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

- 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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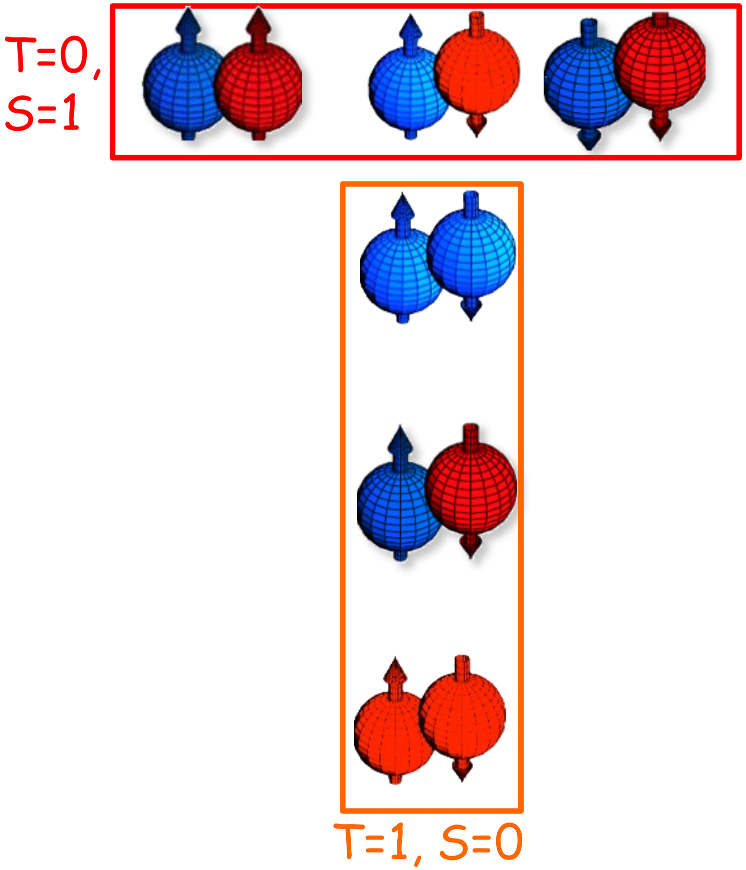
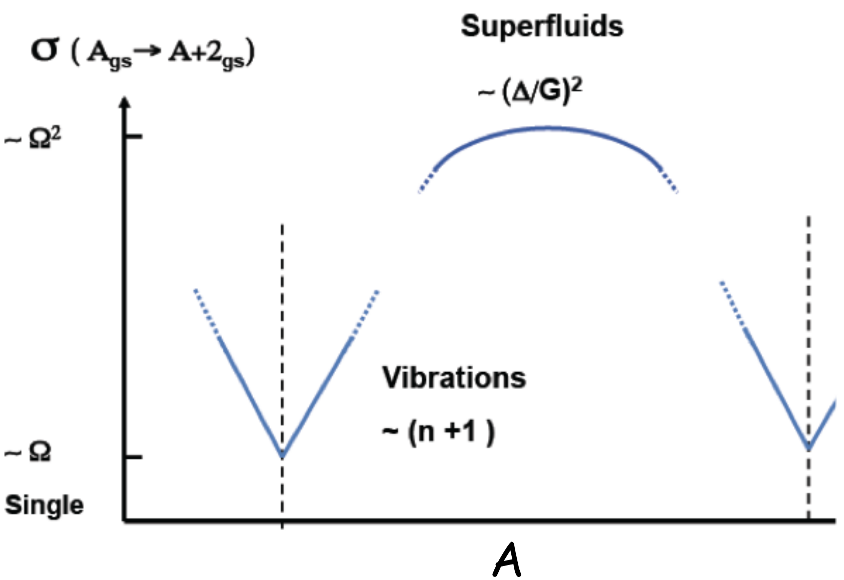
IPN Orsay, assie@ipno.in2p3.fr

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)

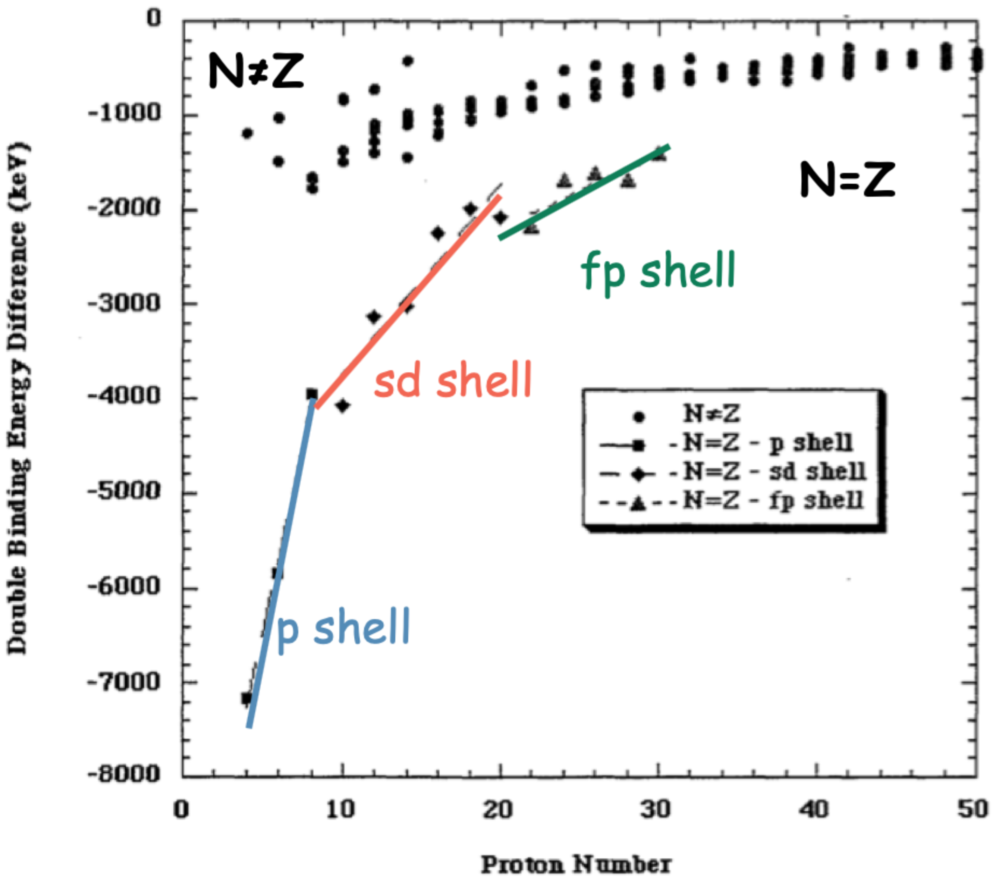
➡ Does T=0 channel creates a correlated state in analogy with superfluids ?

Shell effects on np pairing

- Binding Energies

adapted from O. Juillet

ΔV_{np}=1/4[B(N,Z)-B(N,Z-2)-B(N-2,Z)+B(N-2,Z-2)]



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

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*

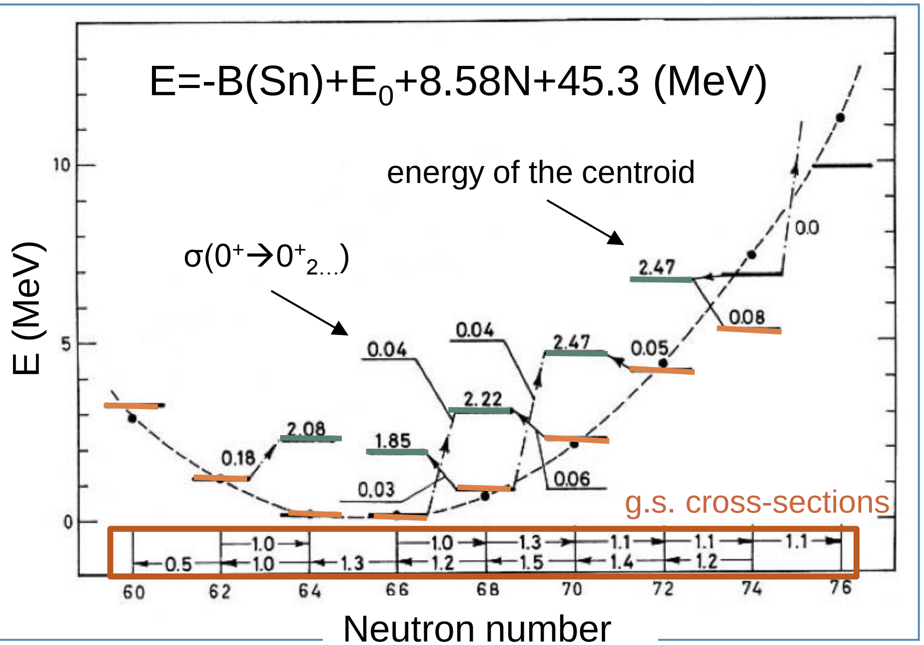
Piet Van Isacker PRL (2005)

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

➕ **The "smoking gun"?** ➖ **beam intensities >10^4pps**

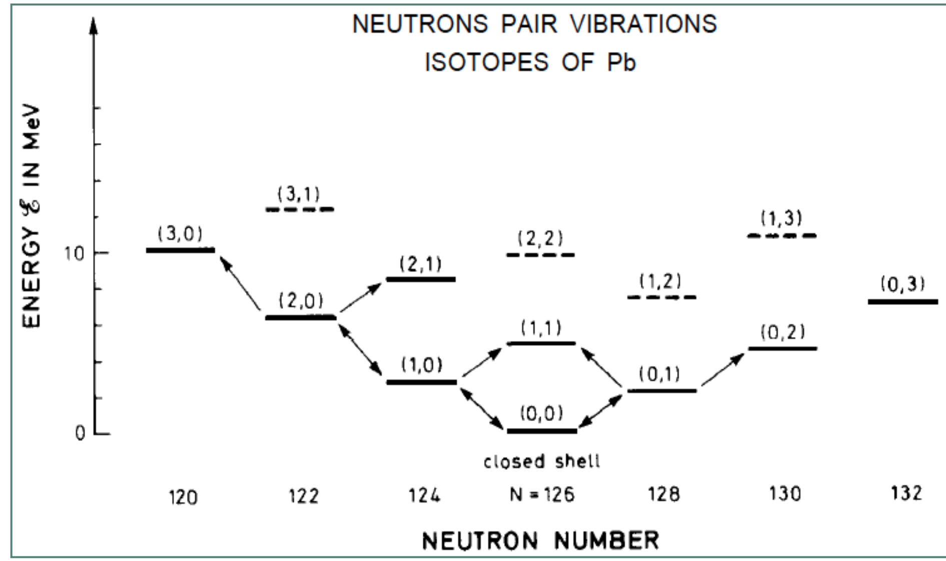
Rotational vs. vibrational pairing

(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

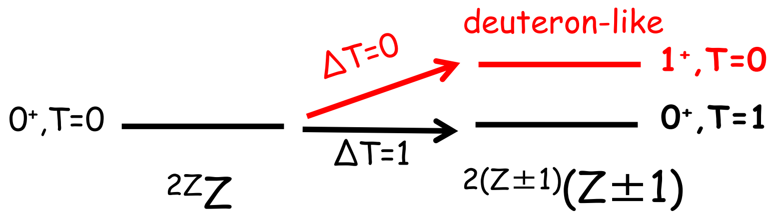
Probing isoscalar pairing through transfer reactions

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^+)/σ (1^+)= gives the relative strength of T=0/T=1 pairing



Experimental aspects

reaction	beam E	direction	selectivity
(p,^{3}He)	>20 MeV	forward	ΔT=0,1
(^{3}He,p)	low <5MeV	backward	ΔT=0,1
(d,α)(α,^{6}Li)	>20 MeV	forward	ΔT=0
(α,d)(^{6}Li, α)	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*

