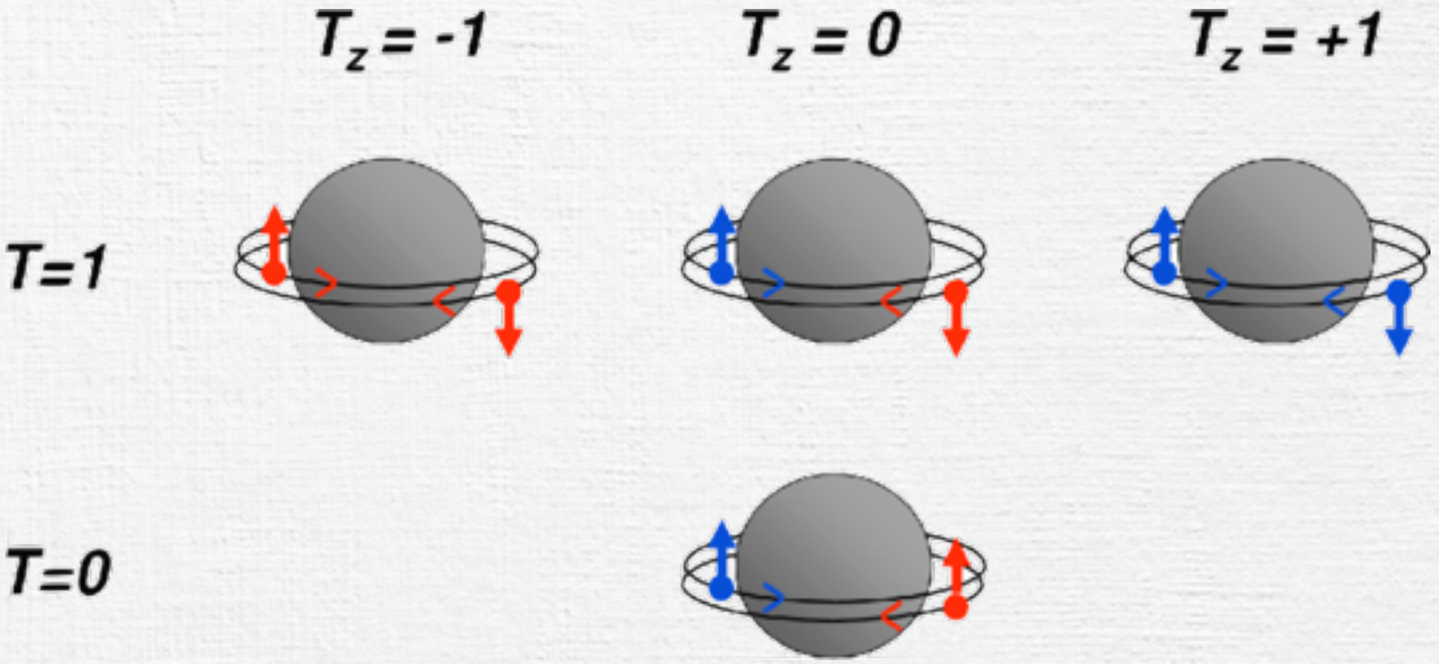
Systematic study of neutron-proton pairing in *sd*-shell nuclei via (p,^{3}He) and (^{3}He,p) transfer reactions

Y. Ayyad
(NSCL)

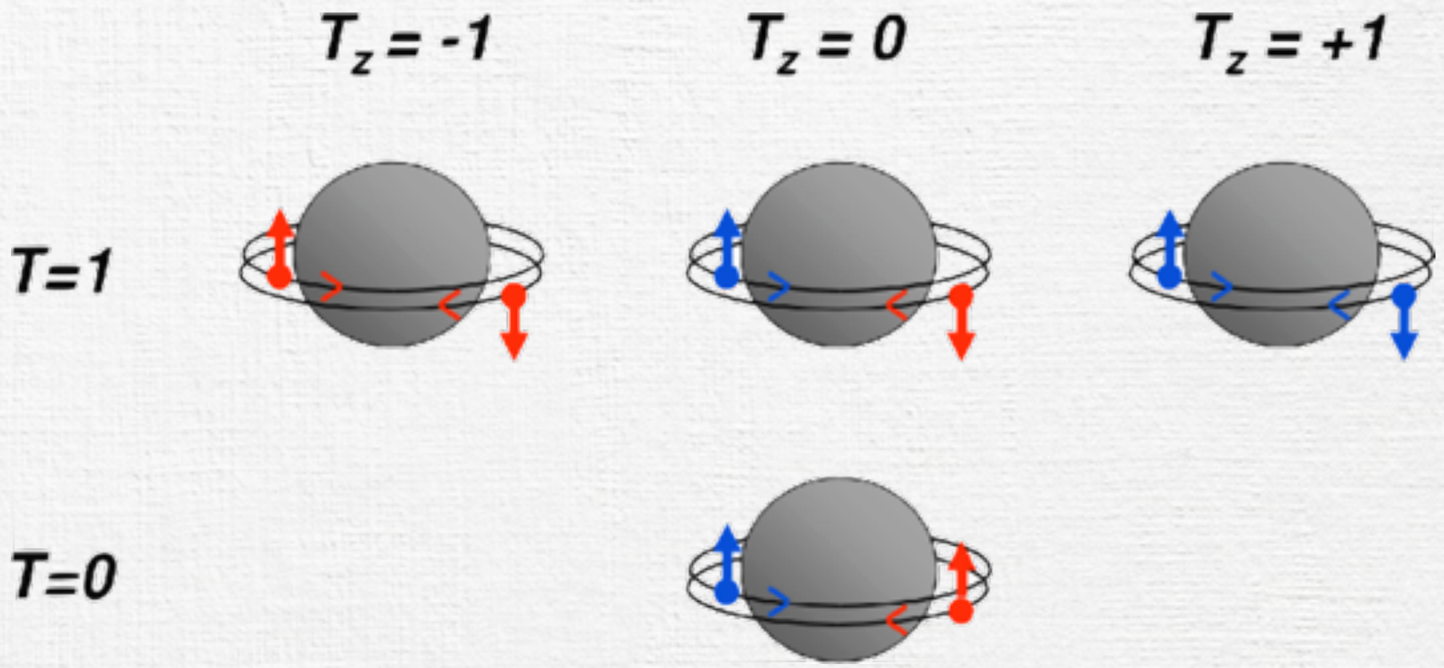
- The elusive T=0 np pairing
- Systemtics studies on sd-shell nuclei
- Conclusions and perspectives

Isovector and Isoscalar pairing

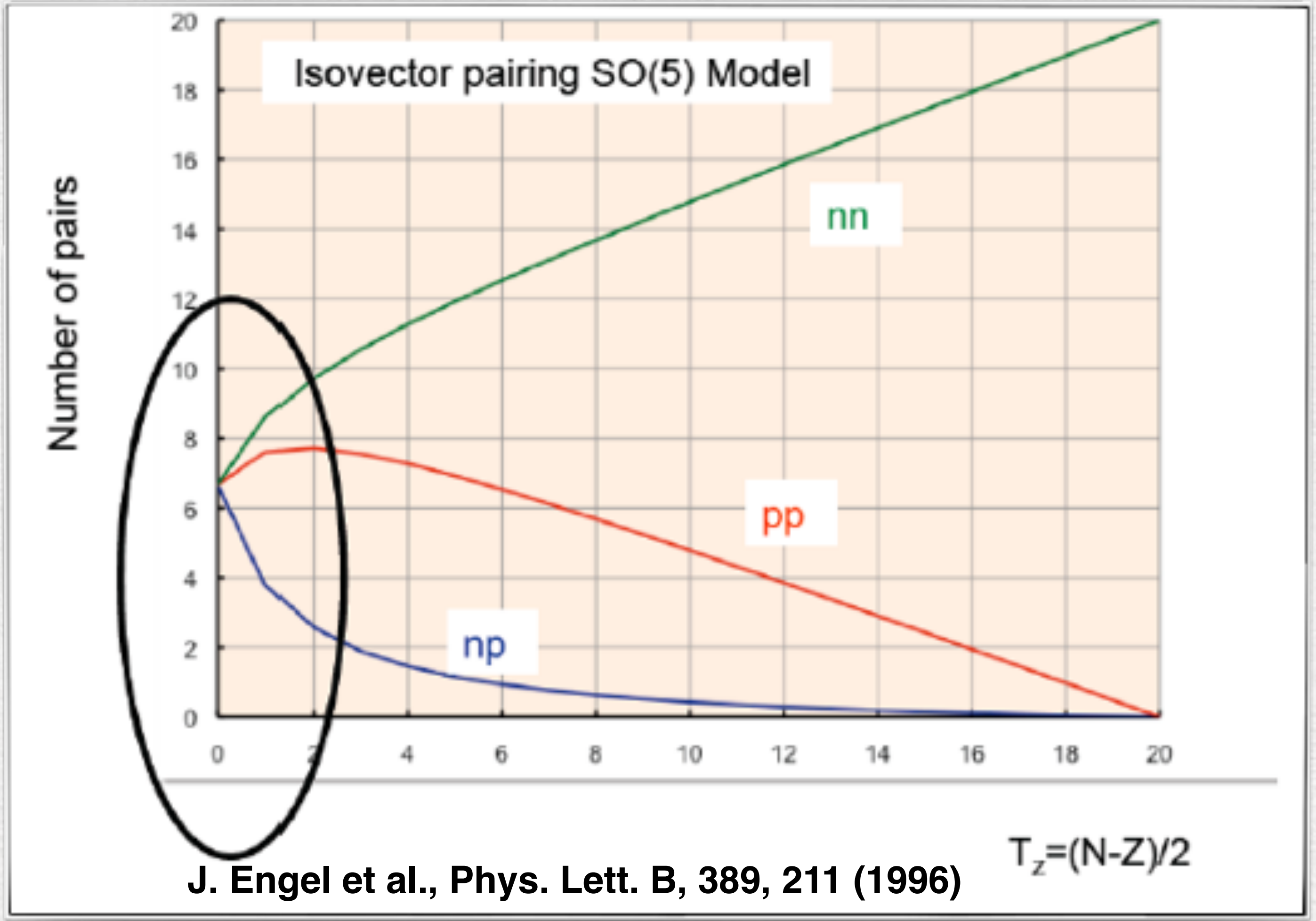


- Isovector (T=1, S=0): nn, pp and np
- Isoscalar (T=0, S=1): deuteron-like np

Isovector and Isoscalar pairing

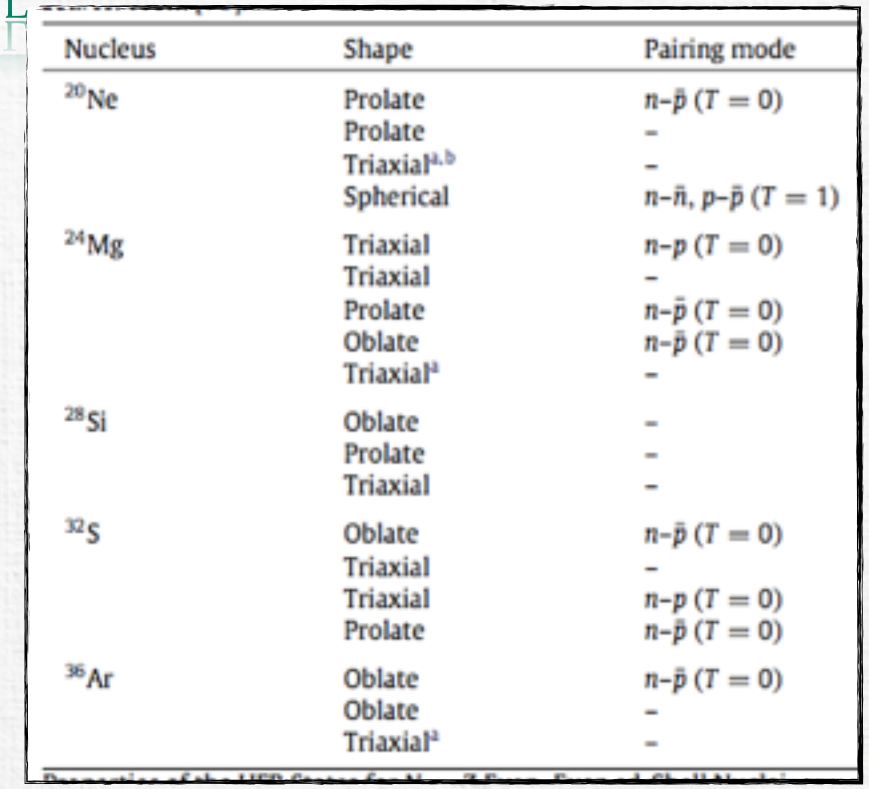


N=Z: Strong spatial overlap between n and p in same valence shell



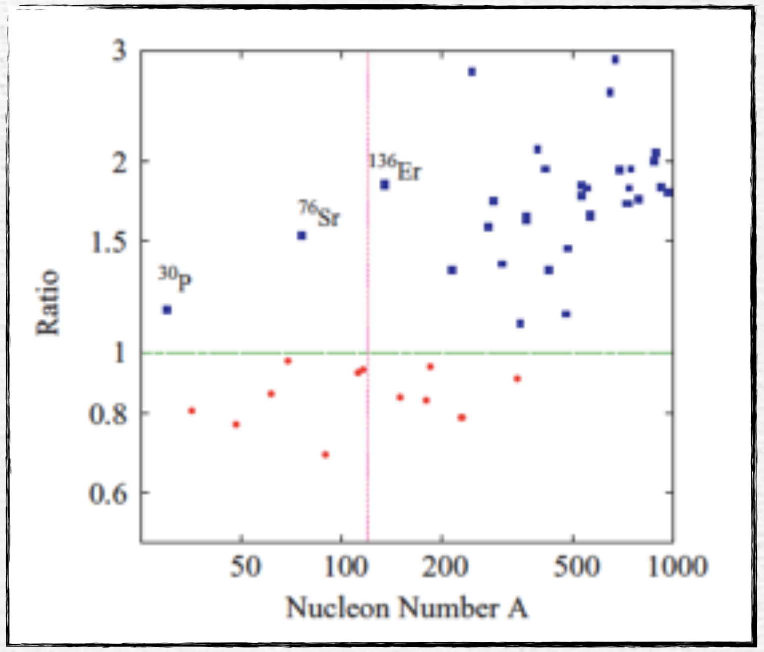
J. Engel et al., Phys. Lett. B, 389, 211 (1996)

Expectations from theory



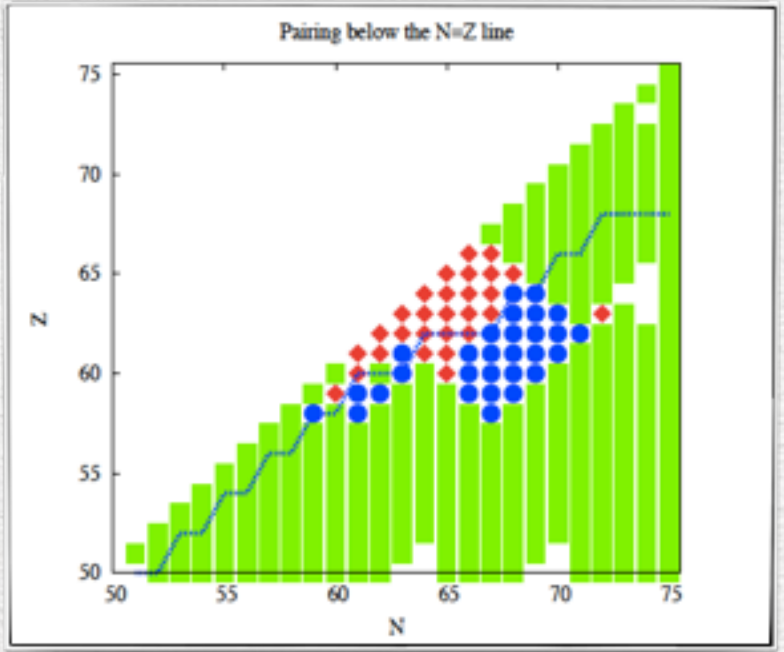
Nucleus	Shape	Pairing mode
^{20}Ne	Prolate	n–$\bar{p}$ ($T = 0$)
	Prolate	–
	Triaxial[a,b]	–
	Spherical	n–$\bar{n}$, p–$\bar{p}$ ($T = 1$)
^{24}Mg	Triaxial	n–p ($T = 0$)
	Triaxial	–
	Prolate	n–$\bar{p}$ ($T = 0$)
	Oblate	n–$\bar{p}$ ($T = 0$)
	Triaxial[a]	–
^{28}Si	Oblate	–
	Prolate	–
	Triaxial	–
^{32}S	Oblate	n–$\bar{p}$ ($T = 0$)
	Triaxial	–
	Triaxial	n–p ($T = 0$)
	Prolate	n–$\bar{p}$ ($T = 0$)
^{36}Ar	Oblate	n–$\bar{p}$ ($T = 0$)
	Oblate	–
	Triaxial[a]	–

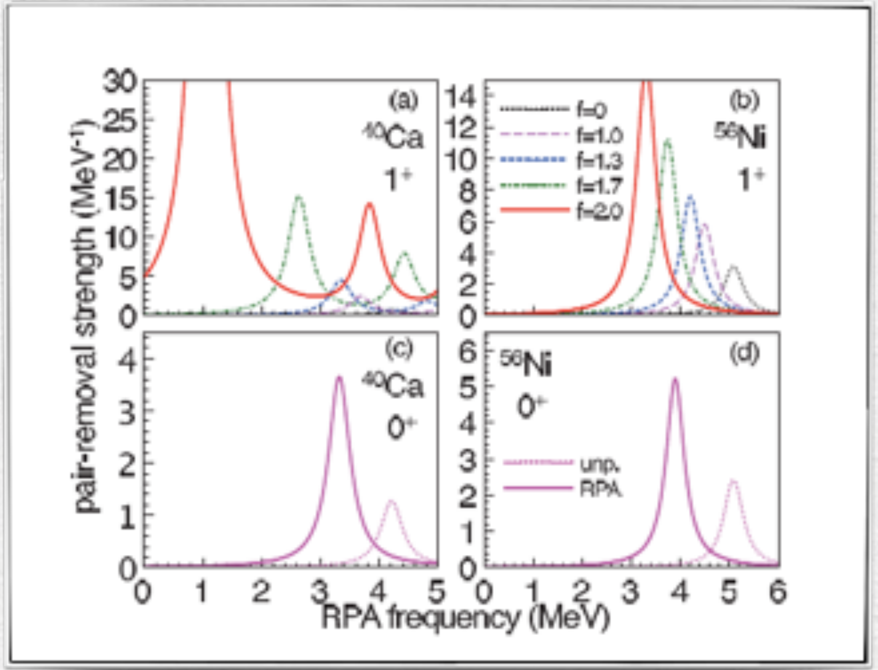
Back in the 70's… HFB calculations with exclusive T=0 and T=1 modes. N=Z nuclei show T=0 in the ground state.
A.L. Goodman, Adv. Nucl. Phys. 11, 263 (1979).



