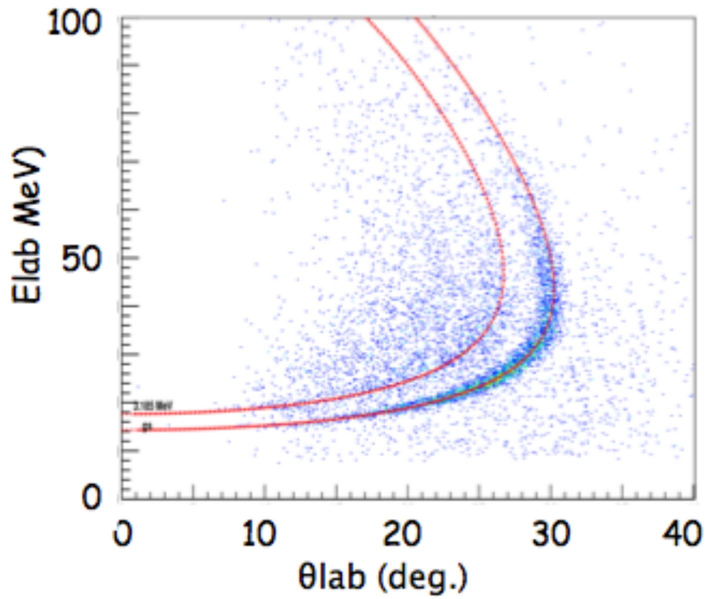


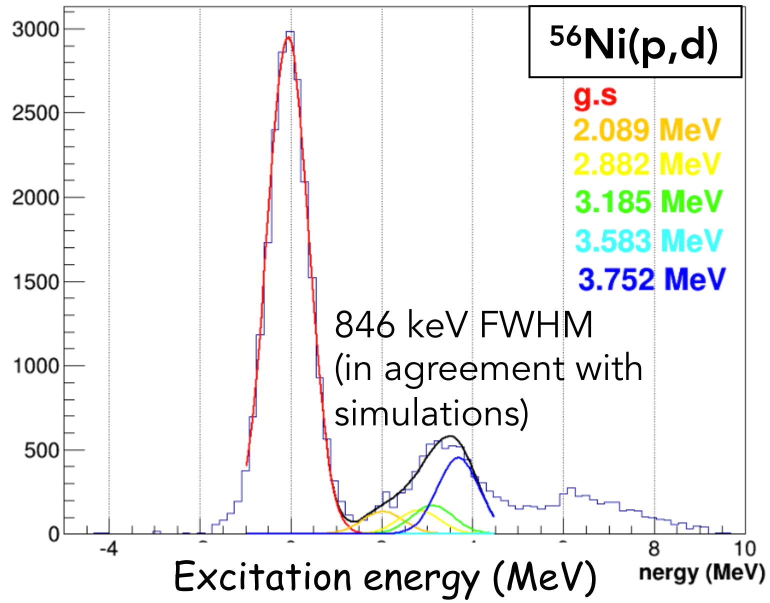


^{56}Ni(p,d) reaction as calibration

^{56}Ni(p,d)^{57}Ni for calibration

- already measured (Sanetullaev et al, PLB 2014)
- energy calibration of MUST2
- alignement of CATS-MUST2
- resolution = 846 keV (FWHM)
  as expected from simulations





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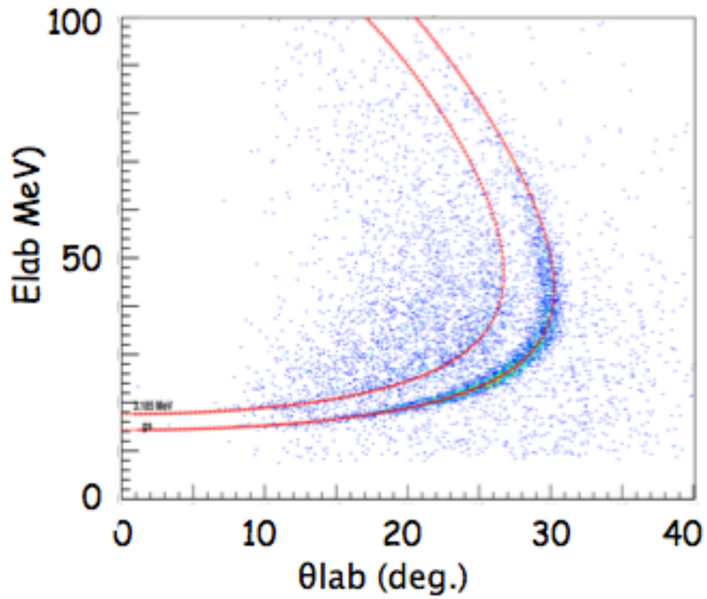
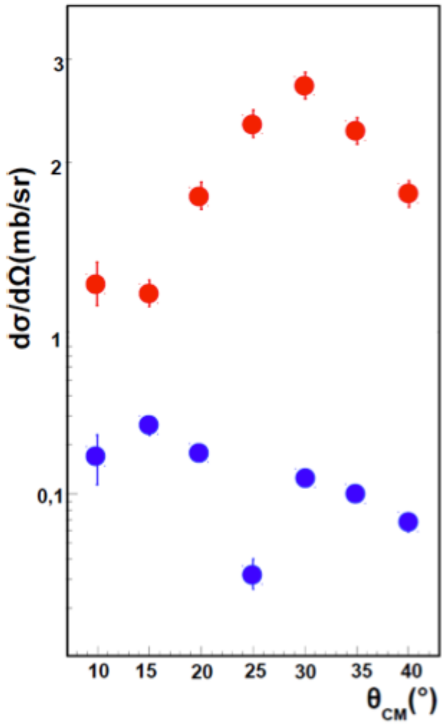
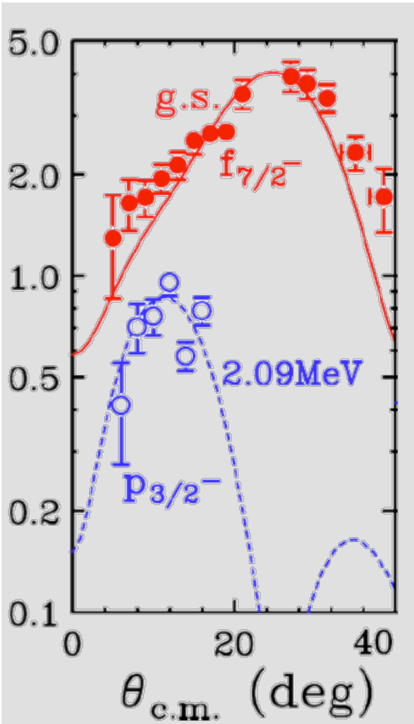
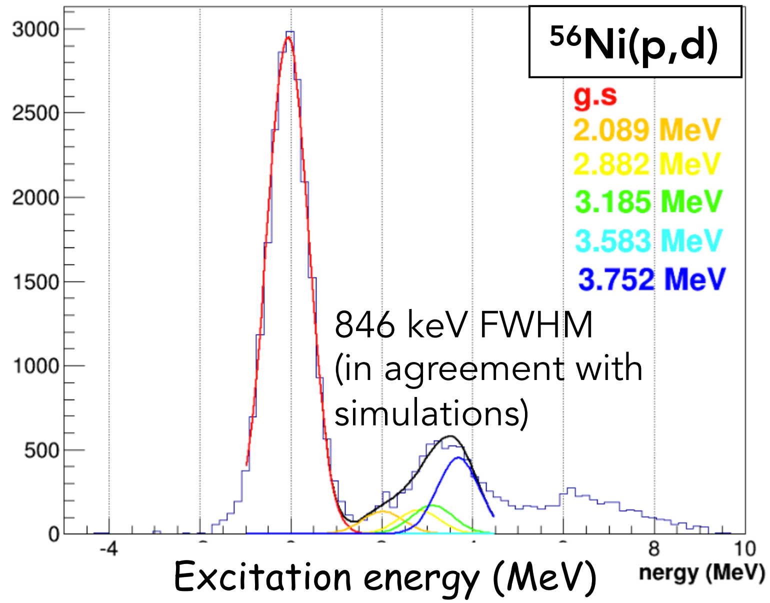


