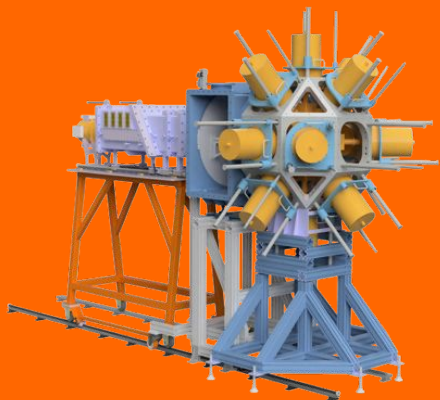
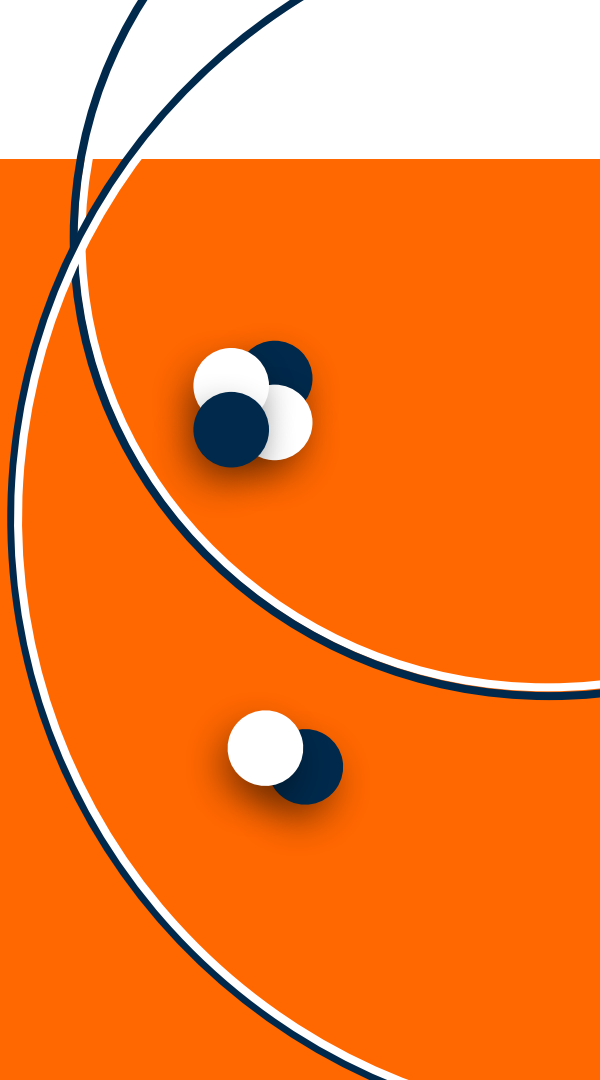


$^{48}\text{Cr}(p, ^3\text{He})^{46}\text{V}$ reaction to study proton-neutron pairing



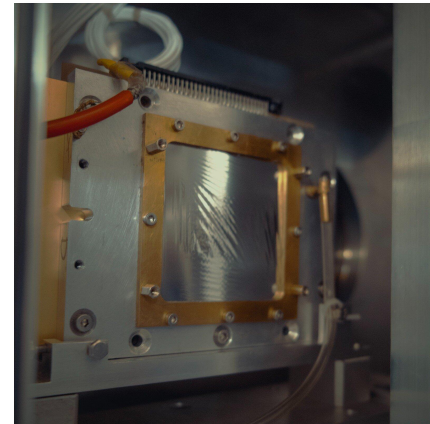
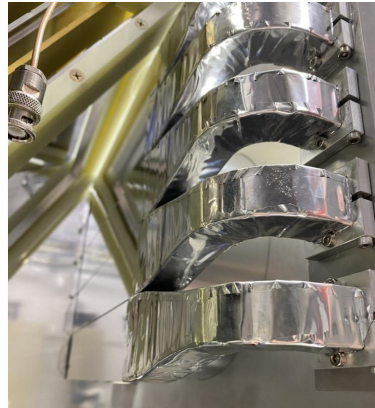
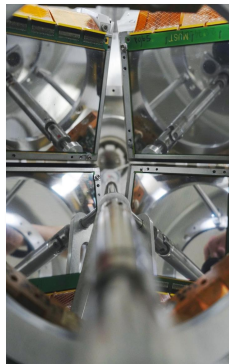
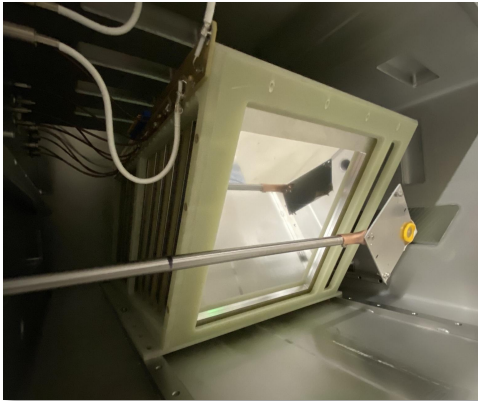
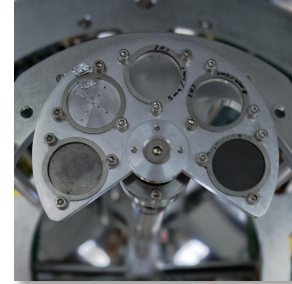
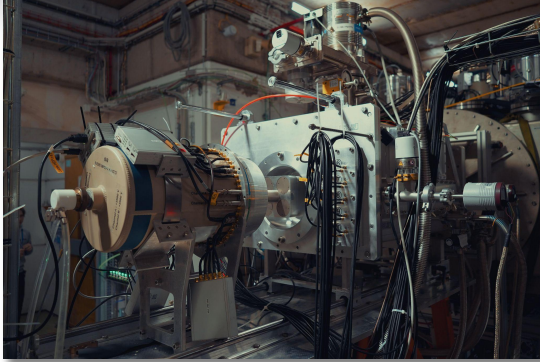
Hugo Jacob, hjacob@ijclab.in2p3.fr
ESNT WS
15/05/2025