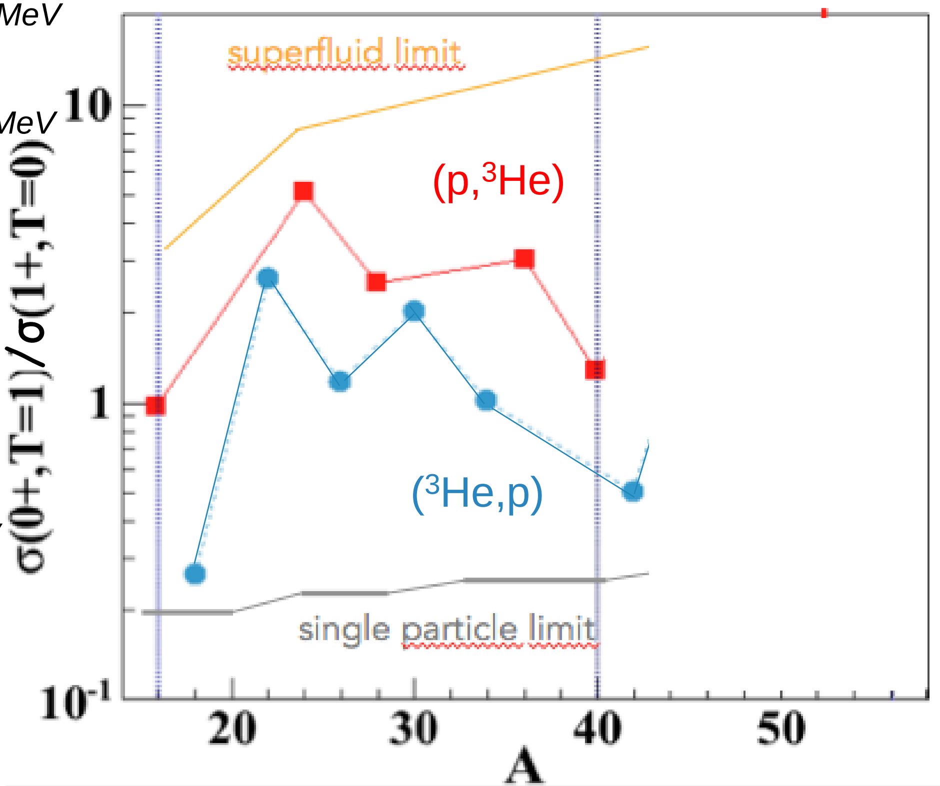
very scarce literature for (p,^{3}He)

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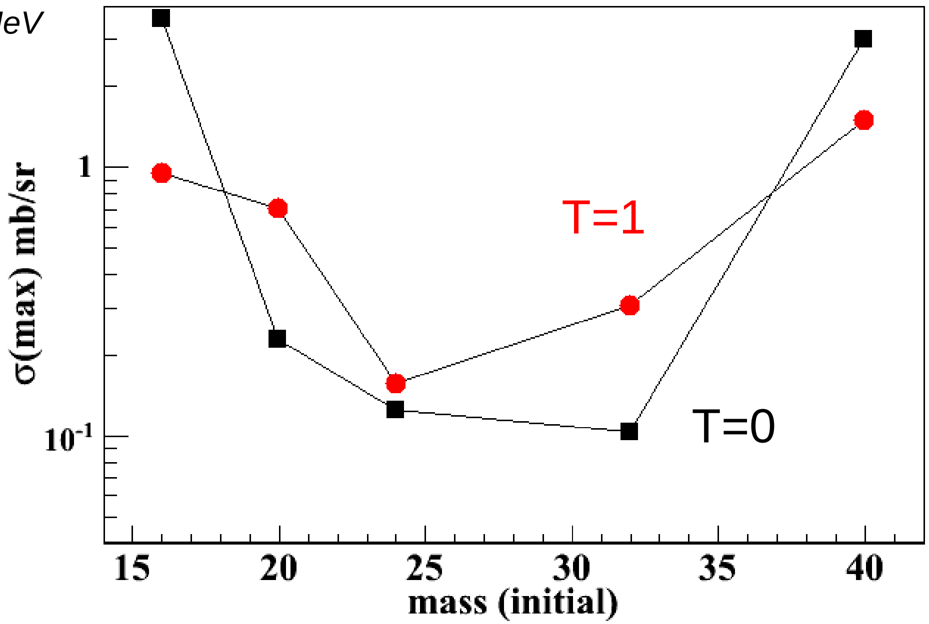
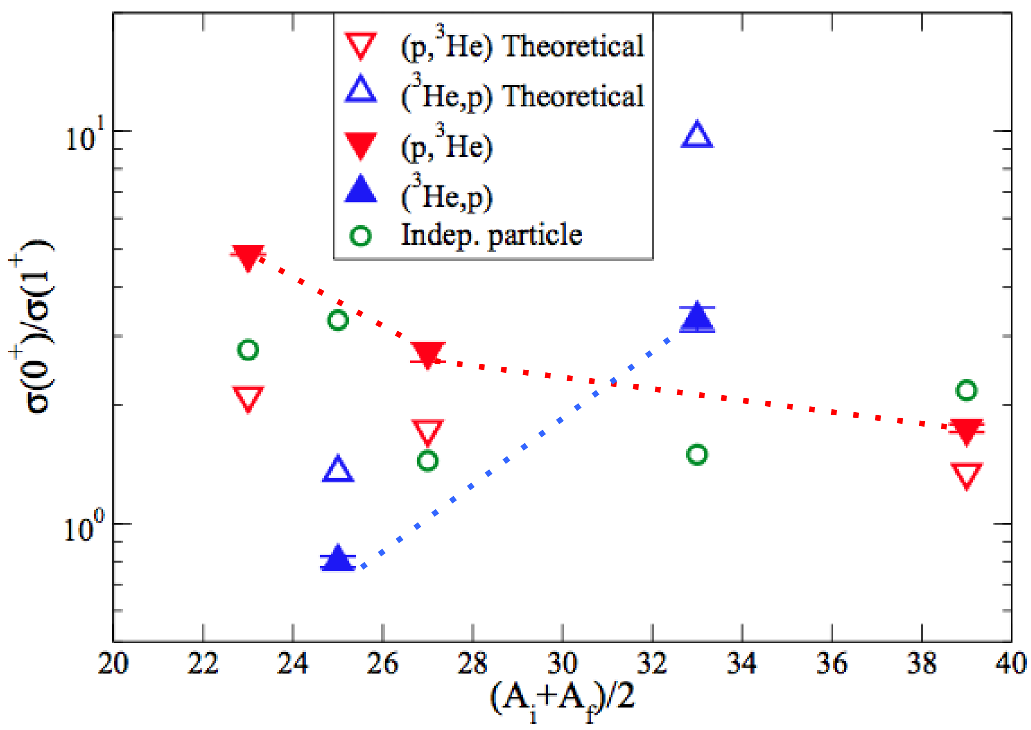
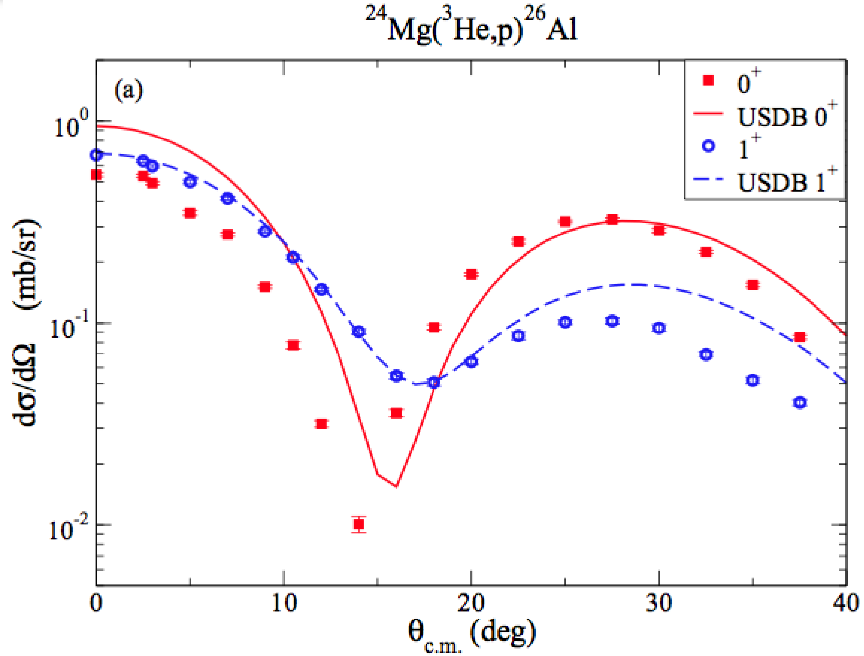
(^{3}He,p) reaction only



Systematics of dσ(0+)/dσ(1+)

- **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*
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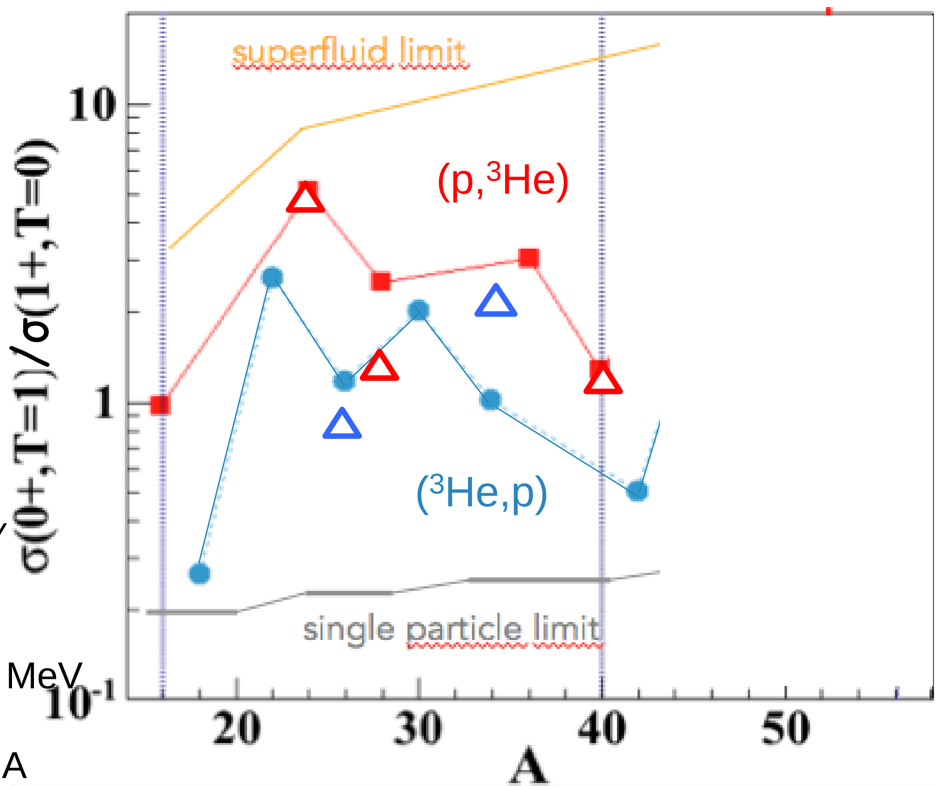

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Theory : J. Lay (INFN-Padova) 2nd order DWBA