g.s. angular distribution
and DWBA $f_{7/2}$ SF=6.8 (id. PLB2014)



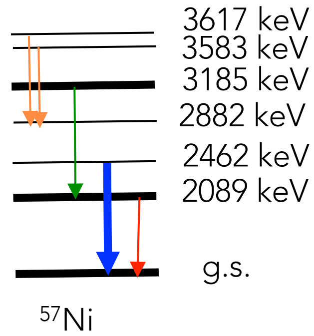




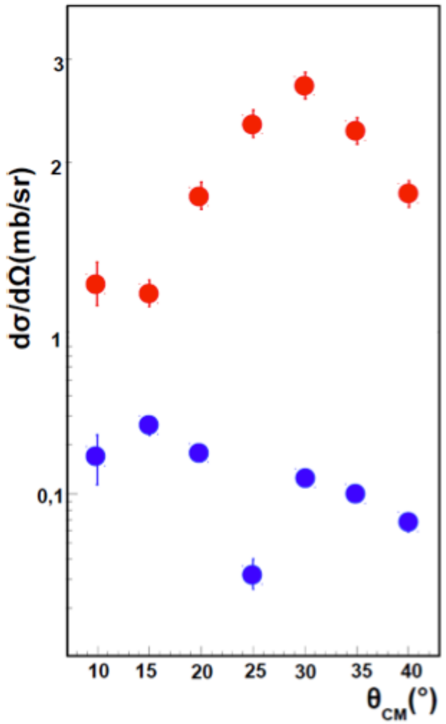
$^{56}Ni(p,d)$ reaction as calibration

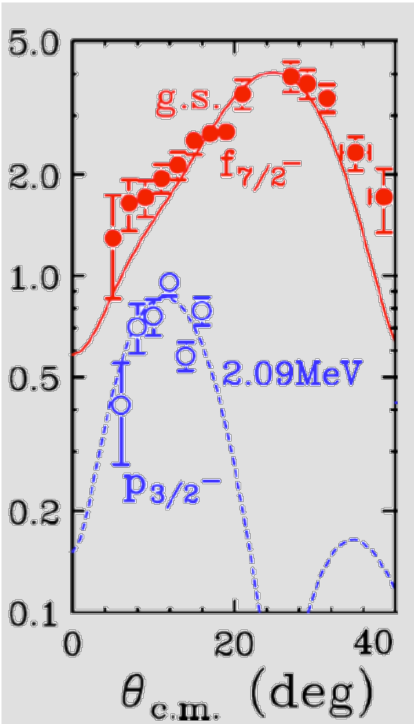
$^{56}Ni(p,d)^{57}Ni$ for calibration

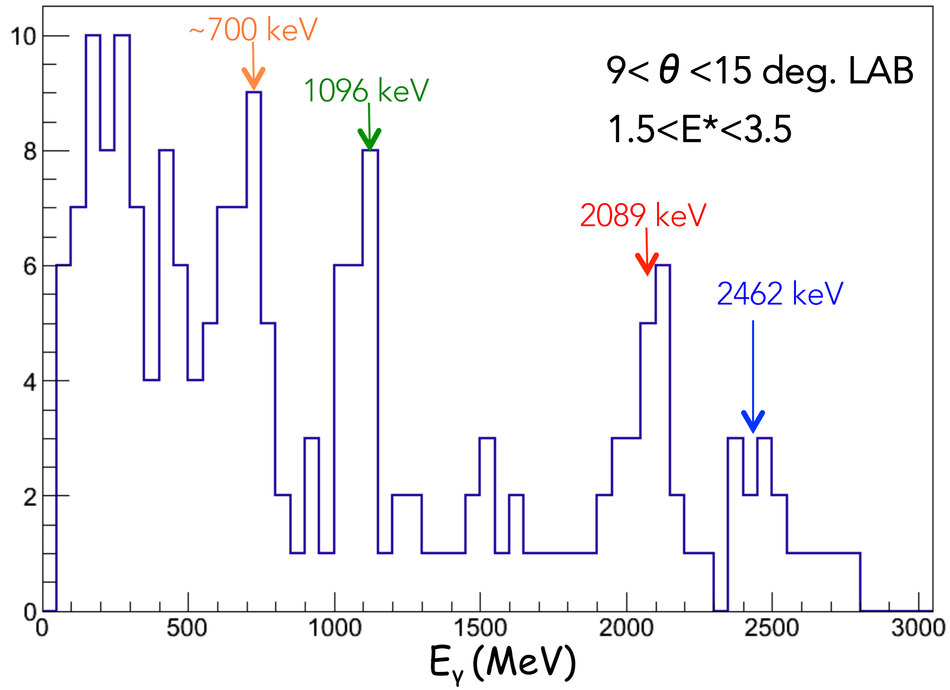
- already measured (Sanetullaev et al, PLB 2014)
- resolution = 846 keV (FWHM)
  as expected from simulations



g.s. angular distribution
and DWBA $f_{7/2}$ SF=6.8 (id. PLB2014)







