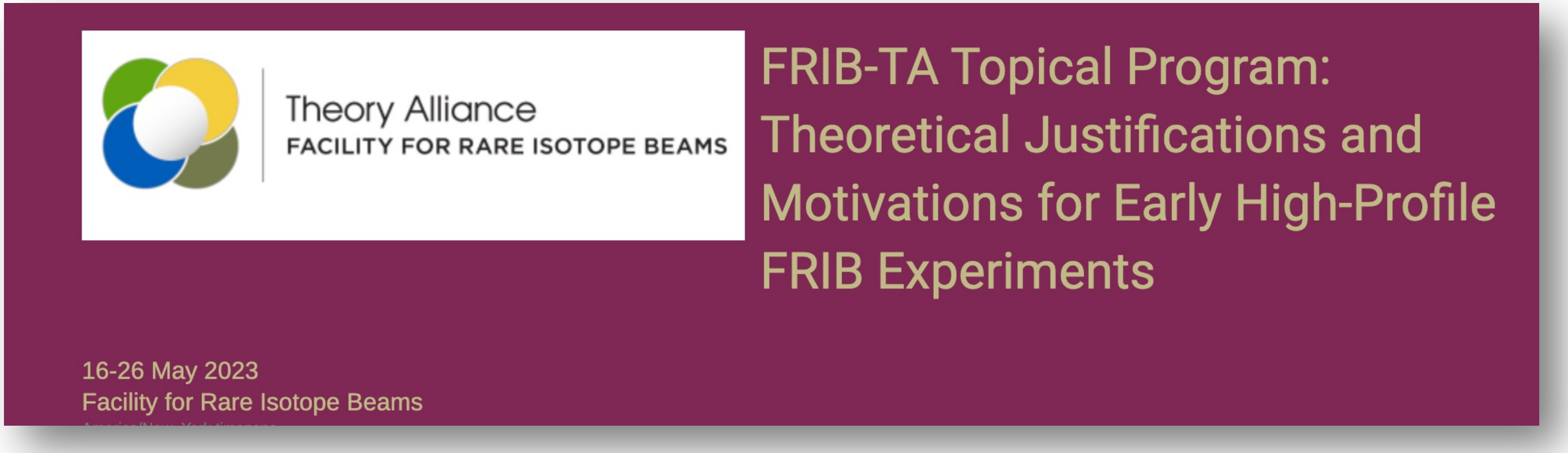
Pairing in Exotic Nuclei

Augusto O. Macchiavelli

Physics Division, Oak Ridge National Laboratory



Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

FRIB-TA Topical Program: Theoretical Justifications and Motivations for Early High-Profile FRIB Experiments

16-26 May 2023
Facility for Rare Isotope Beams

OAK RIDGE NATIONAL LABORATORY
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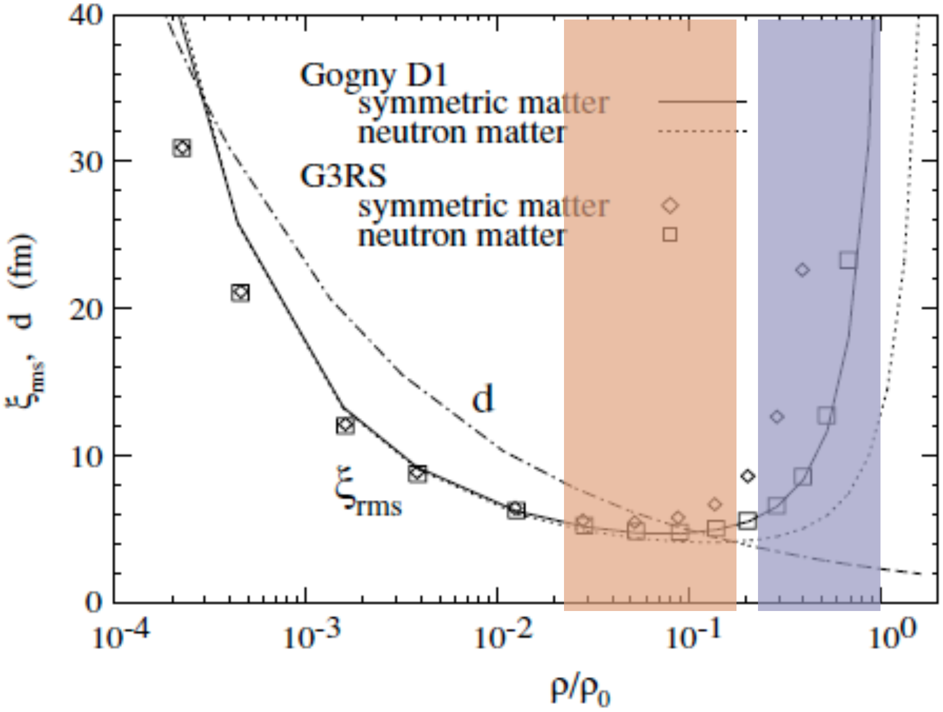
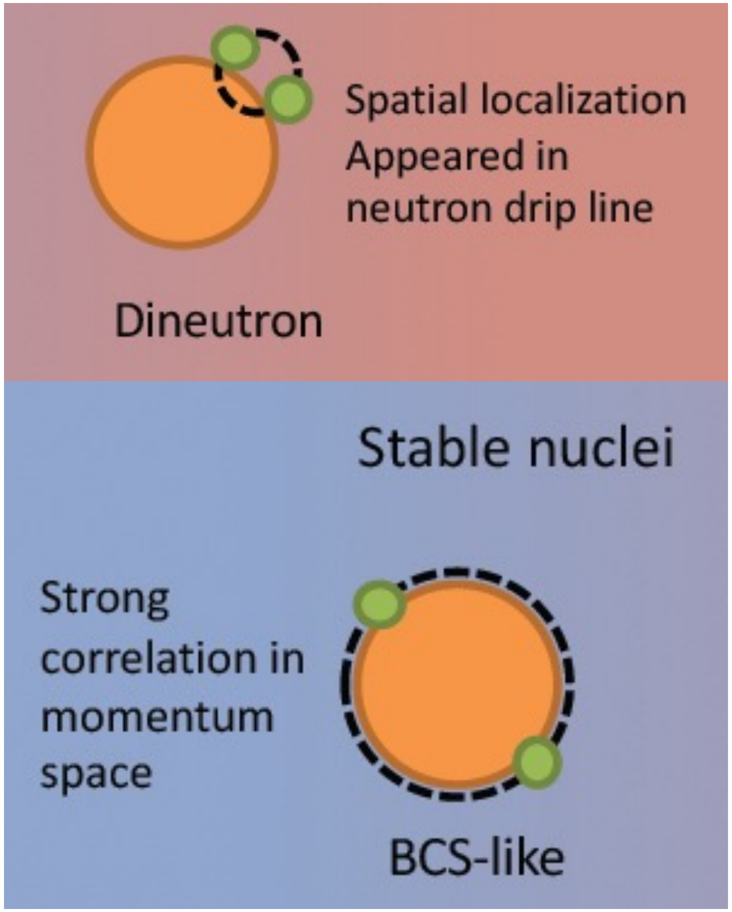
Motivation

The evolution of pairing correlations in exotic nuclei is a topic of great interest in nuclear structure, in particular pairing in neutron-rich isotopes and the role of weak binding.



Matsuo *et al*. PRC 73 (2006) 044309
Pillet *et al*. PRC 76 (2007) 024310

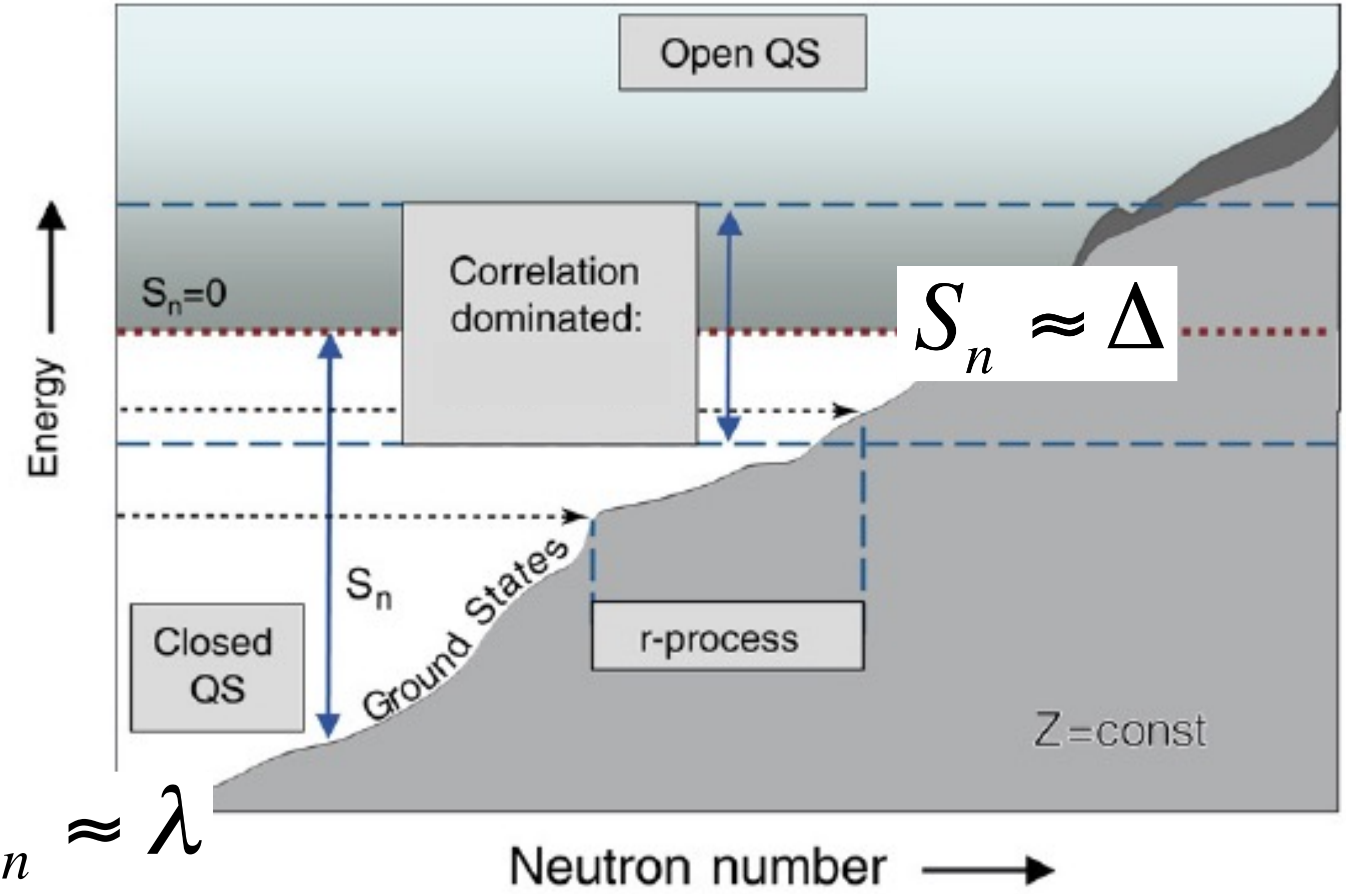


d **Separation**

ζ_{rms} **Correlation Length**

Key observable
→ (t,p) two-neutron transfer reactions

J. Dobaczewski et al. / Progress in Particle and Nuclear Physics 59 (2007) 432–445

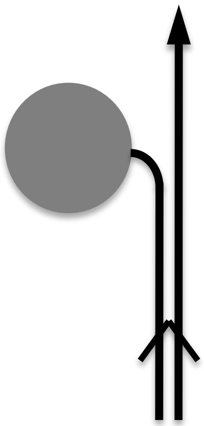


$S_n \approx \Delta$

$S_n \approx \lambda$

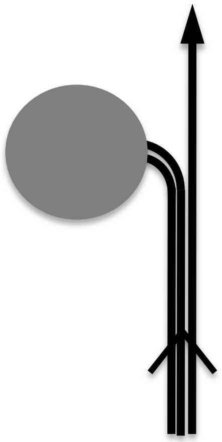
$$S_n \approx \Delta + \lambda$$

Direct Reactions



$< A+1 | a^{+} | A >$

Spectroscopic *(u, v)* Factors



$< A+2 | a^{+} a^{+} | A >$

Constructive interference

Two particle transfer reactions like (t,p) or (p,t), where 2 nucleons are deposited or picked up at the same point in space provide an specific tool to probe the amplitude of this collective motion.

The transition operators <f|a⁺a⁺|i>, <f|aa|i> are the analogous to the transition probabilities BE2's on the quadrupole case.

R.A. Broglia, O. Hansen and C. Riedel, Adv. Nucl. Phys. Vol 6 (1973) 287

D. M. Brink and R.A. Broglia, Nuclear Superfluidity, Cambridge Monographs.

A brief reminder

In superfluid nuclei, where the BCS theory provides a good representation of the ground states, the cross-section for two-neutron transfers from the nucleus A_0 to $A_0 \pm 2$ is given approximately by

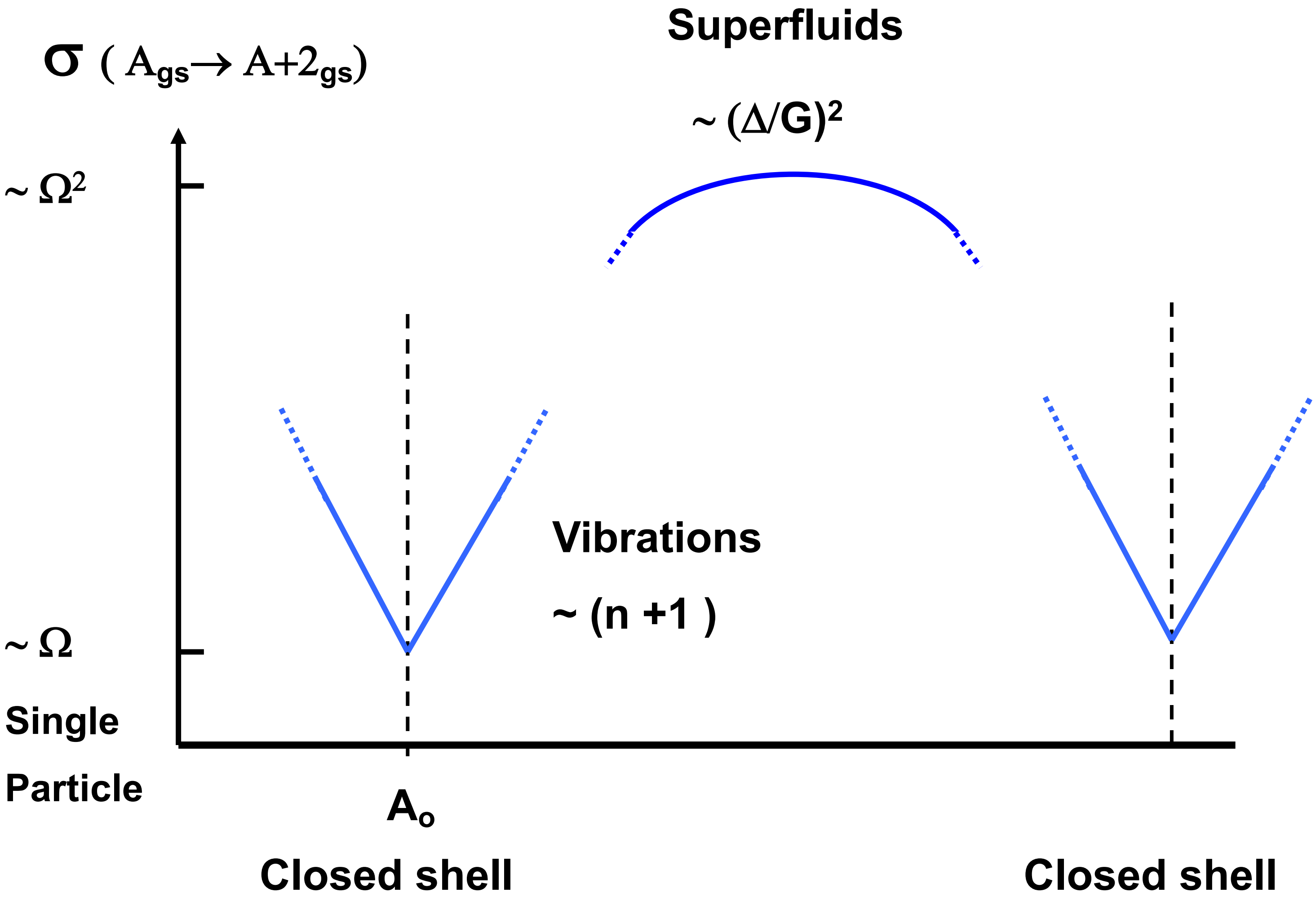
$$d\sigma/d\Omega \approx |\sum_j U_j V_j|^2 (d\sigma/d\Omega)_{2sp} = (\frac{\Delta}{G})^2 (d\sigma/d\Omega)_{2sp}$$

Collective enhancement over *sp* cross-section due to coherent contributions of correlated *nn* pairs

where U_j and V_j are the probability amplitudes for the orbit j to be empty and occupied respectively, Δ is the pairing gap and G is the strength of the pairing interaction.