Reaction mechanism effect : some aspects

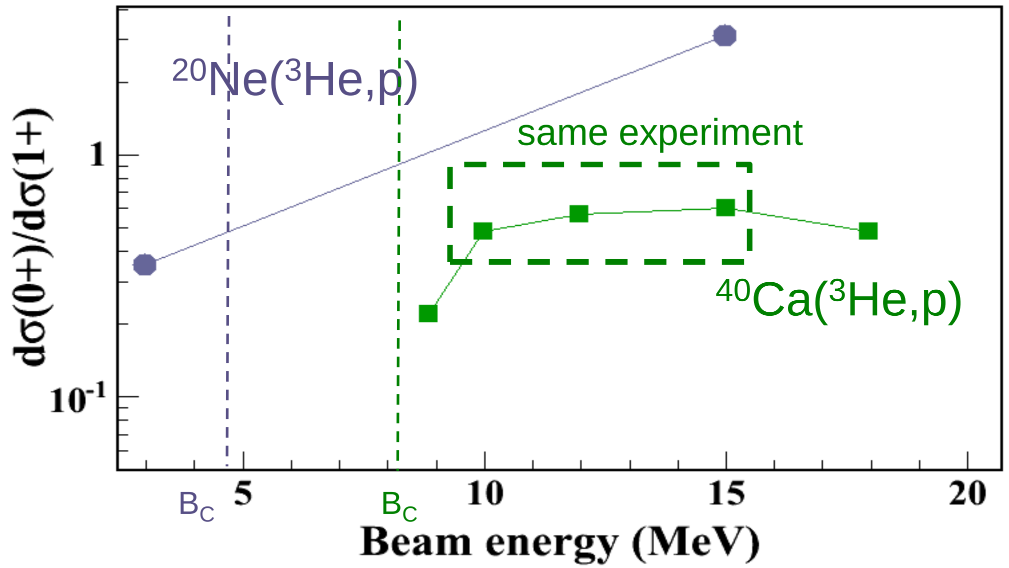
- Beam energy

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

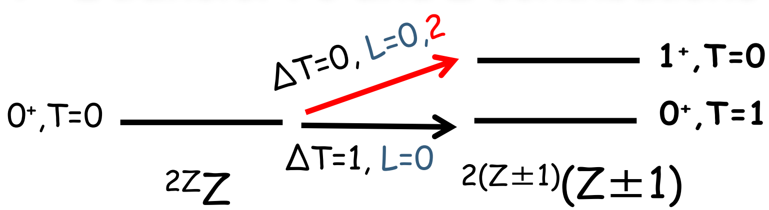
Sherr, Ann. Phys. 66 (1971) 548 → 8.9 - 26 MeV
Pülhhofer, NPA 116 (1968) 516 → 18 MeV
Zurmulhe Nucl. Phys. 80 (1966) 259 → 10-12-15 MeV

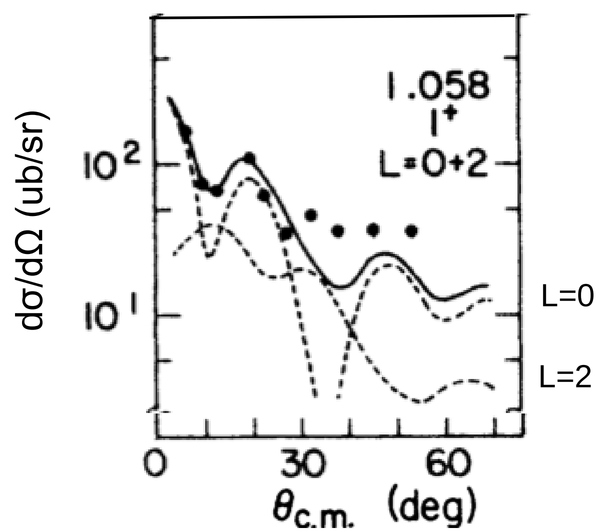
$^{20}Ne(^3He,p)$

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



- L transfer : 0 and 2 contributions





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 :