Outline

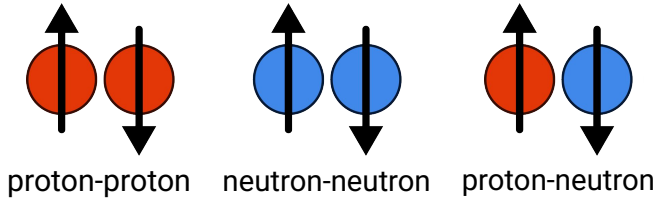
- Scientific motivations
- Experimental setup
- Data analysis
- Preliminary results



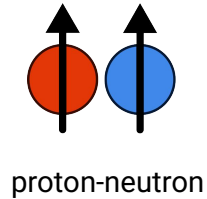
Scientific motivations

Proton-neutron pairing

Isovector ($J=0, T=1$)



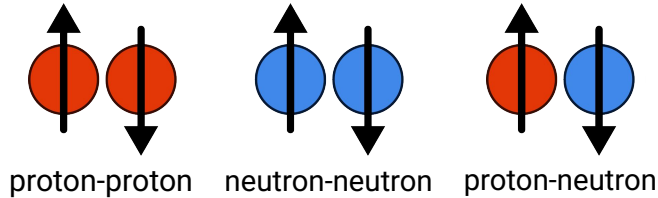
Isoscalar ($J=1, T=0$)



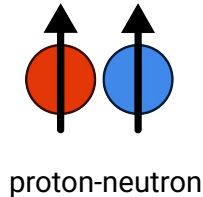
- Observable mostly, if not only, in $N=Z$ nuclei
- 2 different channels available, with different strengths
- Deuteron only bound in isoscalar channel ($J=1, T=0$)
- Pairing effects depend on the collectivity of the shell

Proton-neutron pairing

Isovector ($J=0, T=1$)

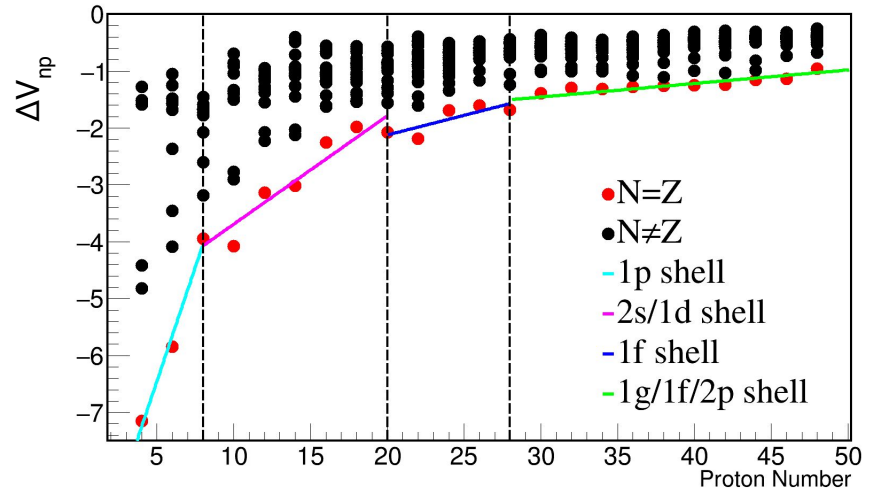


Isoscalar ($J=1, T=0$)



- Observable mostly, if not only, in $N=Z$ nuclei
- 2 different channels available, with different strengths
- Deuteron only bound in isoscalar channel ($J=1, T=0$)
- Pairing effects depend on the collectivity of the shell

Binding energy anomaly in $N=Z$ nuclei



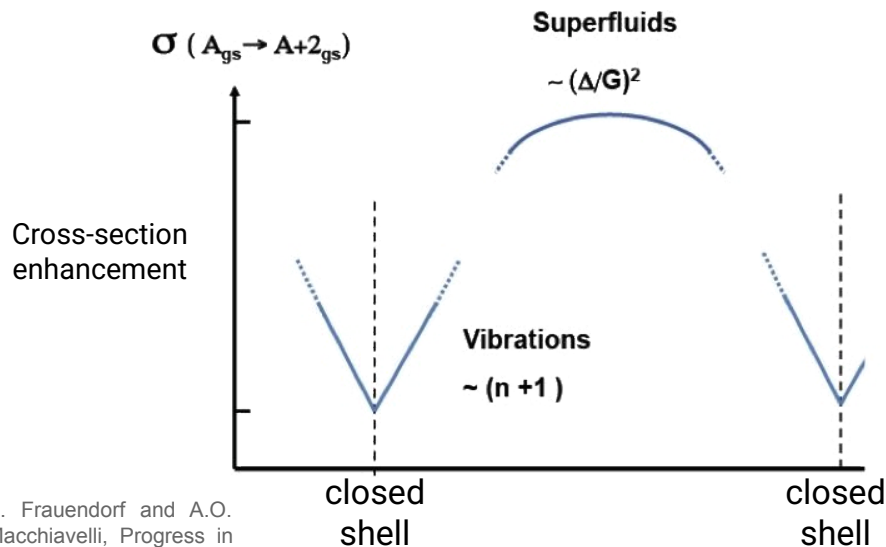
Double binding energy formula:

$$\Delta V_{np} = 1/4(B(N,Z) - B(N,Z-2) - B(N-2,Z) + B(N-2,Z-2))$$



Data from ENSDF using TkN software

Two-nucleon transfer reaction

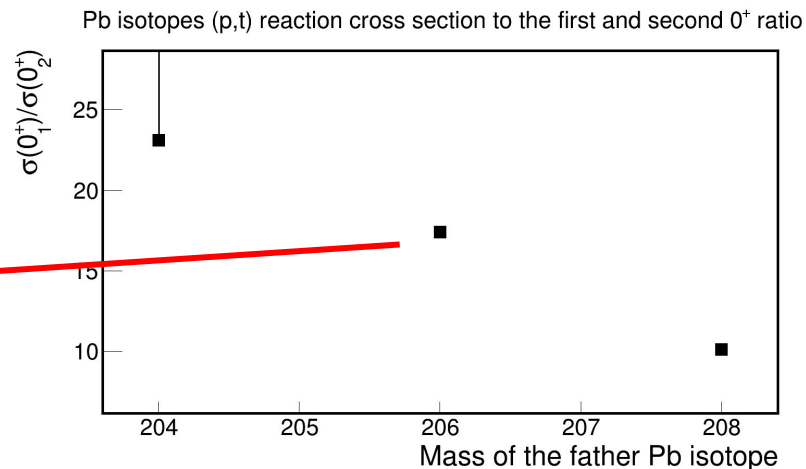
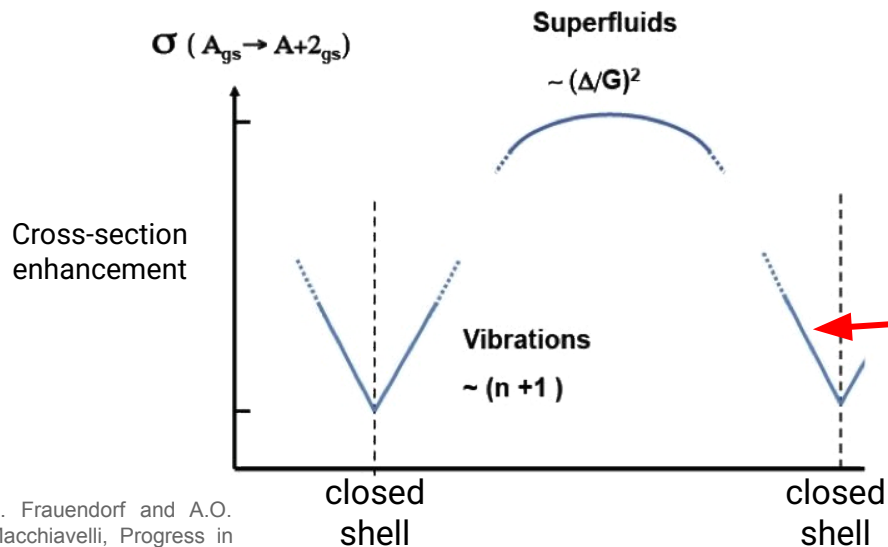


S. Frauendorf and A.O. Macchiavelli, Progress in Particle and Nuclear Physics, 24-90 78, 2014

- Near closed shell, cross-section increasing proportionally to the number of pairs (vibrational)
- In the middle of the shell, cross-section depends on the gap and pairing strength (rotational)

Historical neutron-neutron results

- ^{208}Pb is a double shell closure, vibrational behavior for neutron-neutron pairs in stable Pb isotopes



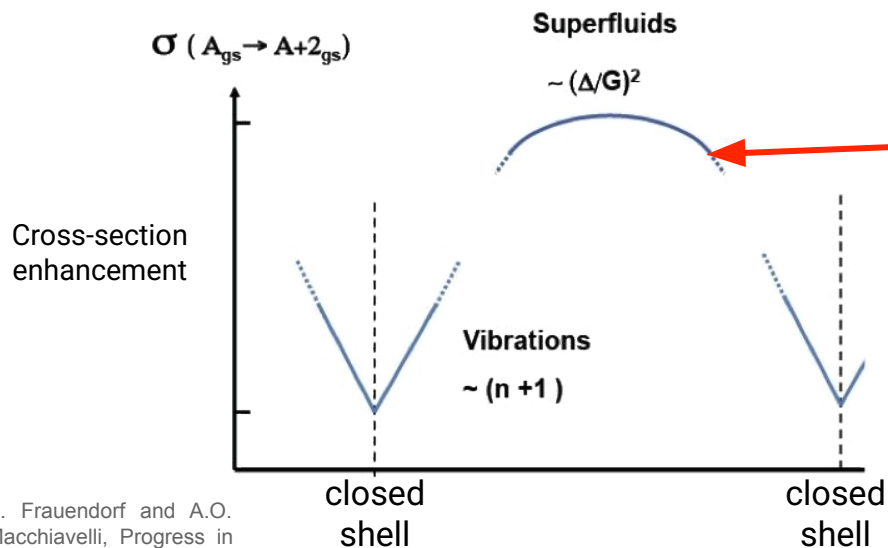
S. Frauendorf and A.O. Macchiavelli, Progress in Particle and Nuclear Physics, 24-90 78, 2014

Near closed shell, cross-section increasing proportionally to the number of pairs (vibrational)

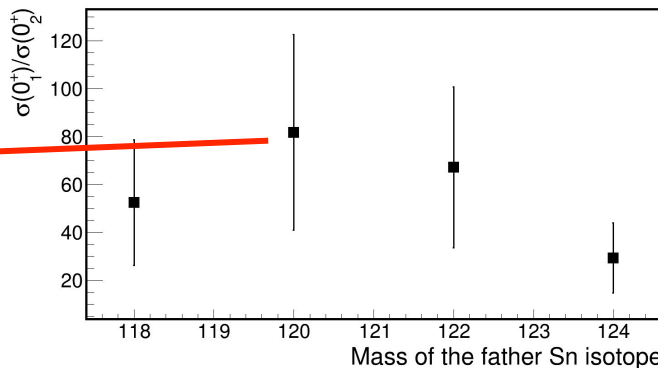
- In the middle of the shell, cross-section depends on the gap and pairing strength (rotational)

Adapted from D. M. Brink, R. A. Broglia, Nuclear Superfluidity
Data from W. A. Lanford, Phys. Rev. C **16**, 988

Historical neutron-neutron results



Sn isotopes (p,t) reaction cross section to the first and second 0^+ ratio



- Sn is a proton shell closure, but stable Sn isotopes are in the middle of a neutron shell: superfluid behavior for neutron-neutron pairs