Ratio of spin-triplet to spin-singlet correlation energies. Spin-triplet pairing exists in N=Z around A = 130-140
G. F. Bertsch and Y. Luo, Phys. Rev. C 81, 064320 (2010)

Mixing of spin-singlet and spin-triplet for N>Z near the proton dripline. Island of isoscalar pairing.
 A. Gezerlis , G.F. Bertsch and Y.L. Luo, Phys. Rev. Lett. 106, 252502 (2011)

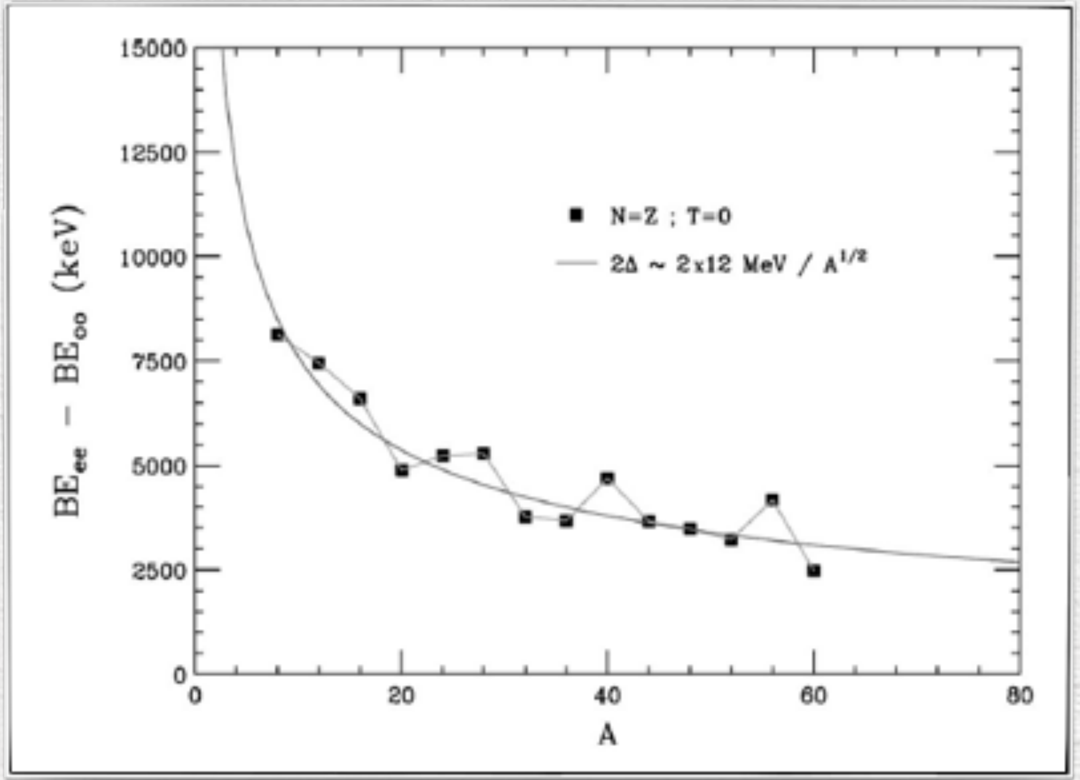


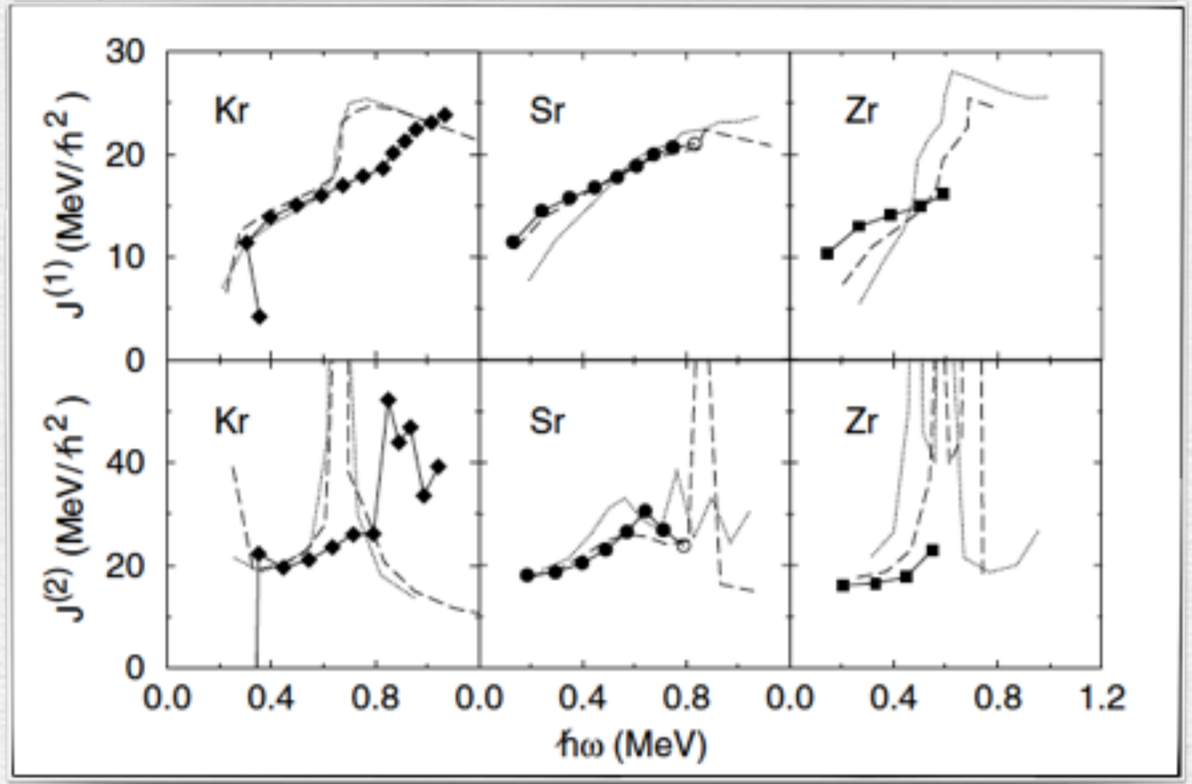


Particle-Particle Random Phase Approximation. Strong collectivity of T=0 np pairing vibration enhances the np-transfer strength to 1$^+$
K. Yoshida, Phys. Rev C 90, 031303(R) (2014)

The elusive isoscalar pairing

- Extra binding energy of N=Z nuclei (“Wigner energy”): A strong evidence of isovector pairing but no evidence for isoscalar (A.O. Machiavelli et al , Phys. Rev. C 61, 041303 (2000)
- Rotational properties (high-spin aspect): np correlations induce “delayed alignments”: Increase in rotational energy to break T=0 pairs. Sensitive to normal pairing and shape degree of freedom (S. M. Fischer et al., Phys. Rev. Lett. 87 13 (2001))





The elusive isoscalar pairing

Pairing vibrations around ^{56}Ni

T=0 collective effects as vibrational phonon?

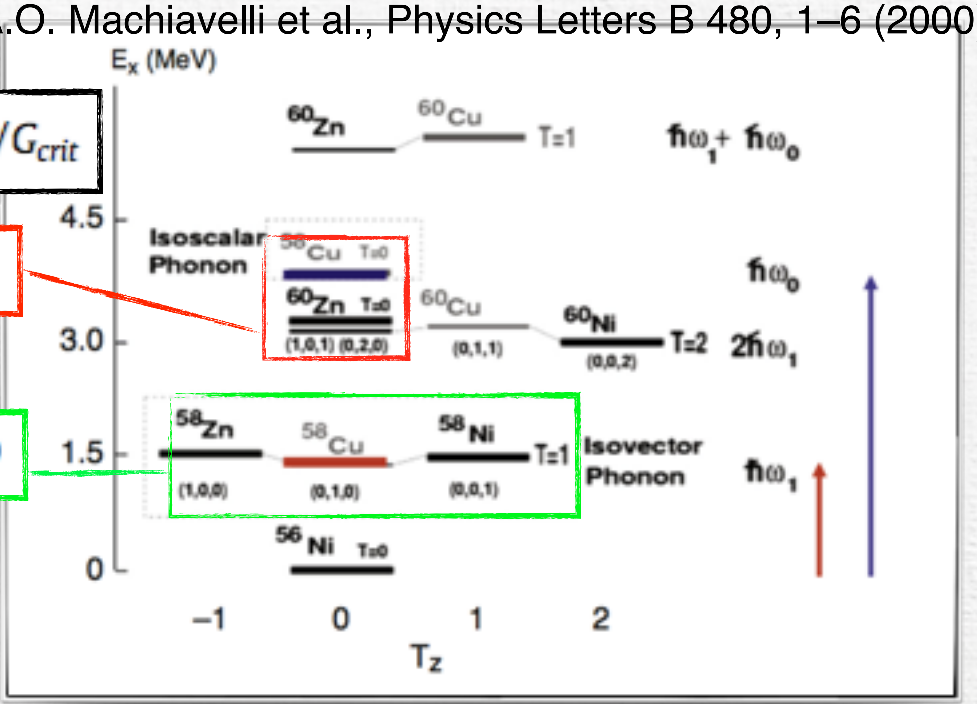
$$\hbar\omega_T = D\sqrt{1-y_T}$$

$$y_T = 2G_T\Omega/D = G_T/G_{\mathrm{crit}}$$

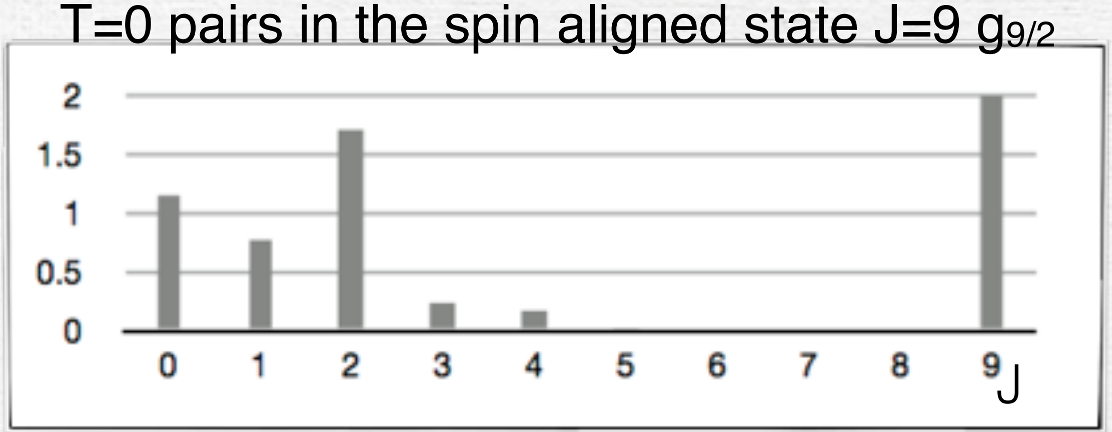
A.O. Machiavelli et al., Physics Letters B 480, 1–6 (2000)

$$G_0/G_{\mathrm{crit}} \lesssim 0.2$$

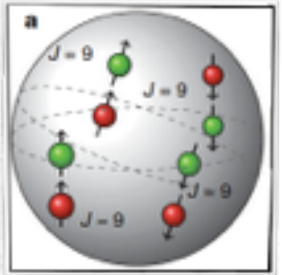
$$G_1/G_{\mathrm{crit}} \approx 0.9$$

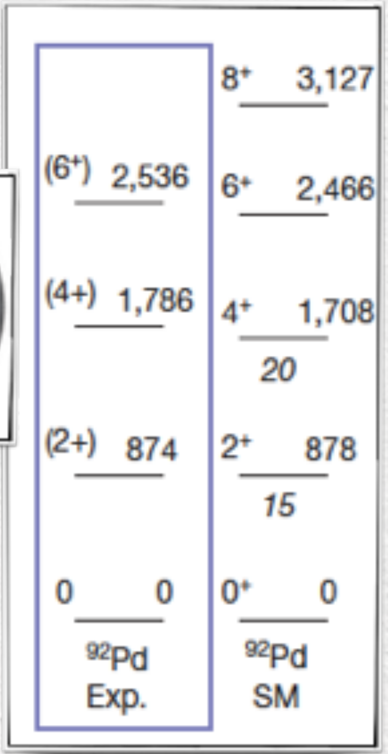


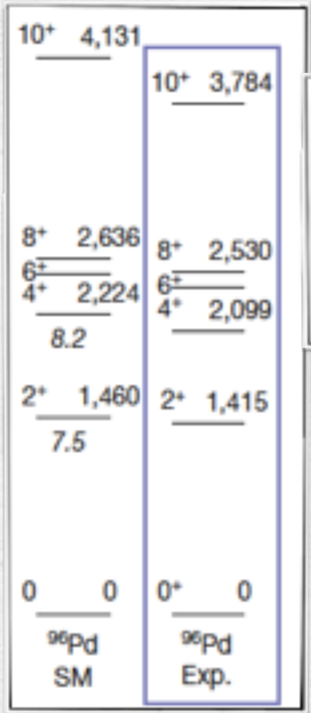
T=0 pairs in the spin aligned state J=9 $g_{9/2}$

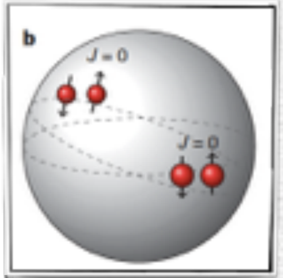


K. Neergård Phys. Rev. C 88, 034329 (2013)

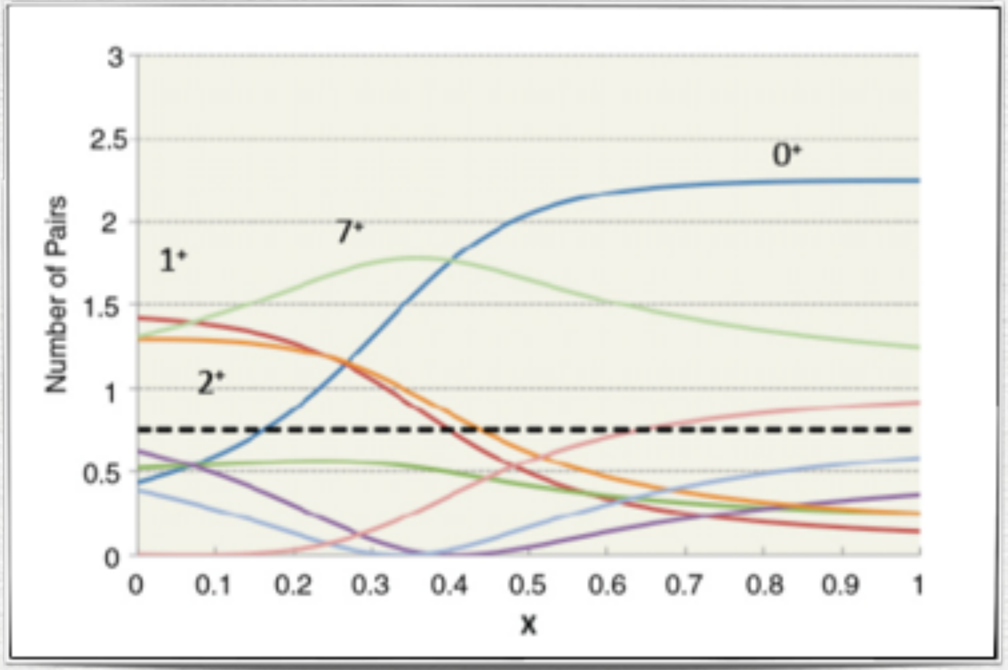








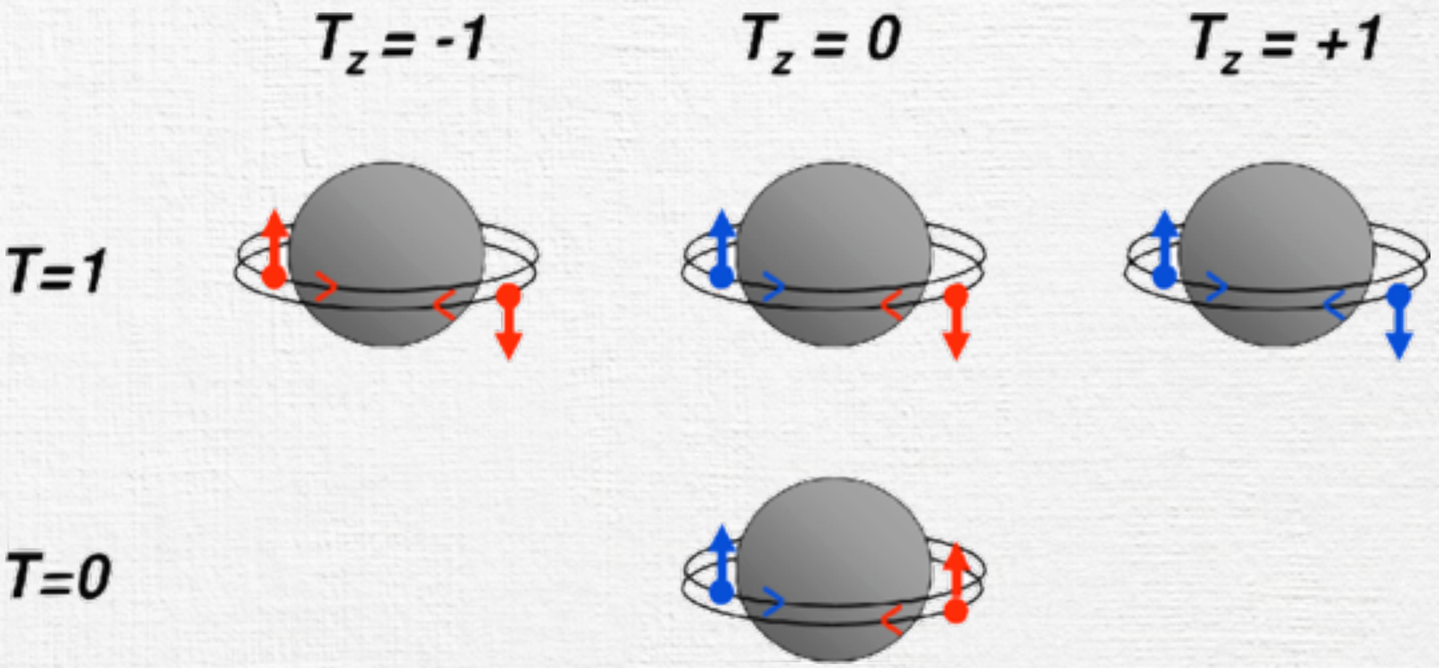
^{92}Pd: T= 0 Spin-aligned isoscalar proton neutron scheme (Independent of angular momentum). B. Cederwall et al., Nature, 469, 6 (2011)



Isoscalar ← → Isovector

S. Frauendorf and A.O. Macchiavelli
Progress in Particle and Nuclear Physics 78, 24–90 (2014)

Isovector and Isoscalar pairing



- Isoscalar (T=0) np pairing is not well established
- Interplay of T=0 and T=1 np, nn, np pairs?
- Nature of T=0 pair in nuclear medium?
- Collective modes arising from T=0?
- Strong presence of tensor force?