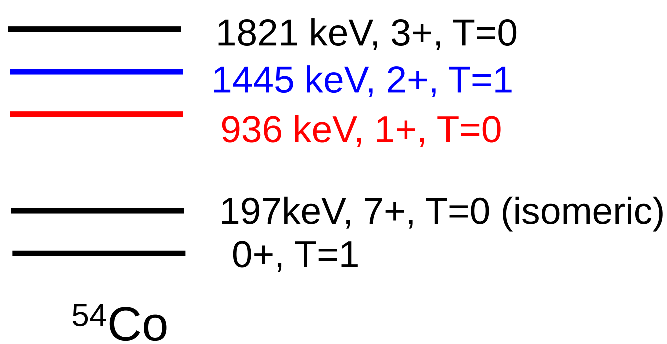
  ^{56}Ni (p,^{3}He) ^{54}Co

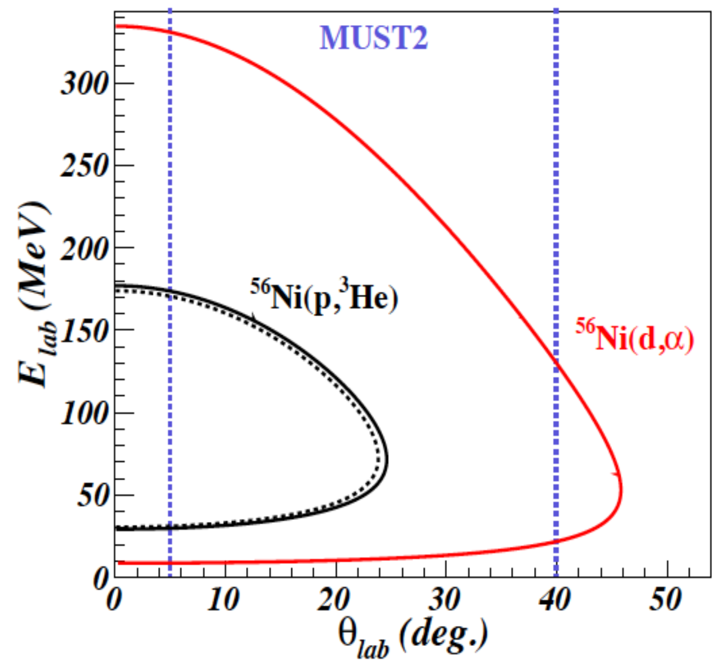
  ^{56}Ni (d,^{4}He) ^{54}Co

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

- thick targets : 7 mg/cm^2

- Odd-Odd nucleus level Scheme

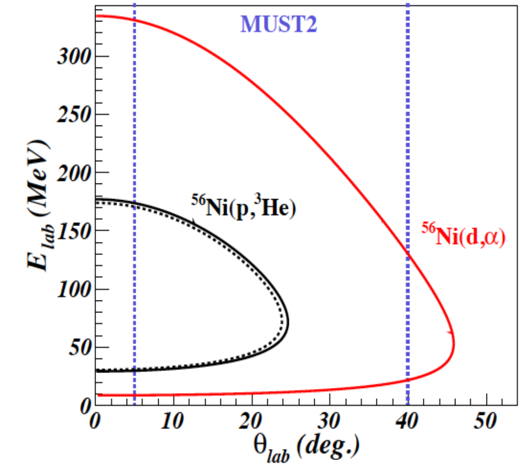


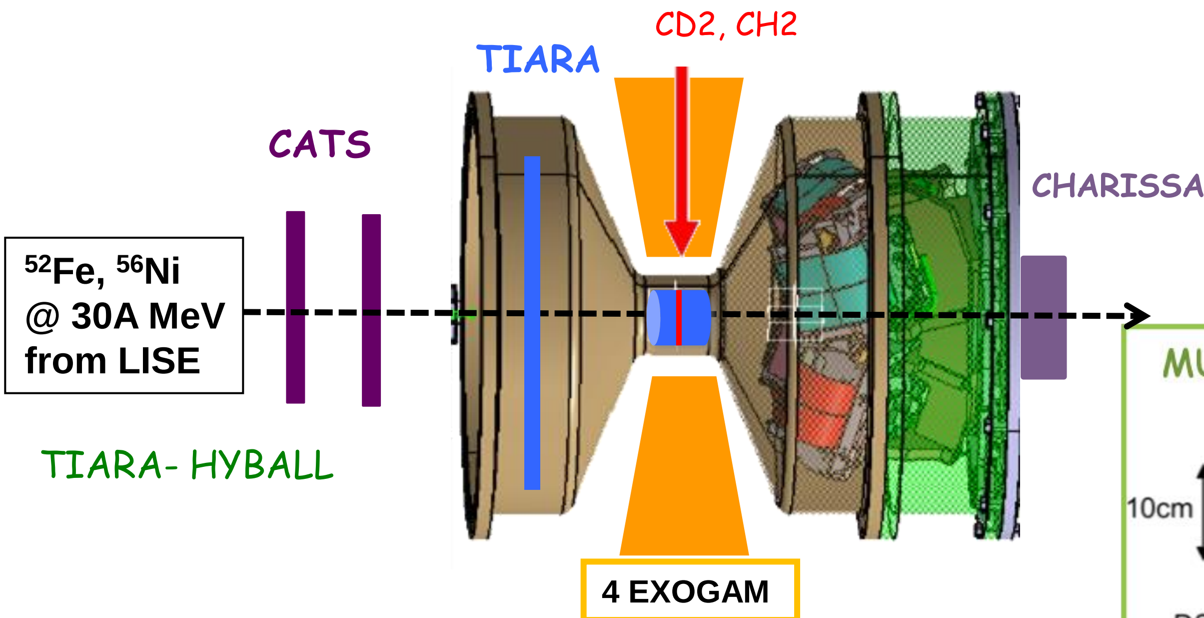


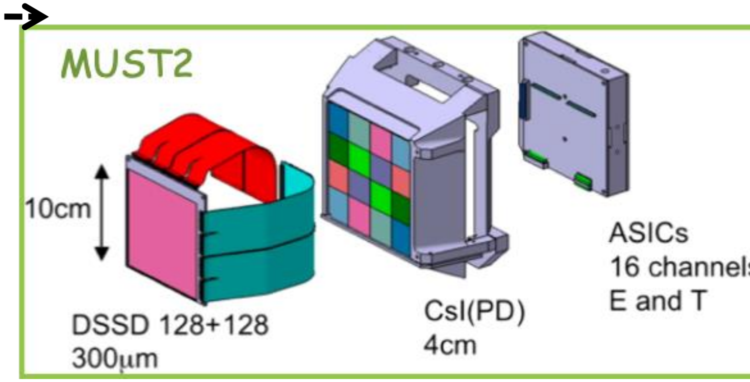
Experimental set-up

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

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



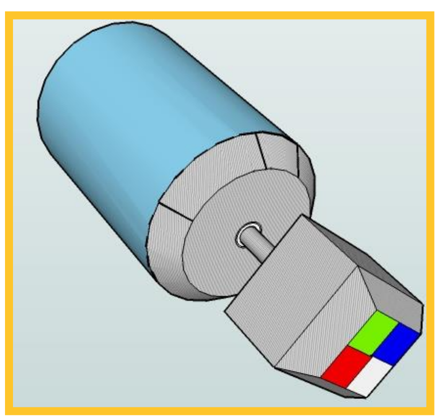


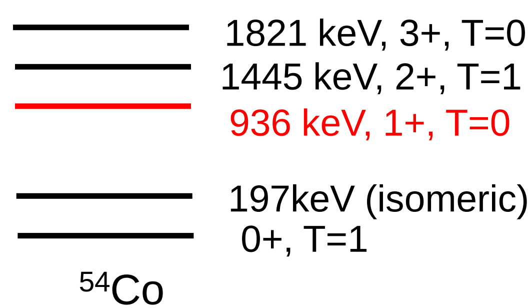


Efficiency ~8%@ 1 MeV

Energy resolution 3 keV

Doppler broadening 80 keV





The (p,^{3}He) 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

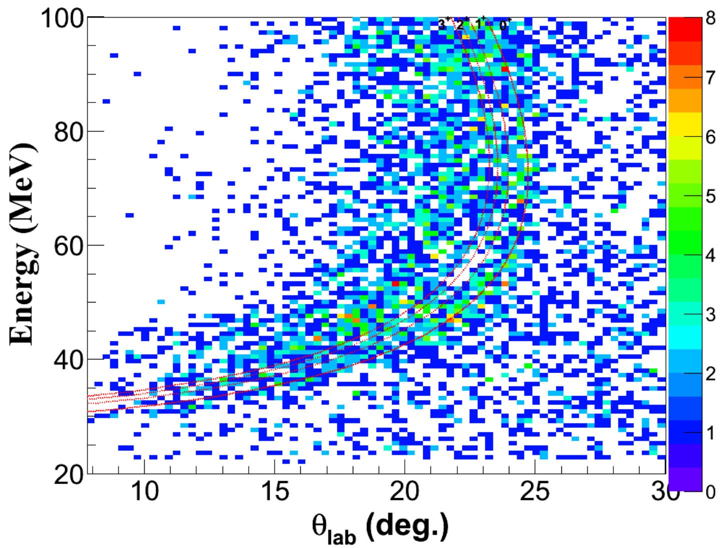
initial g.s. (e-e) J=0+, T=0

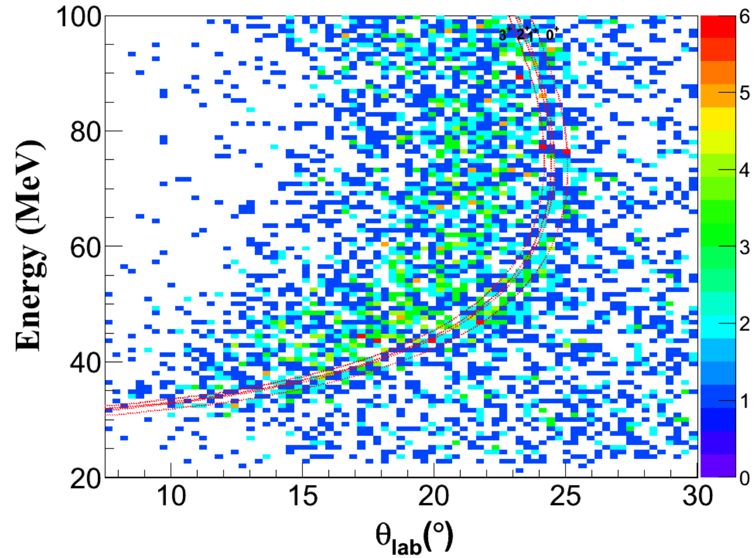
final { g.s. (o-o) J=0+, T=1
1st exc. J=1+, T=0

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

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

matching condition : L ≤ 4





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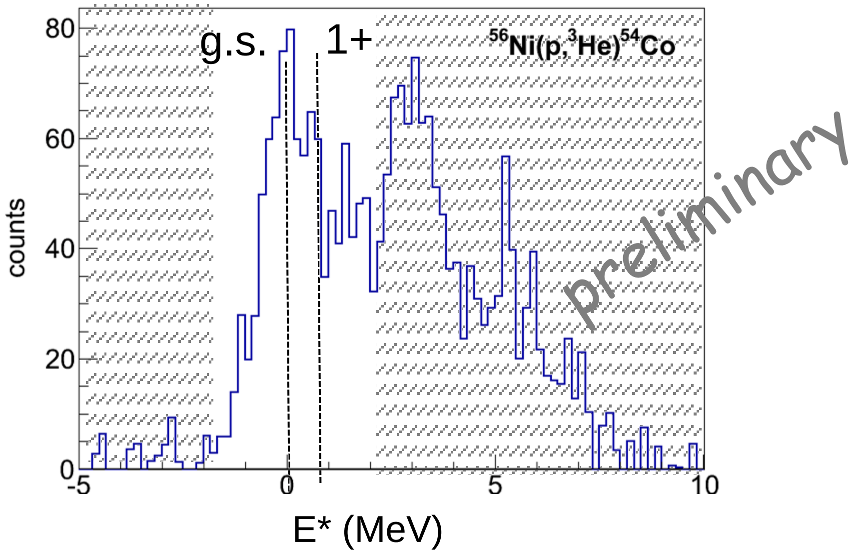
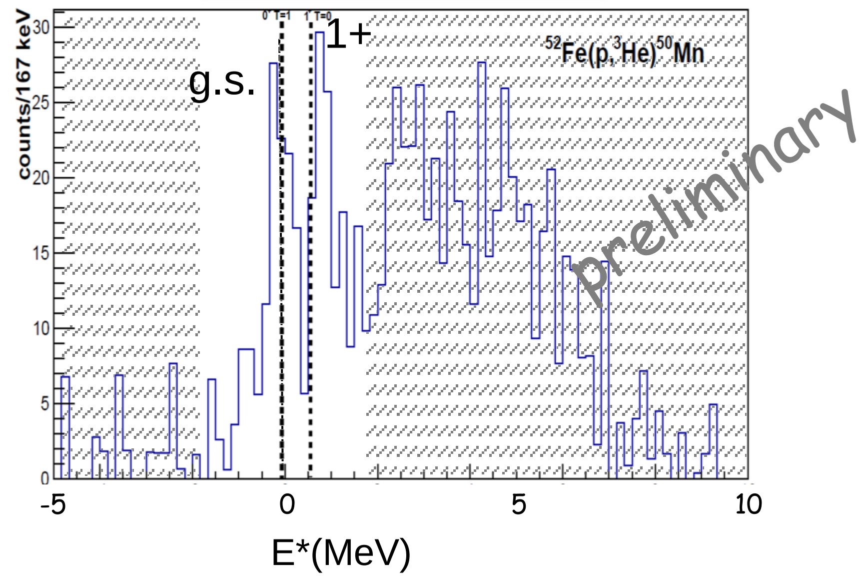
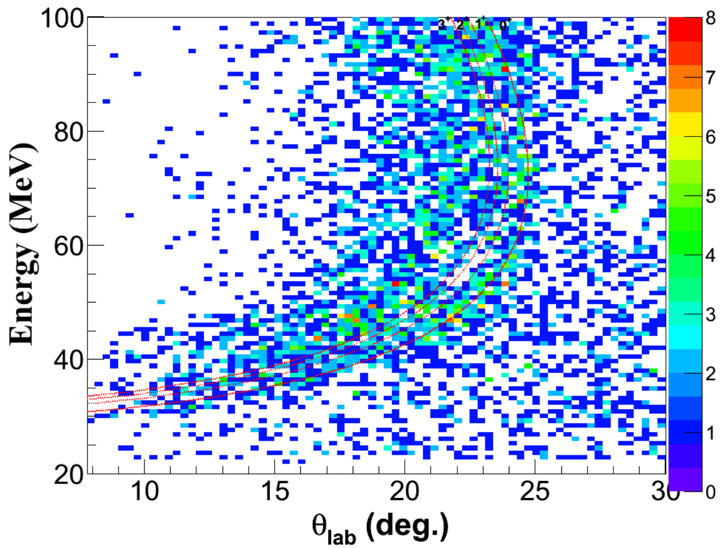
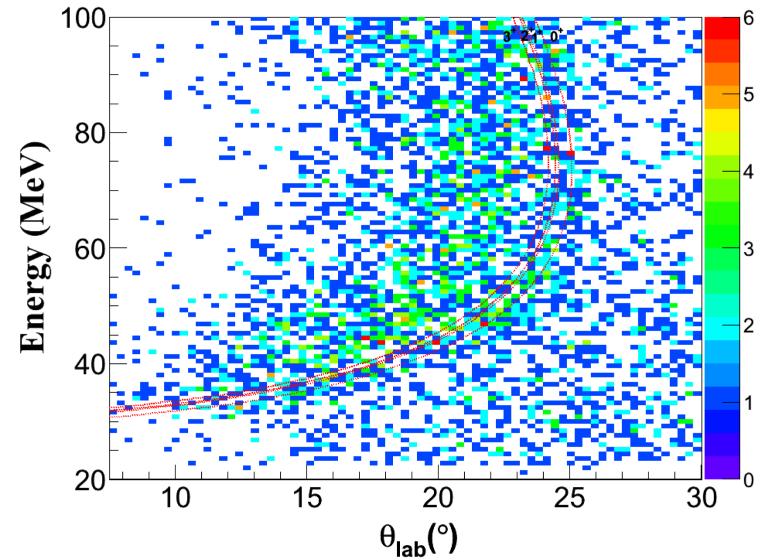
$^{56}Ni(p,^3He)^{54}Co$