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

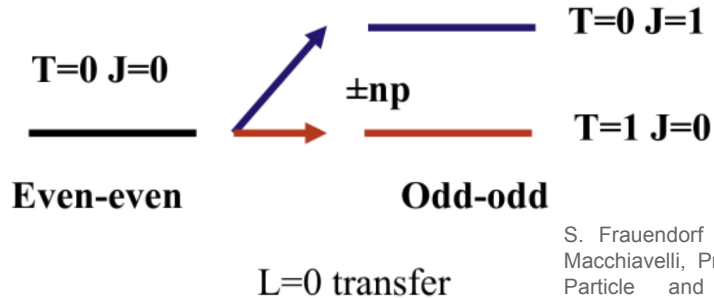
Near closed shell, cross-section increasing proportionally to the number of pairs (vibrational)

- In the middle of the shell, cross-section depends on the gap and pairing strength (rotational)

Adapted from D. M. Brink, R. A. Broglia, Nuclear Superfluidity
 Data from D. G. Fleming *et al.*,
 Nuclear Physics A 157, 1-31, 1970

Cross section ratios

(p,³He) selection rules allow to populate both low-lying states

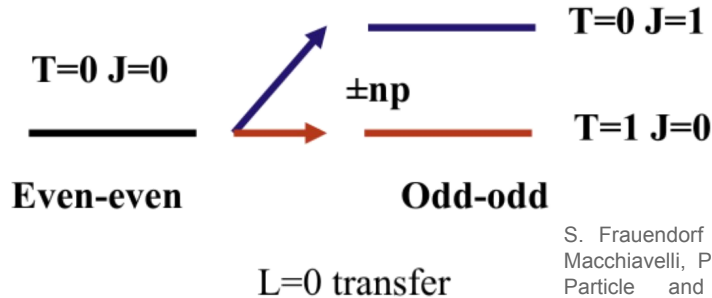


S. Frauendorf and A.O. Macchiavelli, Progress in Particle and Nuclear Physics, 24-90 **78**, 2014

- Transfer to (T=0, J=1) state gives information on isoscalar pairing strength, and similarly for (T=1, J=0) and isovector pairing strength.
- Same reaction mechanism: L=0 transfer (DWBA) necessary to discriminate L=2

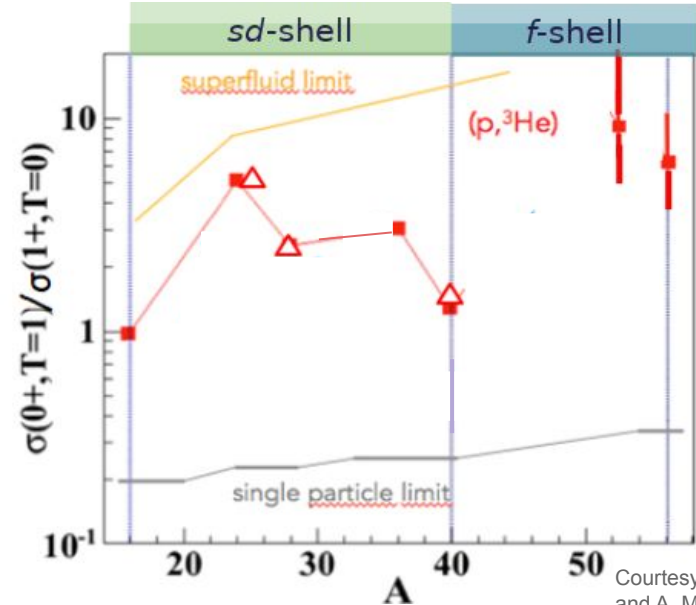
Cross section ratios

(p,³He) selection rules allow to populate both low-lying states



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

- Transfer to ($T=0, J=1$) state gives information on isoscalar pairing strength, and similarly for ($T=1, J=0$) and isovector pairing strength.
- Same reaction mechanism: $L=0$ transfer (DWBA) necessary to discriminate $L=2$

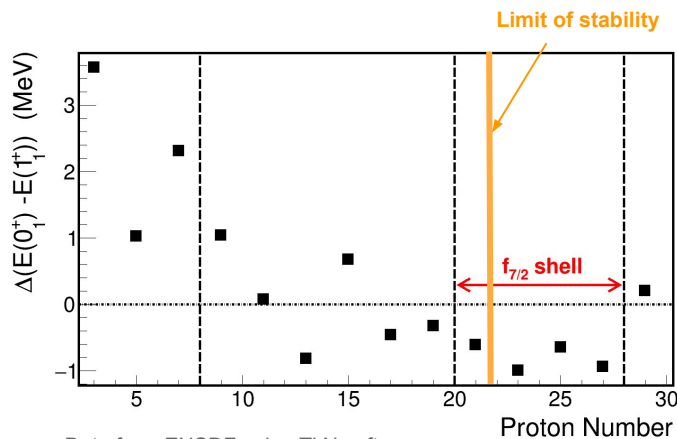


Courtesy of M. Assié and A. Macchiavelli

- Cross section ratio: useful to get rid of experimental biases
- Proton-neutron pairs: cross-section ratio shows the competition between isoscalar and isovector pairing channels

Pairing in $f_{7/2}$ shell

Pairing states energy difference in
N=Z nuclei



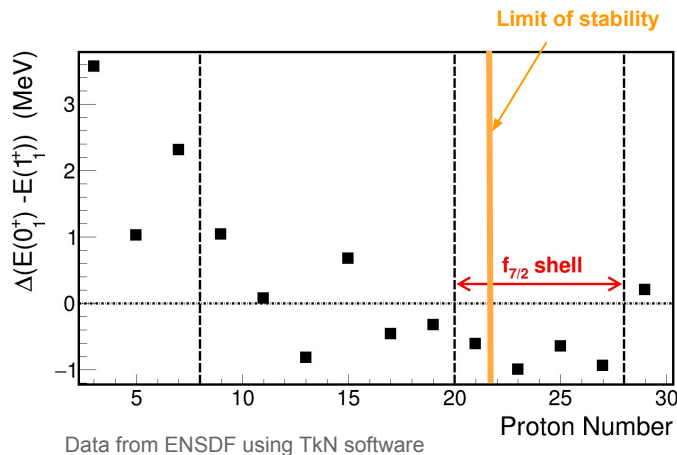
Data from ENSDF using TkN software

- Pairing lowers related states energy
- 0^+ g.s. in $f_{7/2}$ could indicate stronger isovector strength in this shell