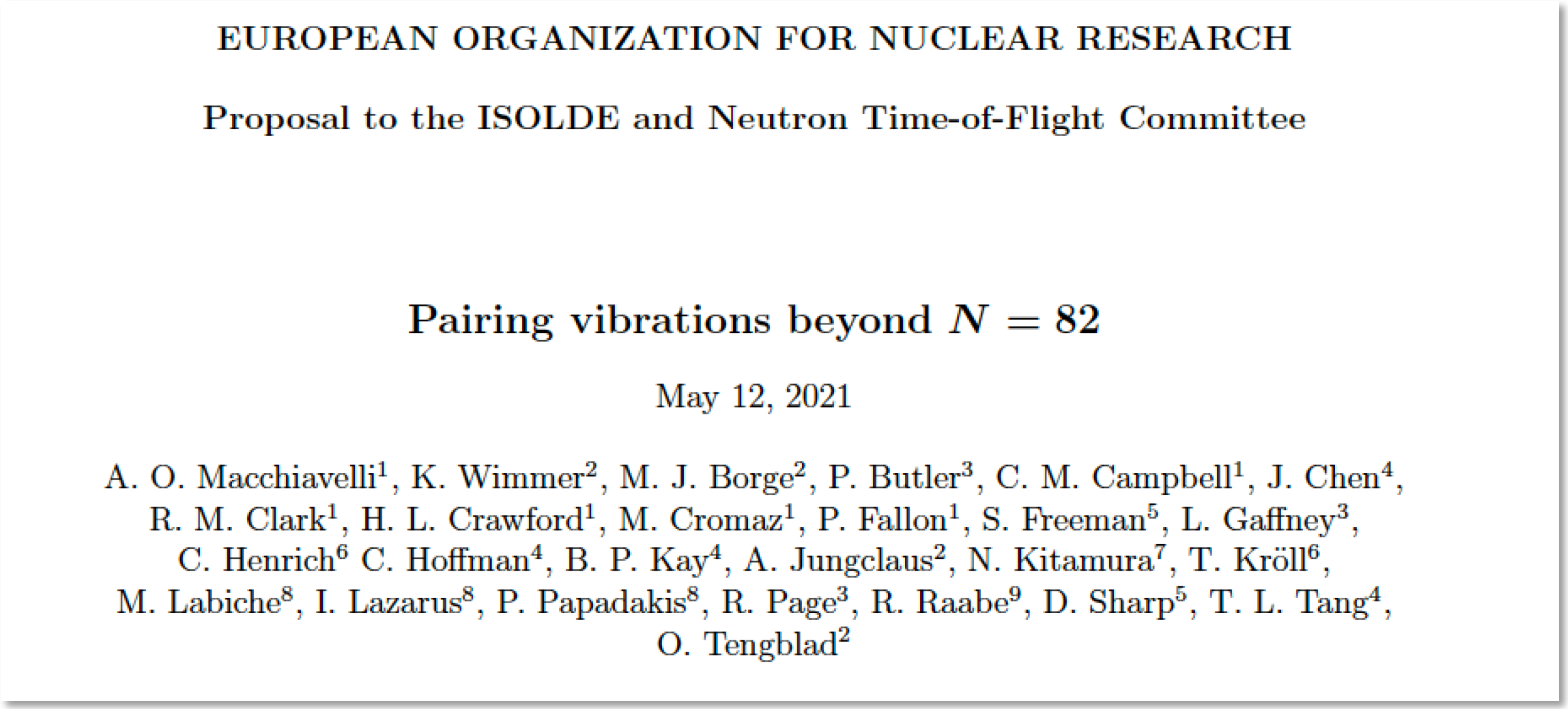
With typical values of $\sim 12/\sqrt{A}$ MeV and $G \sim 20/A$ MeV, the enhancement factor is $\sim A/4$, increasing with A as expected from the larger number of available orbits for the pairs to scatter into

S. Yoshida, Nucl. Phys. 33 (1962) 685.



Systematic relative measurements and within a given nucleus.

An example:



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Pairing vibrations beyond $N = 82$

May 12, 2021

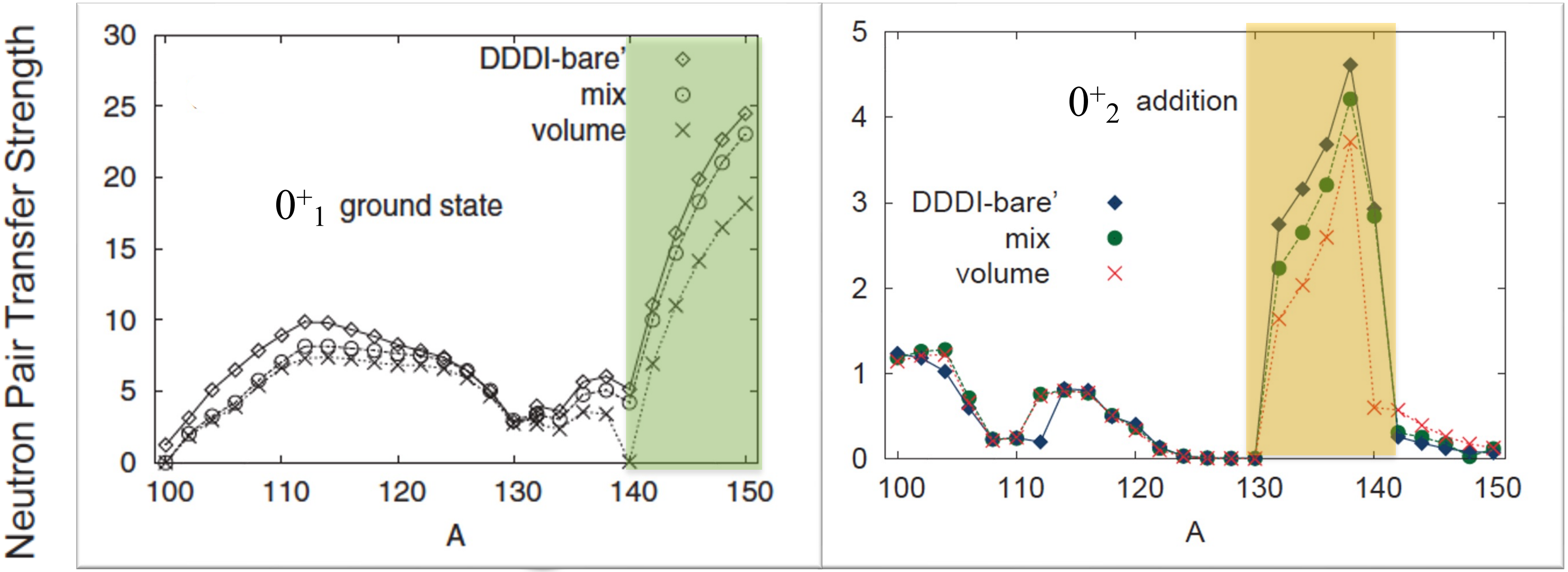
A. O. Macchiavelli[1], K. Wimmer[2], M. J. Borge[2], P. Butler[3], C. M. Campbell[1], J. Chen[4],
R. M. Clark[1], H. L. Crawford[1], M. Cromaz[1], P. Fallon[1], S. Freeman[5], L. Gaffney[3],
C. Henrich[6] C. Hoffman[4], B. P. Kay[4], A. Jungclaus[2], N. Kitamura[7], T. Kröll[6],
M. Labiche[8], I. Lazarus[8], P. Papadakis[8], R. Page[3], R. Raabe[9], D. Sharp[5], T. L. Tang[4],
O. Tengblad[2]

Motivation

PHYSICAL REVIEW C **84**, 044317 (2011)

Anomalous pairing vibration in neutron-rich Sn isotopes beyond the $N = 82$ magic number

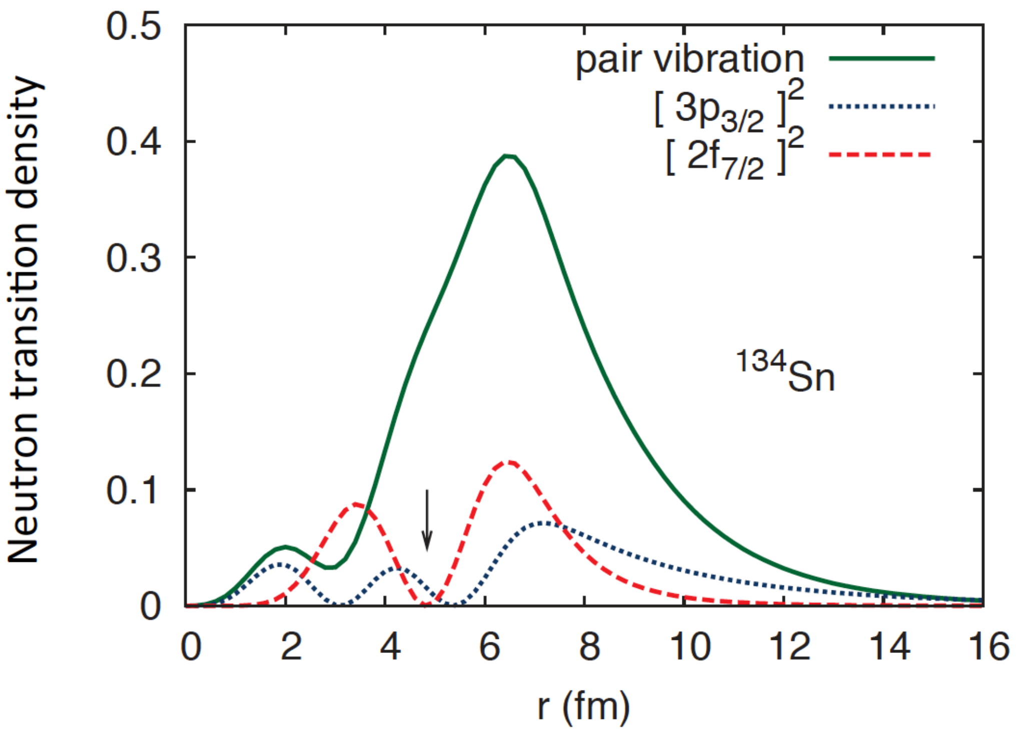
Hirotaka Shimoyama and Masayuki Matsuo



Motivation

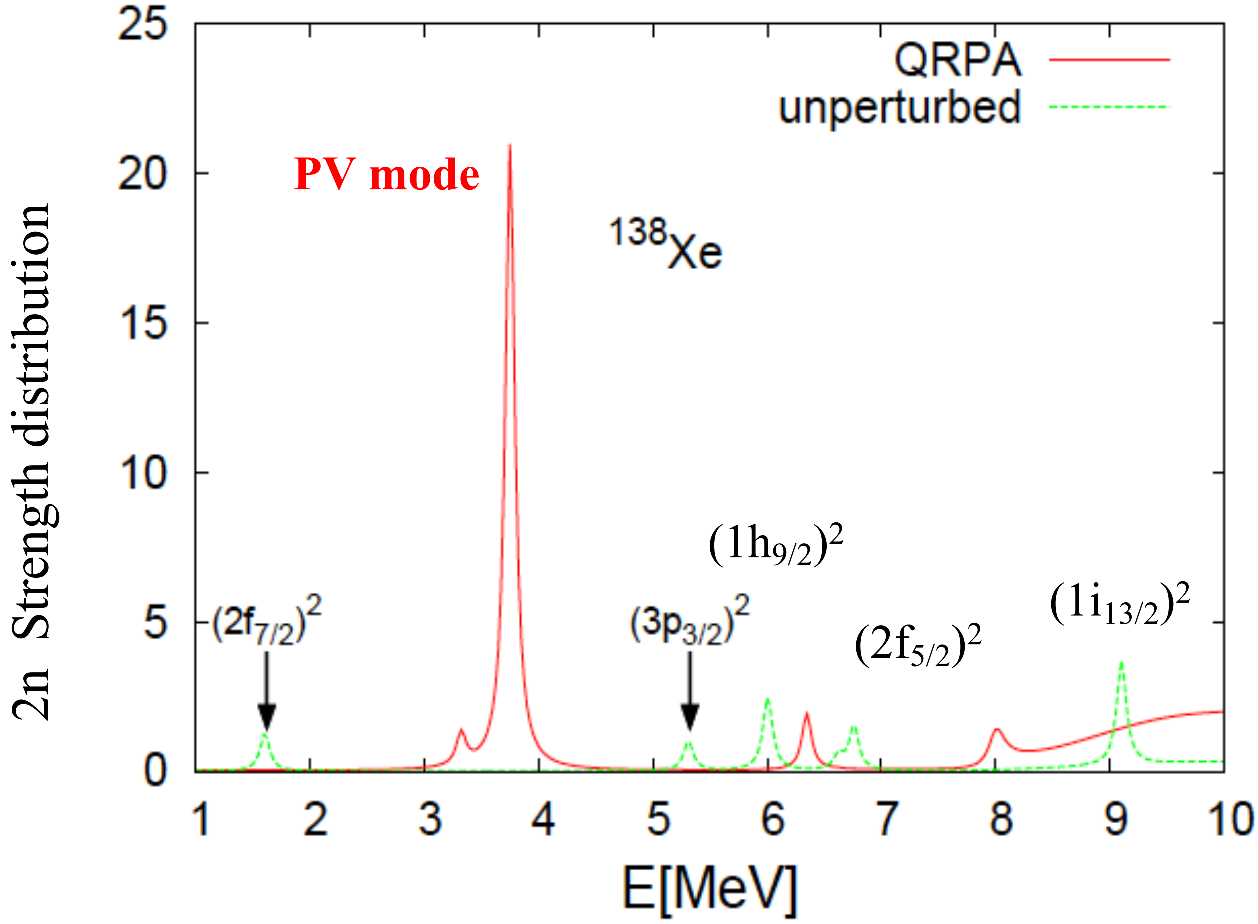
Currently it is not possible to study Sn nuclei with A > 140. However, the region 132 < A < 140 where strong transitions to an excited pairing vibrational 0^+_2 state are predicted is within reach of present accelerator facilities.