Two particle transfer

np transfer in N=Z nuclei
Interacting boson model (IBM-4) predictions

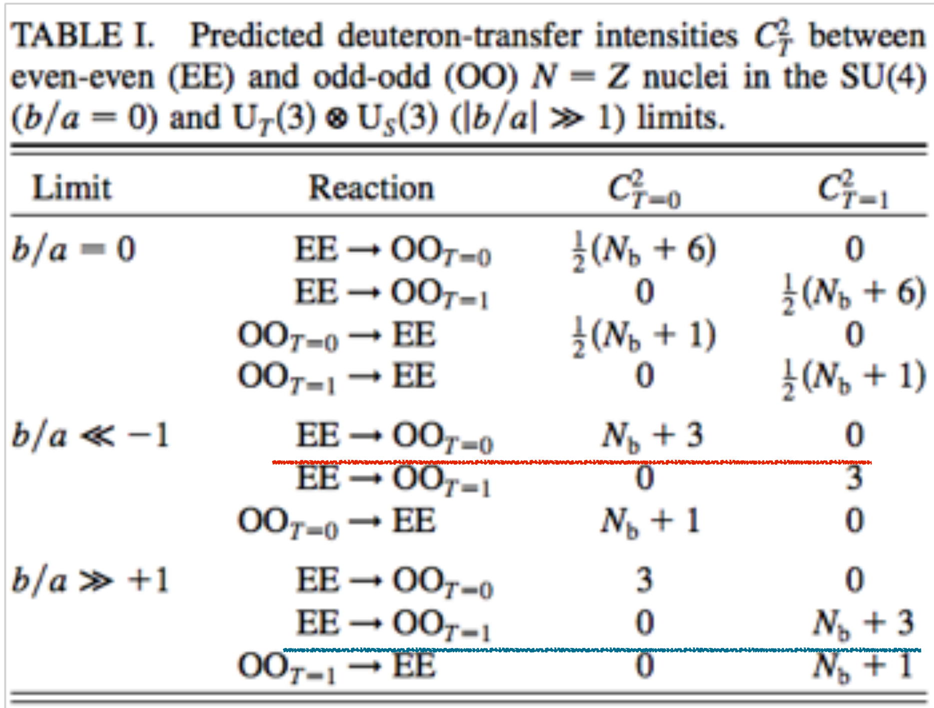


TABLE I. Predicted deuteron-transfer intensities C_T^2 between even-even (EE) and odd-odd (OO) $N = Z$ nuclei in the SU(4) $(b/a = 0)$ and $U_T(3) \otimes U_S(3)$ $(|b/a| \gg 1)$ limits.

Limit	Reaction	$C_{T=0}^2$	$C_{T=1}^2$
$b/a = 0$	$EE \rightarrow OO_{T=0}$	$\frac{1}{2}(N_b + 6)$	0
	$EE \rightarrow OO_{T=1}$	0	$\frac{1}{2}(N_b + 6)$
	$OO_{T=0} \rightarrow EE$	$\frac{1}{2}(N_b + 1)$	0
	$OO_{T=1} \rightarrow EE$	0	$\frac{1}{2}(N_b + 1)$
$b/a \ll -1$	$EE \rightarrow OO_{T=0}$	$N_b + 3$	0
	$EE \rightarrow OO_{T=1}$	0	3
	$OO_{T=0} \rightarrow EE$	$N_b + 1$	0
$b/a \gg +1$	$EE \rightarrow OO_{T=0}$	3	0
	$EE \rightarrow OO_{T=1}$	0	$N_b + 3$
	$OO_{T=1} \rightarrow EE$	0	$N_b + 1$

Van Isacker, Warner and Frank Phys. Rev. Lett. 94, 162502

Cross sections to T=1 and T=0 states through (p,^{3}He) and (^{3}He,p): Correlation strength in the two spin channels

σ

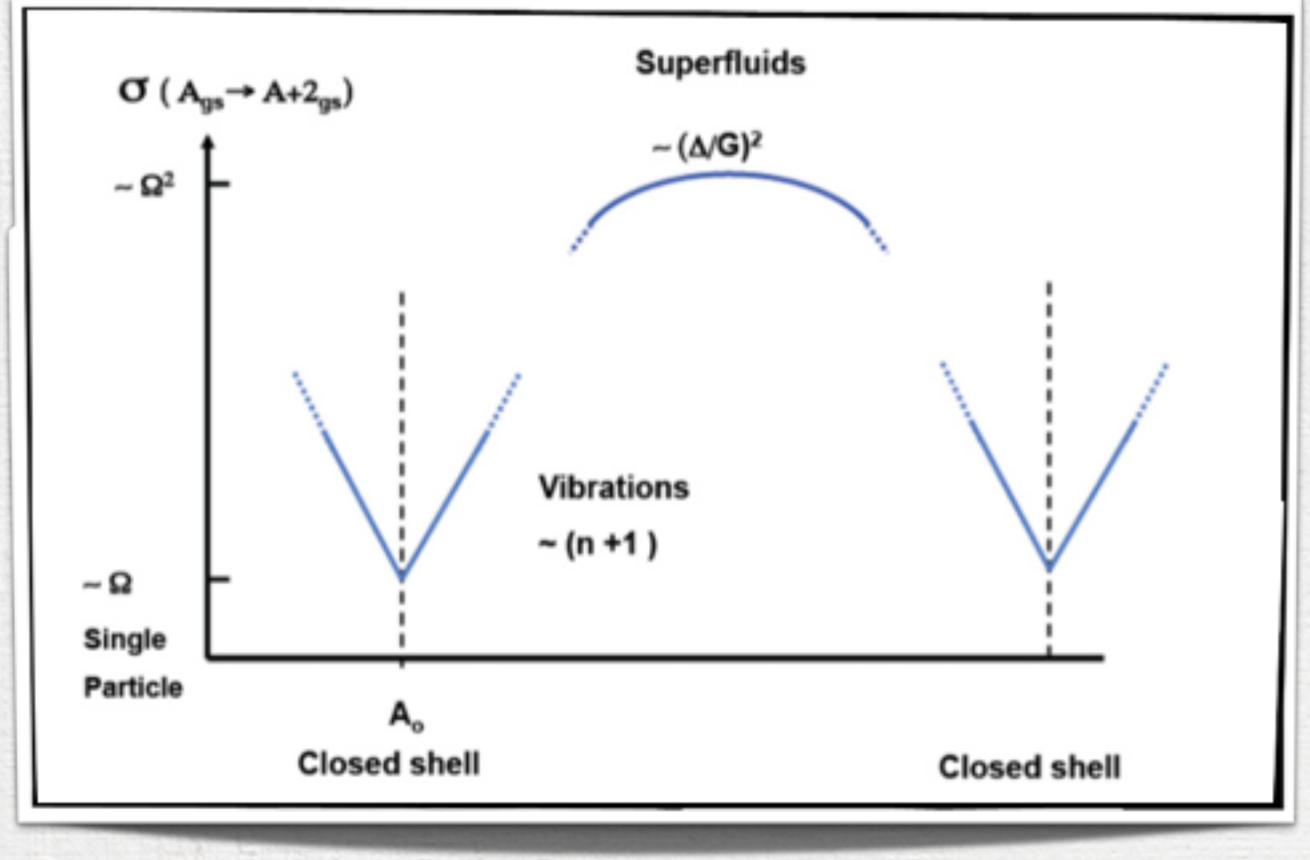
Even-Even
T=0 J=0

Odd-Odd

T=0 J=1

T=1 J=0

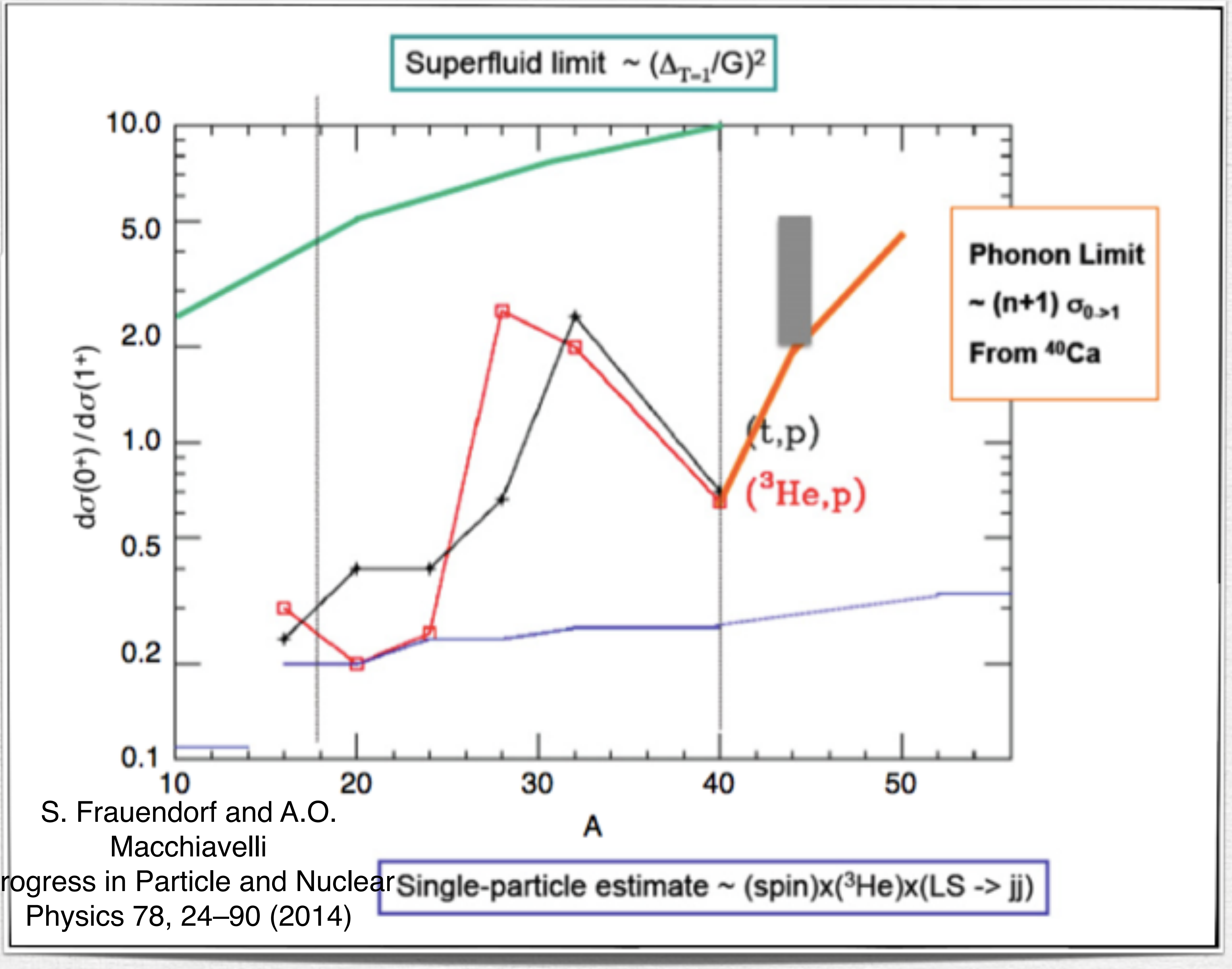
Isoscalar: 1$^+$ contribution larger than 0$^+$



S. Frauendorf and A.O. Macchiavelli
Progress in Particle and Nuclear Physics 78, 24–90 (2014)

Previous measurements

A.O. Macchiavelli et al., ANL Physics Division Annual Report 21, 2002

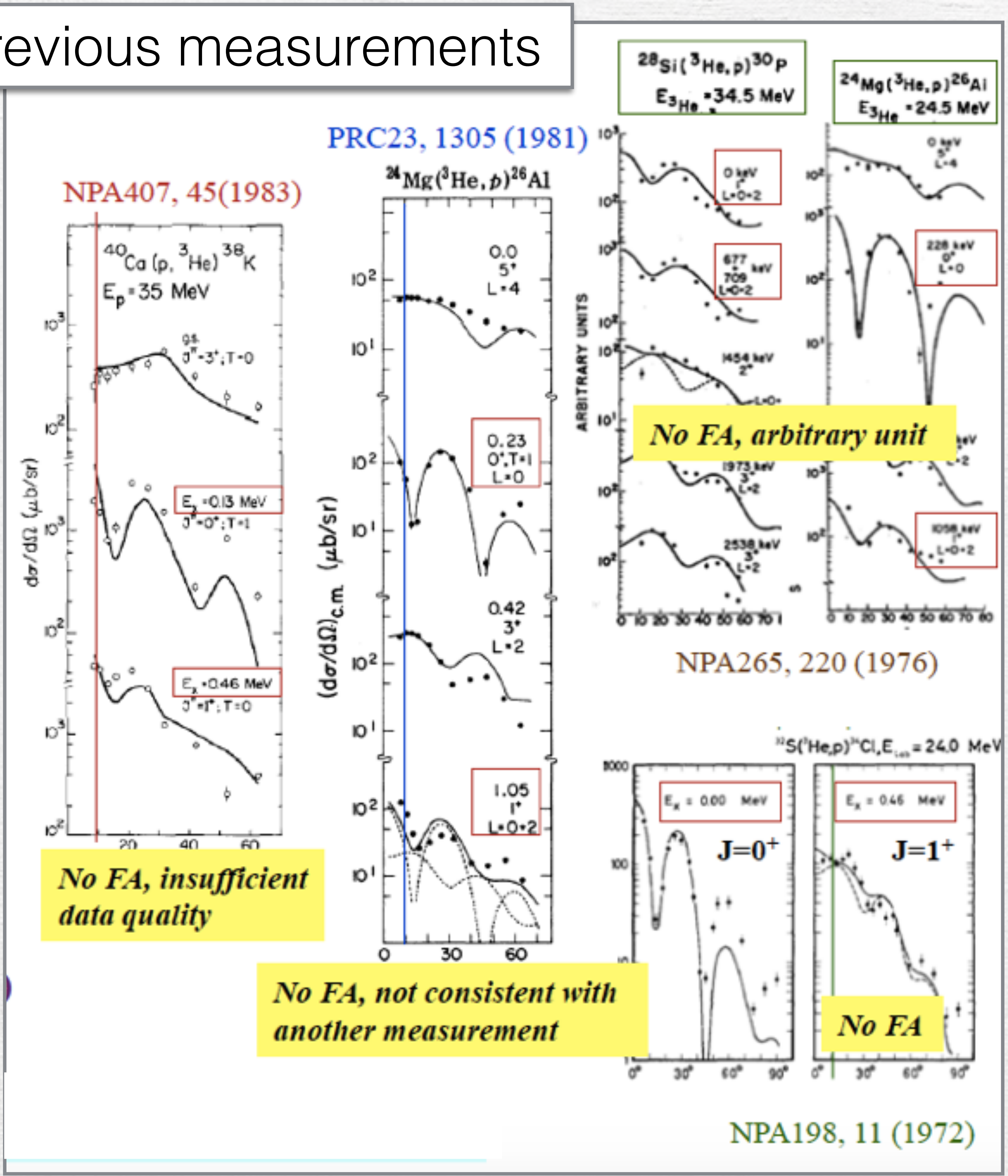


S. Frauendorf and A.O. Macchiavelli
Progress in Particle and Nuclear Physics 78, 24–90 (2014)

- Closed-shell nuclei 16O, 40Ca NOT follow single-particle estimate ?
- No intuitive understanding –20Ne, 24Mg follow single-particle prediction ?
- Doubtful increase of > a factor of 10 from 24Mg to 28Si ?