Pairing in $f_{7/2}$ shell

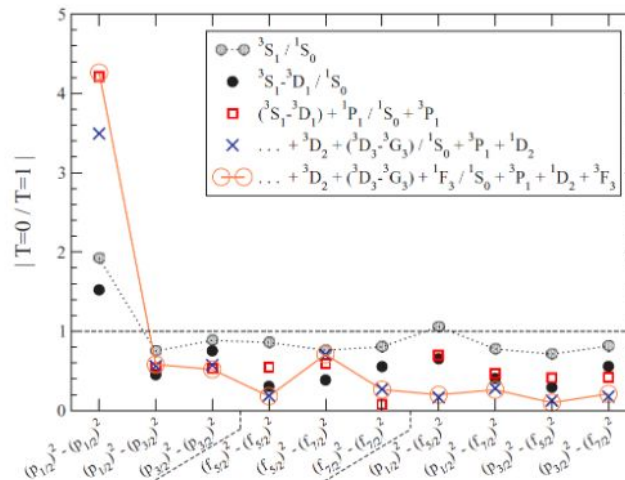
Pairing states energy difference in
N=Z nuclei



- Pairing lowers related states energy
- 0^+ g.s. in $f_{7/2}$ could indicate stronger isovector strength in this shell



Pairing strength ratio by matrix
element in the fp-shell



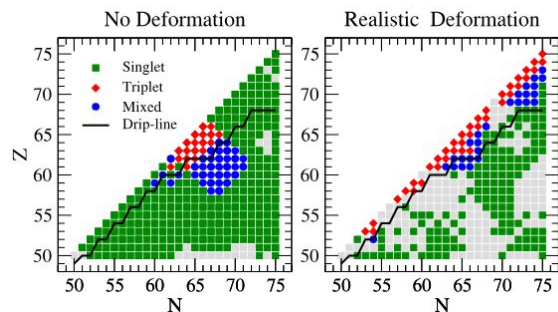
- Addition of partial-waves beyond 1S_0 channel favor T=1 channel in fp-shell
- In-medium nuclear forces seem to have an important impact on pairing forces

S. Baroni, A. O. Macchiavelli and A. Schwenk, Phys. Rev. C **81**, 064308

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

Pairing-deformation interplay

Pairing condensate nature in heavy nuclei

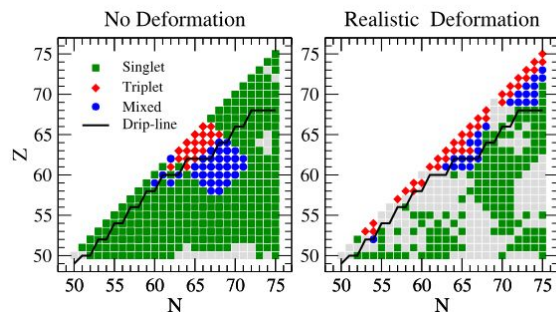


G. Palkanoglou, M.
Stuck and A.
Gezerlis, PRL 134,
032501 (2025)

- Deformation modifies both pairing correlation energy and the condensate nature

Pairing-deformation interplay

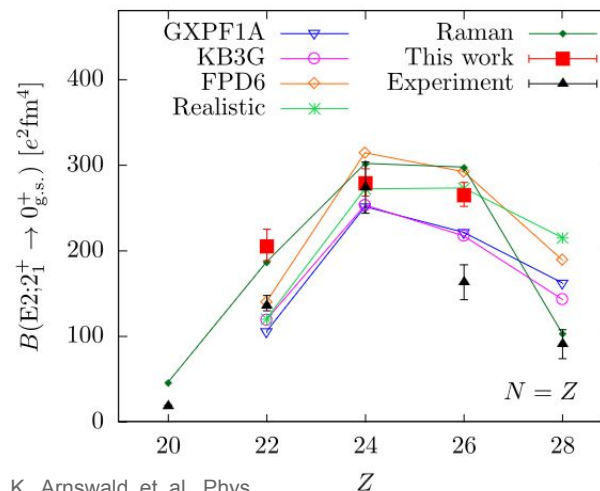
Pairing condensate nature in heavy nuclei



G. Palkanoglou, M. Stuck and A. Gezerlis, PRL 134, 032501 (2025)

- Deformation modifies both pairing correlation energy and the condensate nature

Deformation in N=Z nuclei ($f_{7/2}$ shell)

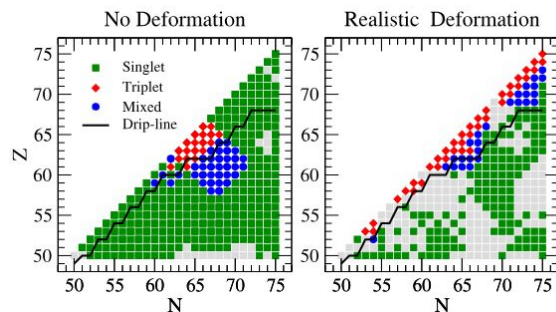


K. Arnsfeld et al. Phys. Lett. B 772 (2017) 599

- ^{48}Cr : good candidate to study interplay between pairing and deformation

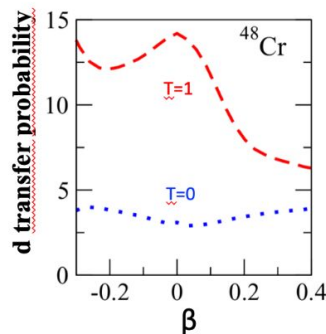
Pairing-deformation interplay

Pairing condensate nature in heavy nuclei



G. Palkanoglou, M. Stuck and A. Gezerlis, PRL 134, 032501 (2025)

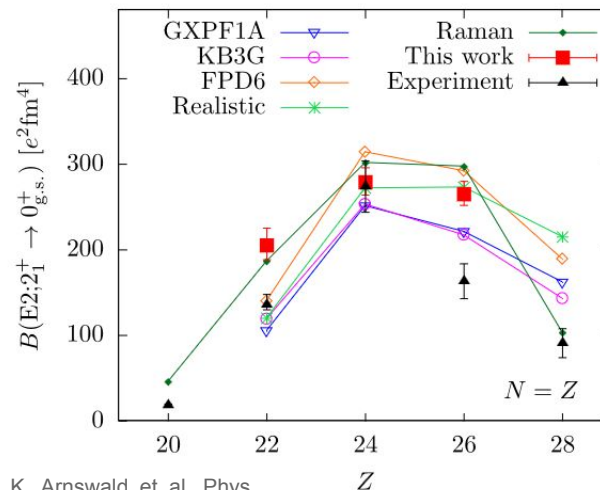
- Deformation modifies both pairing correlation energy and the condensate nature