The first excited 0^+ state can be regarded as a pairing vibrational mode built on the weakly bound $p_{3/2}$ (and $p_{1/2}$ orbits), which show a rather long tail in the transition density extending beyond the nuclear surface, resulting in a large strength, comparable to that populating the ground state.



Motivation

Production of Sn beams challenging, but similar effects are expected in the PV mode in ^{138}Xe
[S. Tamaki. Master thesis, Niigata University, 2016]



Motivation

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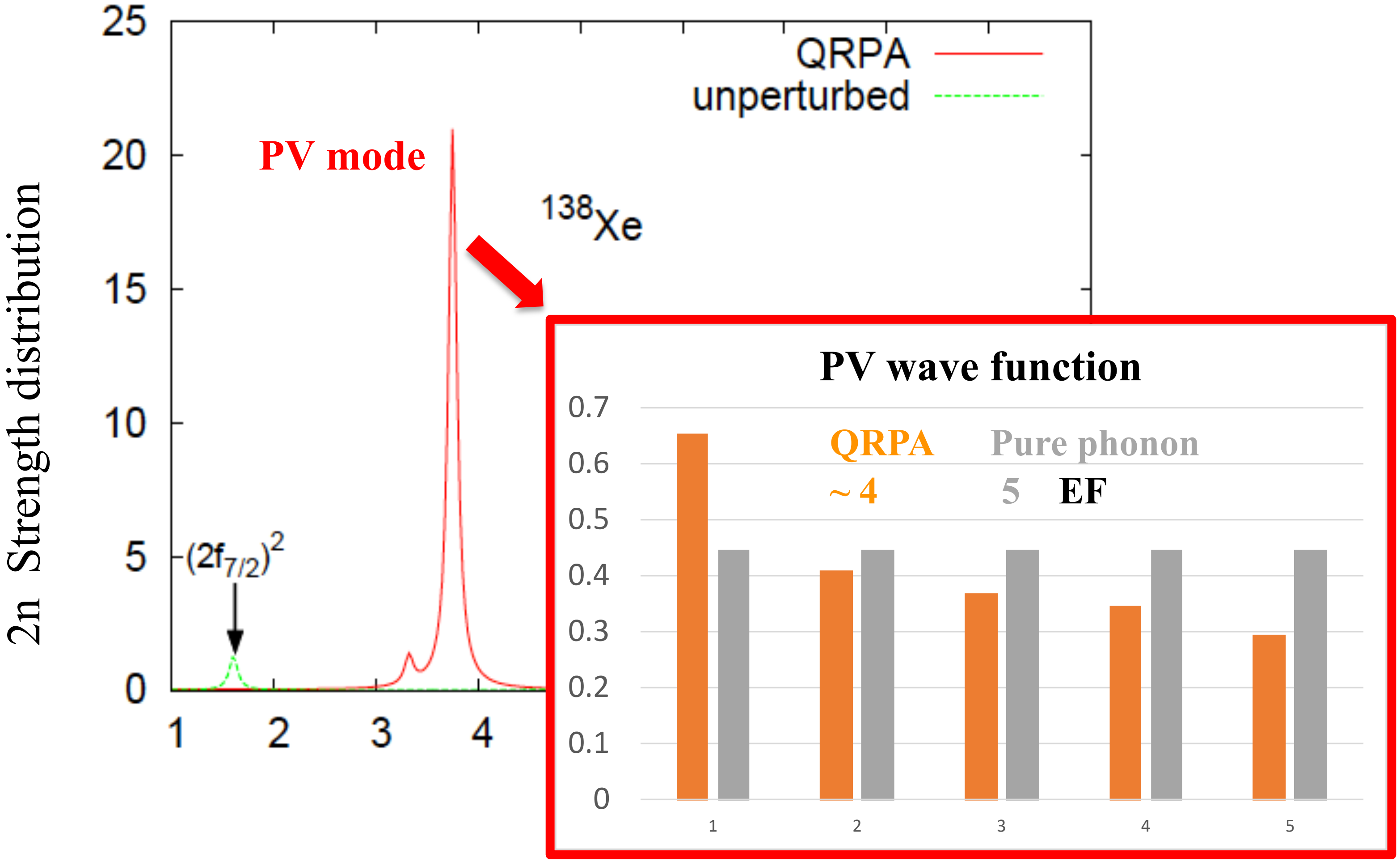
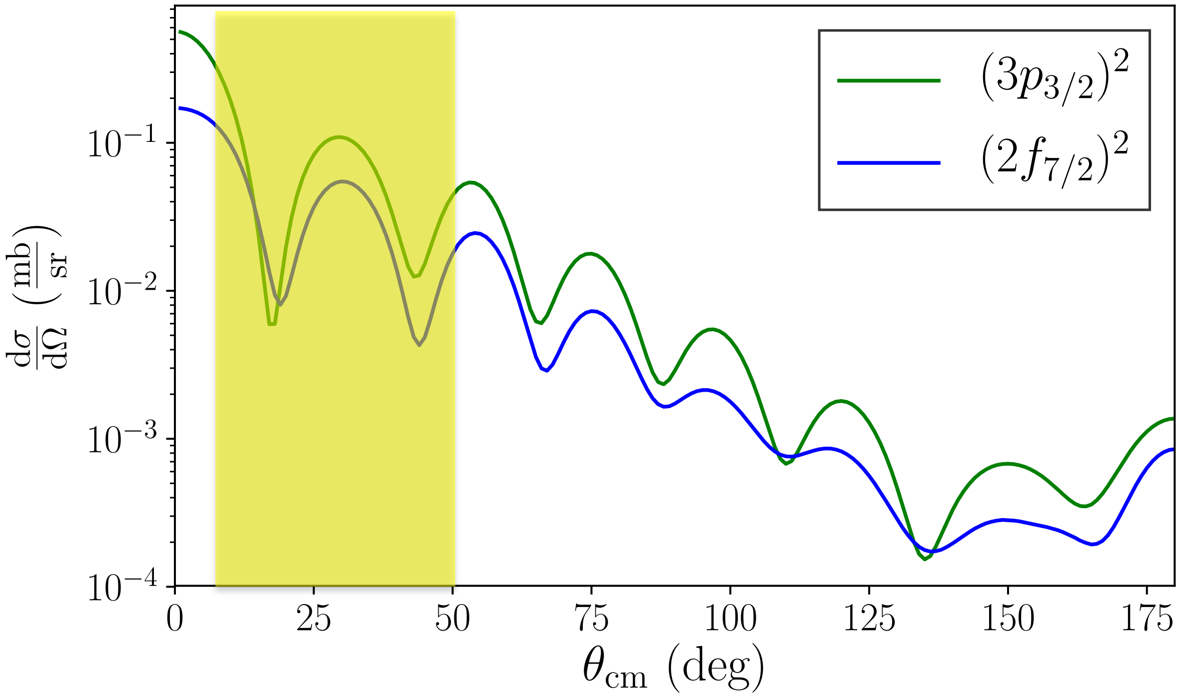


ISS Experiment

^{138}Xe(t,p)^{140}Xe at 7 AMeV focus on L=0 transfers to PV → forward CM angles



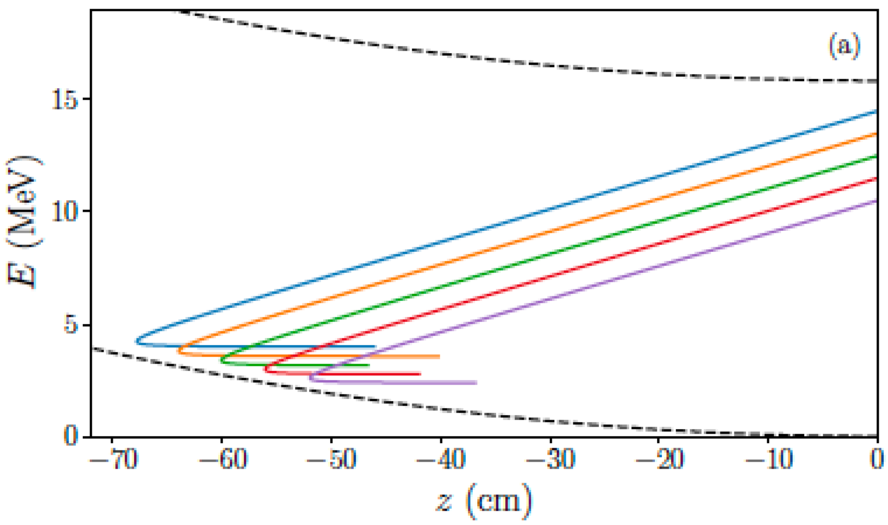
A typical DWBA calculation for j^2 TNA's (FRESCO)

ISS Experiment: Kinematics considerations

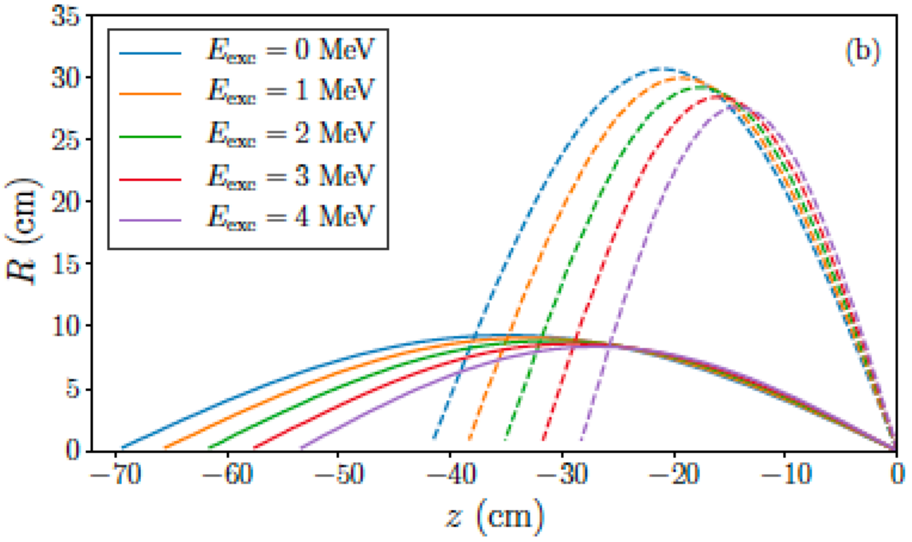
Reaction kinematics for a ^{138}Xe beam at 7 AMeV impinging on the tritium-loaded titanium target. **ISS operating at 2.5 T.**

The reaction kinematics for different excitation energies in ^{140}Xe are indicated by different colors.

Energy of recoiling protons as a function of the position on the ISS silicon array.



Proton orbits for CM scattering angles 10^0(solid lines) and 35^0(dashed lines).

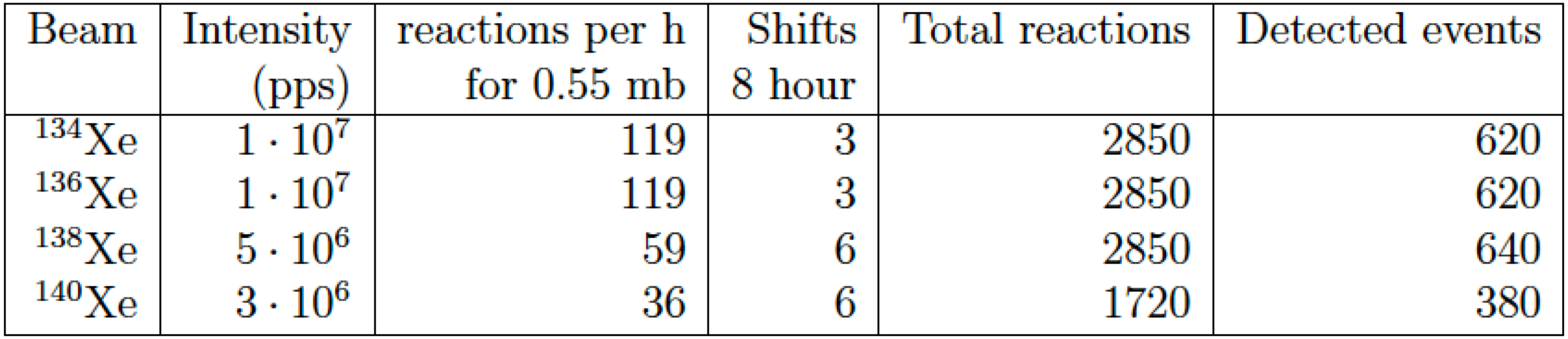


ISS Experiment: Estimated Rates

Count rates estimates for the Xe(t,p) reactions proposed assuming a cross section of 0.55 mb for the pairing vibrational mode (PV).

This is a conservative estimate obtained from the pure $(3p_{3/2})^2$ single-particle configuration
Total counts include the overall efficiency of ISS, in the CM (LAB) angular range $10\text{-}50^0$ $(160\text{-}100^0)$.

Tritium loaded titanium foil (Ti thickness 0.5 mg/cm^2, atomic ratio t/Ti ~ 1 ~ 40$\mu g/cm^2$)

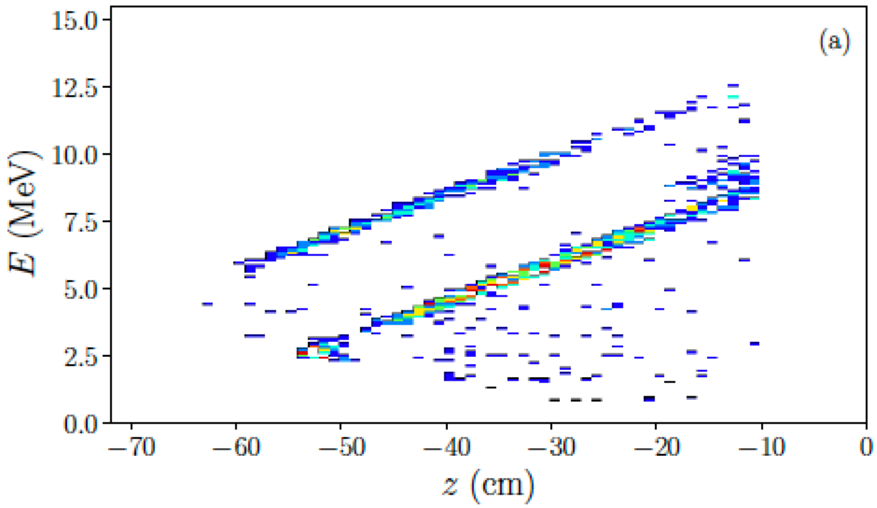


Beam	Intensity (pps)	reactions per h for 0.55 mb	Shifts 8 hour	Total reactions	Detected events
^{134}Xe	$1 \cdot 10^7$	119	3	2850	620
^{136}Xe	$1 \cdot 10^7$	119	3	2850	620
^{138}Xe	$5 \cdot 10^6$	59	6	2850	640
^{140}Xe	$3 \cdot 10^6$	36	6	1720	380

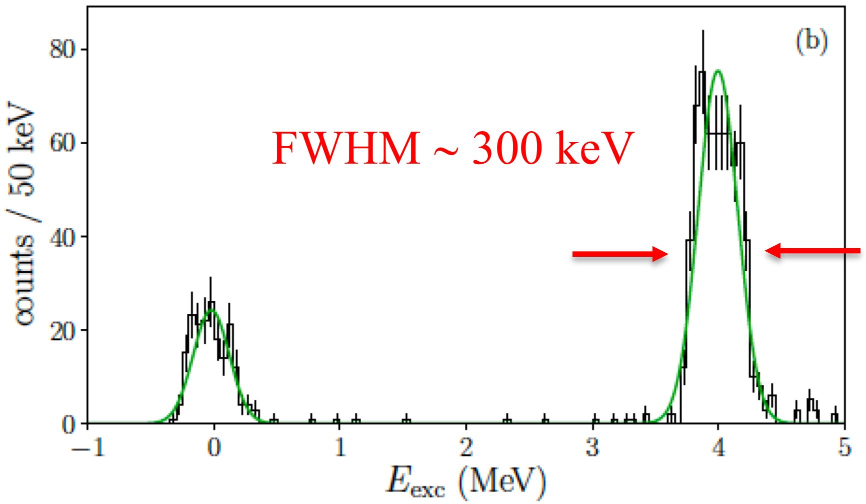
ISS Experiment: Realistic simulations

Simulation for the ^{138}Xe(t, p) reaction for the population of two states at 0 and 4 MeV excitation energy in ^{140}Xe

Proton kinetic energy vs. the distance from the target. The detectors will be placed covering the solid angle from -10 cm



Excitation energy of ^{140}Xe reconstructed from the measured proton energies and positions.