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

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

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

closed shell nucleus | open shell nucleus

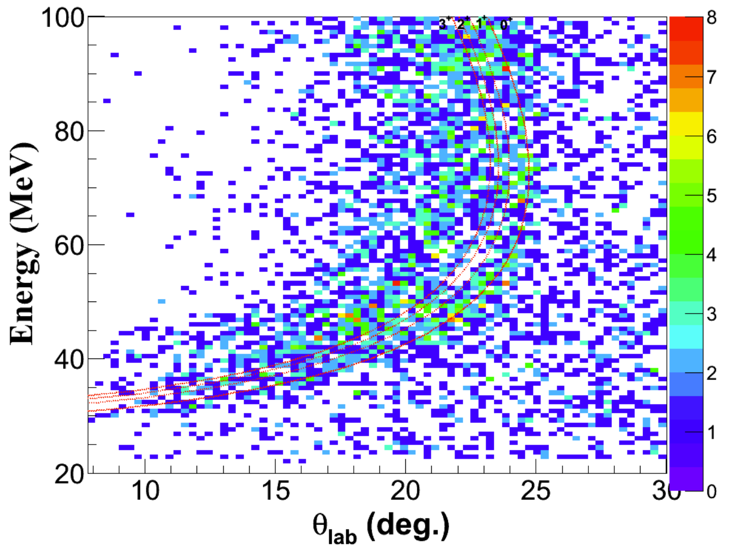
initial g.s. (e-e) J=0+, T=0

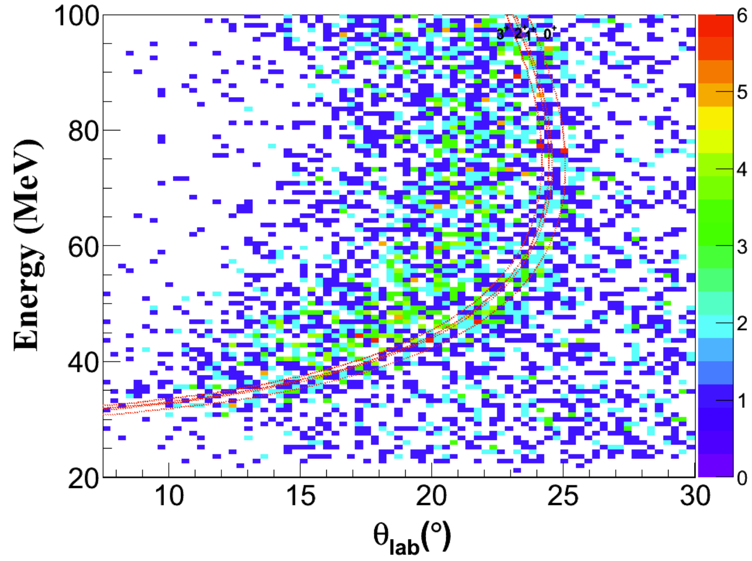
final { g.s. (o-o) J=0+, T=1 ; 1st exc. J=1+, T=0 }