Previous measurements

- L=0 dominates at forward angles
- Crucial role of the reaction mechanism
- Reactions performed under different conditions



NPA407, 45(1983)

No FA, insufficient data quality

PRC23, 1305 (1981)

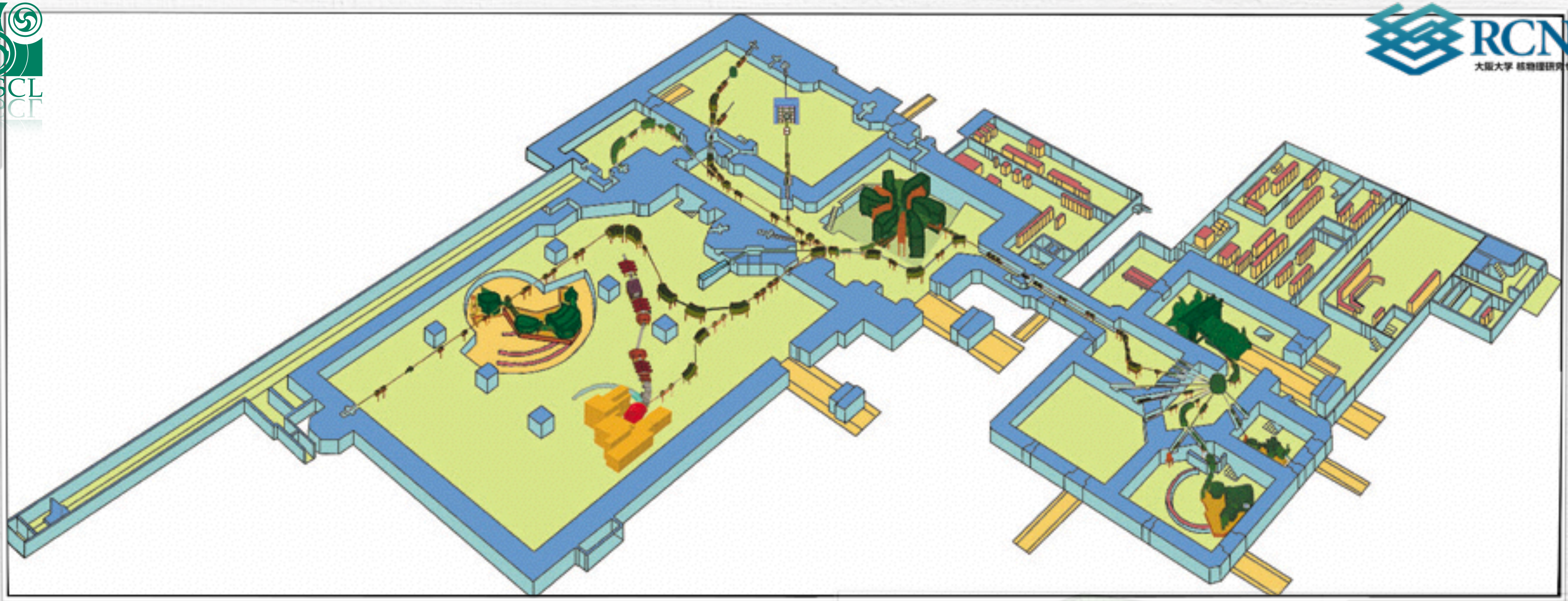
No FA, not consistent with another measurement

NPA265, 220 (1976)

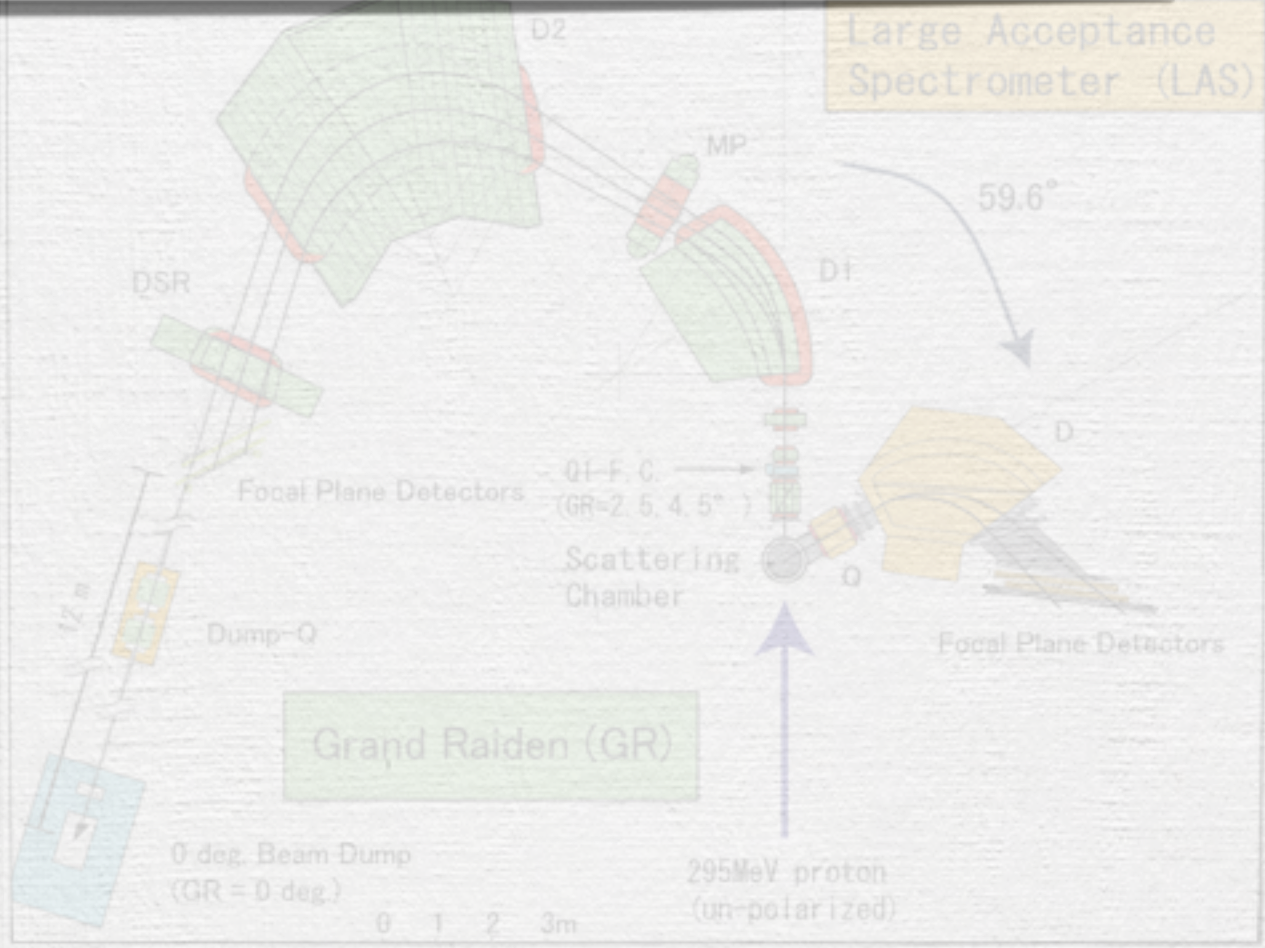
No FA, arbitrary unit

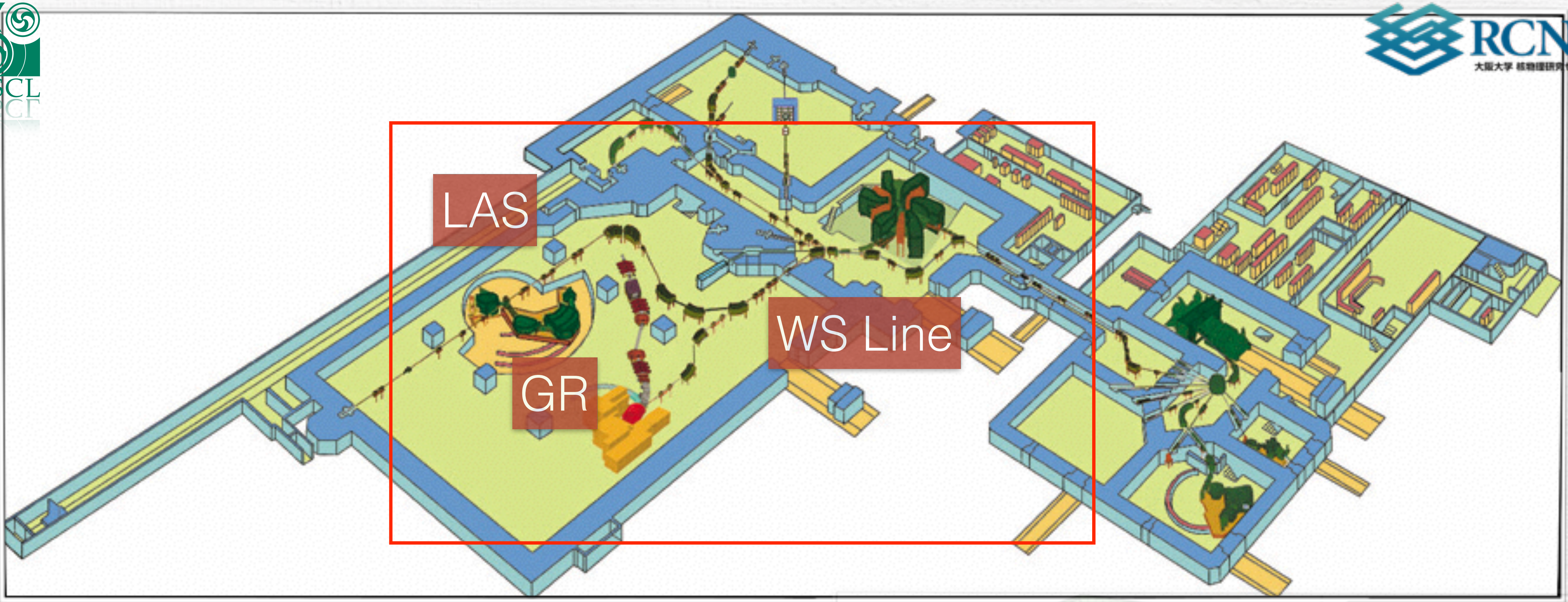
NPA198, 11 (1972)

No FA



New measurements performed at the Research Center for Nuclear Physics (Osaka University)

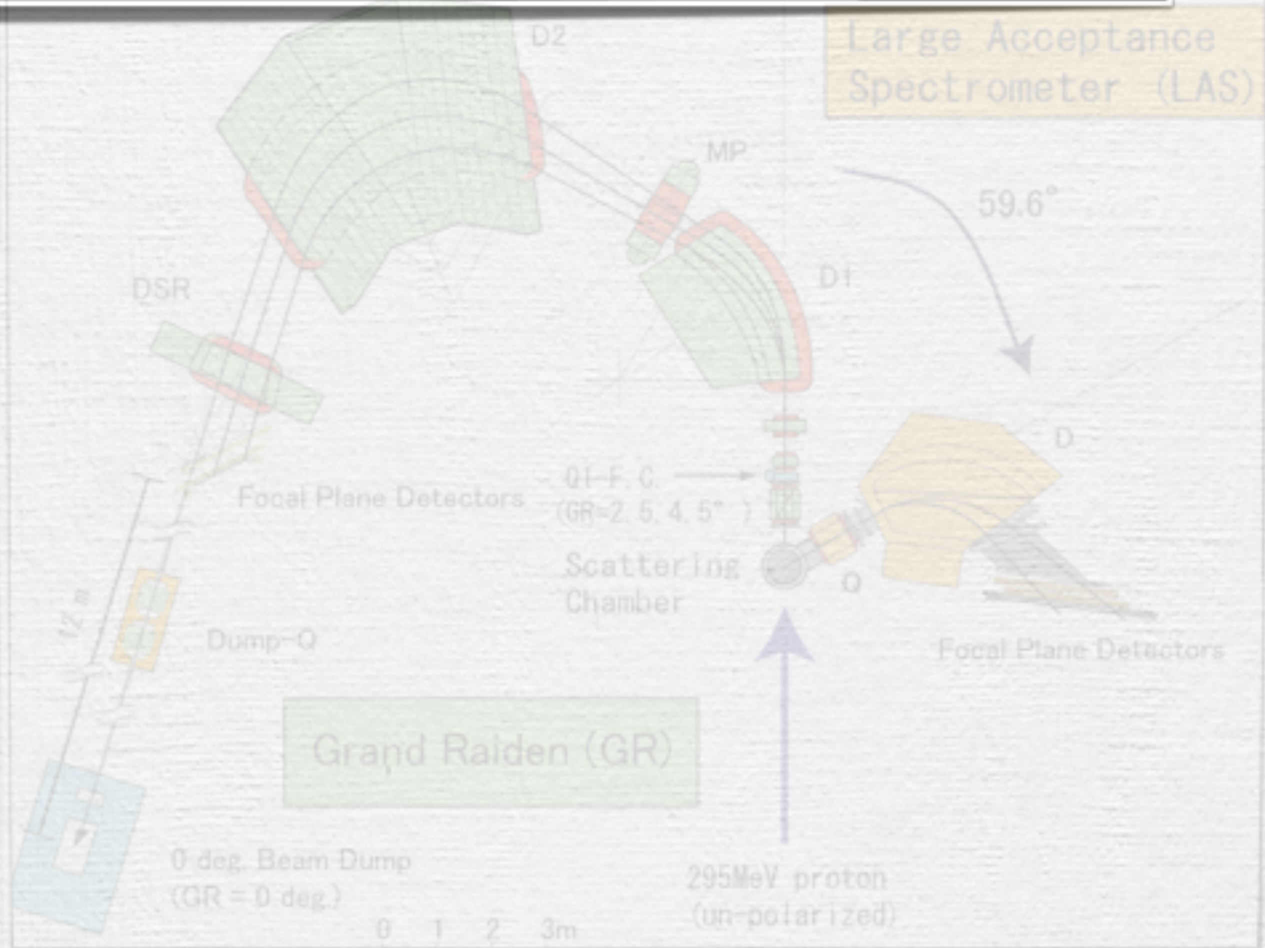




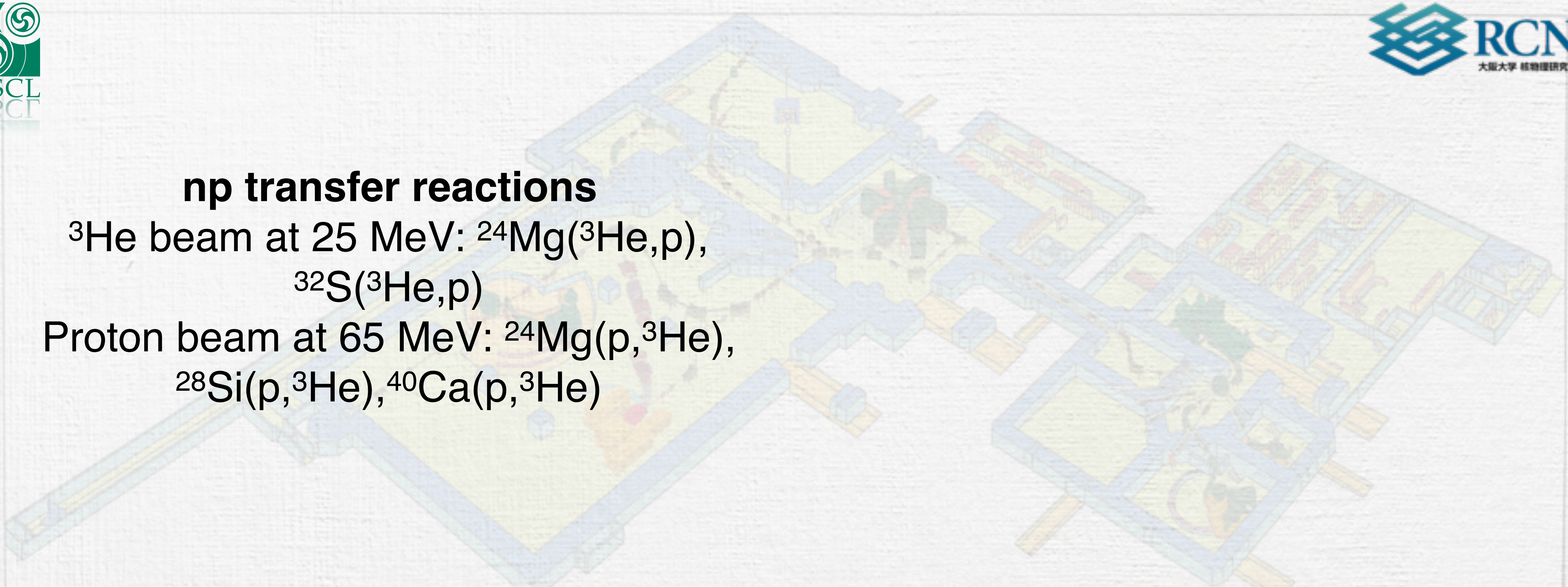
New measurements performed at the Research Center for Nuclear Physics (Osaka University)

WS Line: Dispersion matching. Energy resolution 20-30 keV (FWHM)

Double armed spectrometer: Grand Raiden + Large Acceptance Spectrometer (LAS)