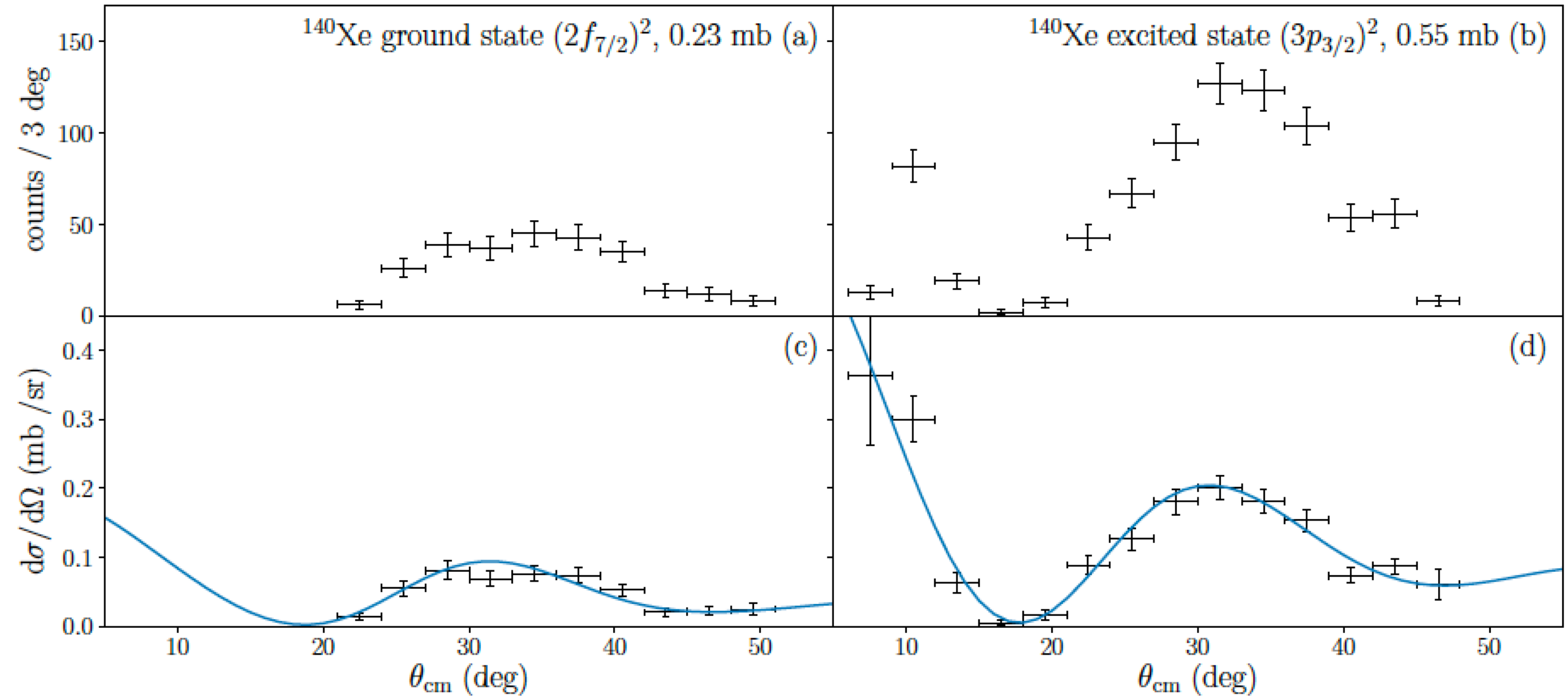


FWHM ~ 300 keV

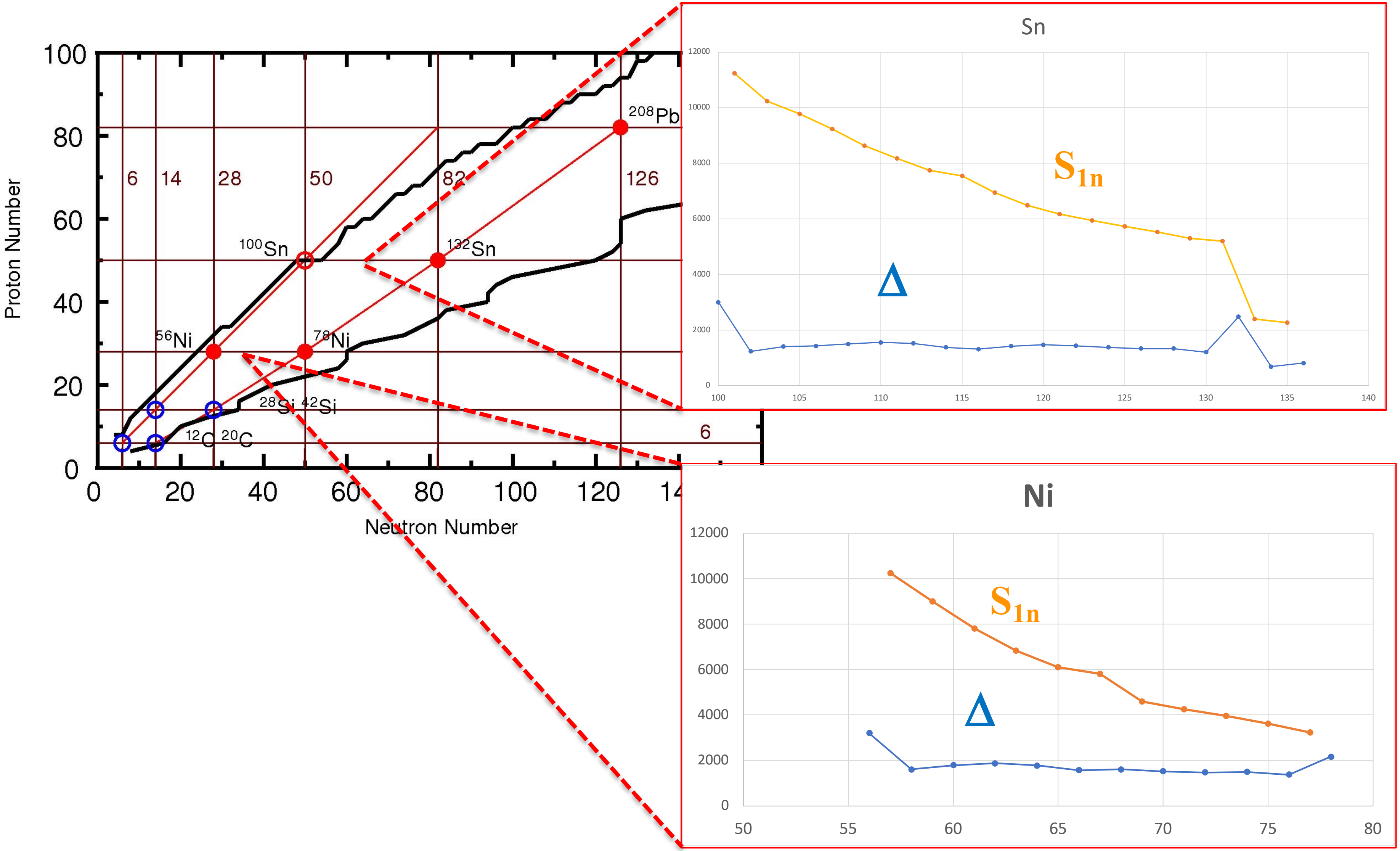
ISS Experiment: Realistic simulations

Analysis of simulated data for the ^{138}Xe(t,p) reaction to two states with $(2f_{7/2})^2$ and $(3p_{3/2})^2$ configurations.

The level of statistics is sufficient to identify the characteristic shape of the differential cross section of 0^+ states.