Q value = -13.5 MeV
E_{beam} =30 A MeV

Q value = -13.35 MeV
E_{beam} =30 A MeV

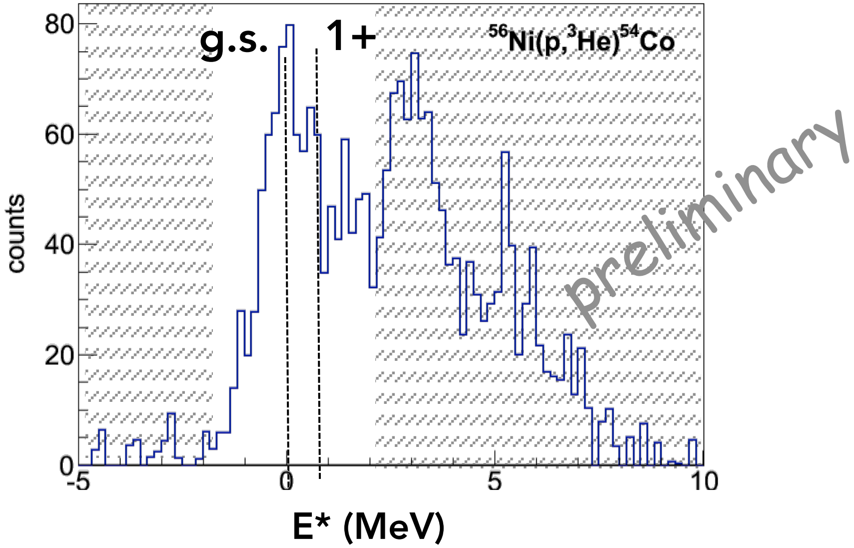
matching condition : L ≤ 4

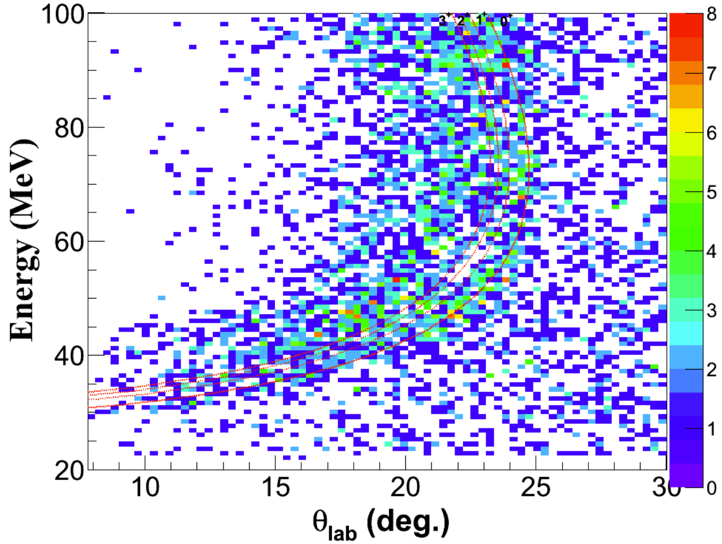




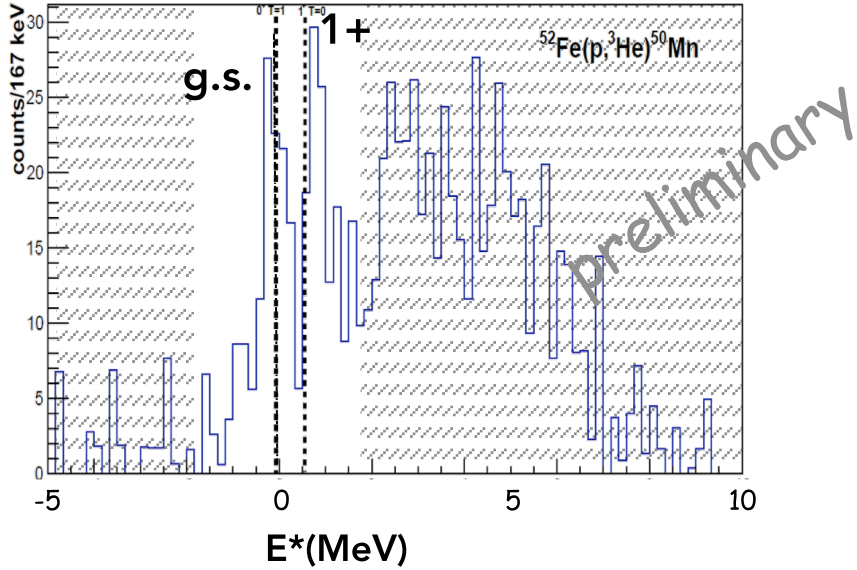
The (p,^{3}He) reaction on ^{56}Ni & ^{52}Fe