- The T=1 channel seems to be more affected by deformation than the T=0

D. Gambacurta, D. Lacroix, Phys. Rev. C 91 (2015) 014308 and D. Lacroix private communication

Deformation in N=Z nuclei ($f_{7/2}$ shell)



K. Arnsward et al. Phys. Lett. B 772 (2017) 599

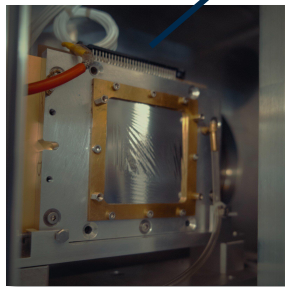
- ^{48}Cr : good candidate to study interplay between pairing and deformation

Experimental setup

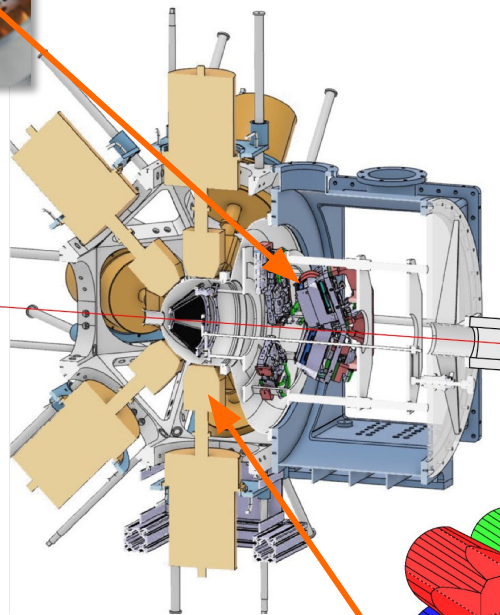
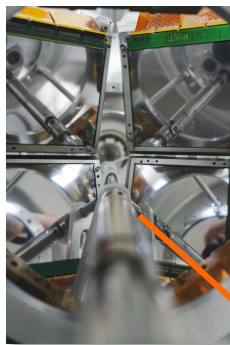
MUGAST@LISE

- ^{48}Cr 30MeV/u beam produced by fragmentation of ^{50}Cr and selected by LISE spectrometer at GANIL
- Impinging beam on a $5\text{mg}/\text{cm}^2$ CH_2 target

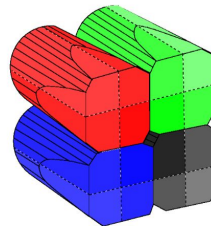
CATS (MWPC)



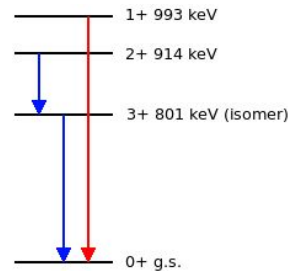
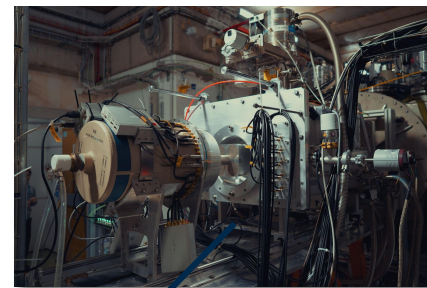
MUST2



EXOGRAM

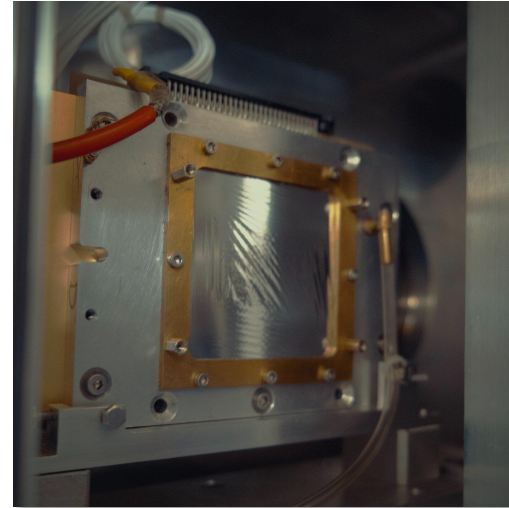
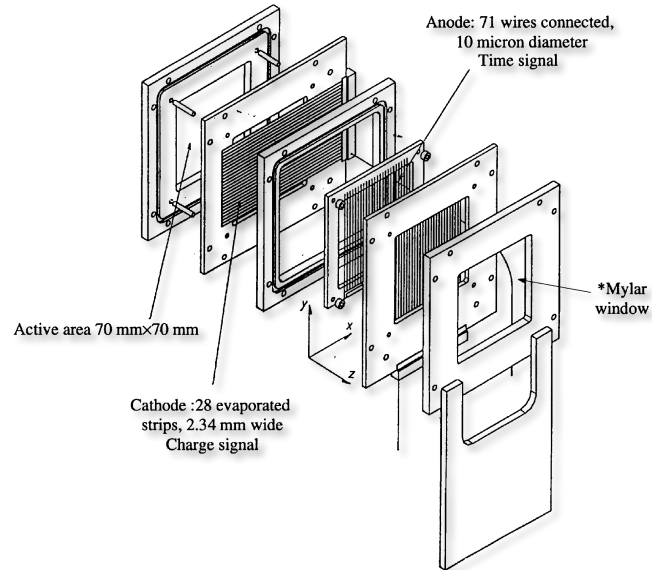