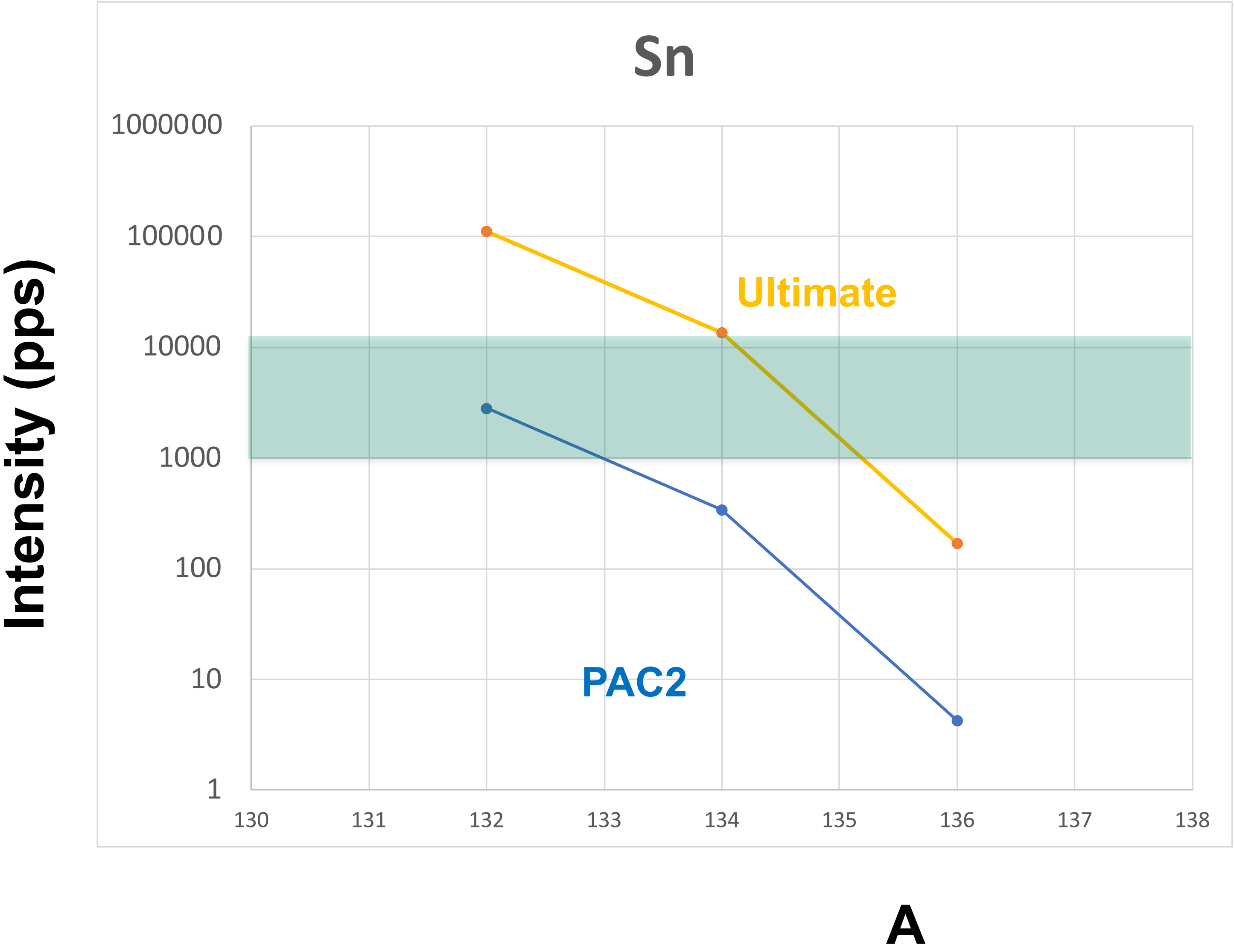


FRIB Experiments

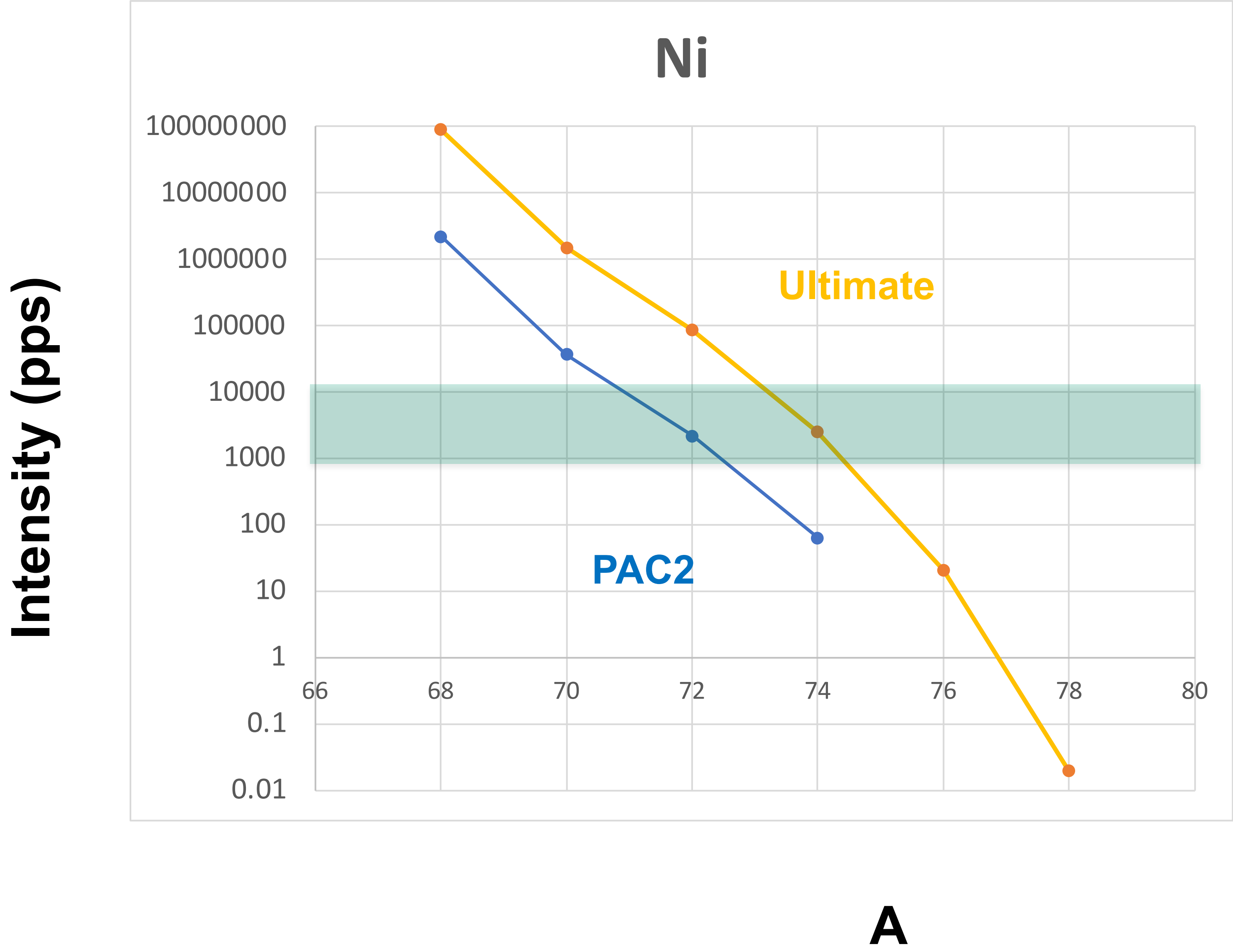


A

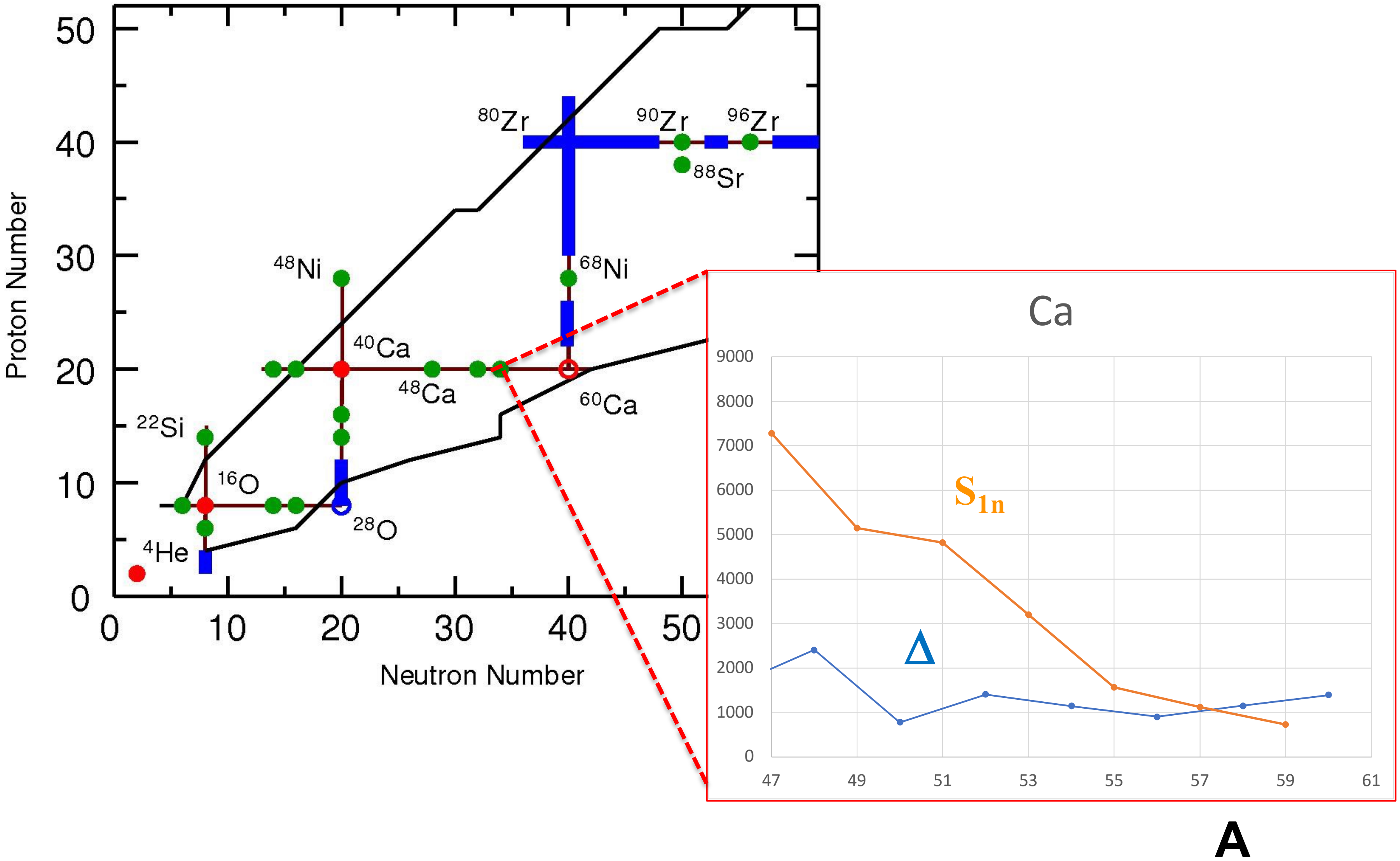
FRIB Experiments



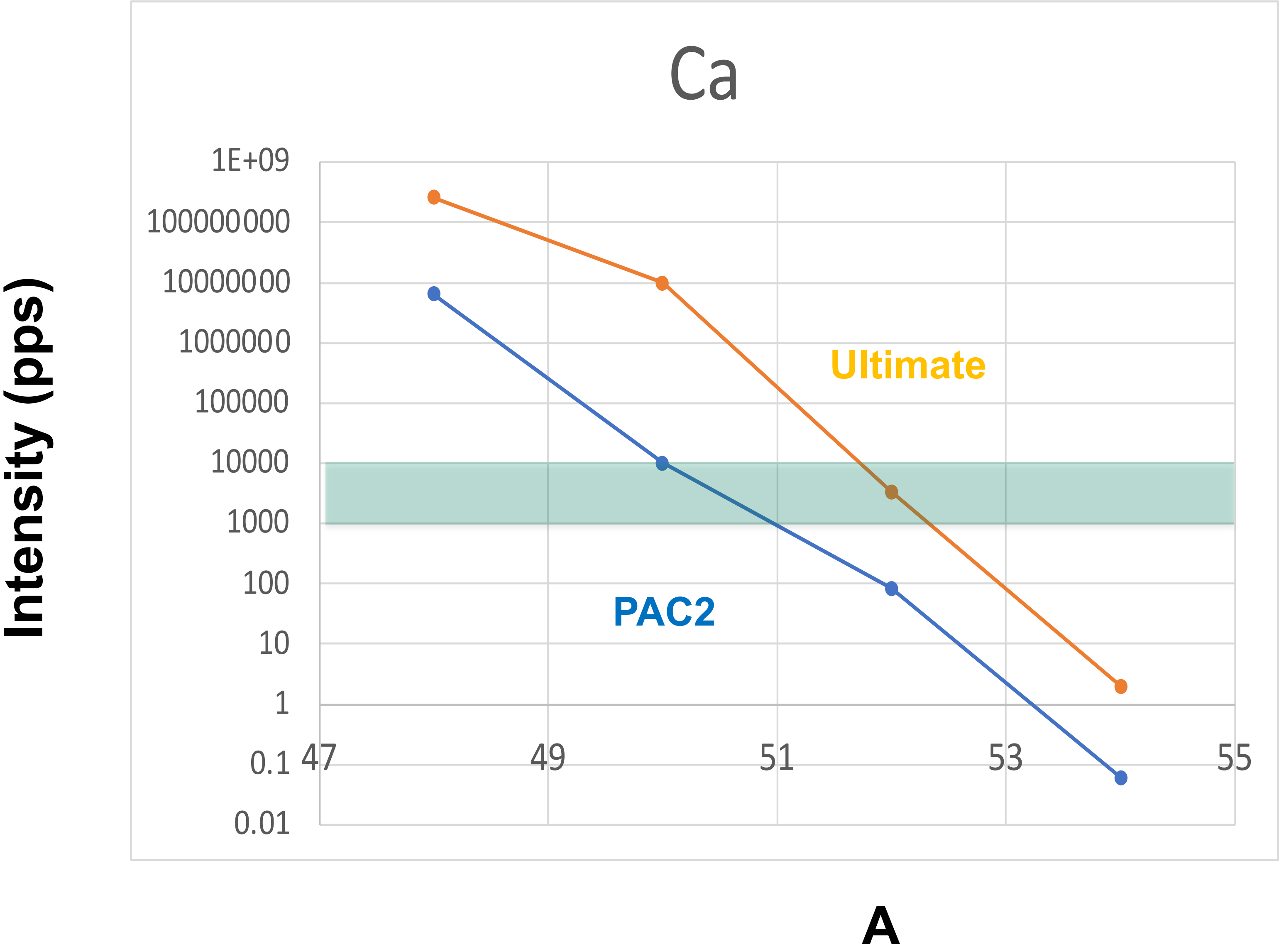
FRIB Experiments



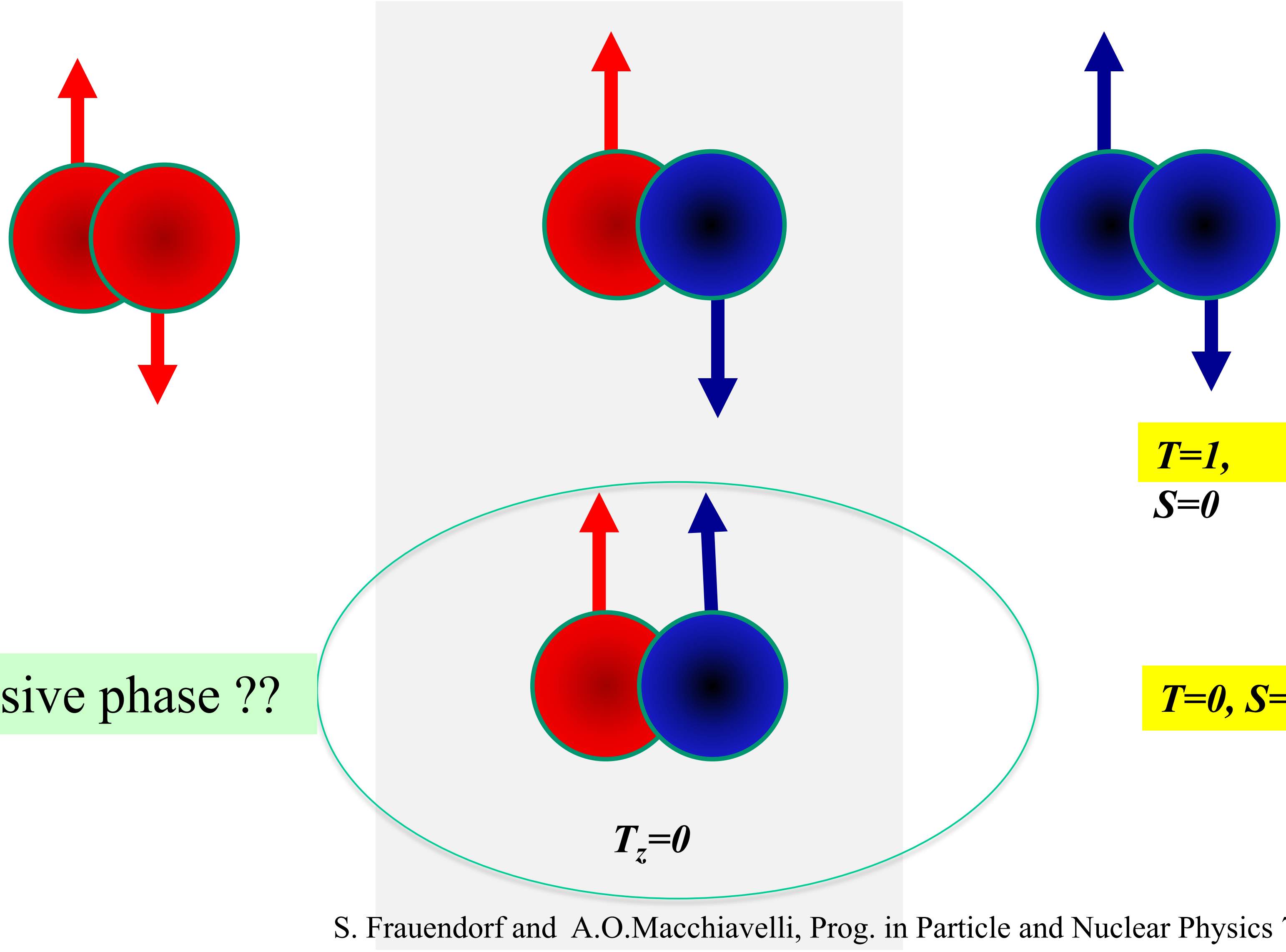
FRIB Experiments



FRIB Experiments



Neutron-Proton Pairing



$T=1$, $S=0$

$T=0$, $S=1$

Elusive phase ??

$T_z=0$

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

N=Z nuclei, unique systems to study *np* correlations

- As you move out of N=Z, T=1 *nn* and *pp* pairs will start to dominate. T=0 excited states.

Role of isoscalar (T=0) and isovector (T=1) pairing

- Large spatial overlap of *n* and *p*
- Pairing vibrations (normal system)
- Pairing rotations (superfluid system)

Does isoscalar pairing give rise to collective modes?