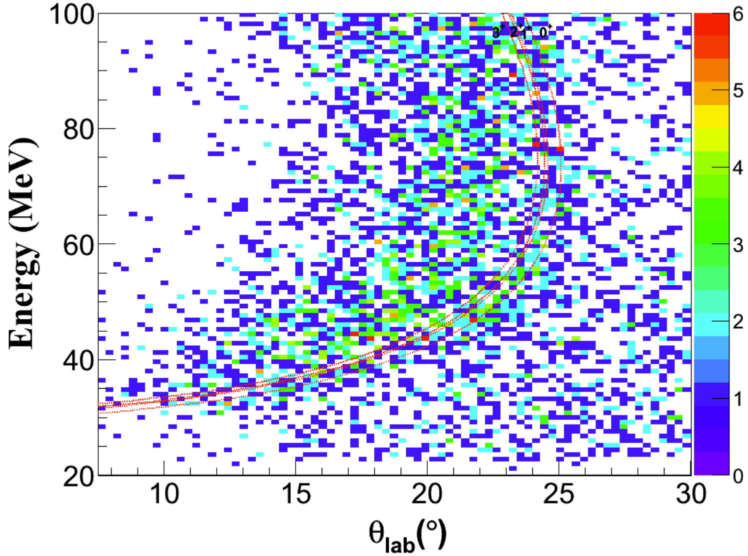
^{56}Ni(p,^{3}He)^{54}Co





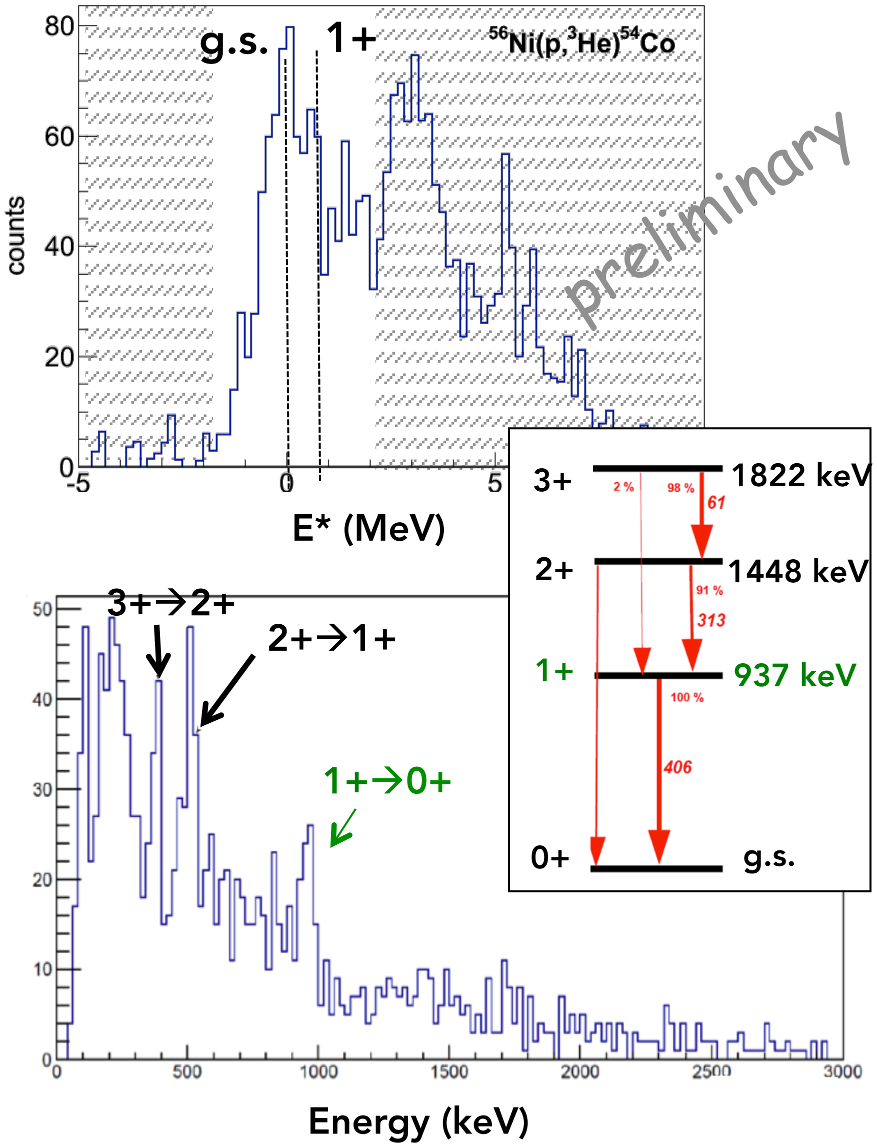
^{52}Fe(p,^{3}He)^{50}Mn



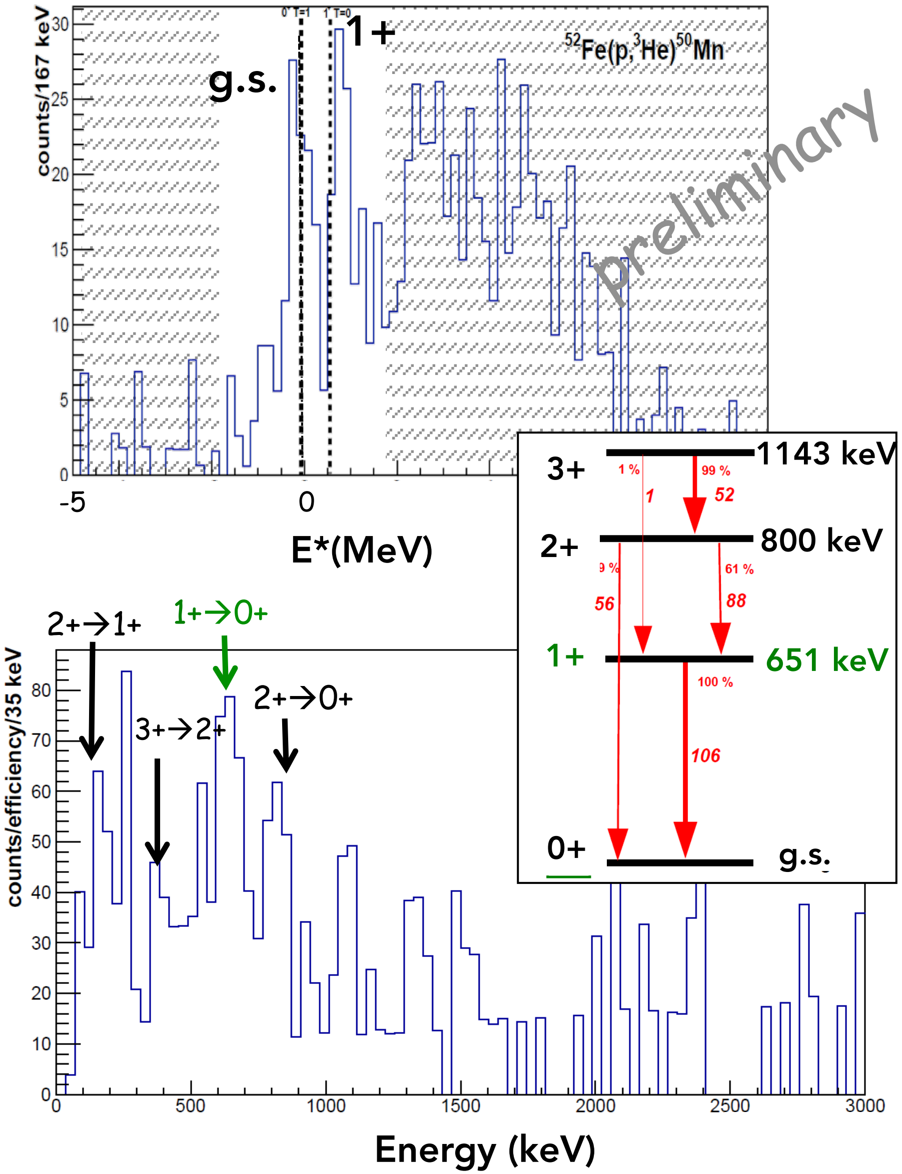


Excitation energy spectra

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

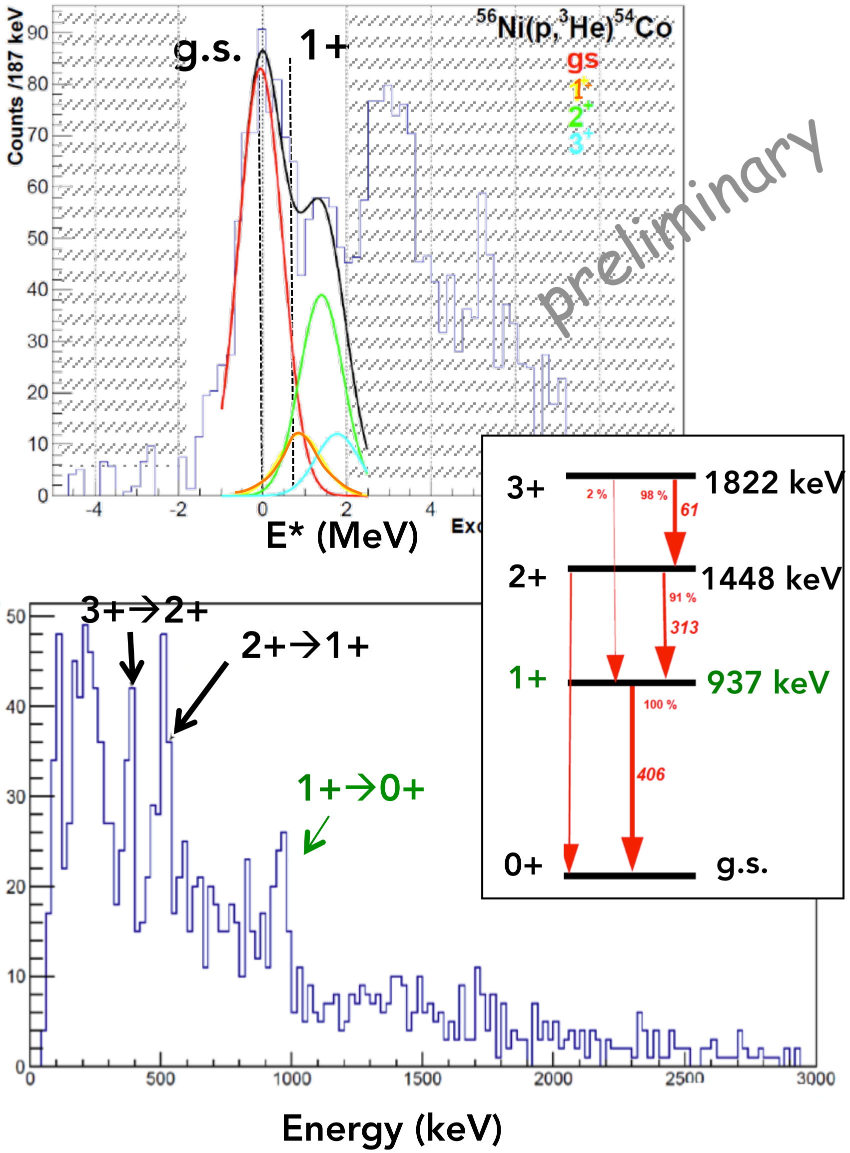


$^{52}Fe(p,^{3}He)^{50}Mn$