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

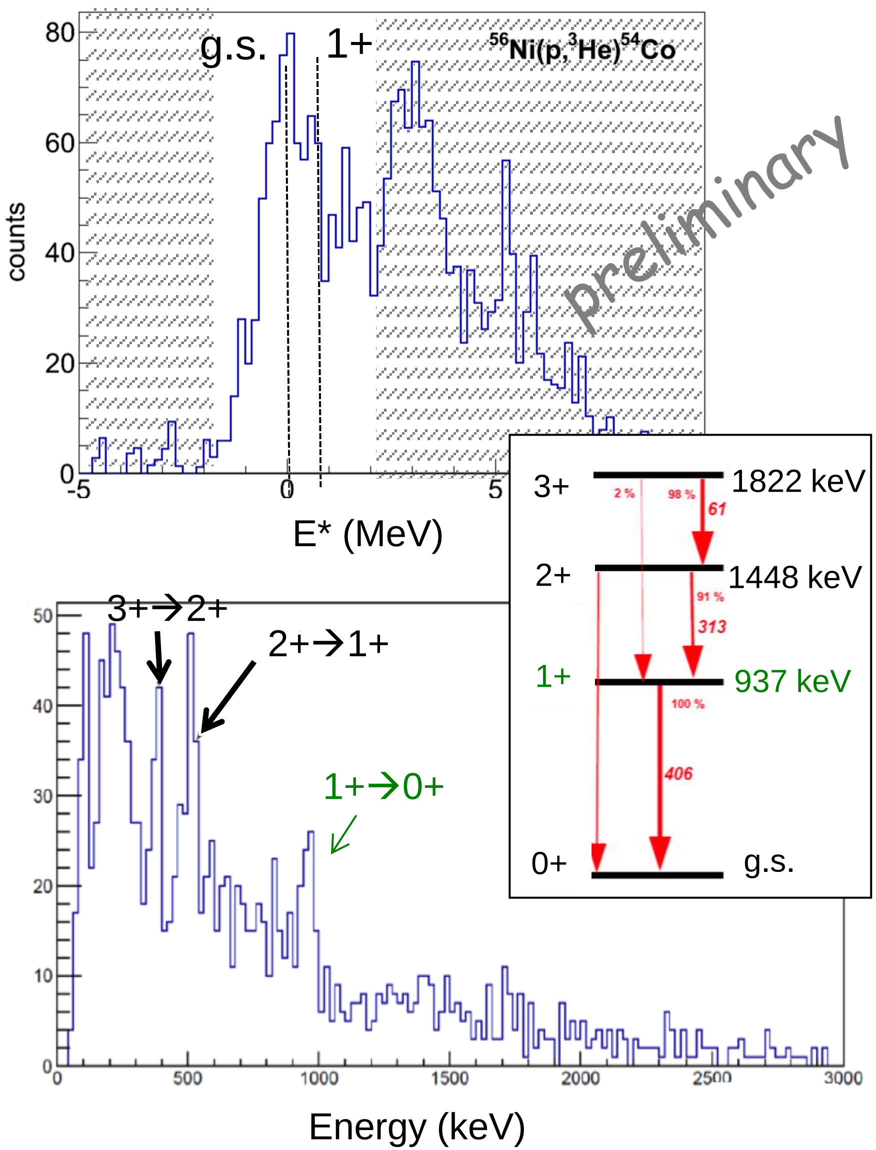






Excitation energy spectra

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



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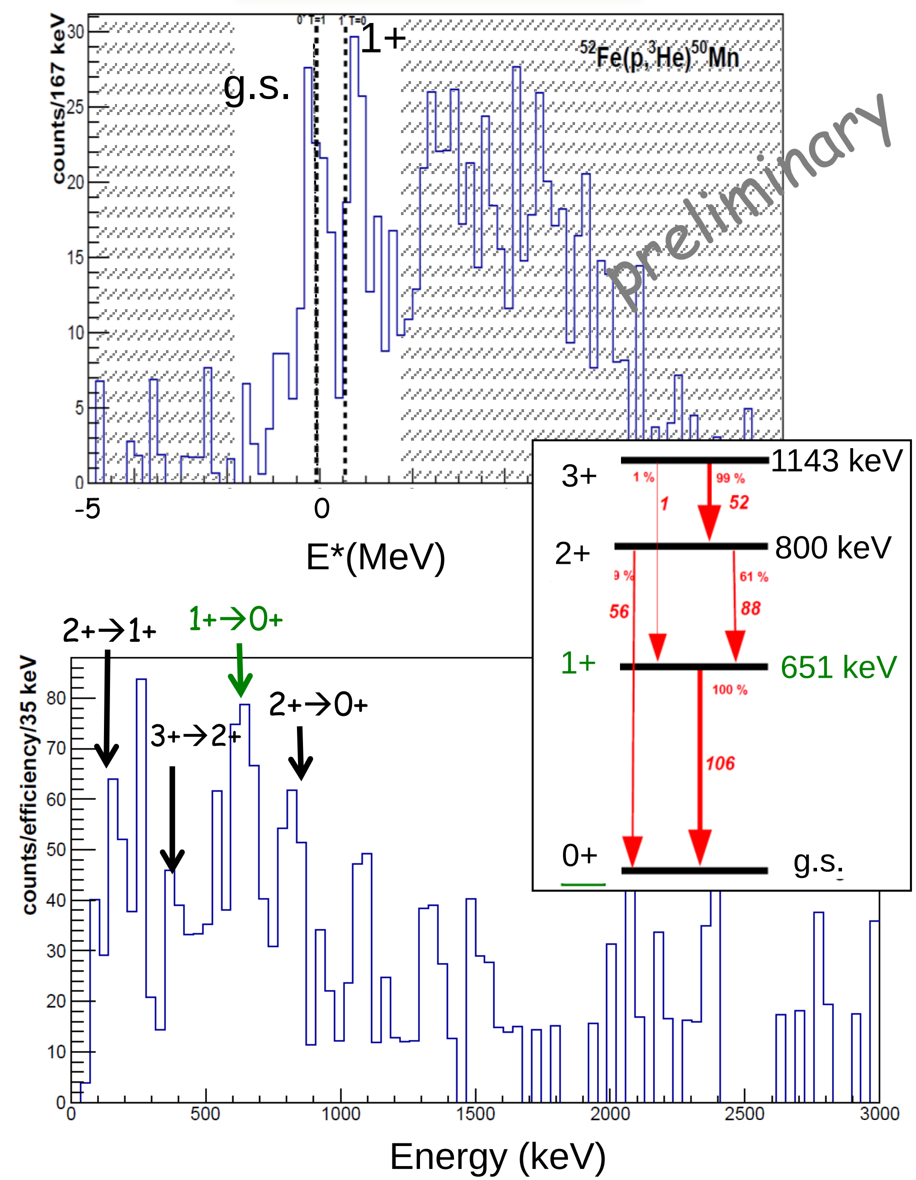

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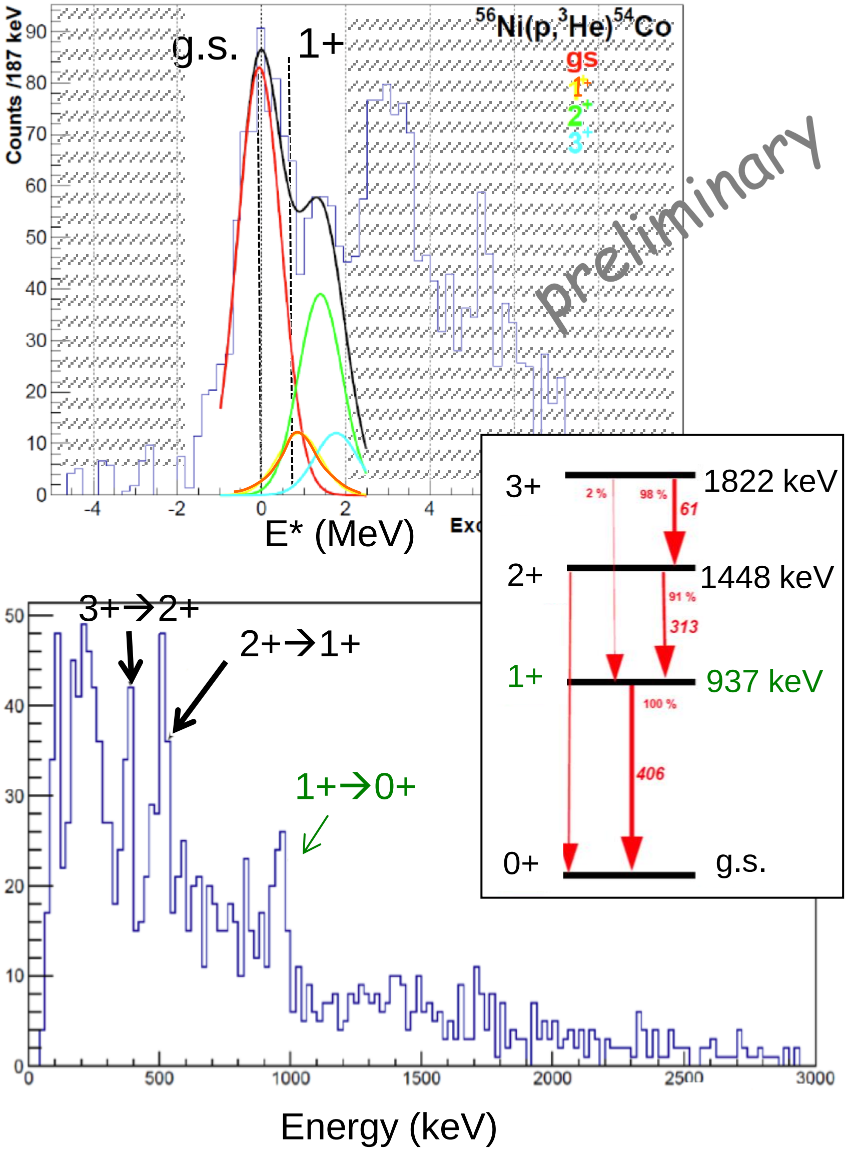

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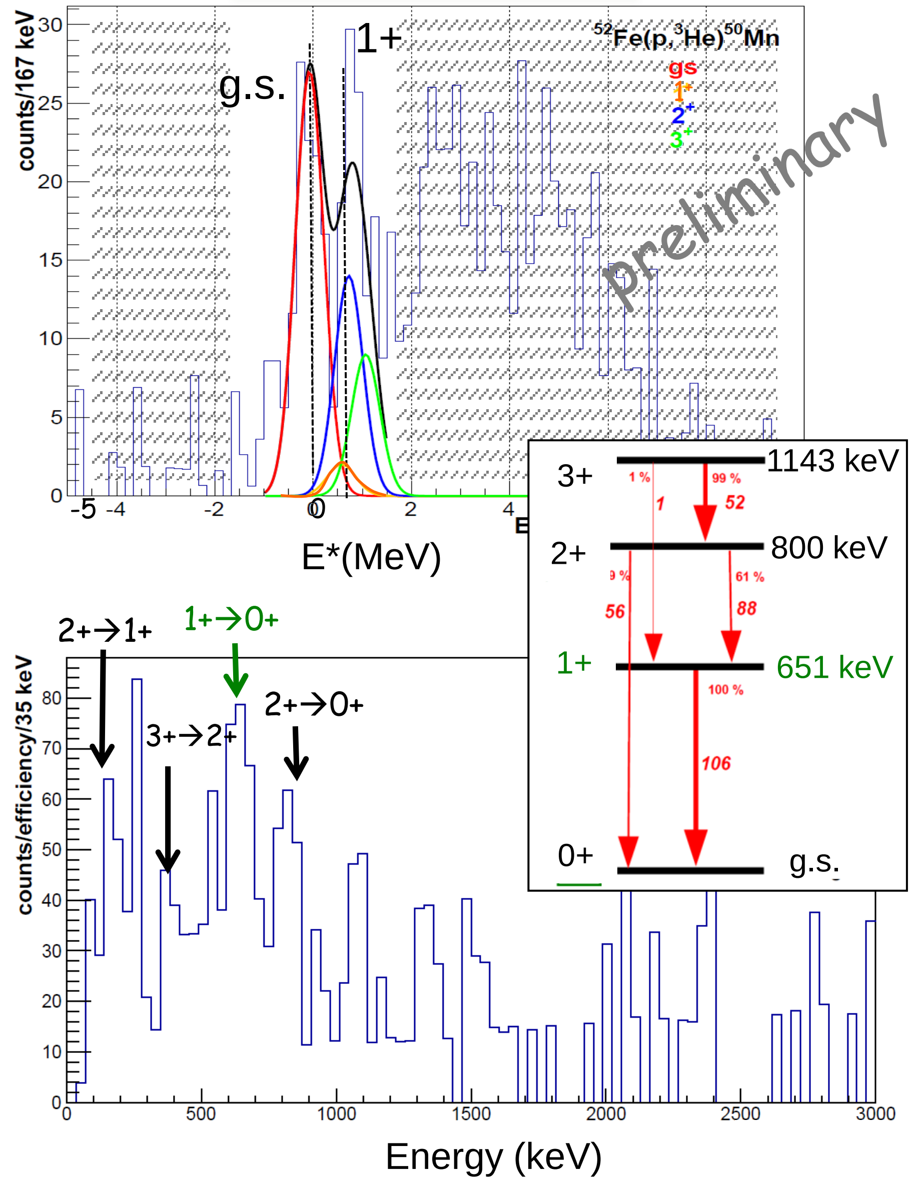
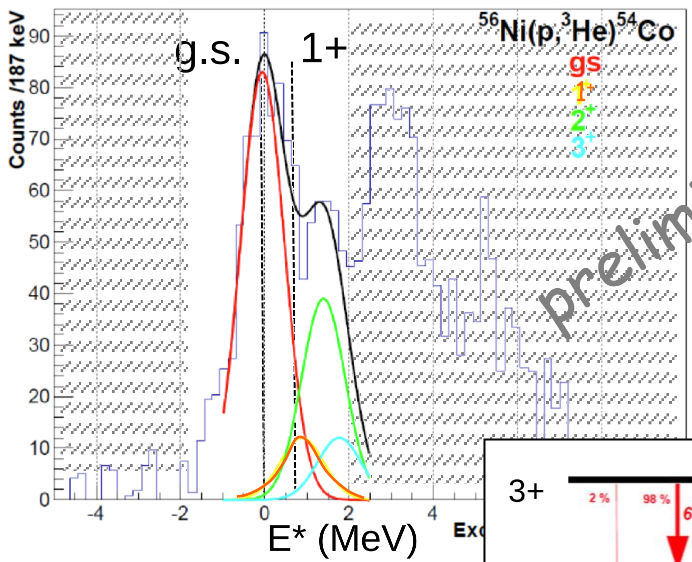
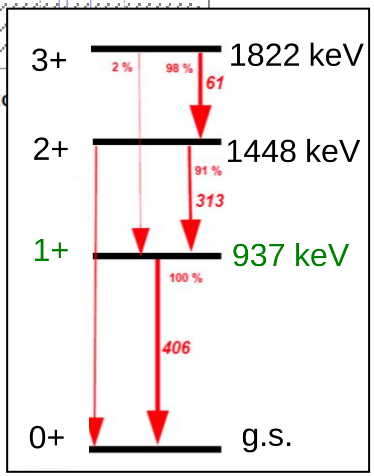
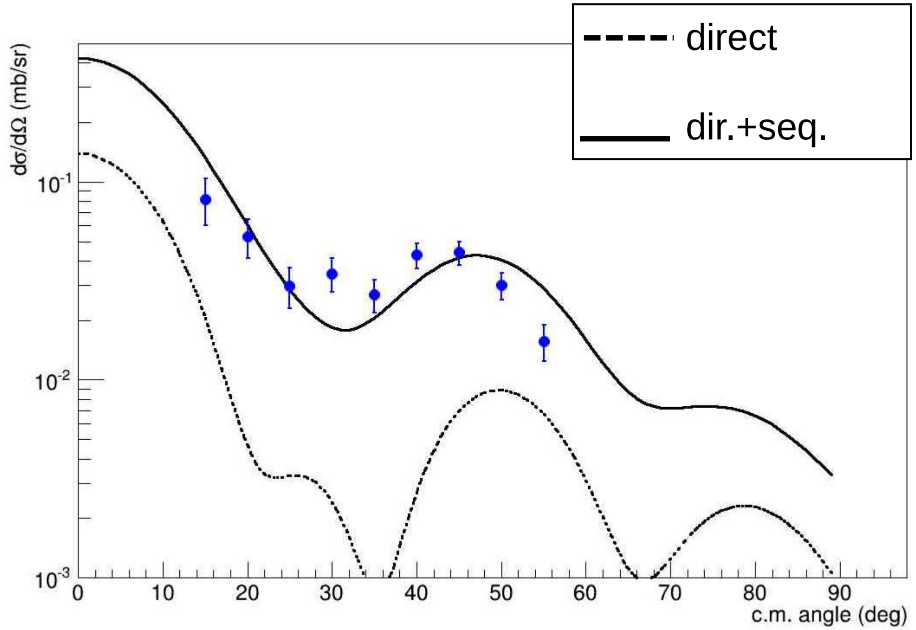


$^{56}Ni(p,^{3}He)^{54}Co$





Angular distribution for g.s.