ZDD



Beam tracking: CATS

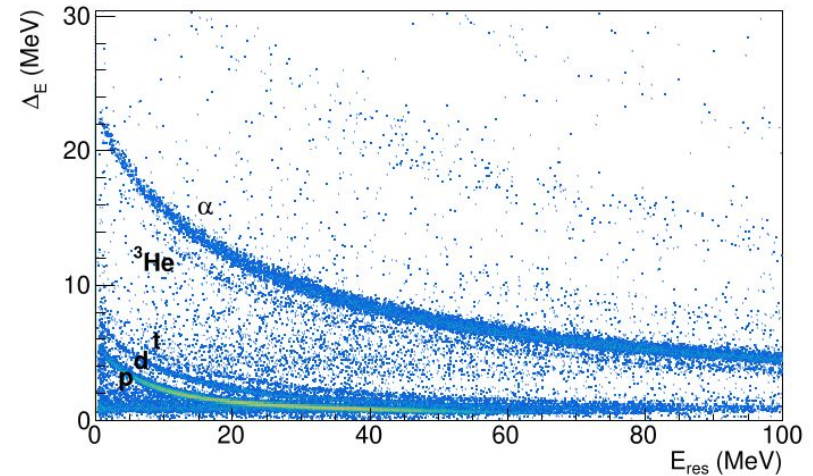
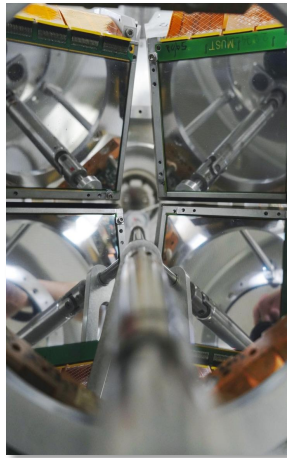
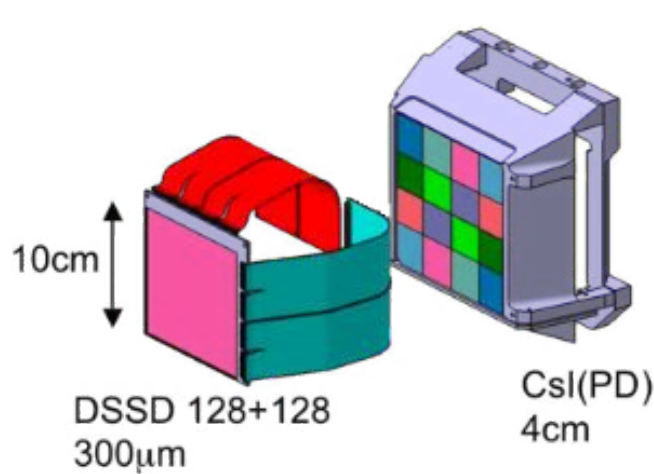
- MWPC gaseous detectors
- Charges collected on wires
- Reconstruction of beam position on wires



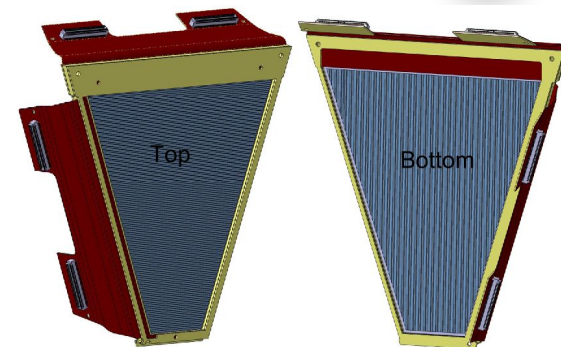
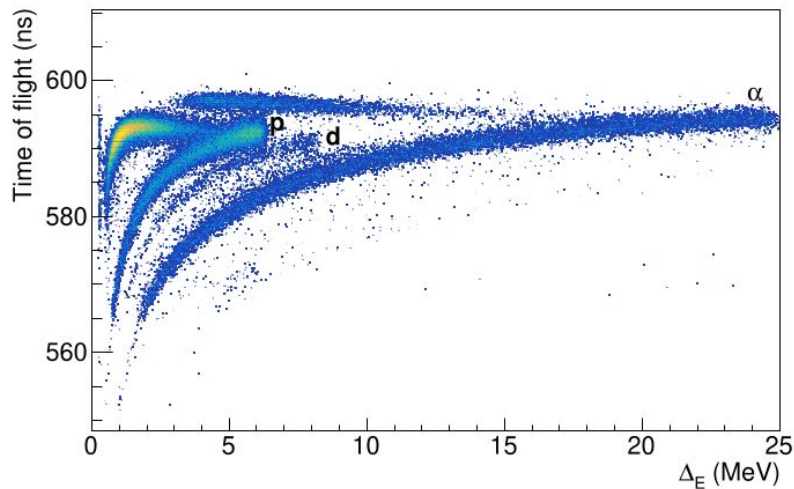
- 2 detectors upstream of the target
- 1 mm resolution position on target
- Beam angle information
- Max intensity of 2.10^5 pps

Light particles: MUGAST

- 4 MUST2 detectors (DSSD + CsI crystals)
- Forward angles (between 5° and 25°)
- E/TOF or $\Delta E/E$ particle identification