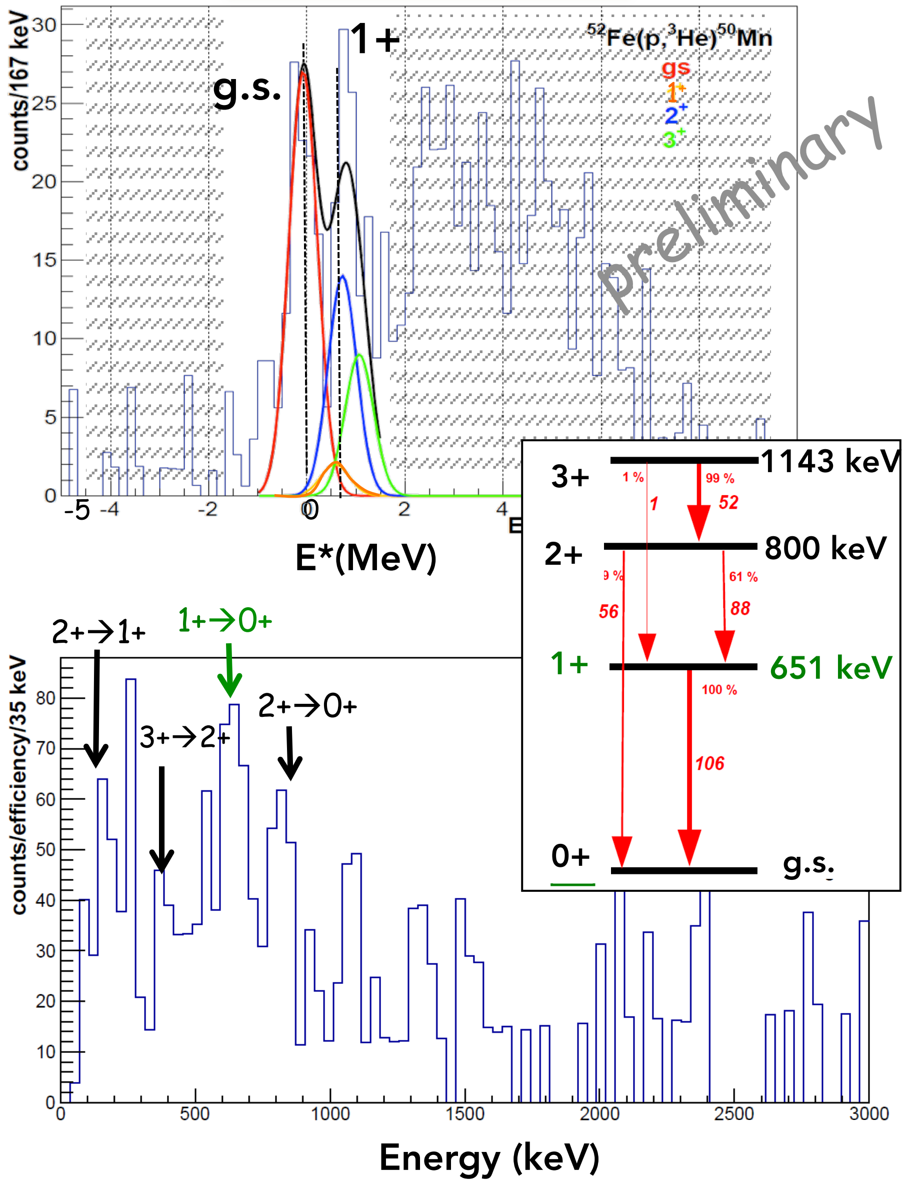


Excitation energy spectra

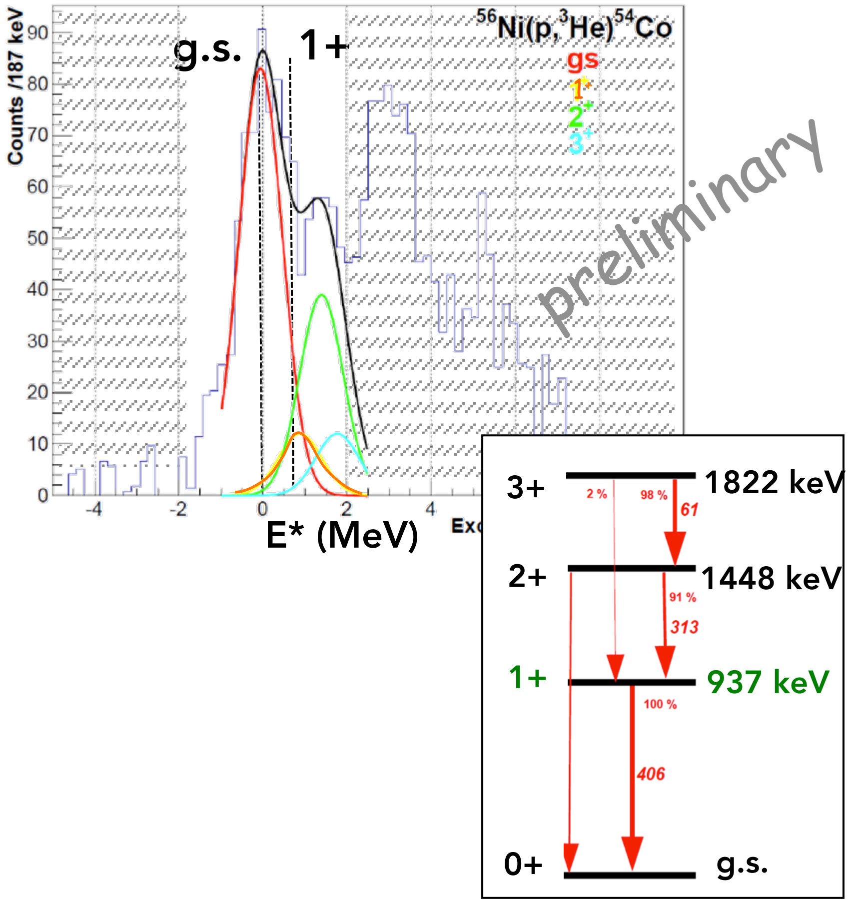
$^{56}Ni(p,^{3}He)^{54}Co$



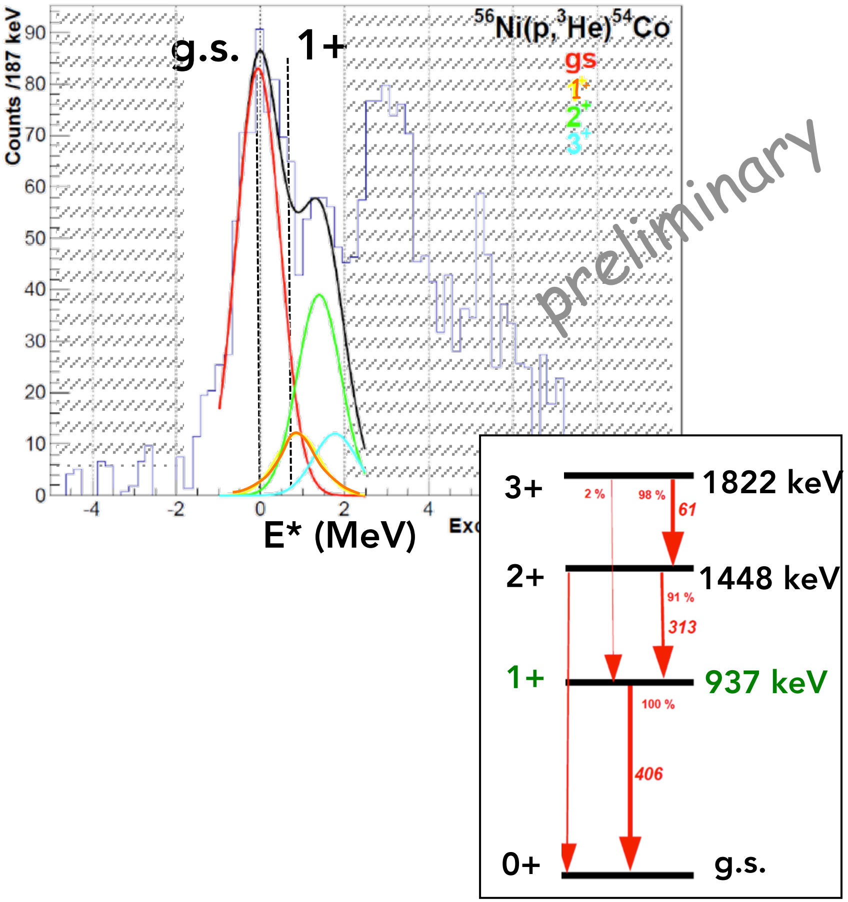
$^{52}Fe(p,^{3}He)^{50}Mn$



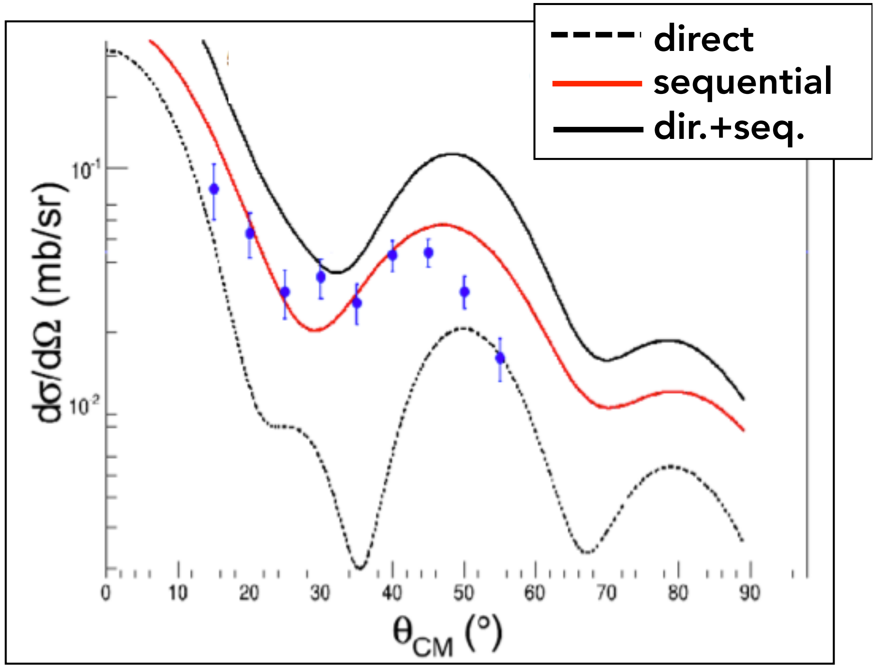
$^{56}Ni(p,^{3}He)^{54}Co$



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