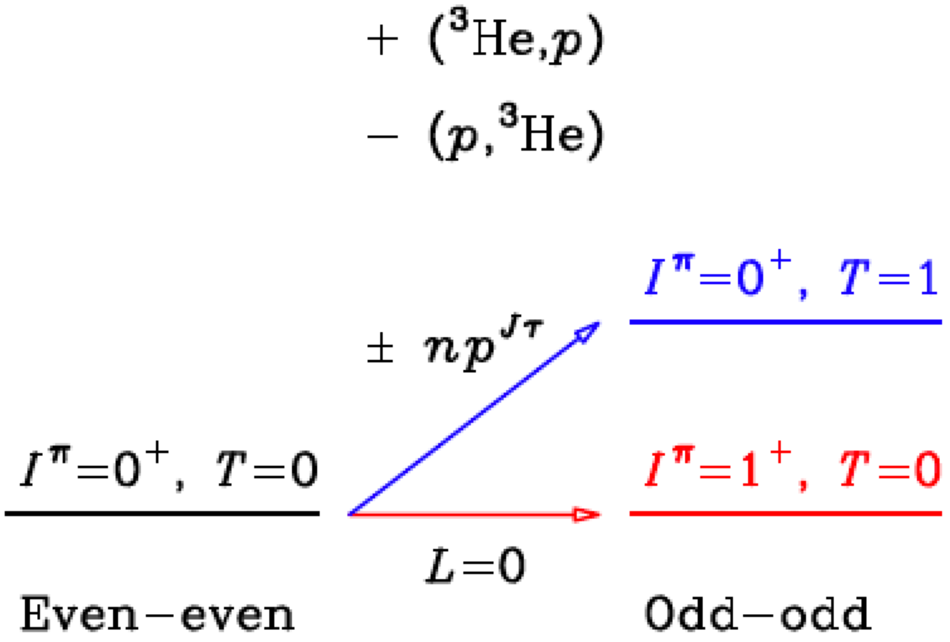
Possible signals

- Binding energy differences
- Low-lying states of odd-odd self-conjugate nuclei
- Rotational properties: moments of inertia, alignments
- Alpha decay, Beta decay, Gamow-Teller
- Radii, Electromagnetic properties
- **Direct reactions** ←

Direct reactions

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

(^{3}He,p) and (p,^{3}He) Transfer Reactions



$+\ (^3\text{He},p)$

$-\ (p,{}^3\text{He})$

$I^\pi=0^+,\ T=1$

$\pm\ np^{J\tau}$

$I^\pi=0^+,\ T=0$

$I^\pi=1^+,\ T=0$

$L=0$

Even−even

Odd−odd

Measure the *np* transfer cross section to T=1 and T=0 states

Both absolute σ(T=0) and σ(T=1) and relative σ(T=0) / σ(T=1) tell us about the character and strength of the correlations

Neutron-proton pairing in the N=Z radioactive *fp*-shell nuclei ^{56}Ni and ^{52}Fe probed by pair transfer

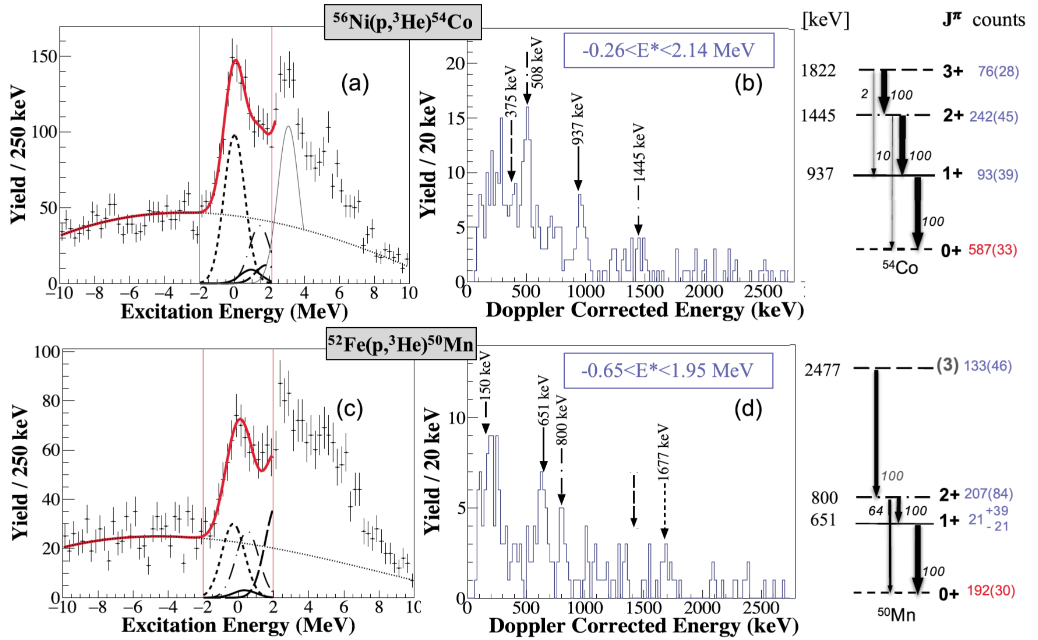
B. LeCrom, M. Assié, et al.
Physics Letters B 829 (2022) 137057

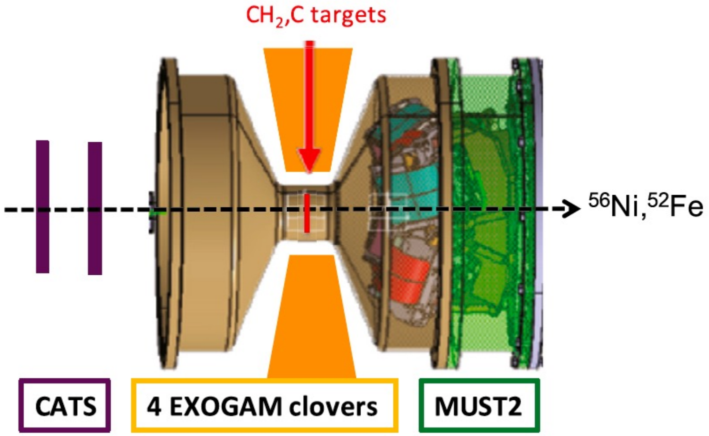
GANIL / LISE

Beams at 30 MeV/A
~ 10^5 pps

B. Le Crom, M. Assié, Y. Blumenfeld et al.

Physics Letters B 829 (2022) 137057





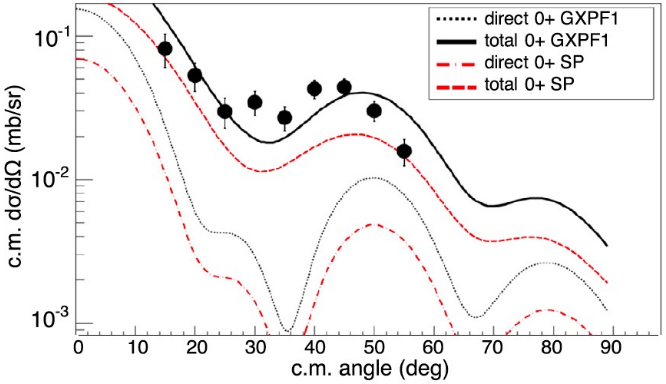


Fig. 3. Angular distribution for ^{56}Ni(p,^{3}He)^{54}Co ground state obtained in this experiment (full dots) compared with second-order DWBA calculations with GXPF1 in black (dotted line for direct transfer and full line for direct+sequential transfer) and with SP configuration in red. The error bars correspond to the statistical ones.

How to assess collective *np* pairing effects ?

Quadrupole collectivity –> $B(E2)$ in Weisskopf units

V.F. Weisskopf, Phys. Rev. 83 (1951) 1073.

Two-particle units in the analysis of two-neutron transfer reactions

R.A. Broglia, C. Riedel and T. Udagawa, Nuclear Physics A184 (1972) 23.

The *np* Weisskopf units

For the case at hand, we look at the experimental ratio in terms of two-particle units:

$$\frac{\mathcal{R}_{01}}{\mathcal{R}_{01,2sp}} = \frac{d\sigma^{01}/d\sigma^{01}_{2sp}}{d\sigma^{10}/d\sigma^{10}_{2sp}}$$

For a single *np* pair transfer, the cross-section factorizes in a structure part, *S*, and a DWBA reaction part, usually calculated with codes such as DWUCK or FRESCO

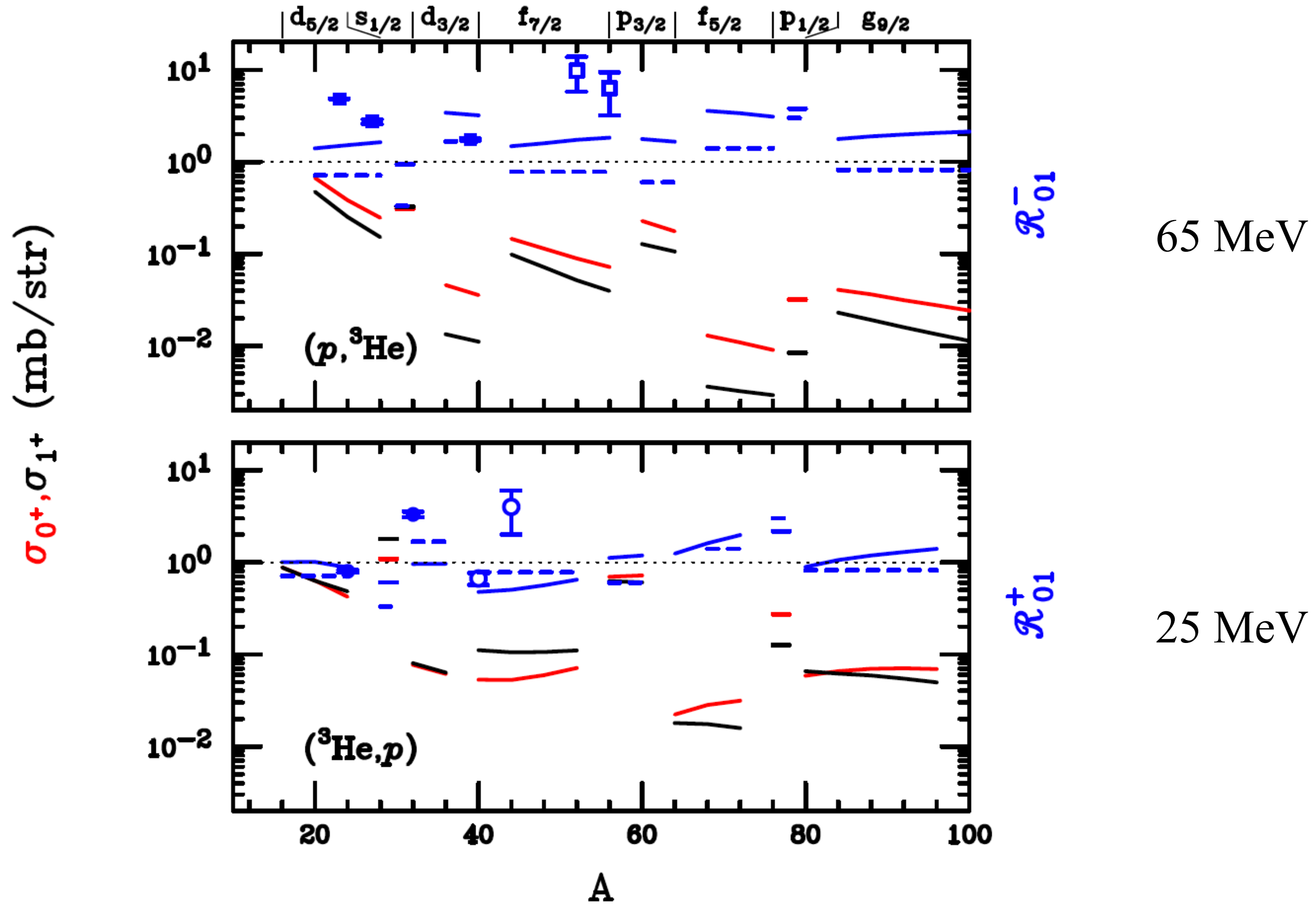
$$d\sigma/d\Omega_{2sp} = \mathcal{S}\sigma_{DW}$$

Being interested only in $L = 0$ transfers, we consider the limit $\theta \to 0$ for the DW cross-sections:

$$\mathcal{R}^{\pm}_{01,2sp} = \frac{\mathcal{S}^{\pm}(0^{+})}{\mathcal{S}^{\pm}(1^{+})} \frac{\sigma^{n\ell j,01}_{DW}}{\sigma^{n\ell j,10}_{DW}}$$

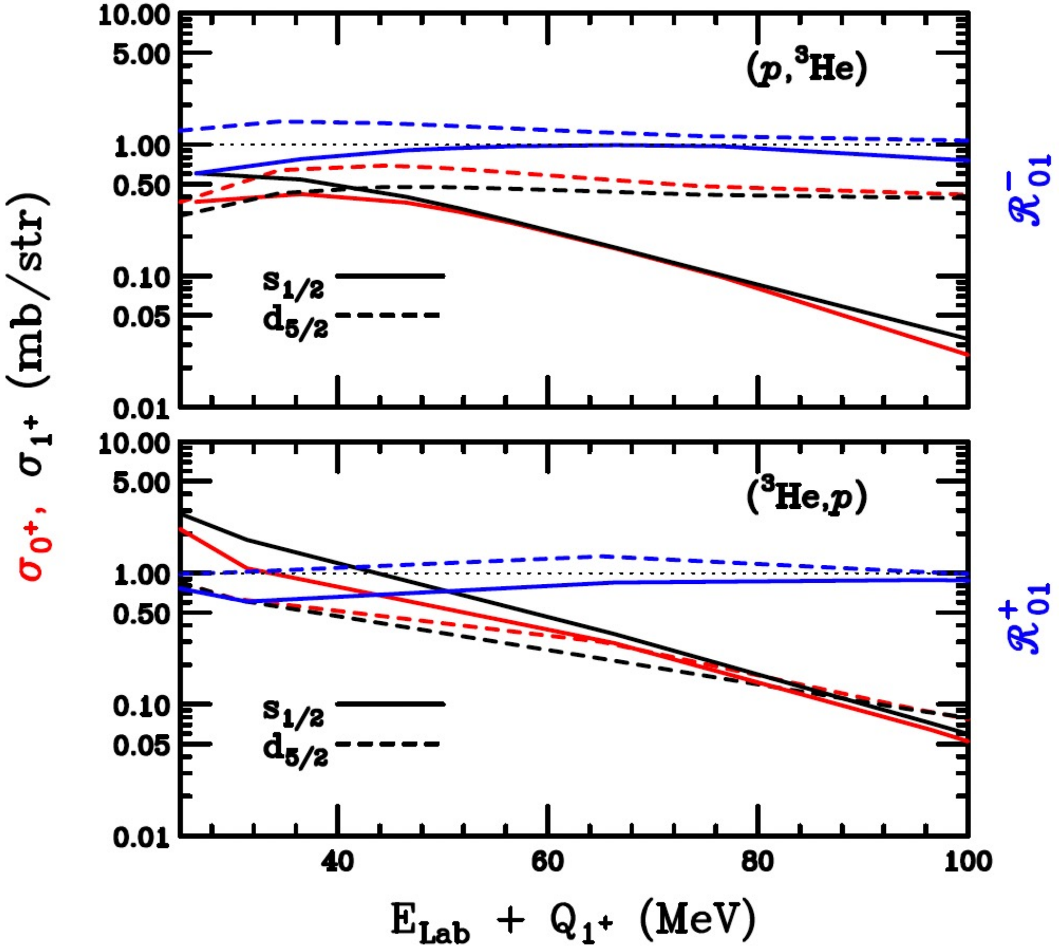
J.A.Lay, Y. Ayyad and A. O. Macchiavelli, Phys. Lett. B824 (2022) 136789

The *np* Weisskopf units



Second-order DWBA calculations with the code FRESCO, with conditions relevant to the filling of the different *(n, l, j)* orbits at the $N=Z$ line, from ^{16}O to ^{100}Sn.