- Direct vs. sequential ?

correlations kept in the sequential transfer ?

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

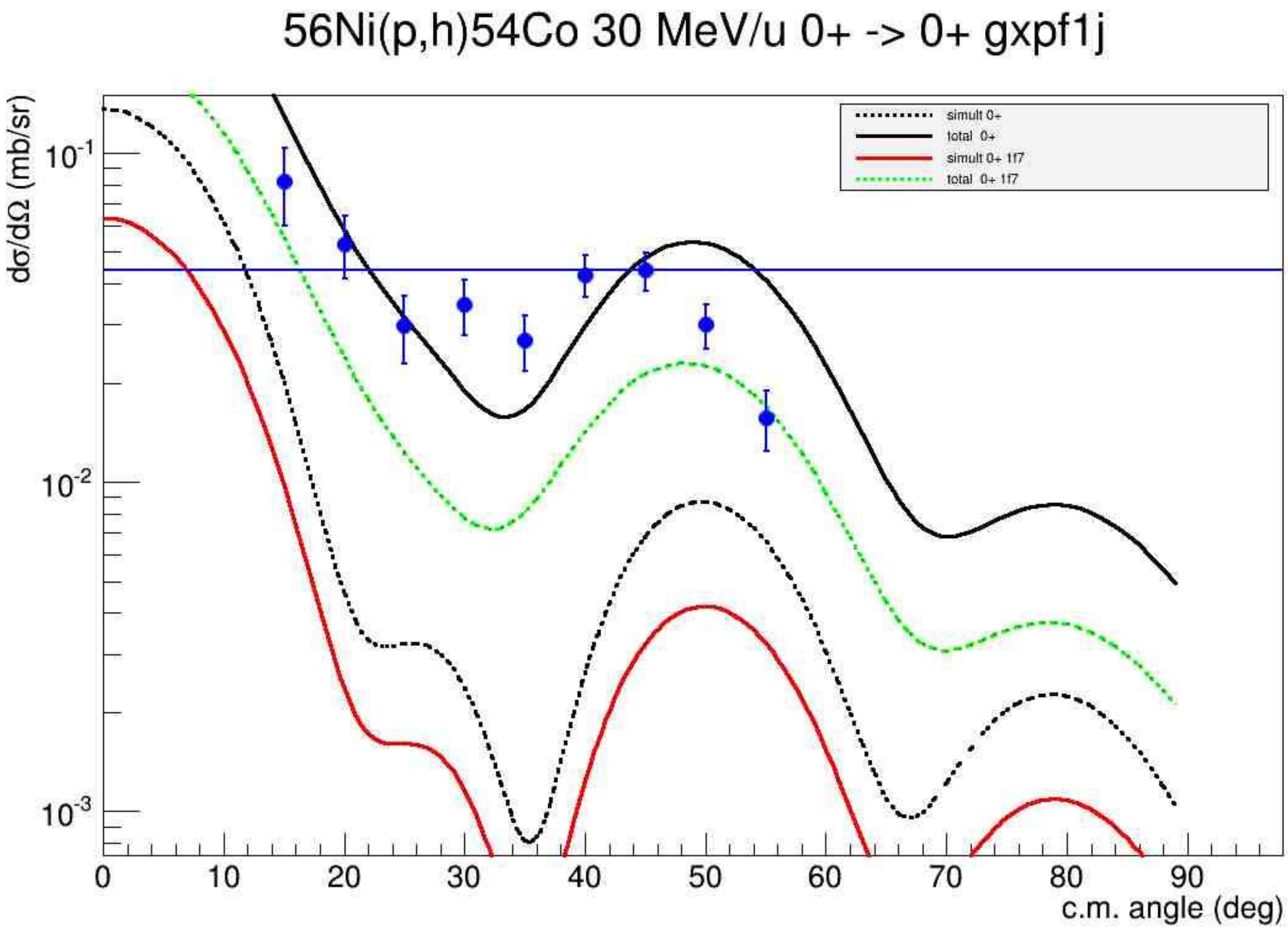
DWBA calculation

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

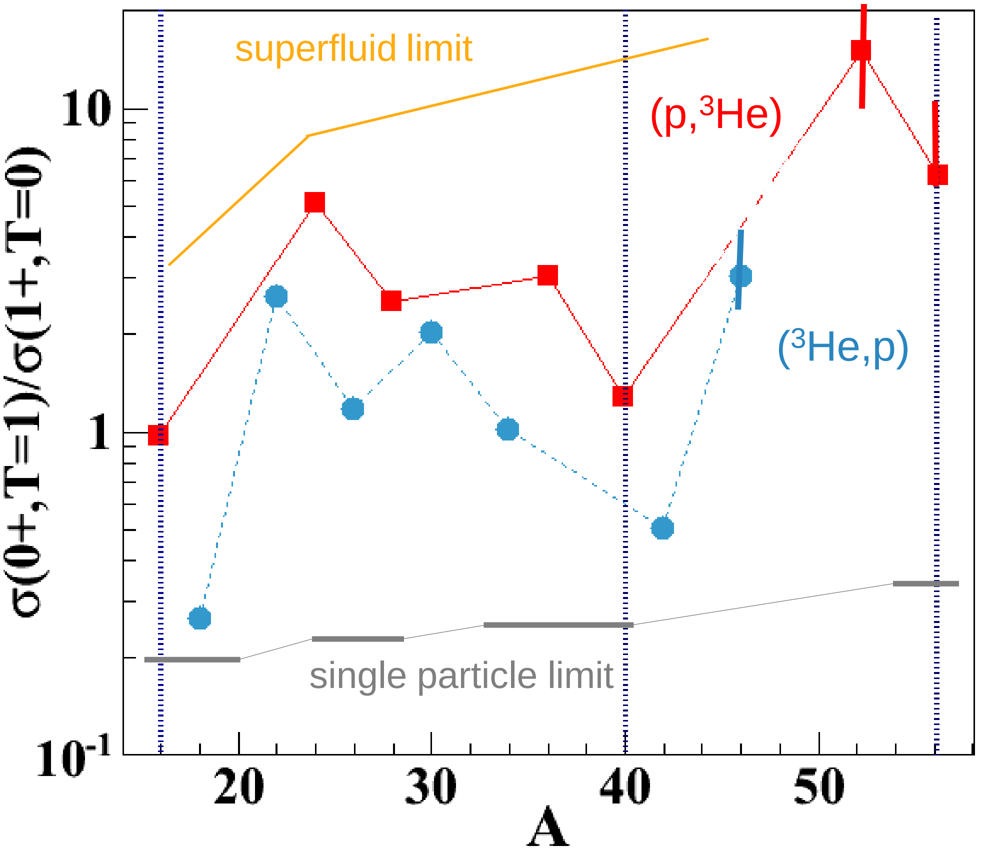
potential set from $^{56}Ni(p,d)$ measurement