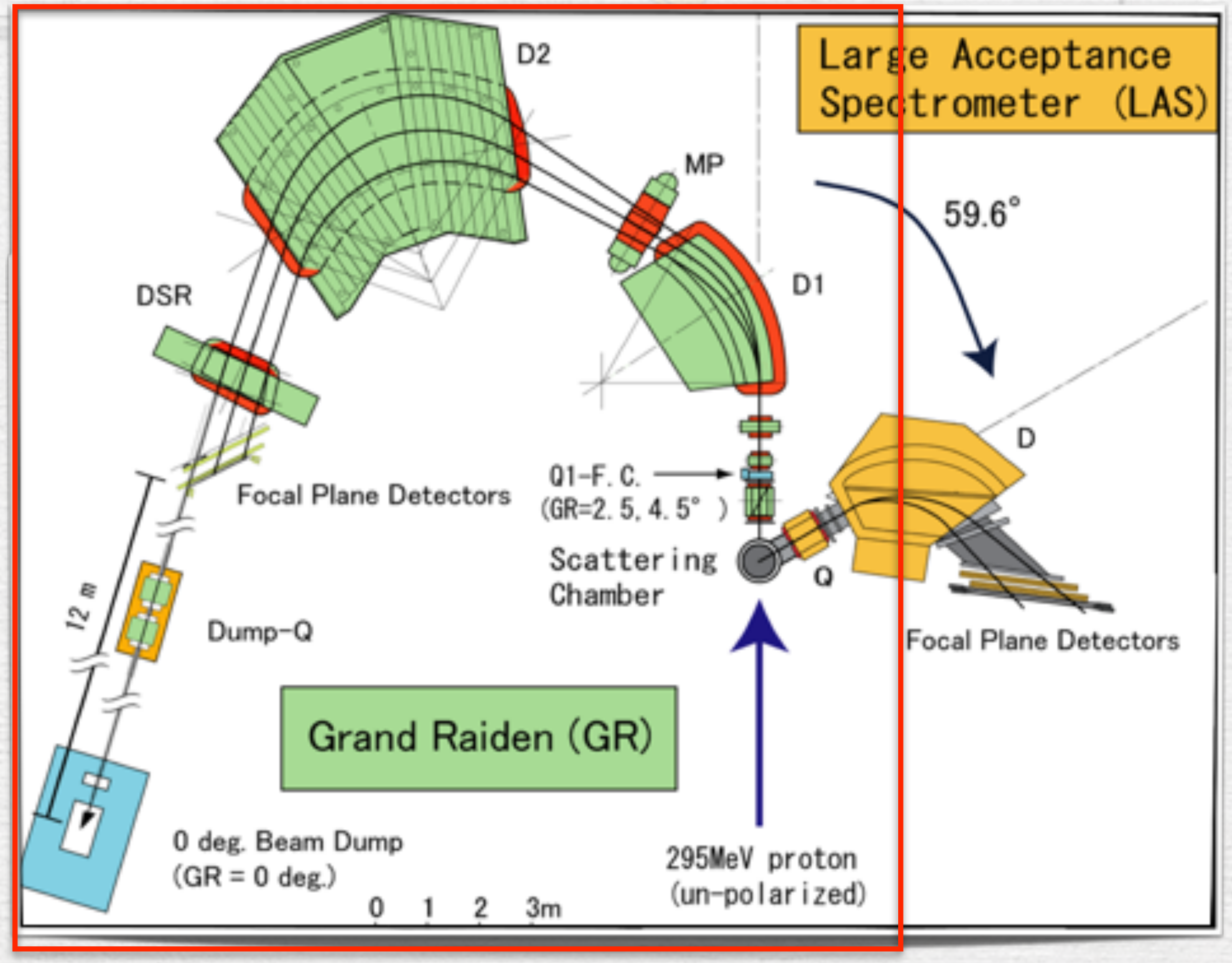

GR
LAS
WS Line



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)



np transfer reactions

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

2n transfer reactions

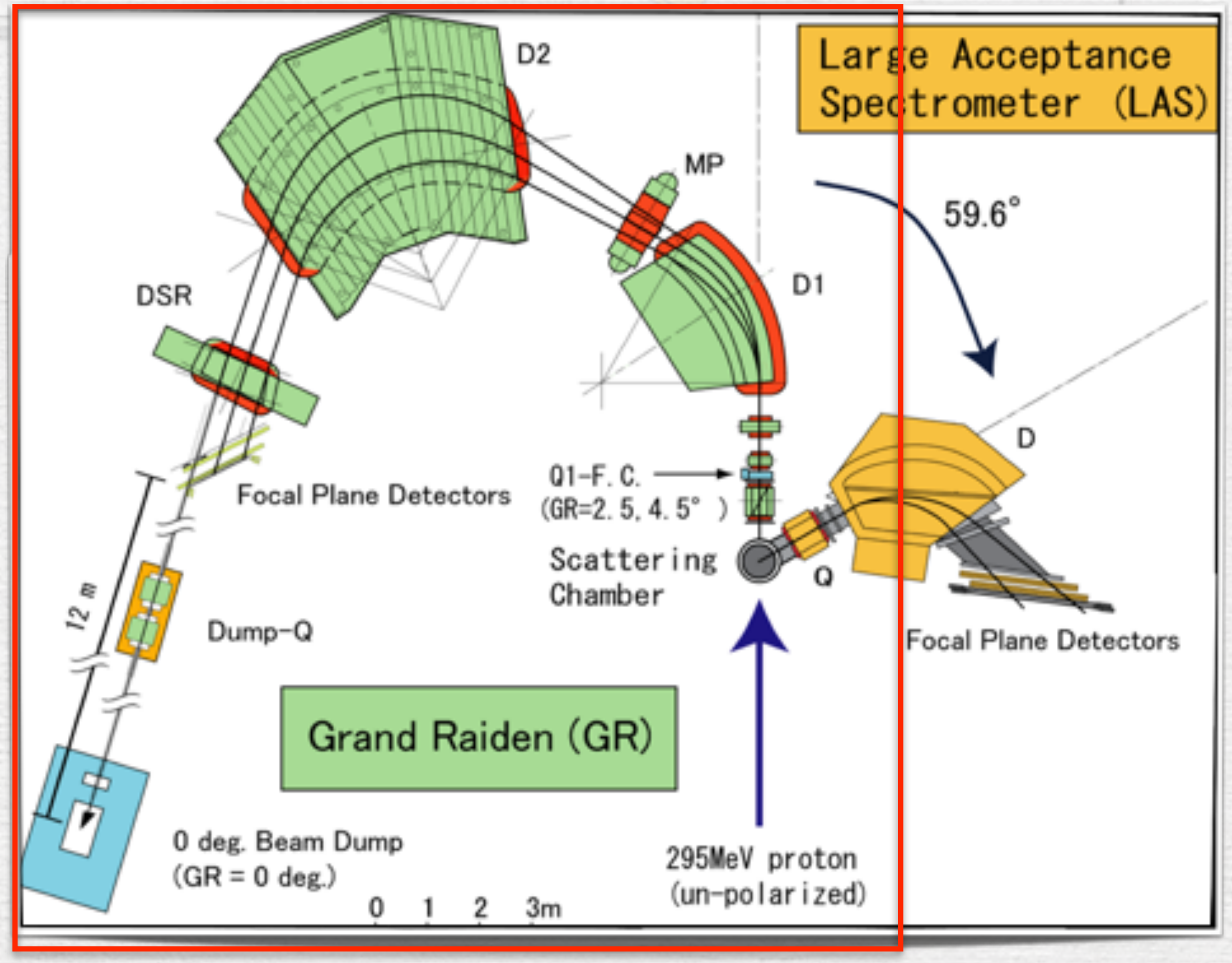
(Comparison to np transfer)

^{24}Mg(p,t),^{28}Si(p,t)

1n transfer reactions

(Experimental spectroscopic factor for 2n transfer calculations)

^{24}Mg(p,d), ^{32}S(p,d), ^{40}Ca(p,d), ^{24}Mg(^{3}He,d)



np transfer reactions

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Elastic scattering (check beam normalization and target thickness measurement)

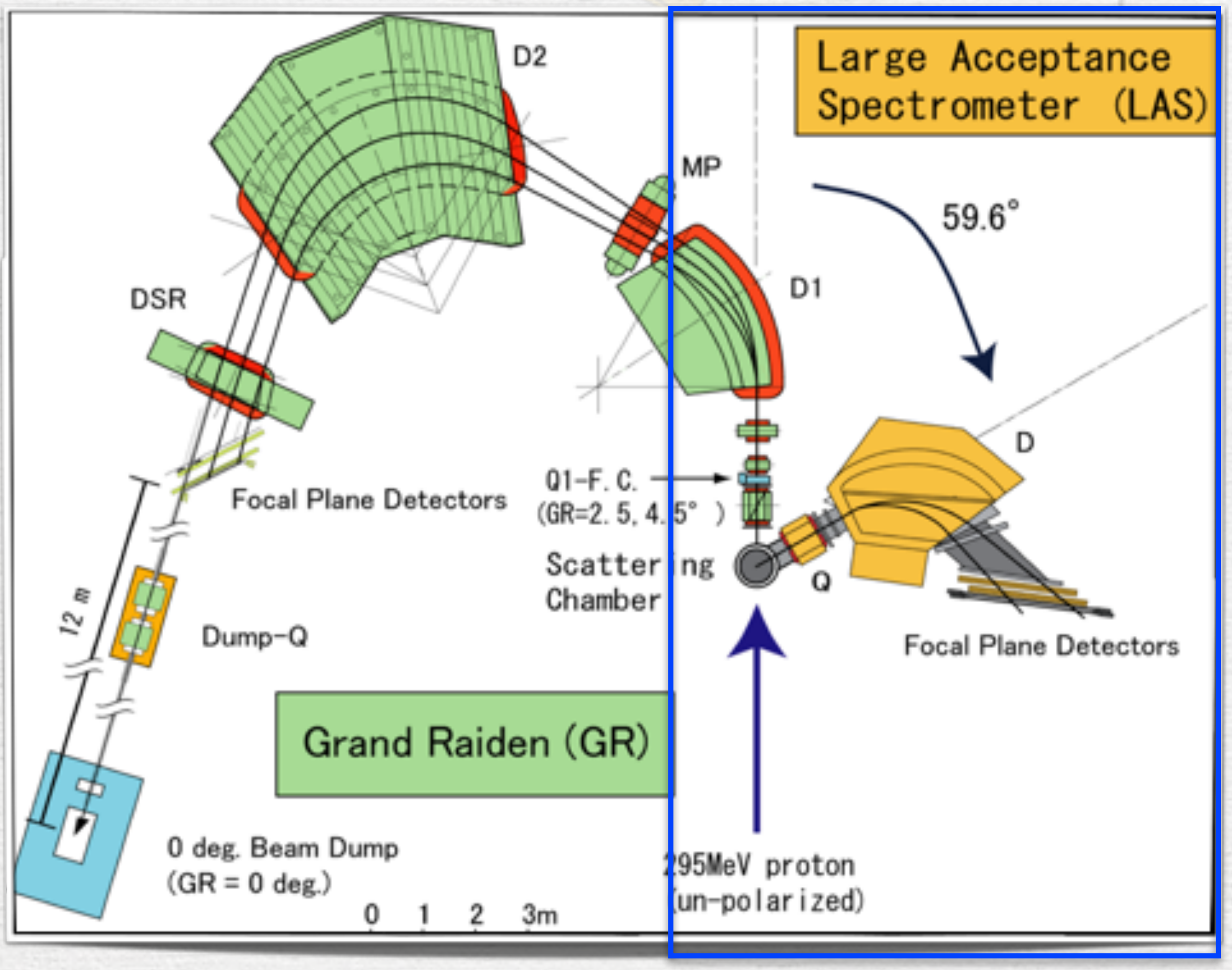
^{24}Mg(^{3}He,^{3}He), ^{32}S(^{3}He,^{3}He), ^{28}Si(p,p), ^{40}Ca(p,p)

2n transfer reactions (Comparison to np transfer)

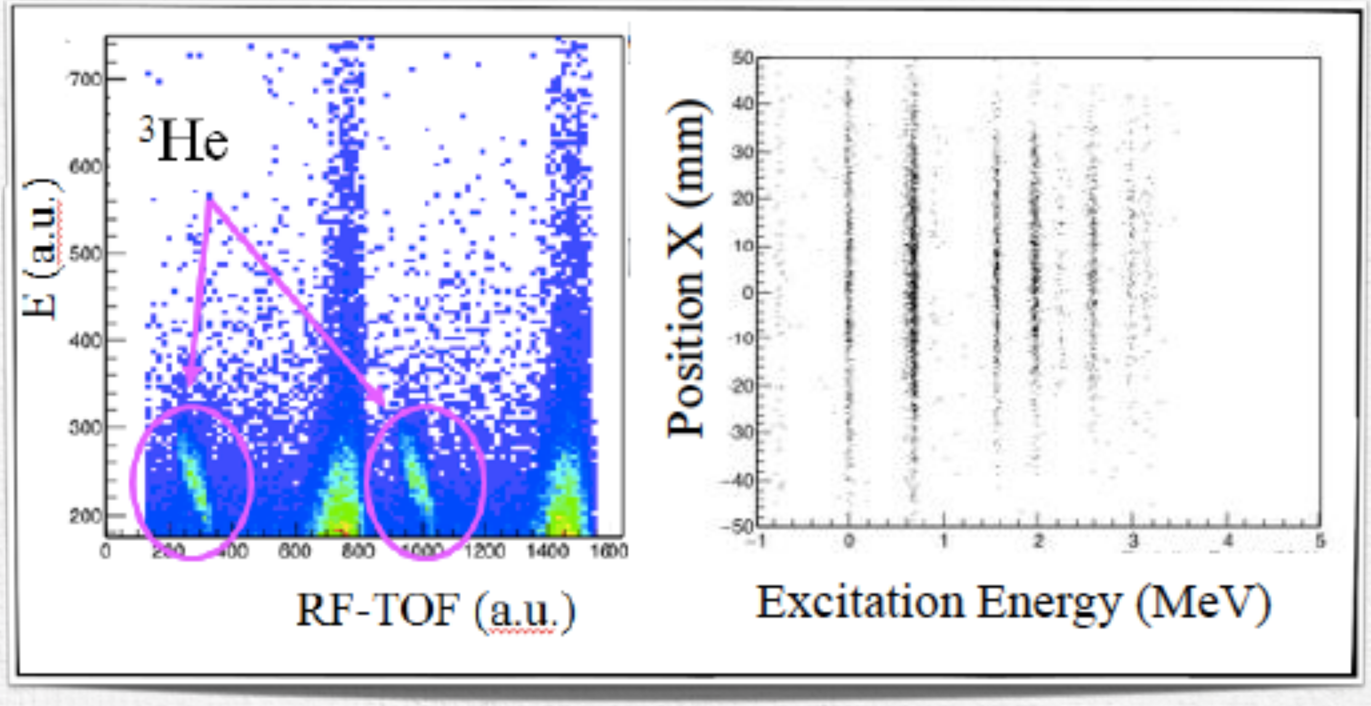
^{24}Mg(p,t),^{28}Si(p,t)

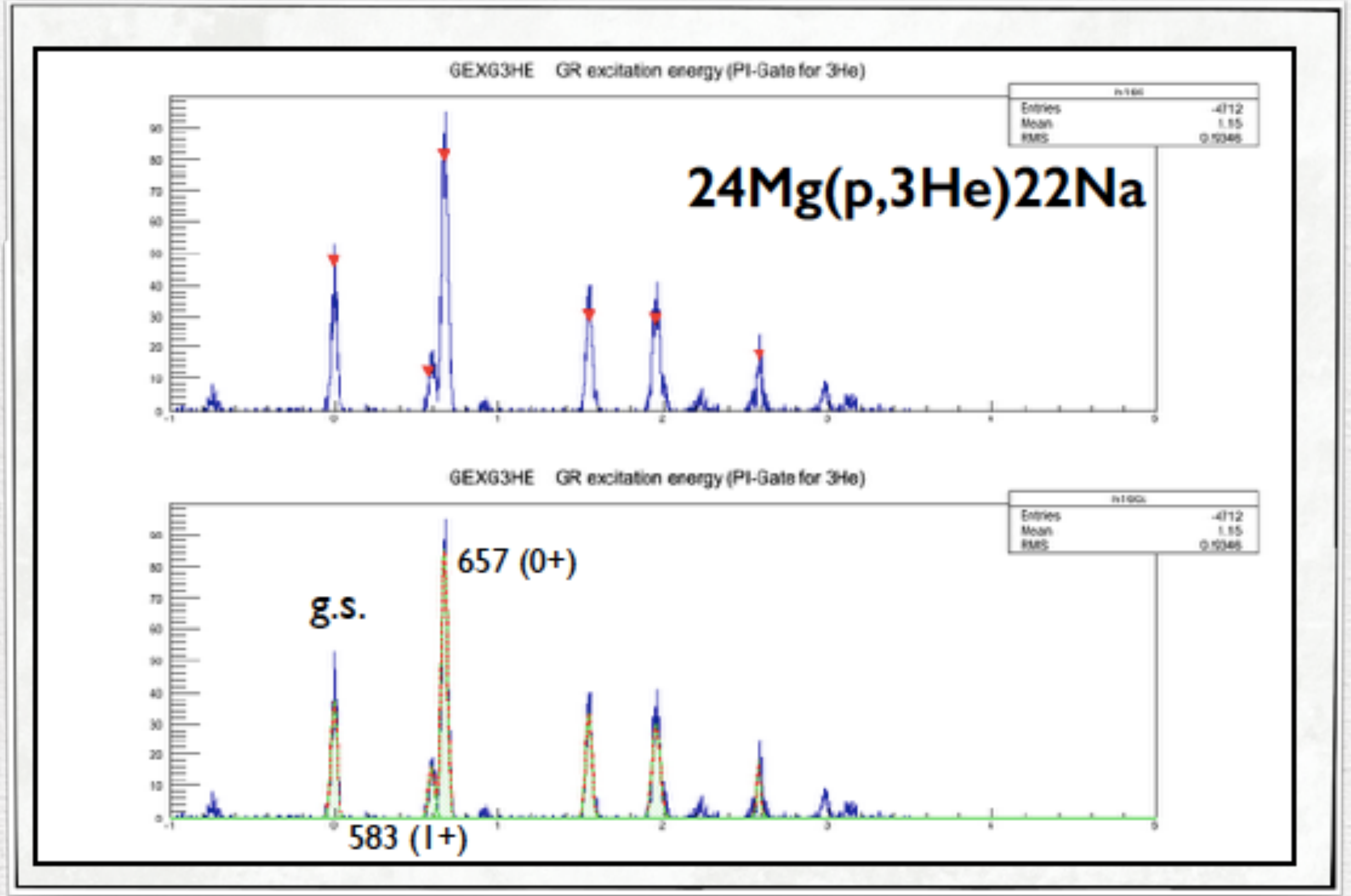
1n transfer reactions (Experimental spectroscopic factor for 2n transfer calculations)

^{24}Mg(p,d), ^{32}S(p,d), ^{40}Ca(p,d), ^{24}Mg(^{3}He,d)