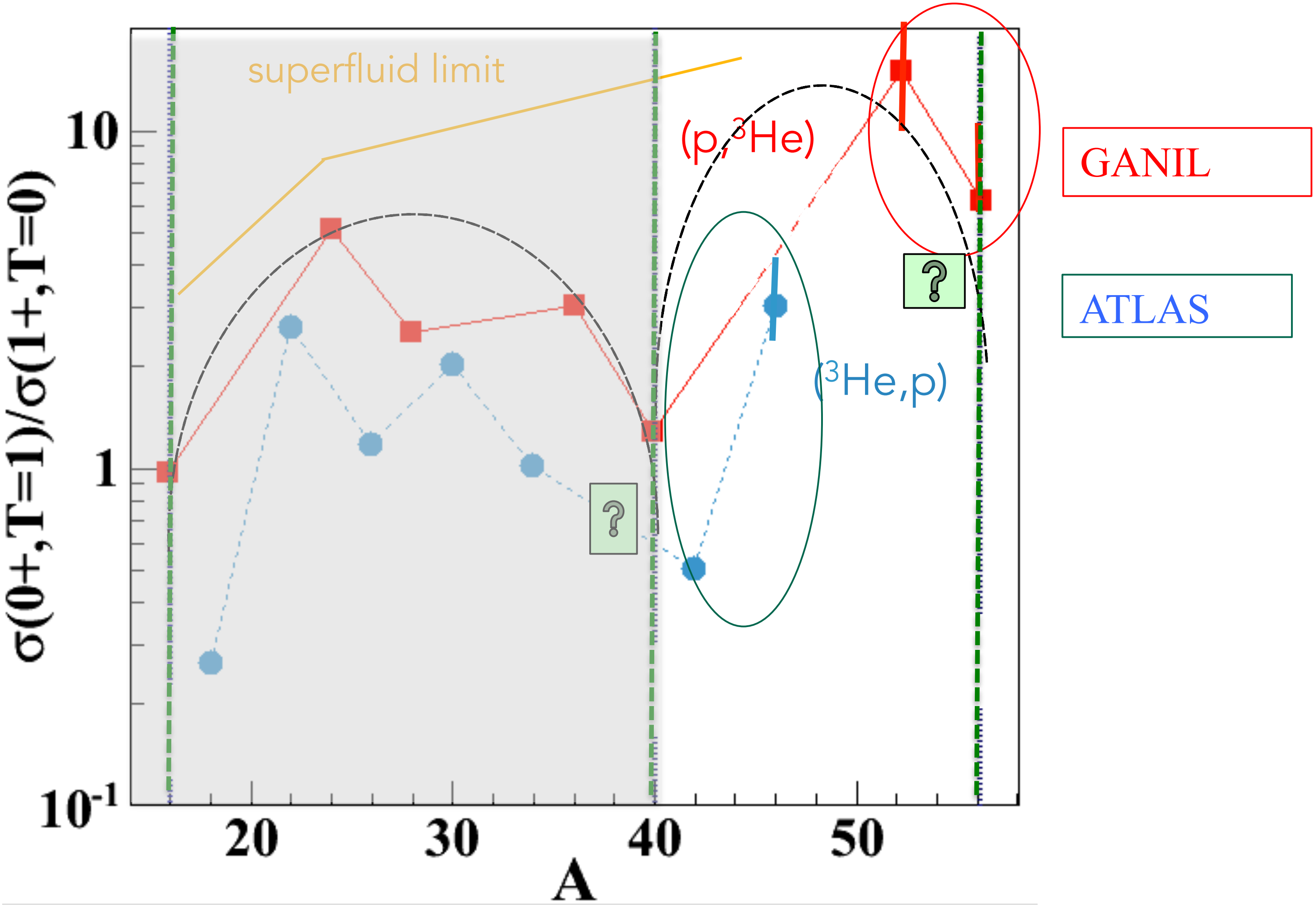
Energy dependence



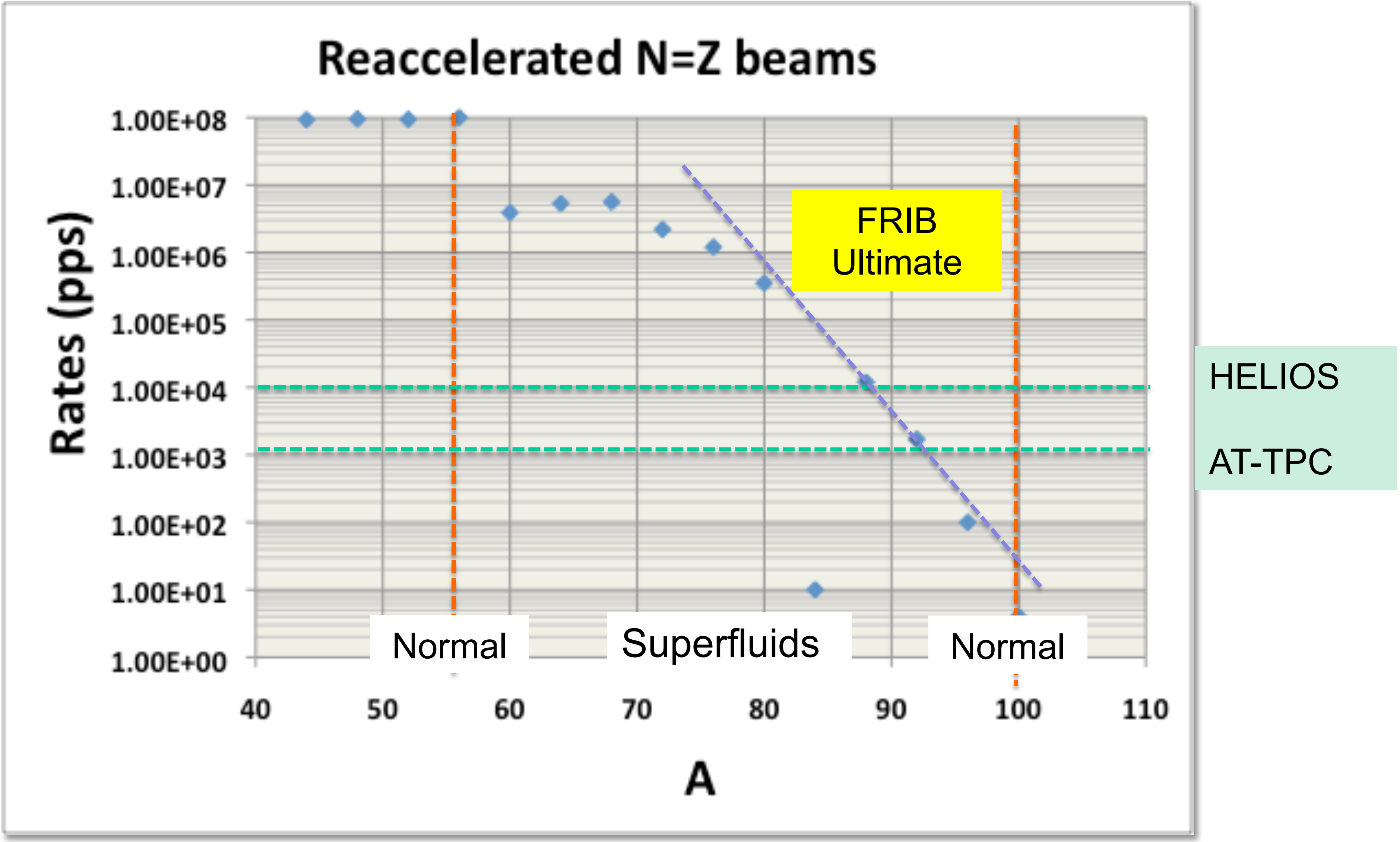
np WU’s as a function of the bombarding energy plus the Q-value to the 1^+state, for the representative cases of the $s_{1/2}$ and $d_{5/2}$orbits.

Note that the ratios are stable even when the cross-sections change by factors of 10-100, and thus reflect a robust measure of the structural properties

Systematic of (^{3}He,p) and (p,^{3}He) N=Z nuclei



FRIB ReA and AT-TPC, ^{36}Ar and ^{52}Fe E2104. Ayyad, Macchiavelli, *et al.*


Reaccelerated N=Z beams
Rates (pps)
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
40
50
60
70
80
90
100
110
A
FRIB Ultimate
HELIOS
AT-TPC
Normal
Superfluids
Normal

Summary

1) For experiment - what specific observables can you measure.
Please address explicitly what is possible with FRIB beams of up to 20kW
beam power (presumably PAC3 intensity) and give an outlook to 100 kW and full power.

Exclusive measurements of angular distributions, cross-sections, E_x and I^π

Nuclear structure (TNAs, collective form factors) and reaction models (DWBA, CC)
Continuum effects on both aspects

Potential effects anticipated for Ca, Ni and Sn isotopic chains

Heavy N=Z nuclei will require further theoretical developments of the structure part

2) For theory - what are the observables that will have the most impact for advancing the science in connection with your theoretical methods.
What types of theoretical advances are required?

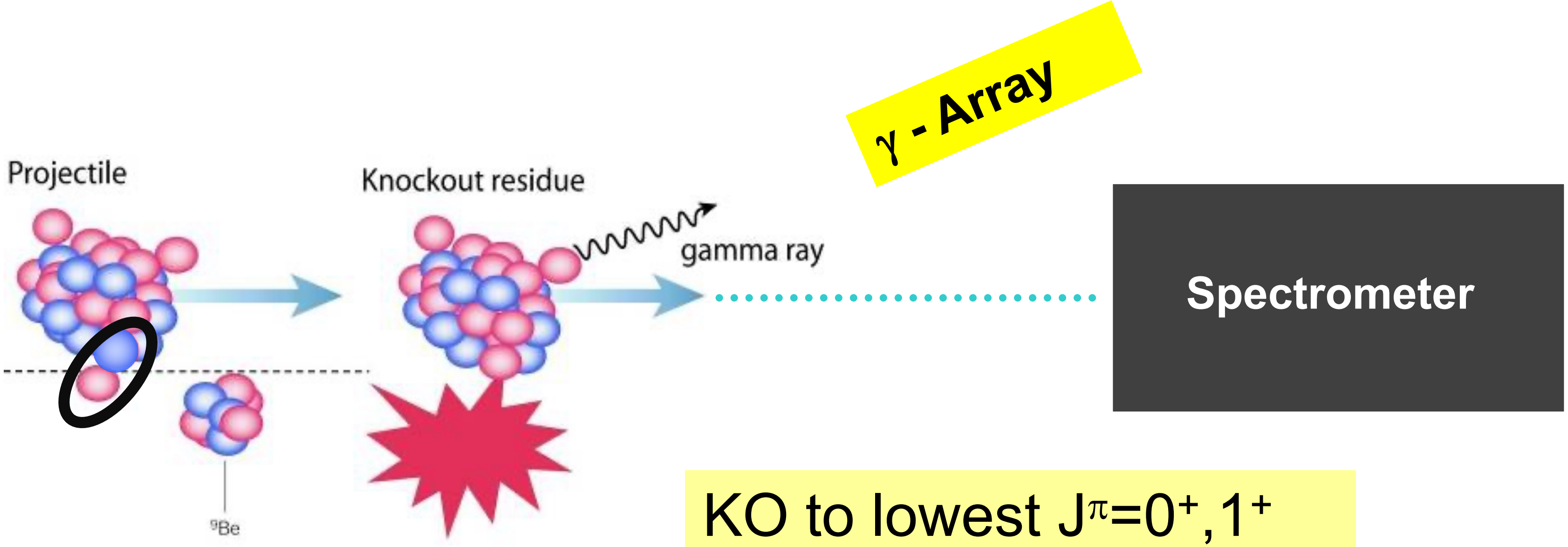
3) For all - Is there is a specific mass region that you are interested in, please specify the early, intermediate, and ultimate possibilities these.

The "semi" magic Z=8, 20, 28, and 50 chains are clearly of interest

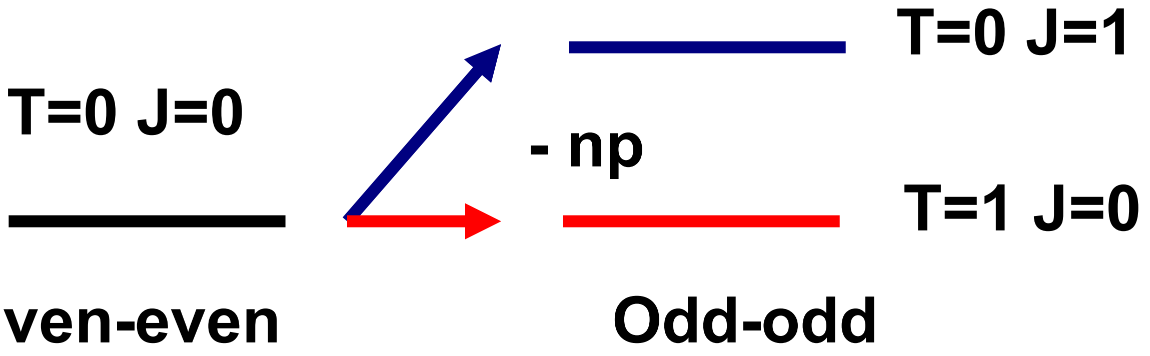
Thank you 1 !

Should we consider *nn or np* knockout reactions?

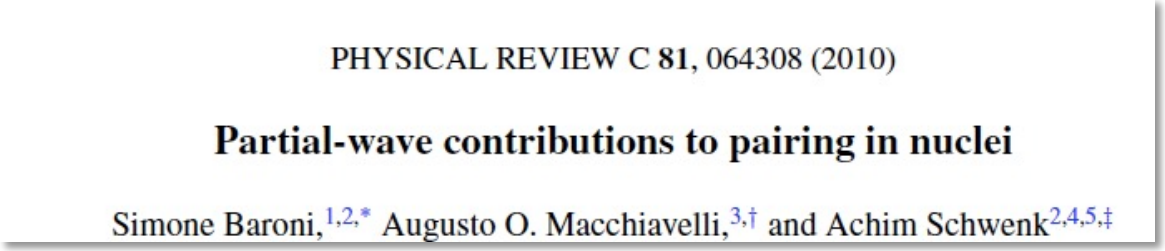
For example: np removal at the N=Z line



KO to lowest $J^{\pi}=0^+,1^+$



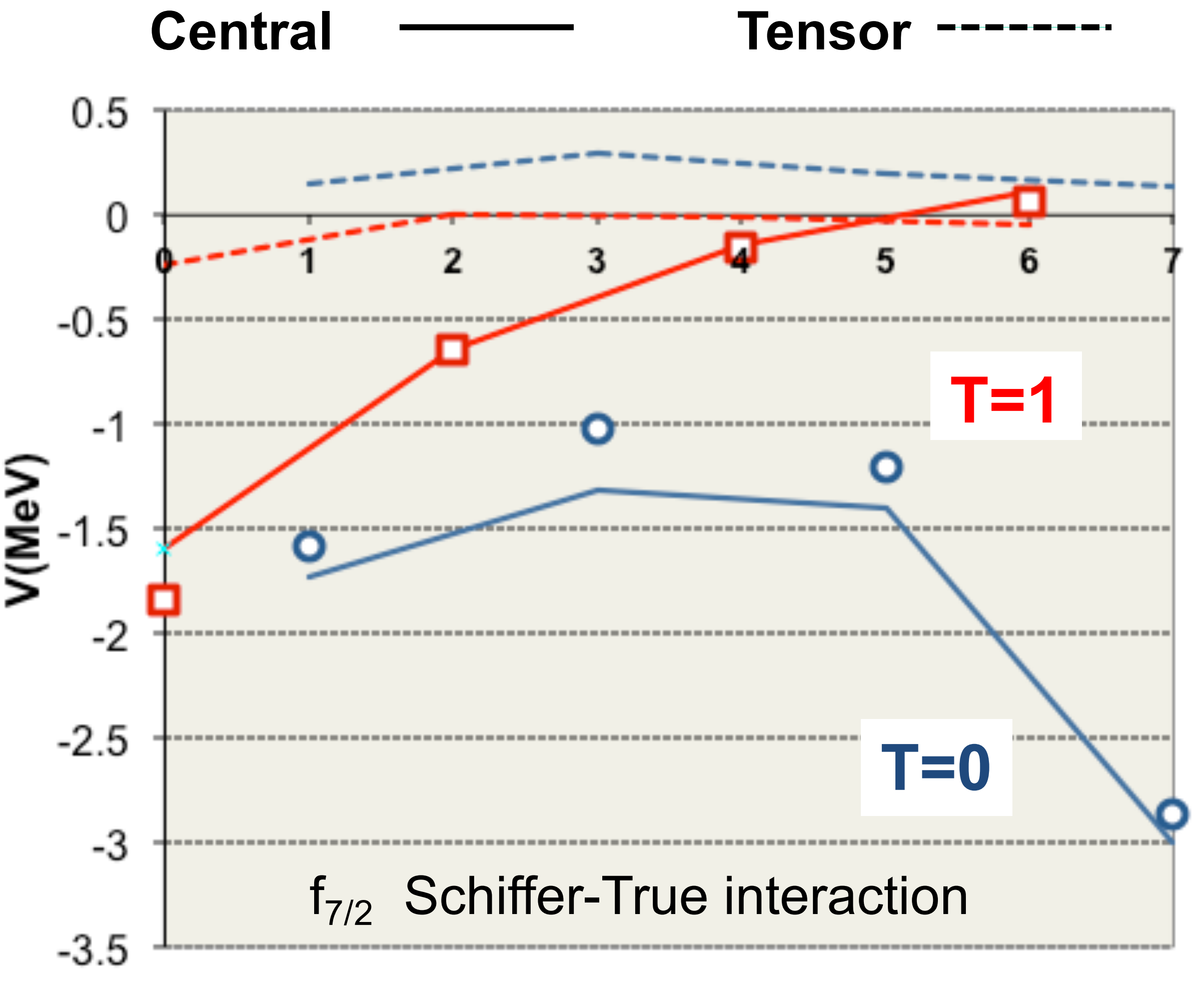
Exclusive measurement - Cross section and momentum distribution