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

Angular distribution + DWBA comparison

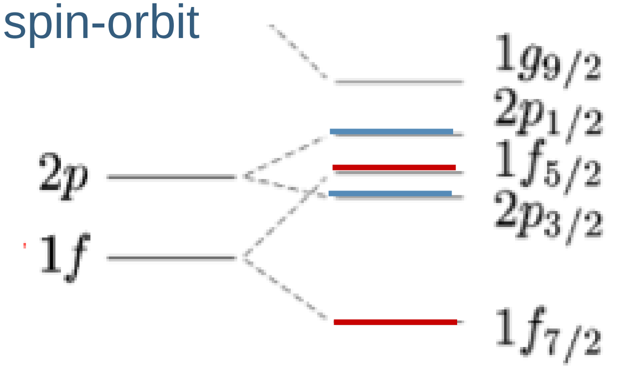


Results for ^{52}Fe and ^{56}Ni



- 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

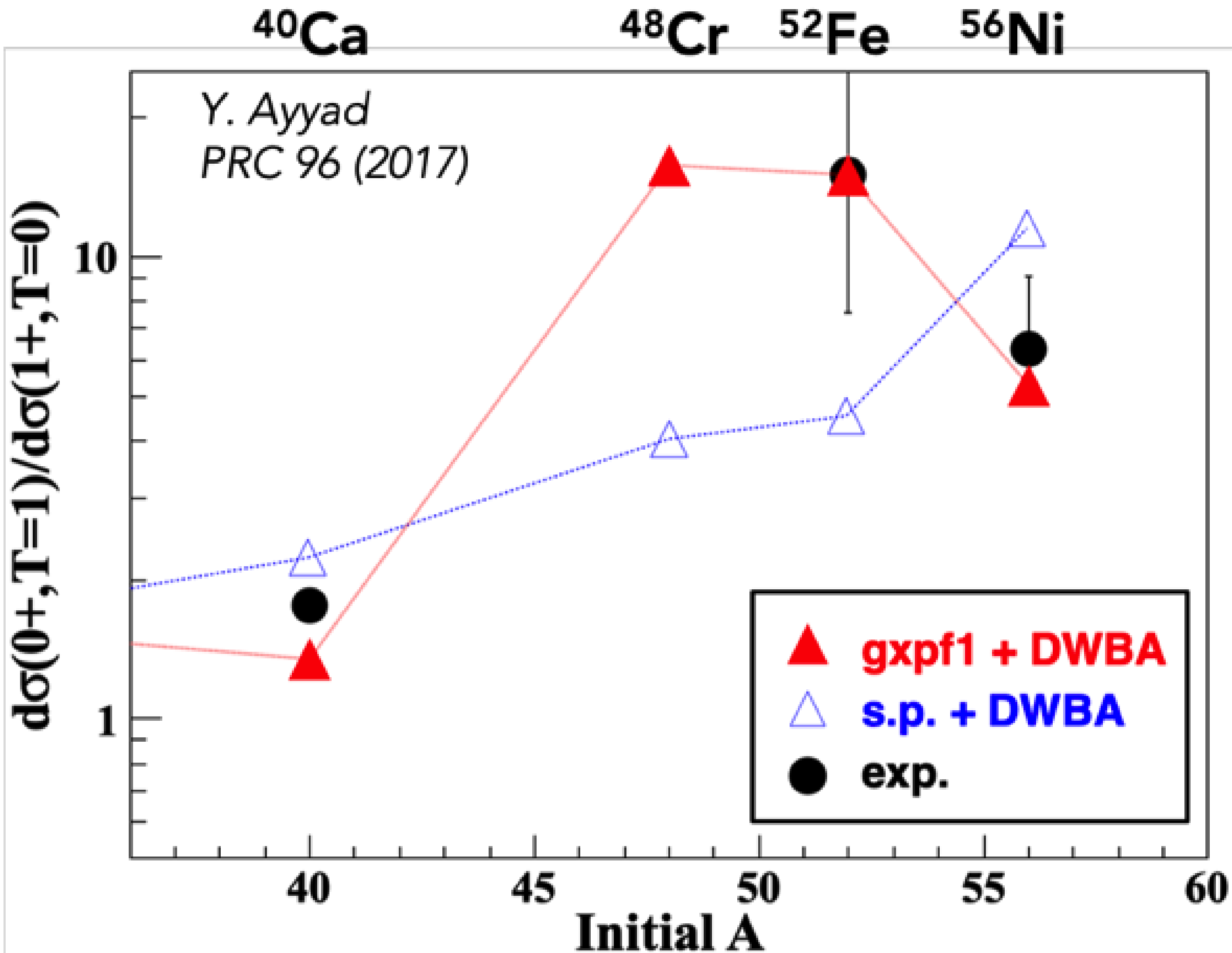
spin-orbit

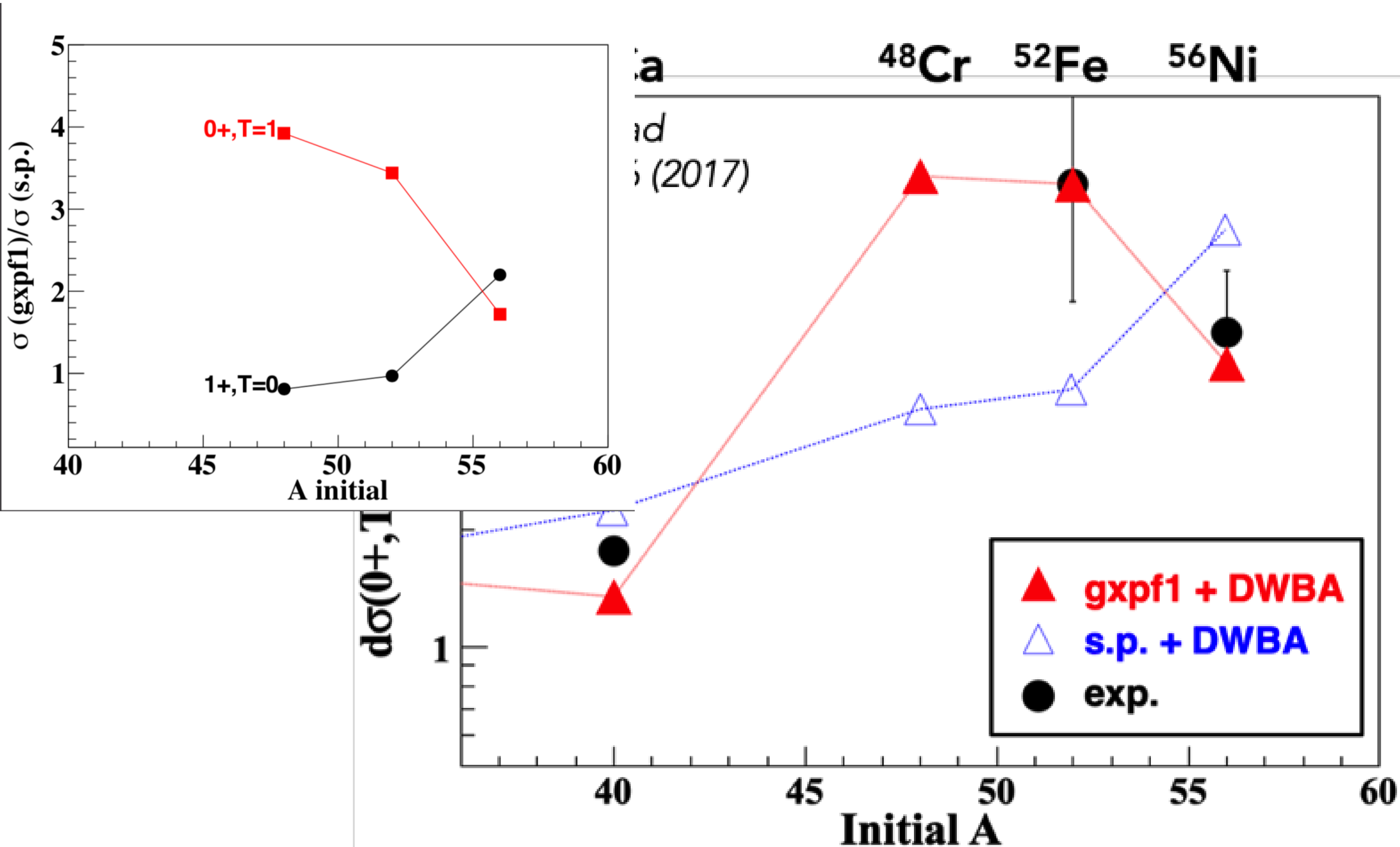


T=1 $(1f_{7/2})^2$ & $(1f_{5/2})^2$
T=0 $(1f_{7/2})^2$ & $(1f_{5/2})^2$ &$(1f_{7/2})(1f_{5/2})$

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

Comparison with DWBA

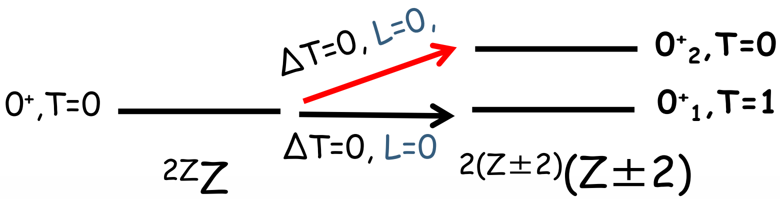


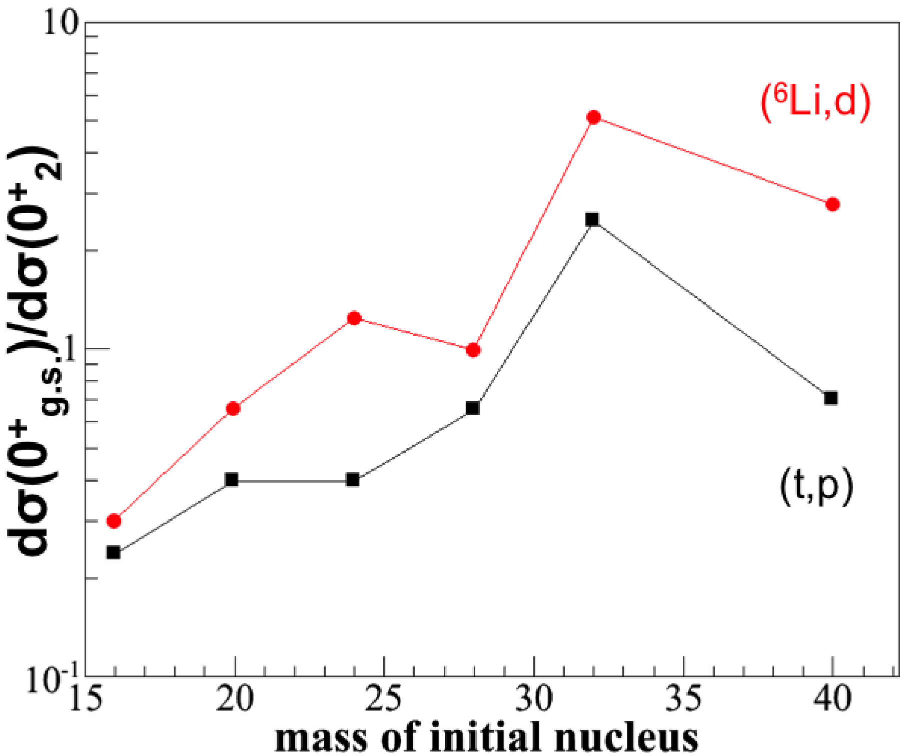

σ (gxpf1)/σ (s.p.)
0+,T=1
1+,T=0
A initial
40
45
50
55
60
1
2
3
4
5
^{48}Cr
^{52}Fe
^{56}Ni
(2017)
gxpf1 + DWBA
s.p. + DWBA
exp.
Initial A
1
dσ(0+, T

Quartetting

Probing quartetting through α-transfer

In the same way as for np pairing or nn pairing, we can study the ratios of cross-section





- Data obtained from 26 to 76 MeV in different experiments
- no error bar
- consistency of the systematic ?
- Systematic very similar to (t,p) --> protons spectator ?

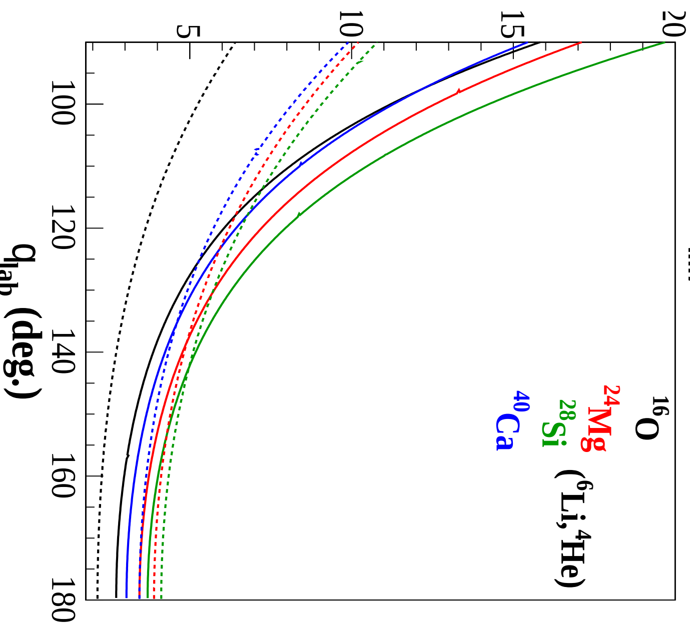
Accepted experiment @ALTO : (^{6}Li,d) & (^{6}Li,α) on sd-shell nuclei

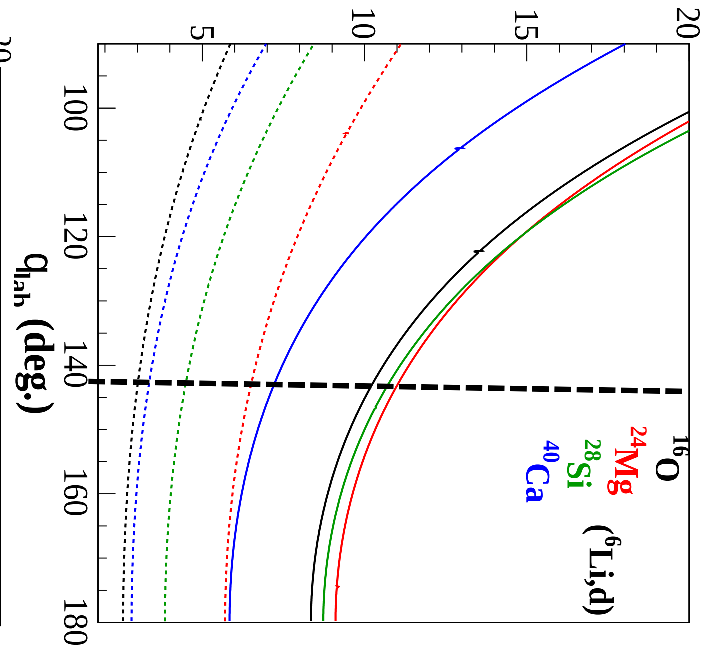
(^{6}Li,d) & (^{6}Li, α) on ^{16}O, ^{24}Mg, ^{28}Si, ^{40}Ca in inverse kinematics with MUGAST

Both reactions are selective in ΔT=0, so we will only populate T=0 states

➡ Aim for (^{6}Li,d) : study quartetting effects (ratios of cross-sections)

➡ Aim for (^{6}Li, α) :study the reaction mechanism for L=0, T=0 transfer on ^{40}Ca & ^{28}Si at energies from 1 to 4 MeV/u