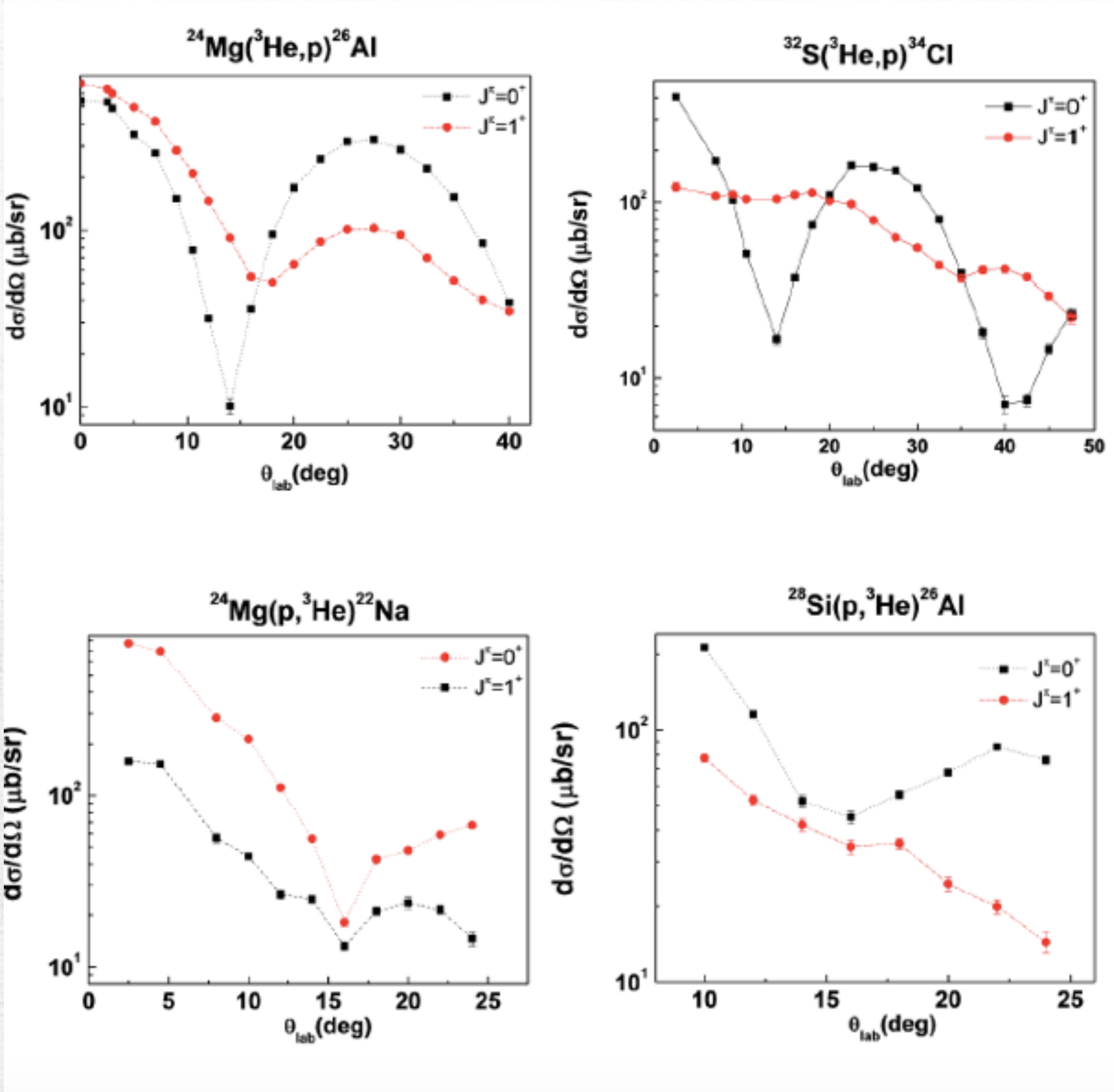
Data analysis

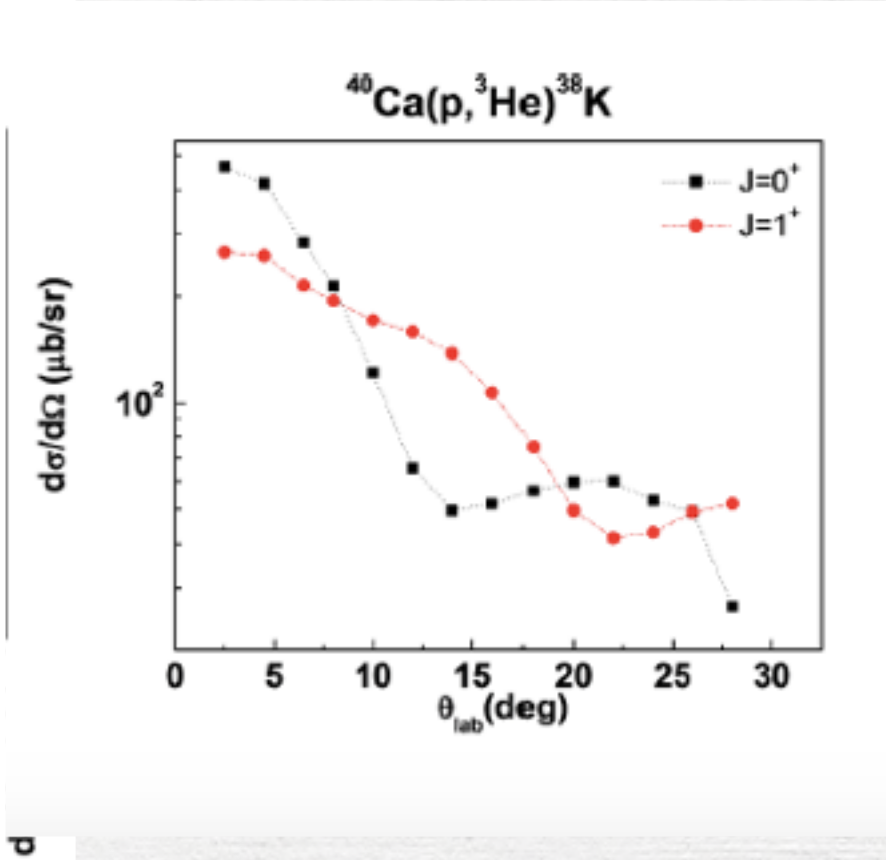




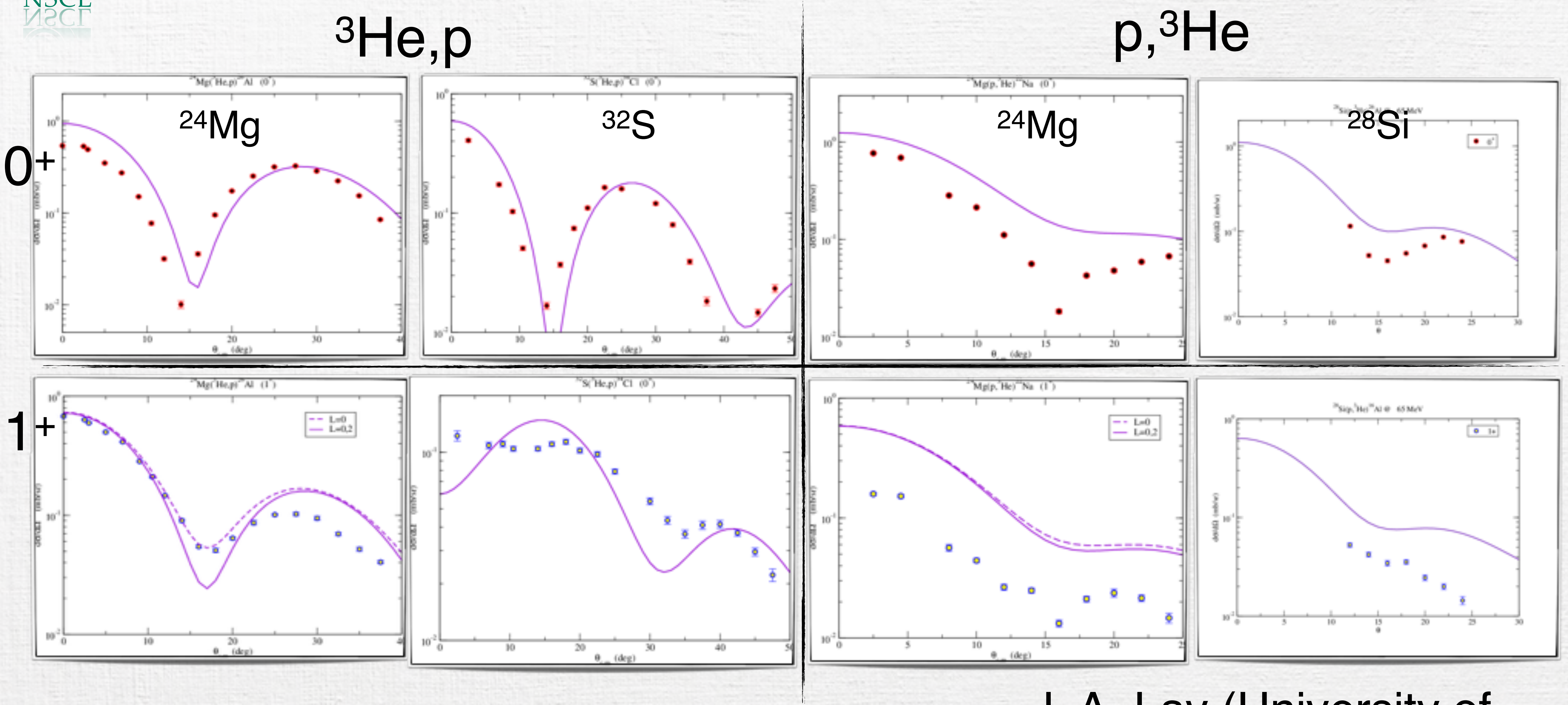
- p and 3He identified by time of flight & energy in focal plane
- Excitation energy spectra kinematically corrected (no position dependence)
- 0+and 1+states unambiguously identified for each reaction
- Absolute cross sections
- Resolution: 40 keV(target: 300 µg/cm2)
- Background subtracted
- Correction of target thickness
- Measurements at every 2° interval to angular distributions with 2 peaks
- Measurements at very forward angles

Differential cross sections J=0⁺ and J=1⁺





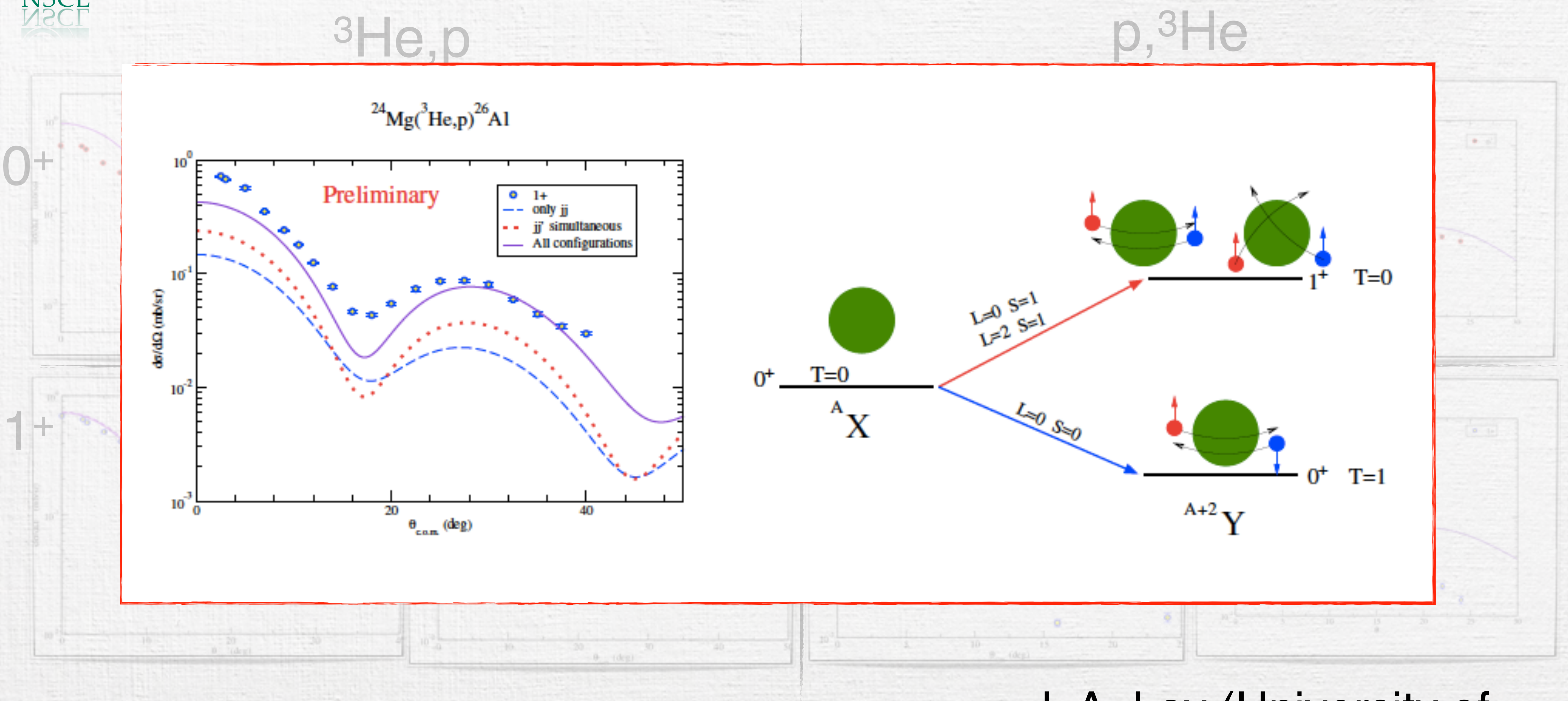
Second order DWBA calculations



J. A. Lay (University of Padova)

- Reaction mechanism: Fresco calculations
- Simultaneous and sequential transfer
- Potentials: Menet (p), Lohr-Haemberli (d), Bechetti-Greenlees (^{3}He)
- Shell Model calculations: USDB interaction