PHYSICAL REVIEW C **81**, 064308 (2010)

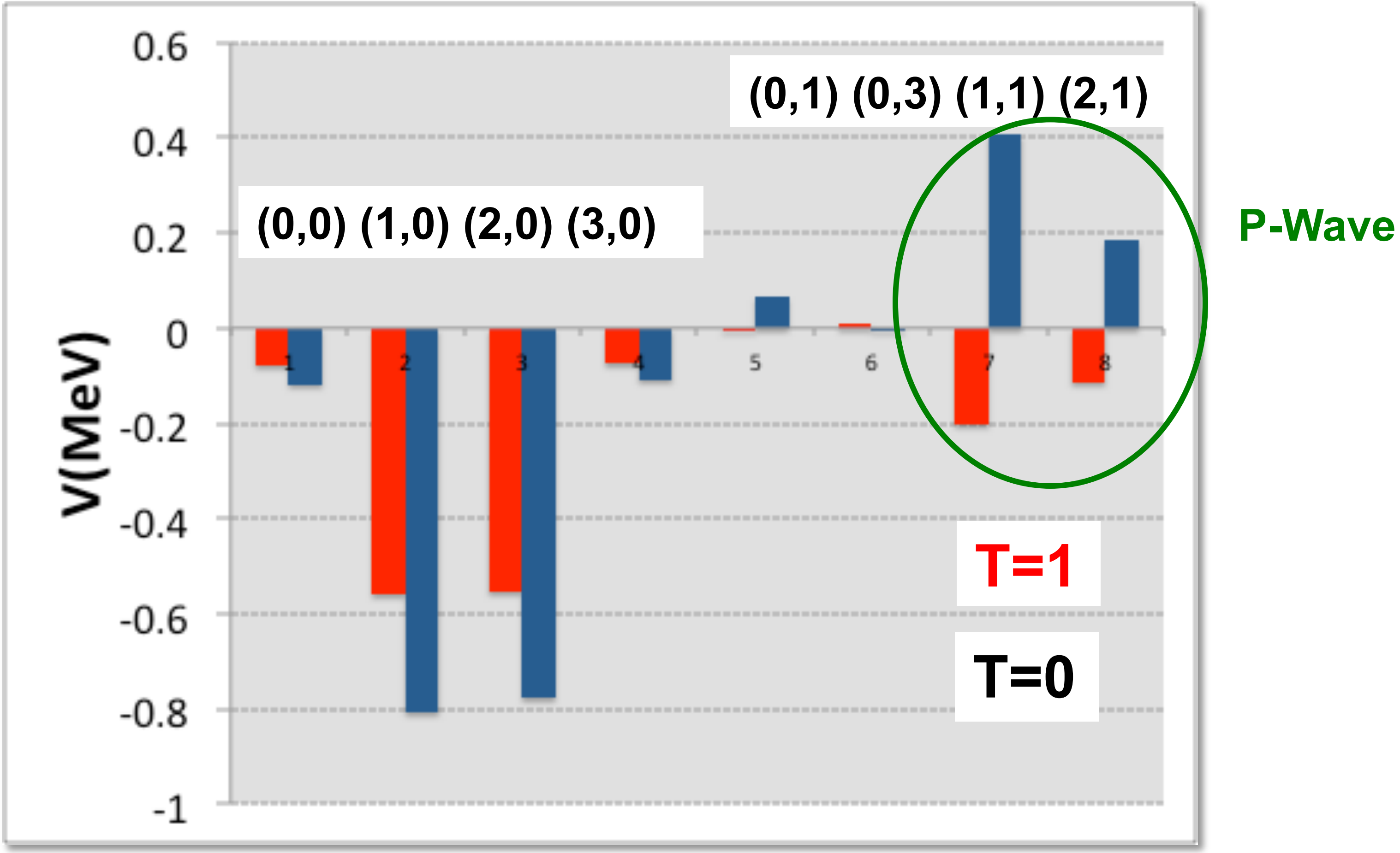
Partial-wave contributions to pairing in nuclei

Simone Baroni,[1,2,*] Augusto O. Macchiavelli,[3,†] and Achim Schwenk[2,4,5,‡]

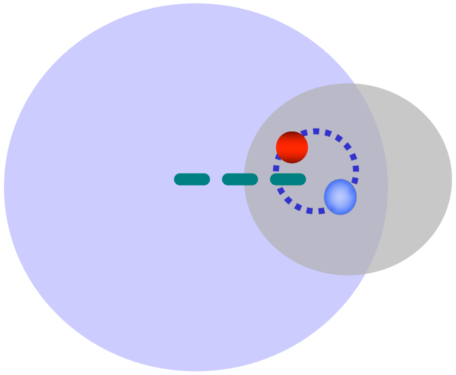


Partial Wave Contributions

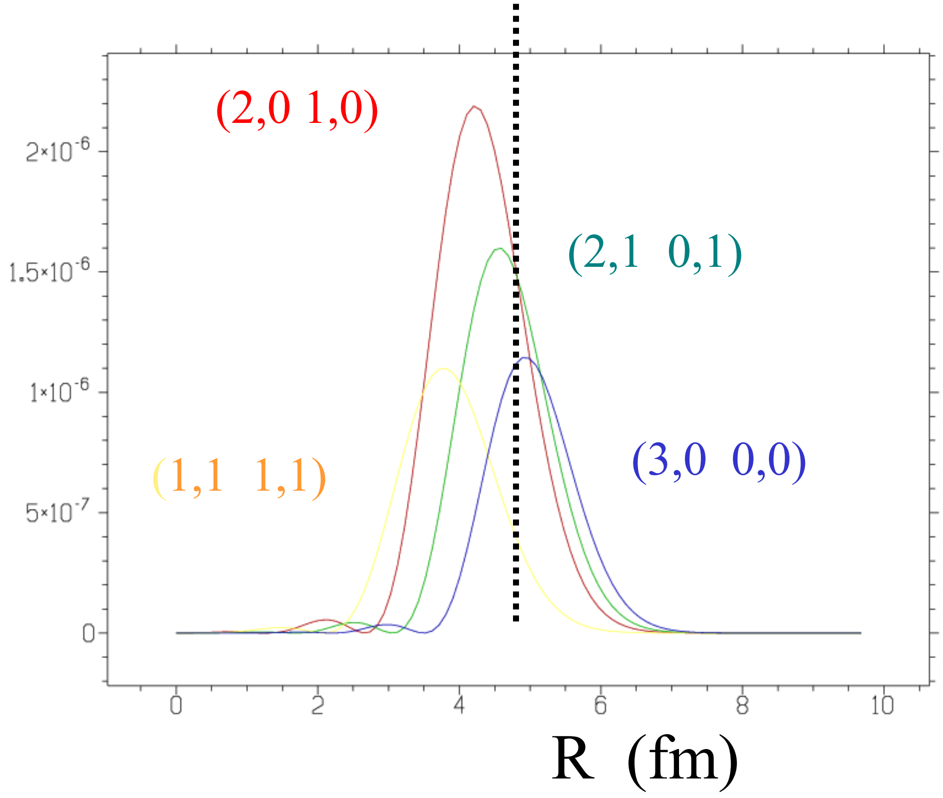
(N, Λ , **n, λ**)



Qualitative Form-Factor for the KO of an L=0 pair



(N, Λ   n, λ)



⇨   S- and P- waves

Other topics

An Active Target Tritium TPC

Y. Ayyad, IGFAE, Universidade de Santiago de Compostela
A.O. Macchiavelli, Physics Division – ORNL

Maximize physics reach on N/Z

Large efficiency and resolving power

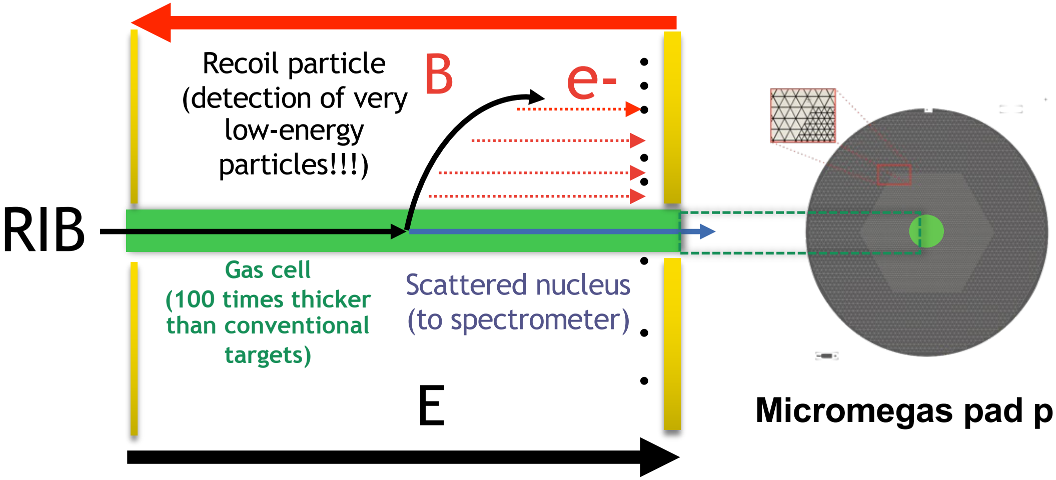
Target and detector in one device

While one could consider reactions such as $(^{18}O,{}^{16}O)$, **(t,p) reactions clearly stand as the best tool to study pairing correlations in nuclei**

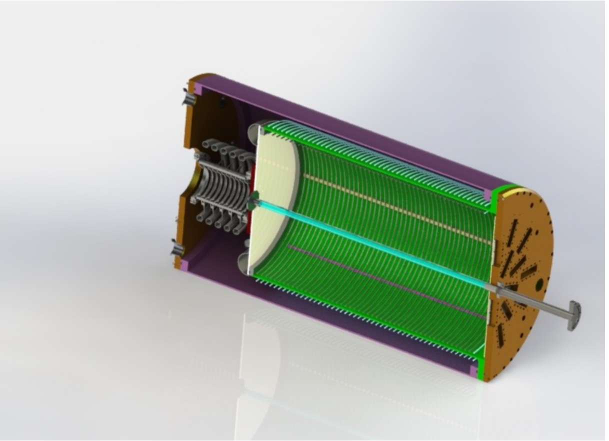
A dedicated
Active Tritium Target TPC (AT^{3}PC)

D. Bazin, T. Ahn, Y. Ayyad, S. Beceiro-Novo, A.O.Macchiavelli, W. Mittig, J.S. Randhawa
Low energy nuclear physics with active targets and time projection chambers,
Progress in Particle and Nuclear Physics, Volume 114 (2020)

Conceptual design of the AT^{3}PC



Micromegas pad plane



Mylar cell 1 cm diameter

200 torr of **pure** tritium ~ 20Ci

Equivalent to 3.2 mg/cm^2

(~ 100 times thicker than current foils)

Advantages

- Also for rare gases: ^{3}He → **(^{3}He,p) for *np* pairing at N=Z**
- Improved rate capabilities with two isolated regions: gas cell and drift volume.
- Confinement of beta particles inside the cell due to the magnetic field.

Challenges

- **Tritium poses a hazard. Several safety layers will be required. Double/Triple enclosing volumes**
- Preserve the homogeneity of the electric field along the beam axis
- Proper material for the cell (mylar, boron nitride, kevlar, graphene…)
- Reconstruction of vertex. Energy and angular resolution
- Design of pad plane: Granularity and geometry

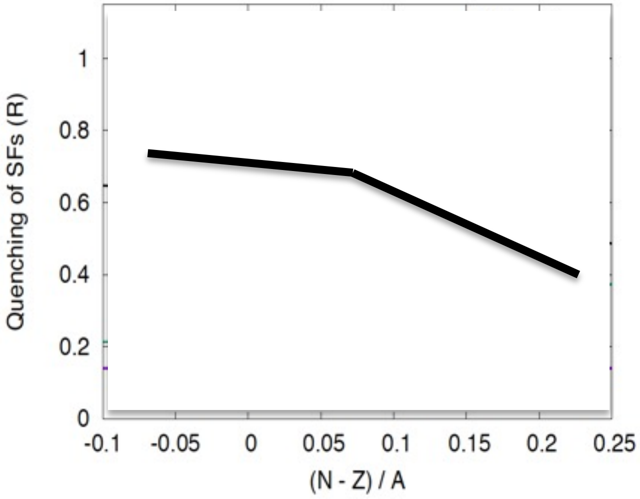
Work is on-going …. Stay tuned

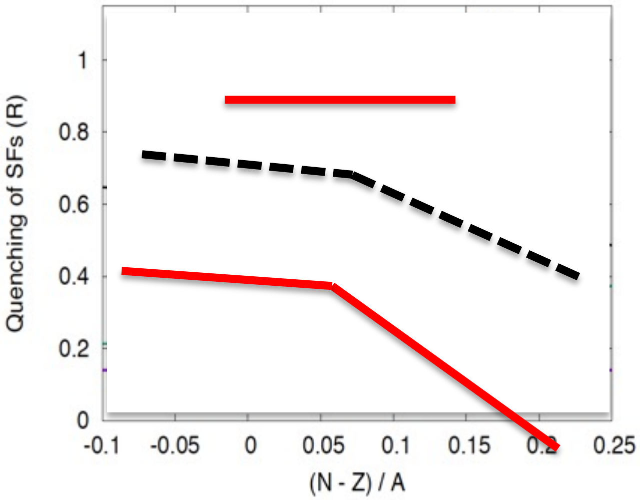
The relation of single-particle SF's quenching and that of TNA's ?

?????

One-nucleon direct reaction

Two-nucleon direct reaction





Thank you 2 !