Angular distribution for g.s.



DWBA calculation

with form factors from Sagawa-san including other shells than $f_{7/2}$

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

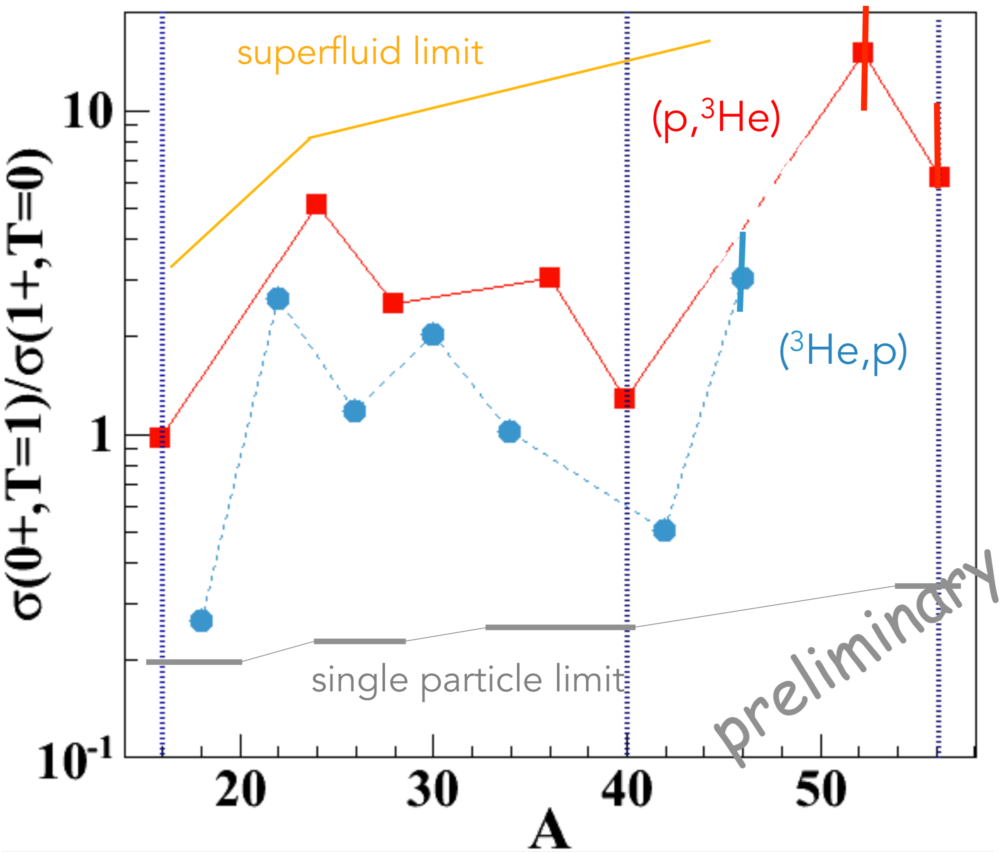
Also measured :
- elastic scattering
- $^{55}Co(p,d)^{54}Co$ (intermediate reaction)