Second order DWBA calculations



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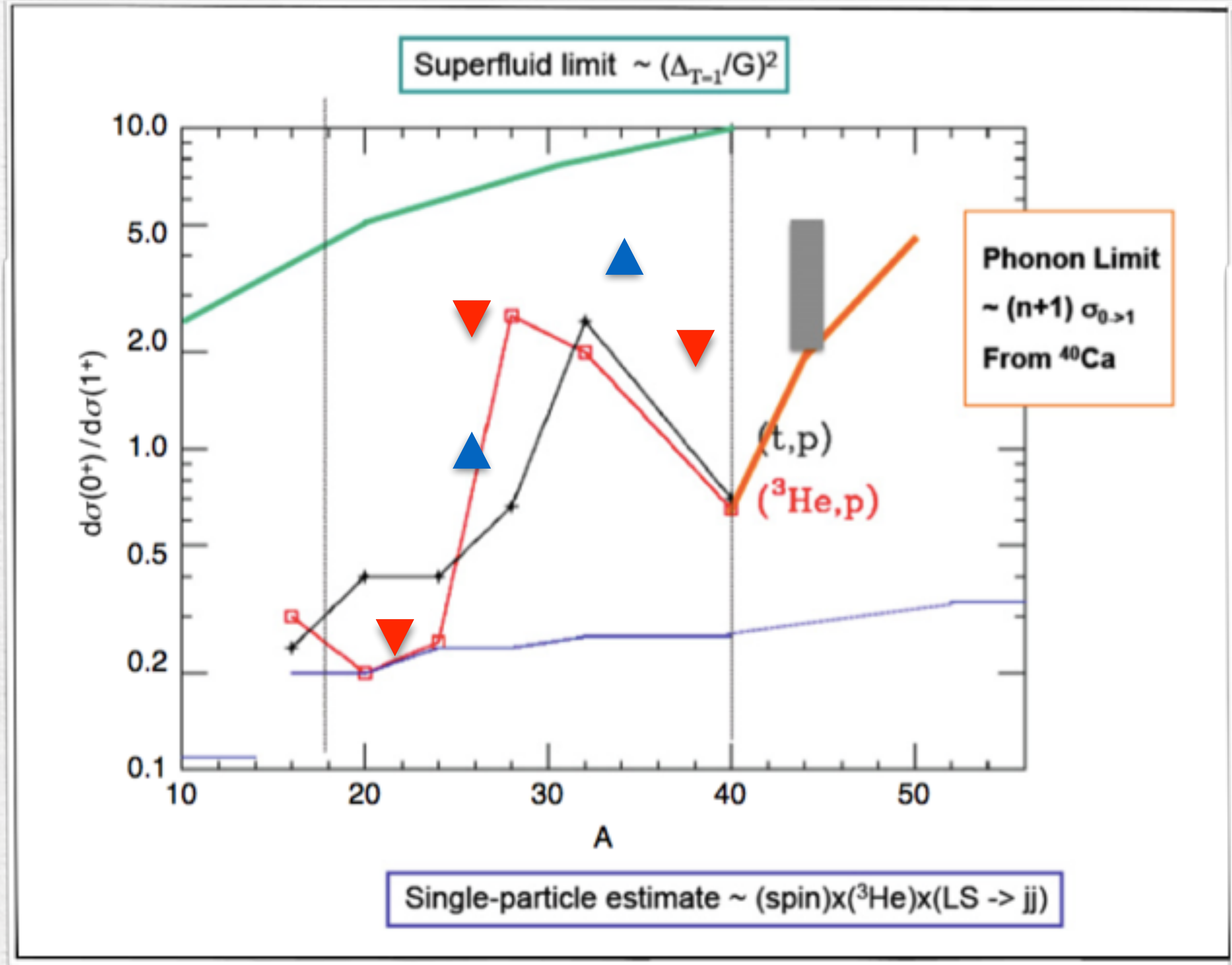
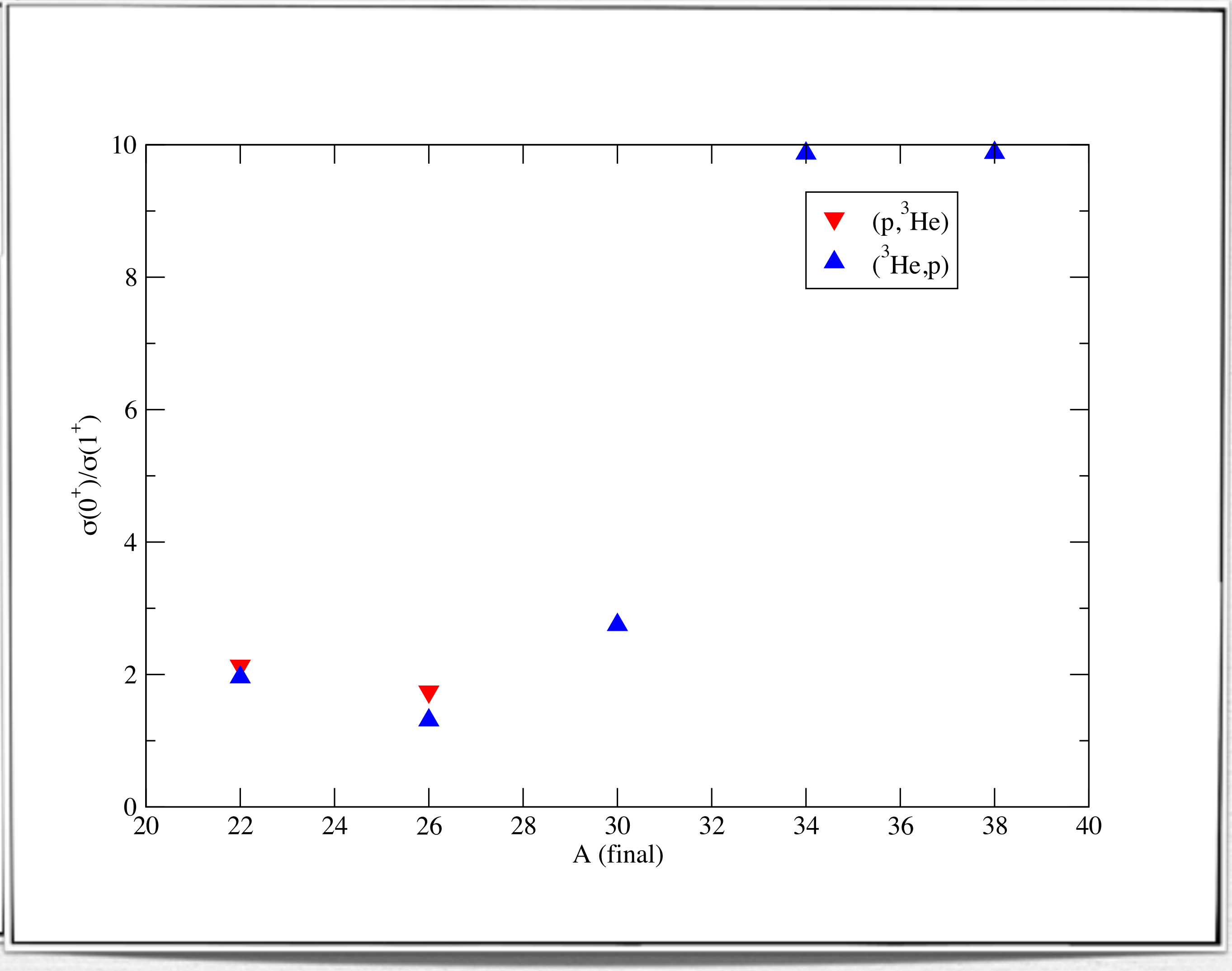
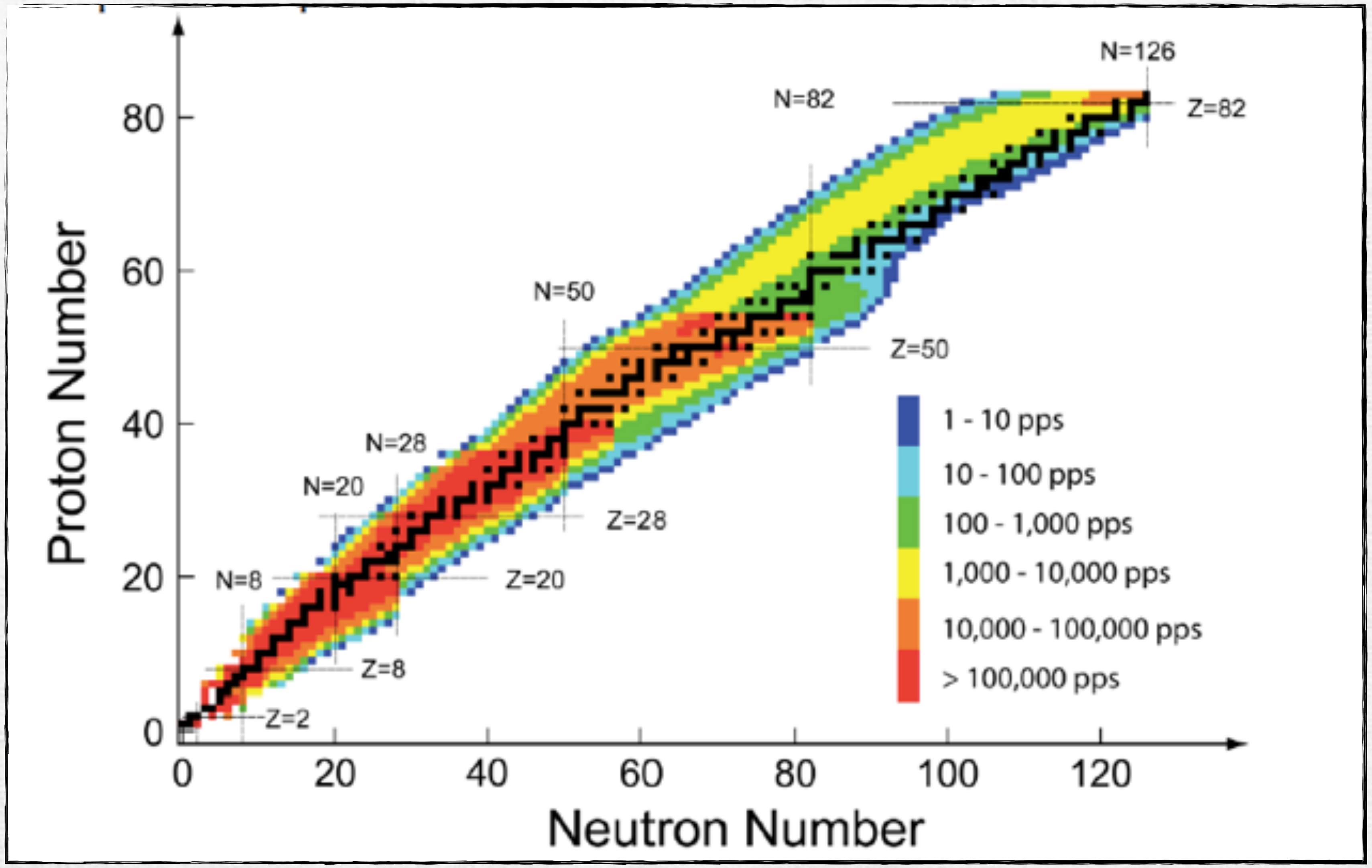
dσ(0+)/dσ(1+) ratios





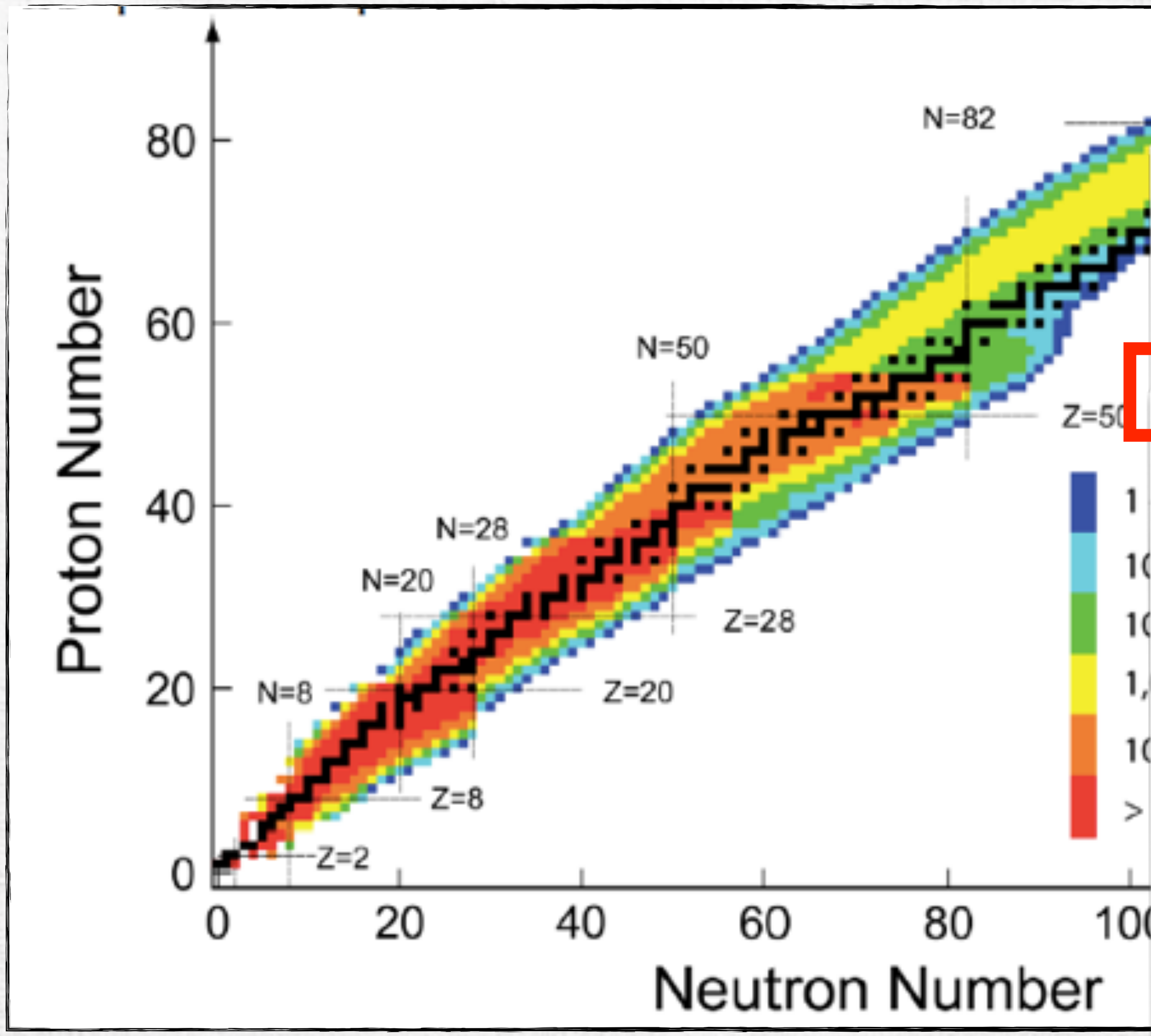
Future perspectives

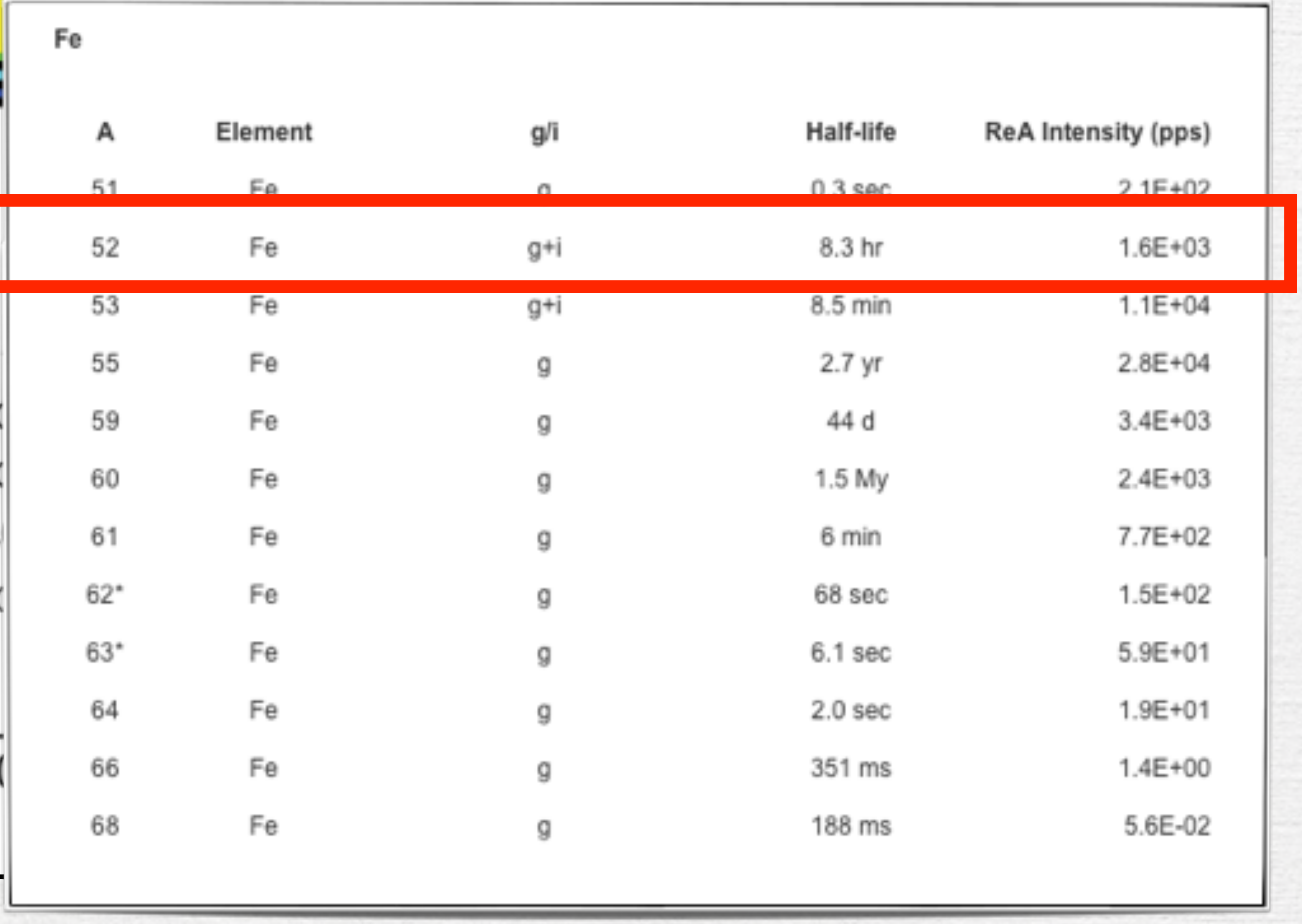
Reaccelerated beams at NSCL



Future perspectives

Reaccelerated beams at NSCL



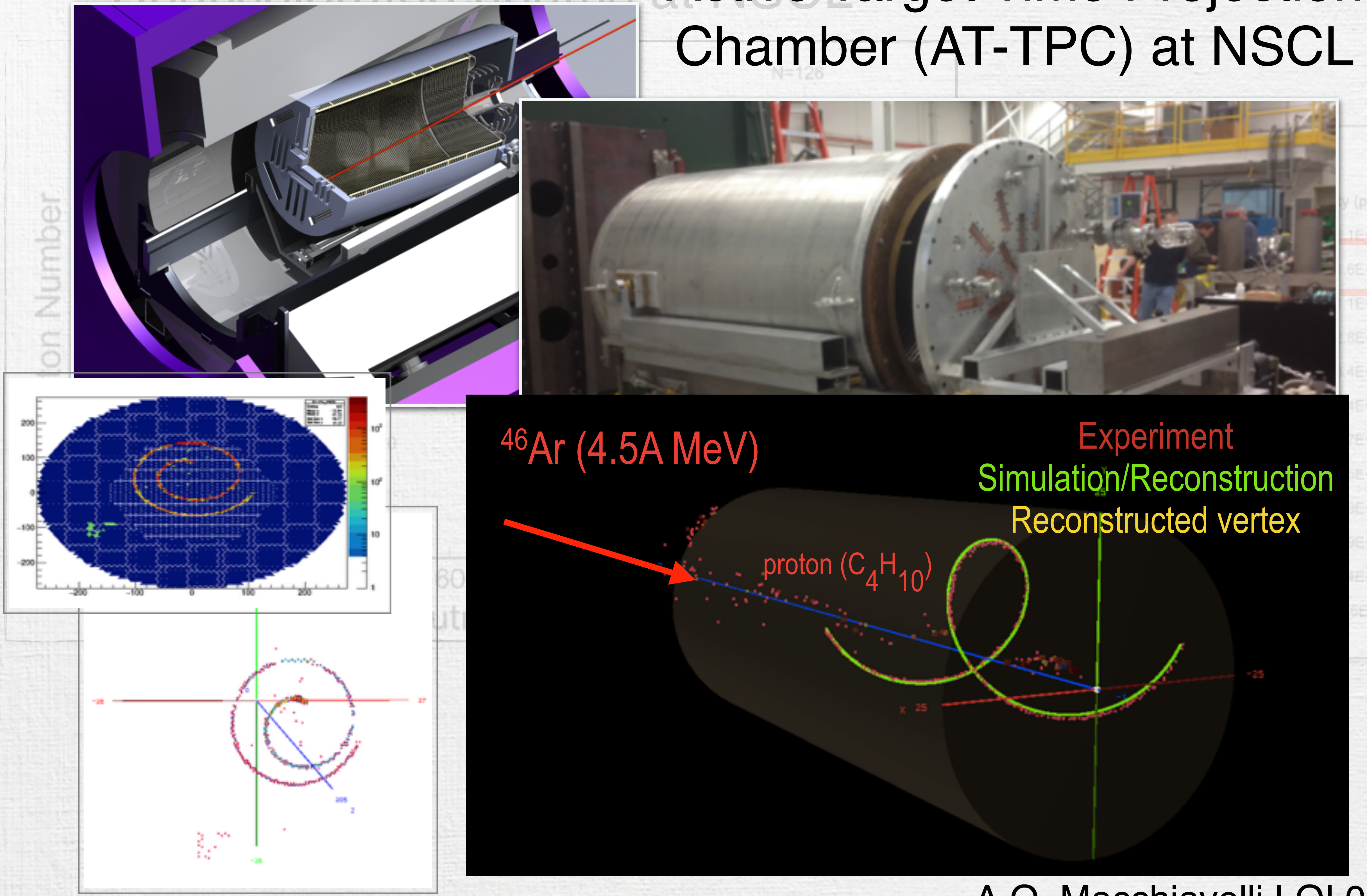


Fe

A	Element	g/i	Half-life	ReA Intensity (pps)
51	Fe	g	0.3 sec	2.1E+02
52	Fe	g+i	8.3 hr	1.6E+03
53	Fe	g+i	8.5 min	1.1E+04
55	Fe	g	2.7 yr	2.8E+04
59	Fe	g	44 d	3.4E+03
60	Fe	g	1.5 My	2.4E+03
61	Fe	g	6 min	7.7E+02
62*	Fe	g	68 sec	1.5E+02
63*	Fe	g	6.1 sec	5.9E+01
64	Fe	g	2.0 sec	1.9E+01
66	Fe	g	351 ms	1.4E+00
68	Fe	g	188 ms	5.6E-02