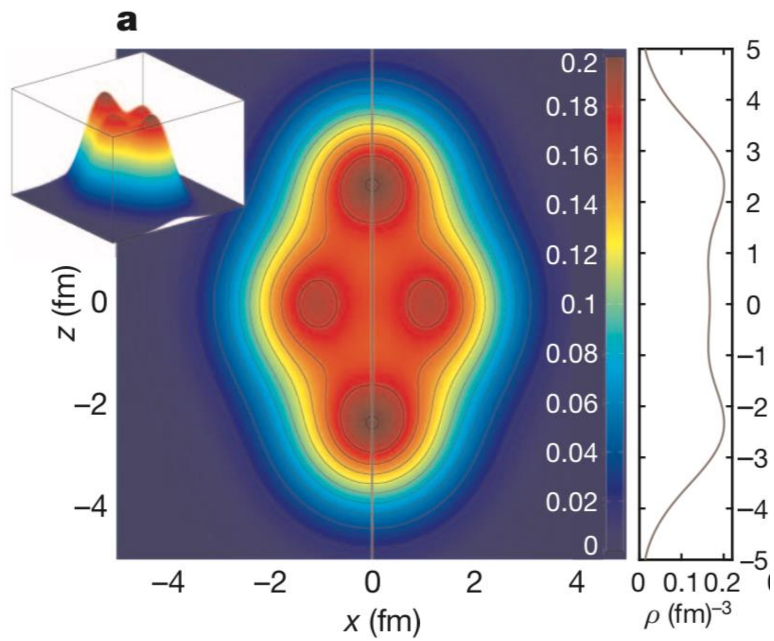


E* resolution= 250 keV (from simulations with 0.5 mg/cm^2 ^{6}LiF)

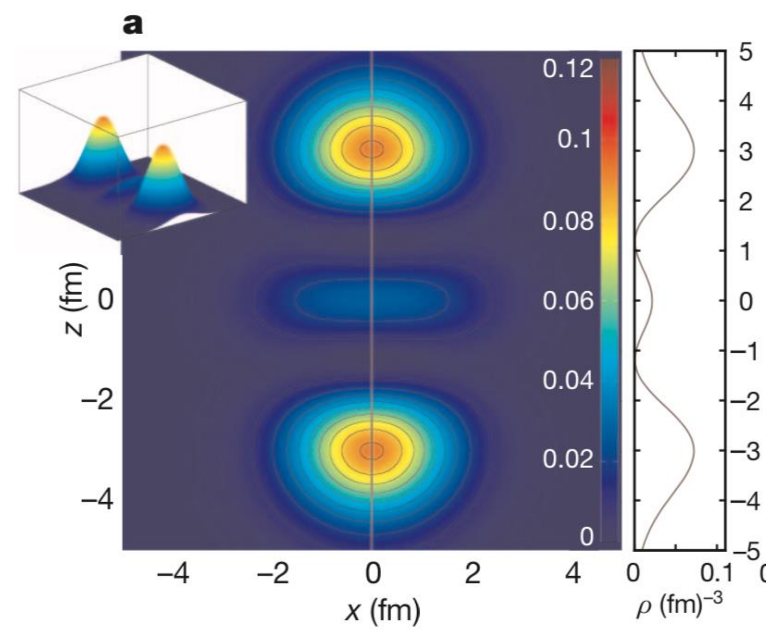
Alpha Clustering in the ground state of alpha-conjugate nuclei

- Alpha clustering in the nuclei predicted close to the emission thresholds (Ikeda diagram)
  BUT coexistence and competition between clustering and mean-field to be studied
  and detailed mechanism of clustering to be understood

- Pronounced localization in the g.s. of alpha-conjugate nuclei : ^{8}Be, ^{12}C , ^{16}O, ^{20}Ne reproduced by RMF & THSR models



^{20}Ne g.s. from RMF, J-P Ebran Nature (2012)



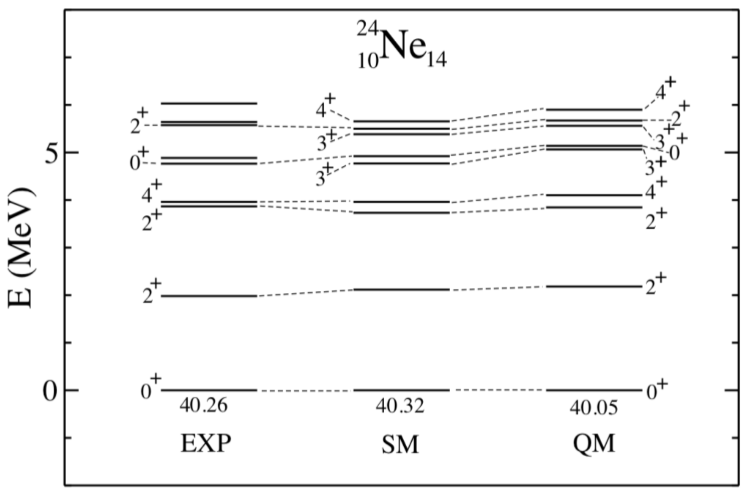
Partial nucleon density

How is the cluster structure affected by adding neutrons ?

- ^{20}Ne : strong admixture of cluster configuration in the ground state.

- EDF calculations : g.s. of ^{22}Ne and ^{24}Ne exhibit a π-bonding,
- Quartet Model : good reproduction of ^{24}Ne level scheme with ^{16}O core+ Quartet=alpha+ Quartet=4n

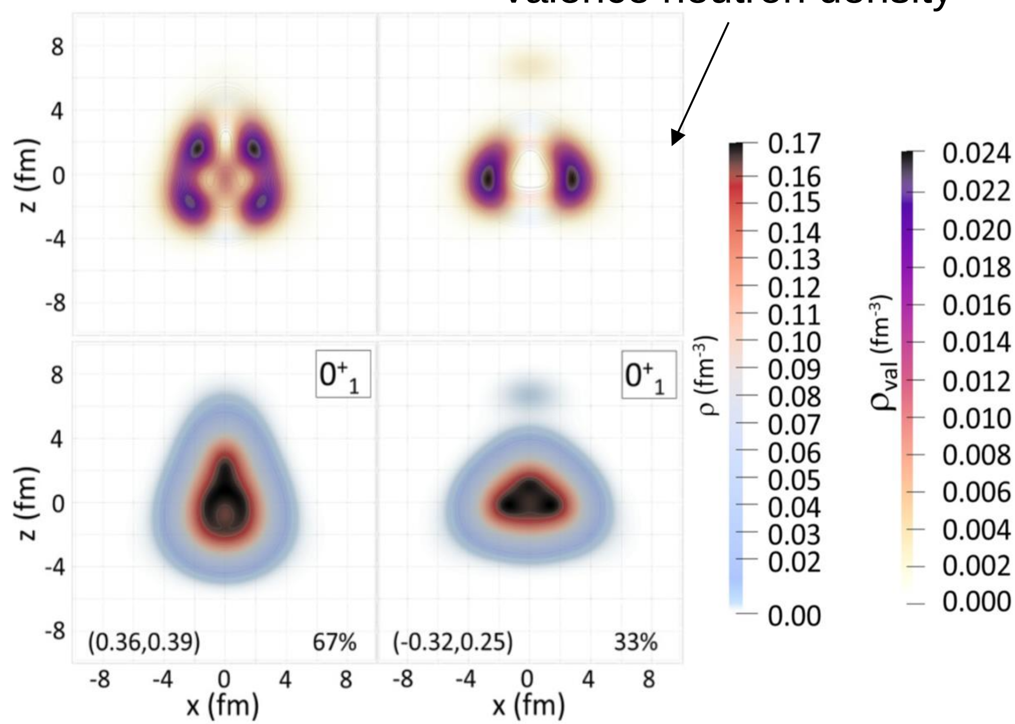
- **Alpha spectroscopic factor in the ground state of ^{20}Ne and ^{24}Ne, to unravel the clustering phenomenon and study the effect of excess neutrons.**



Quartet model

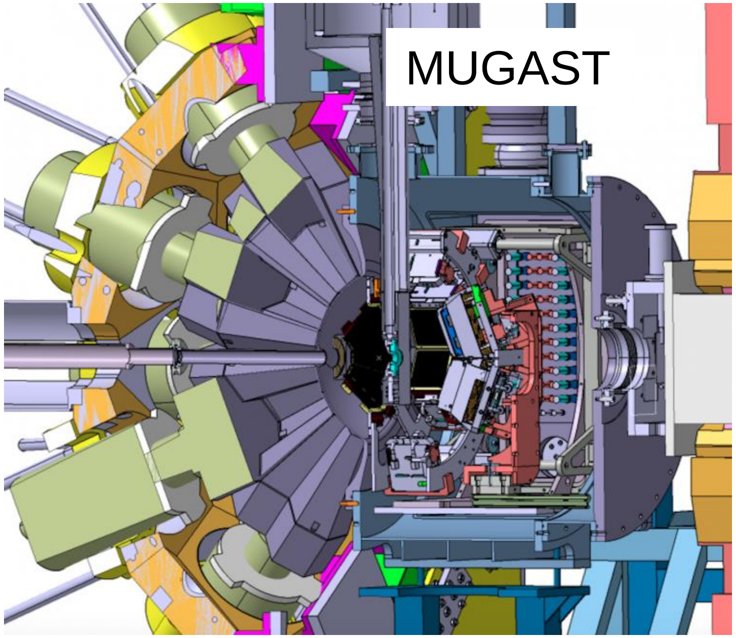
M. Sambataro, N. Sandulescu PRC (2015)

Valence neutron density

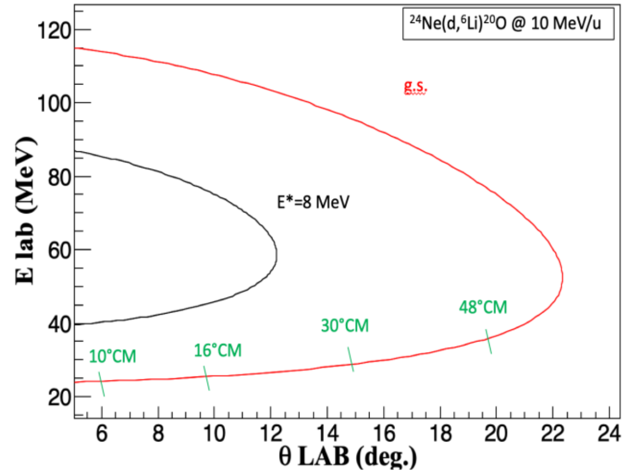


^{24}Ne g.s. from RMF *(P. Marevic et al PRC 2017)*

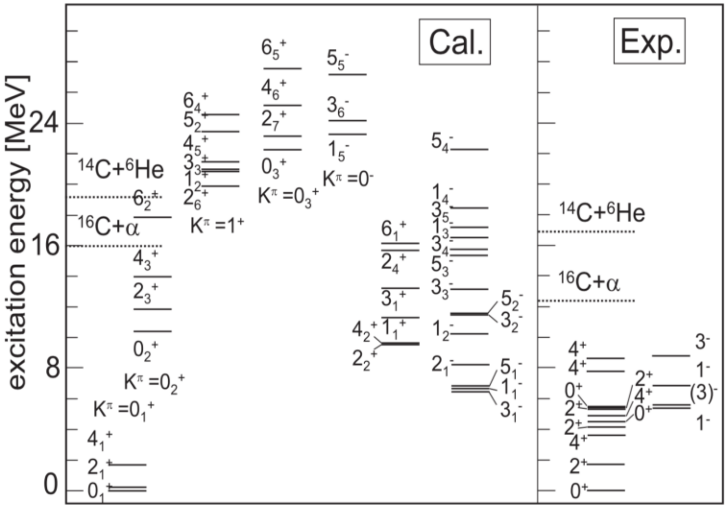
$^{20,24}Ne(d,^{6}Li)^{16,20}O$: investigation of alpha cluster



The alpha clustering in the ground state of ^{20}Ne and ^{24}Ne will be studied through ^{20,24}Ne (d,^{6}Li) ^{16,20}O alpha transfer reaction at 10A MeV.



^{20}O level scheme



Experiment proposed to the forthcoming GANIL PAC (Oct 2019).