▶ Direct vs. sequential ?

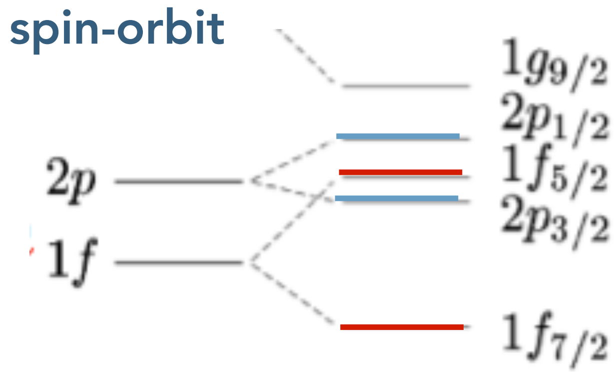
correlations kept in the sequential transfer ?

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

Results for ^{52}Fe and ^{56}Ni



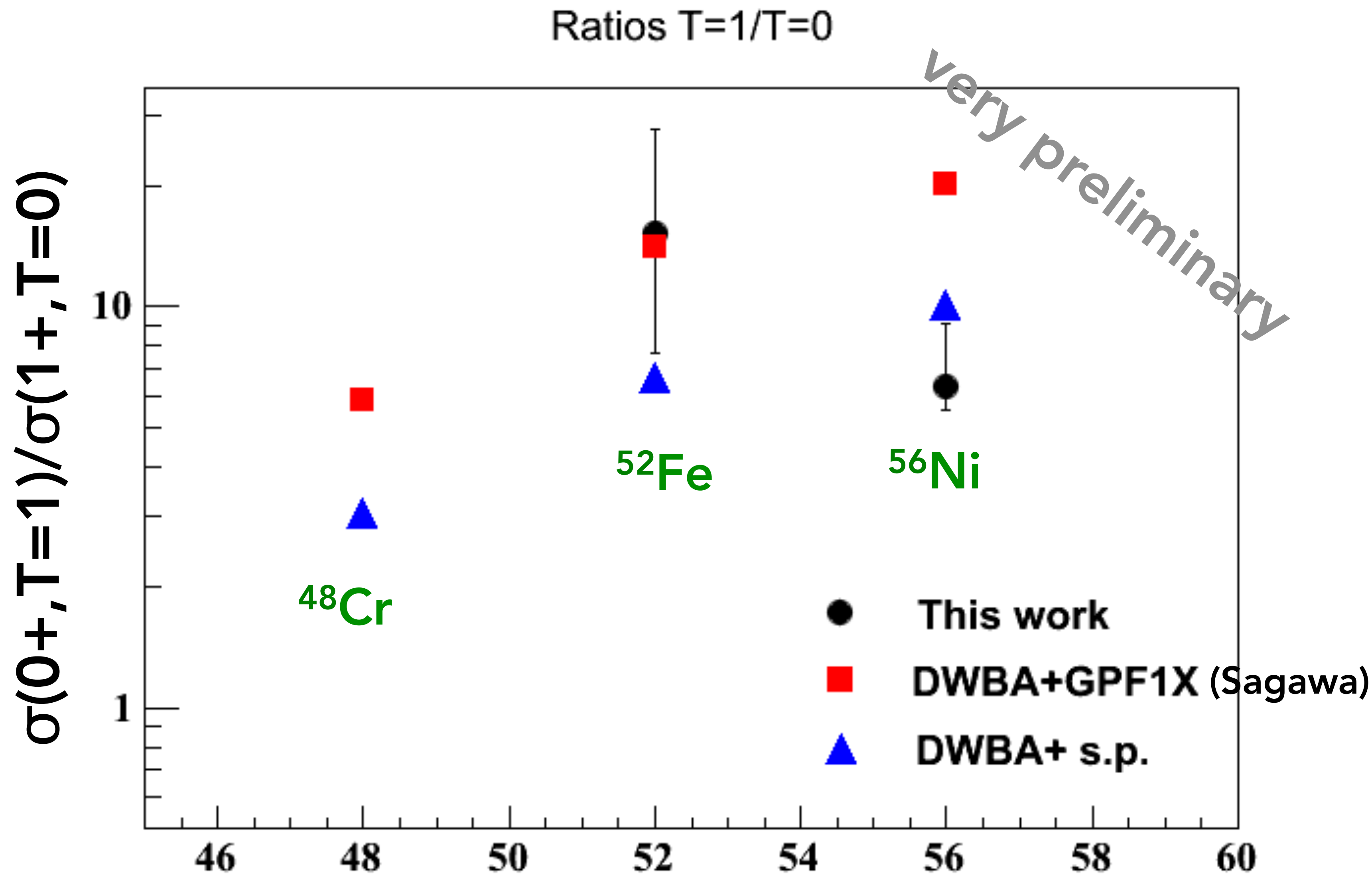
- T=0 states sparsely populated
- ^{56}Ni not following single-particle
- T=0 pairing seems weaker in fp shell than sd shell
- Cross-section for T=0 ~10 ub



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

➡ **Theoretical calculations in agreement with T=0 channel weak in ^{56}Ni & ^{52}Fe**

DWBA calculations



Perspectives

LoI for ^{56}Ni (^{3}He,p) ^{58}Cu with MUGAST + AGATA+ VAMOS