Future perspectives

Active Target Time Projection Chamber (AT-TPC) at NSCL



A.O. Macchiavelli LOI 09051

Conclusions

Systematic study f neutron-proton pairing in the sd-shell

Performed all reactions under the same conditions

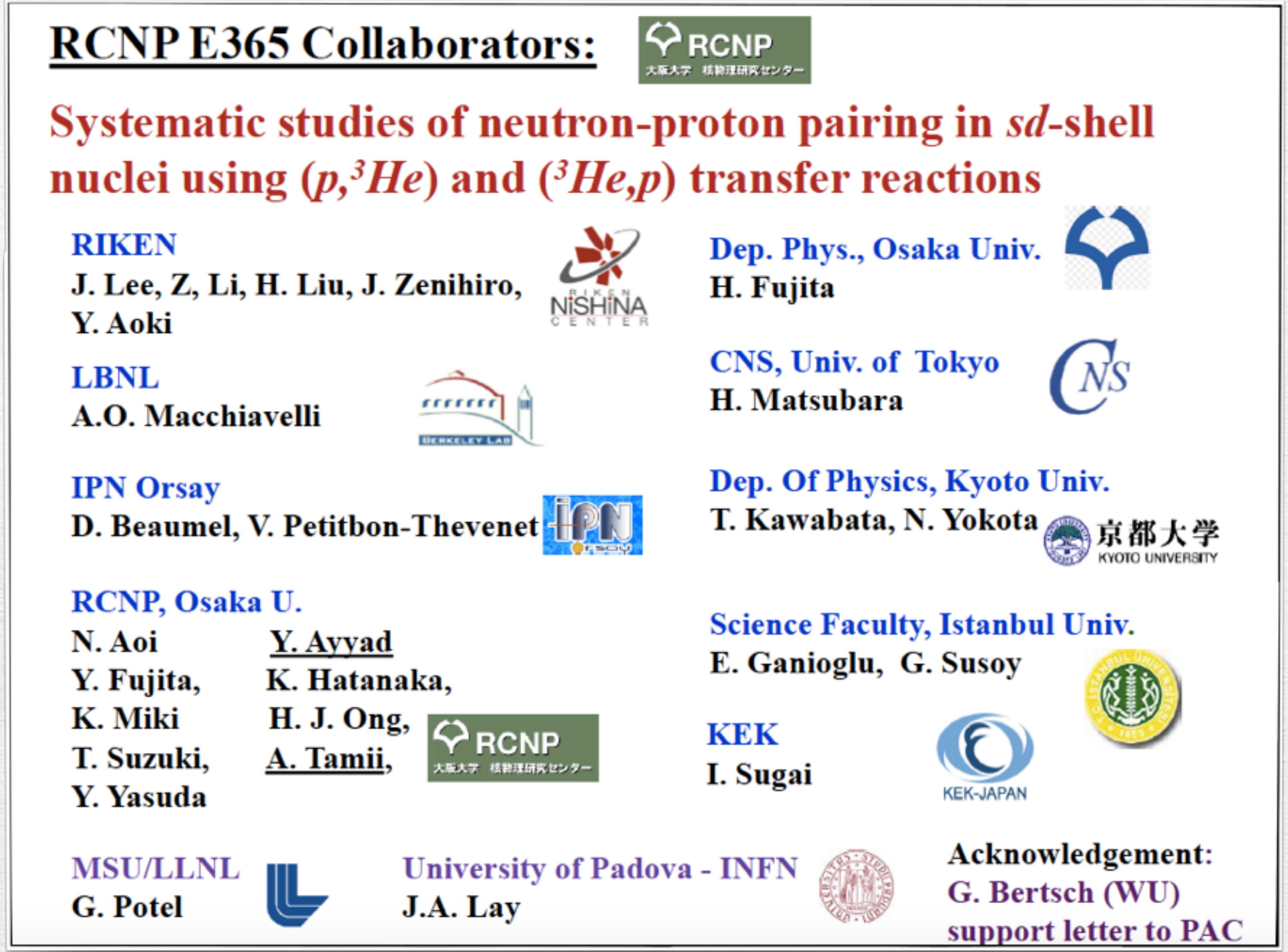
Performed calculation taking into account the reaction mechanism (FRESCO) and structure (USDB)

Obtained dσ(0^+)/dσ(1^+) ratios with high precision

Interpretation of the differential cross sections and ratios

Baseline for systematic studies of np-pairing in heavier nuclei (ReA3 + ATTPC)

Collaboration



RCNP E365 Collaborators:

Systematic studies of neutron-proton pairing in *sd*-shell nuclei using $(p,{}^{3}He)$ and $({}^{3}He,p)$ transfer reactions

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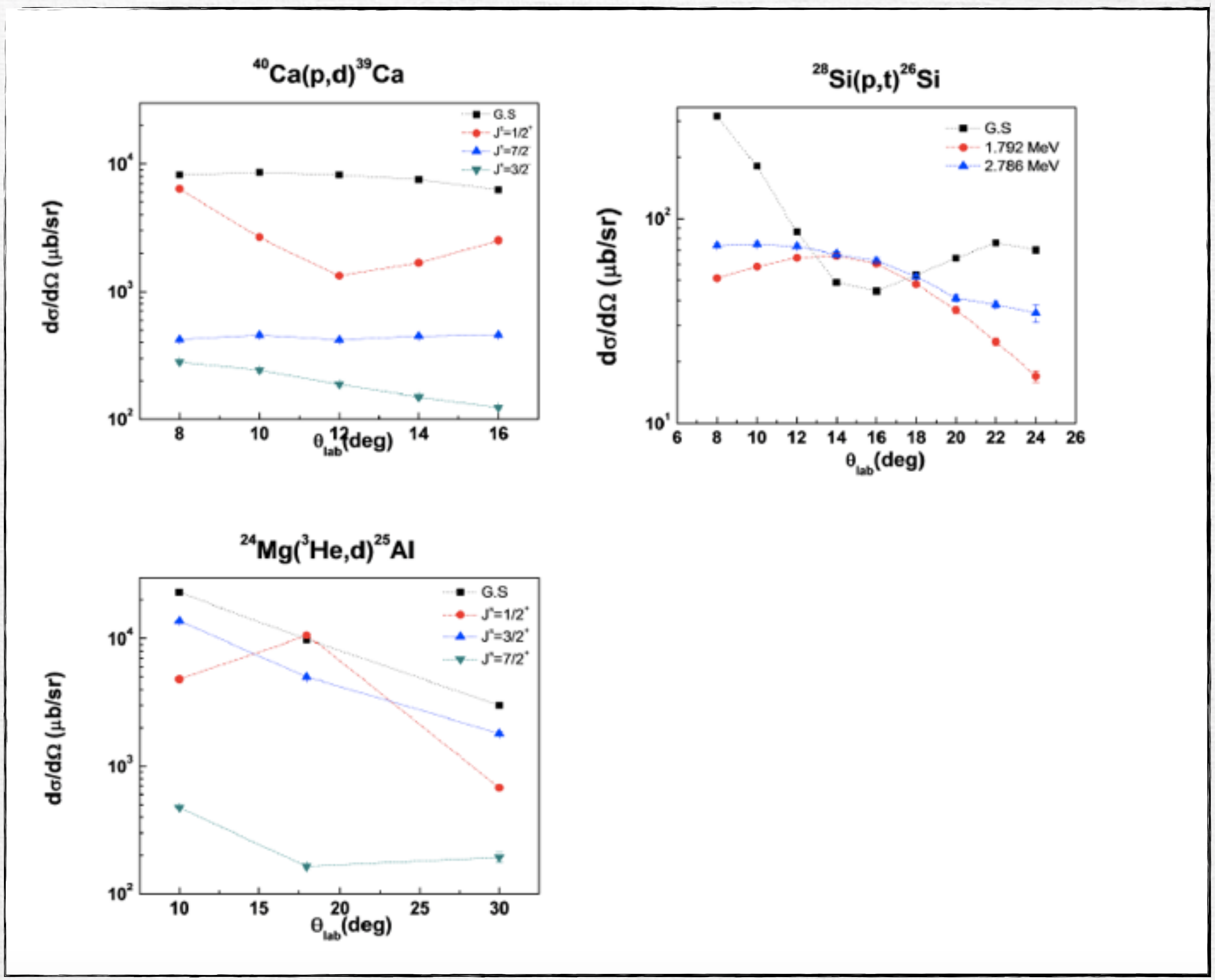
G. Bertsch (WU)
support letter to PAC

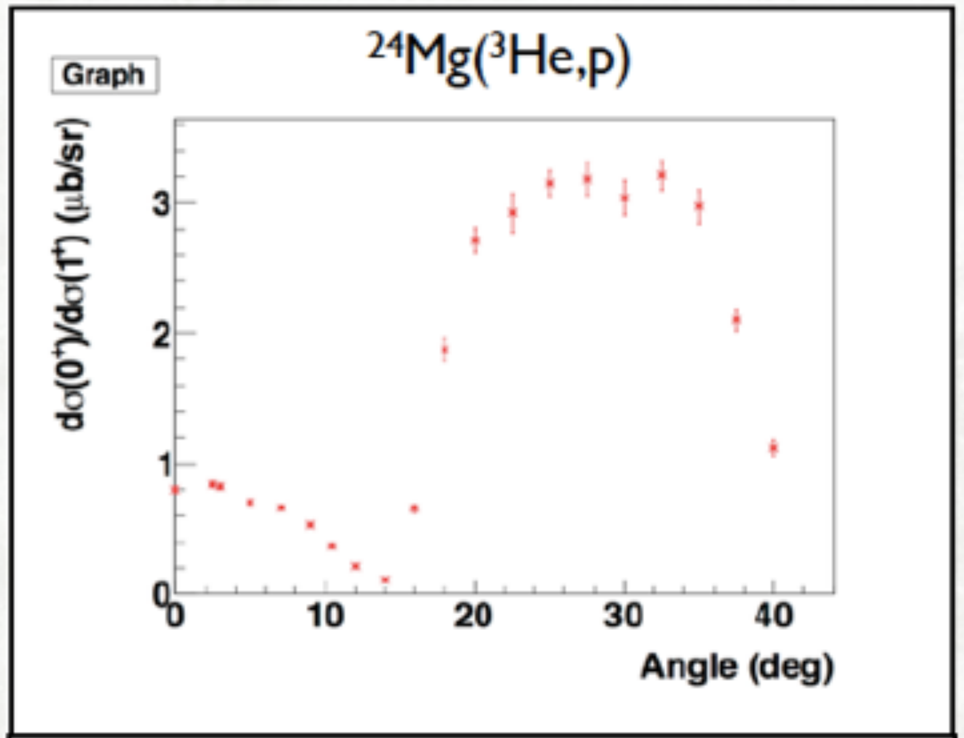
Thank you for your attention!



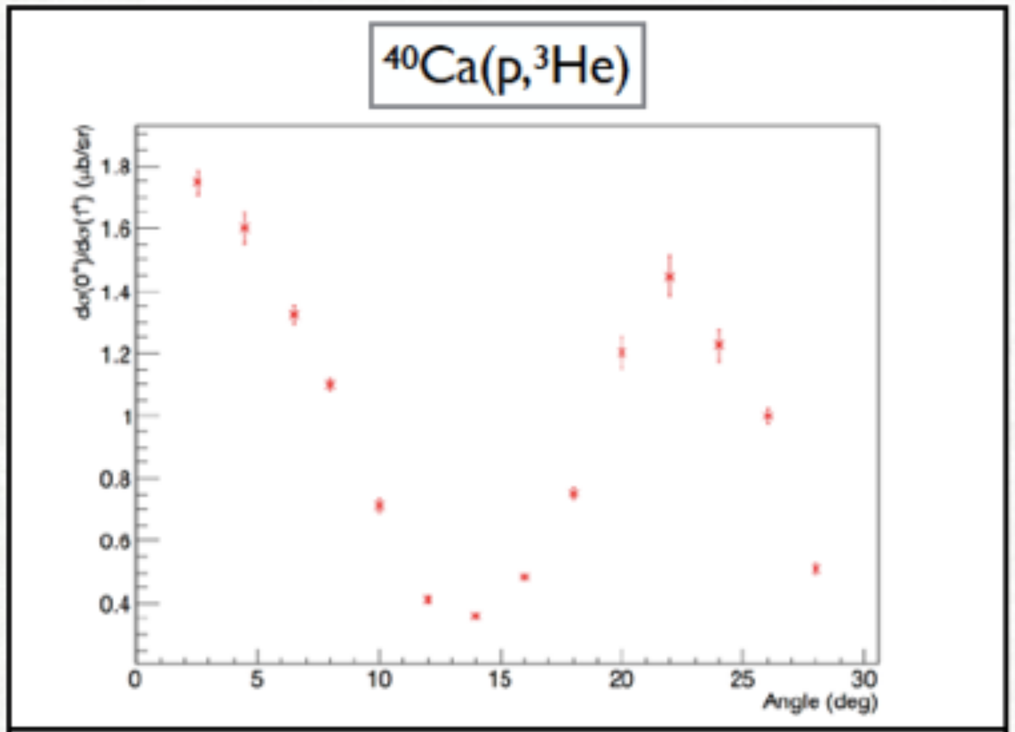
$^{40}Ca(p,d)^{39}Ca$

$^{28}Si(p,t)^{26}Si$

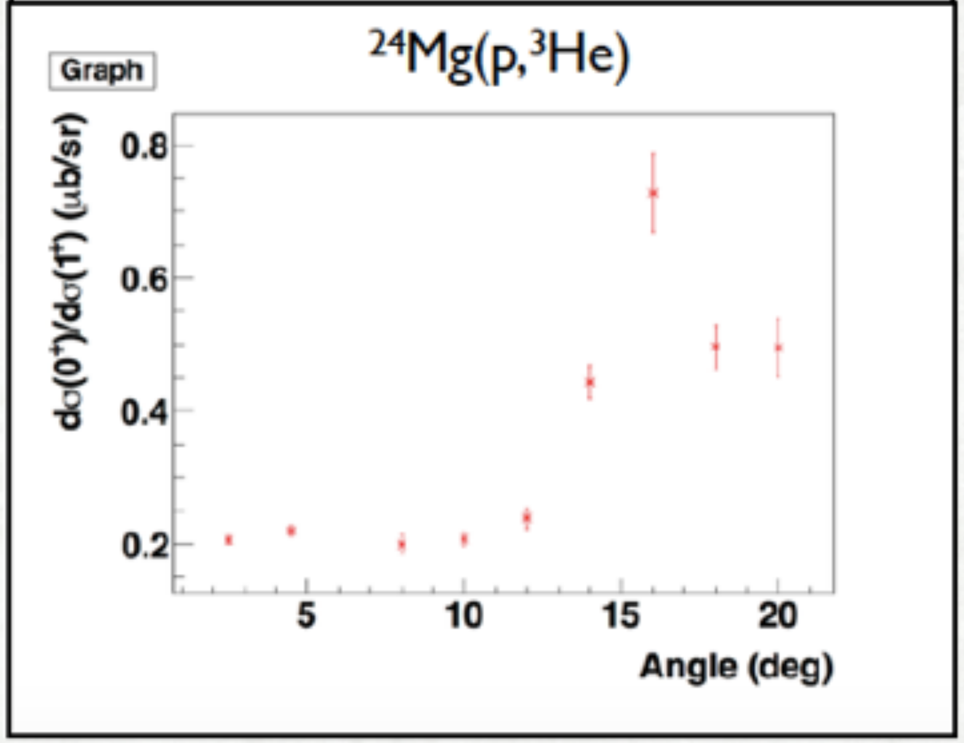
$^{24}Mg(^{3}He,d)^{25}Al$



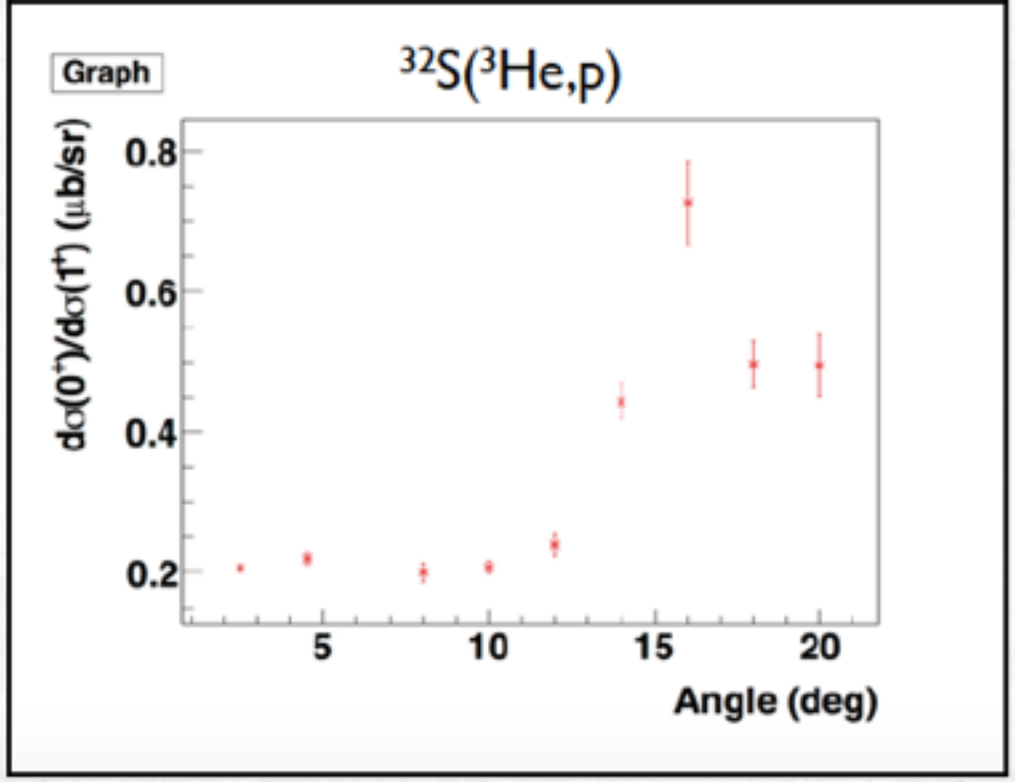
^{24}Mg(^{3}He,p)



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



^{24}Mg(p,^{3}He)



^{32}S(^{3}He,p)