Light particles: MUGAST



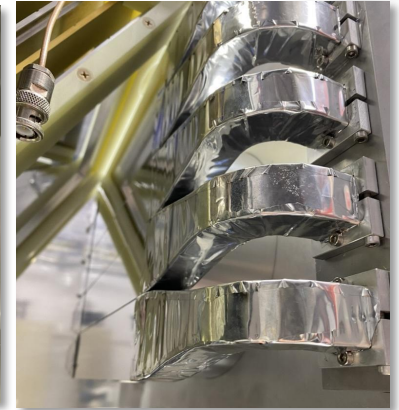
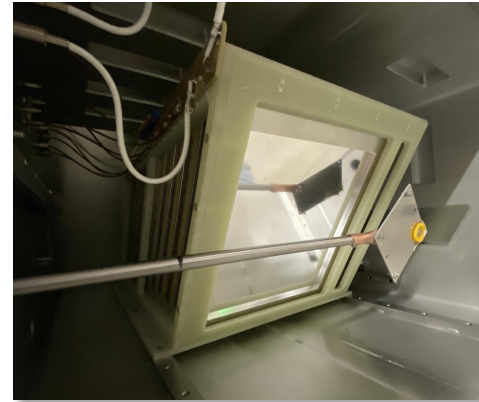
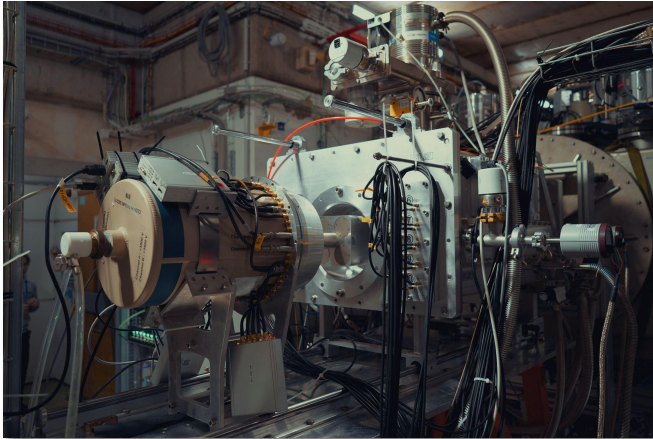
V. Alcindor et al., *Nuovo Cim. C* 47 (2024) 2, 59

M. Assié et al., *NIM A* 1014 (2021) 165743

- 5 MUGAST trapezoids (DSSD (500 μ m))
- Backward angles (between 105° and 160°)
- E/TOF particle identification

Beam-like nucleus: ZDD

- Zero Degree Detection downstream of the reaction target
- Angles between 0° and 2.5°
- Drift chambers, Ionisation chambers, plastics

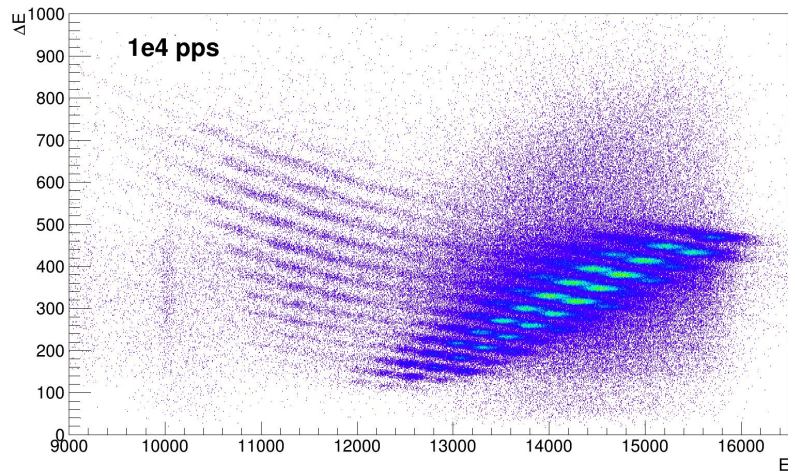


- Beam-like nucleus identification:
- $\Delta E/\text{TOF}$ (IC/TOF Cats-Plastics)
- $\Delta E/E$ (IC/Energy Plastics)

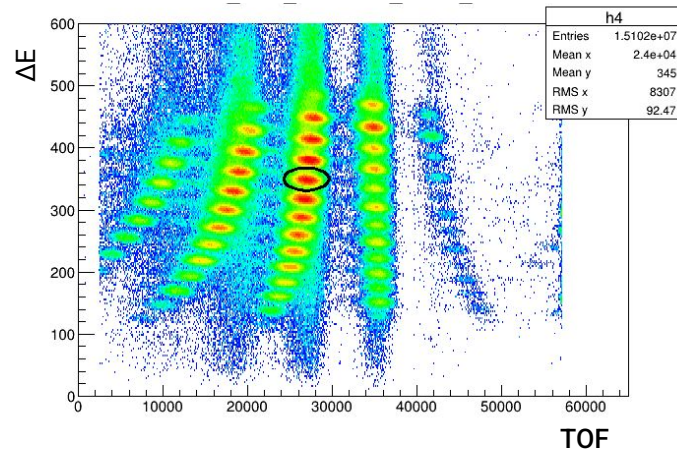
Beam-like nucleus: ZDD

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- Angles between 0° and 2.5°
- Drift chambers, Ionisation chambers, plastics

$\Delta E/E$ ionisation chambers/plastics cocktail beam



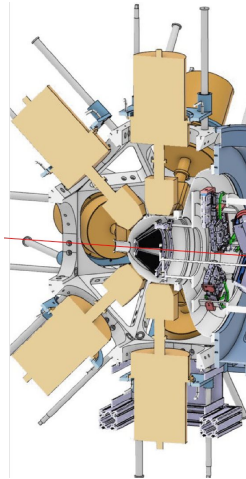
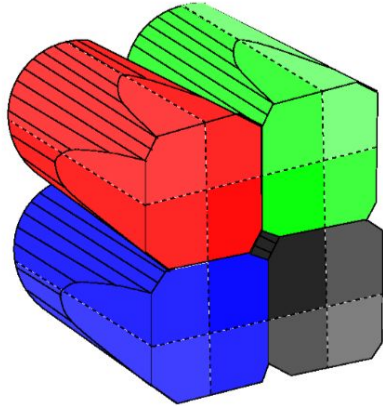
$\Delta E/TOF$ ionisation chambers/HF-plastics cocktail beam



- Heavy recoil identification:
- $\Delta E/TOF$ (IC/TOF Cats Plastics)
- $\Delta E/E$ (IC/Energy Plastics)

Gamma rays: EXOGAM

- 12 EXOGAM Ge clovers around reaction target
- In-flight spectroscopy of target-like nuclei
- 48 crystals at 14 cm: ~5% efficiency at 1 MeV



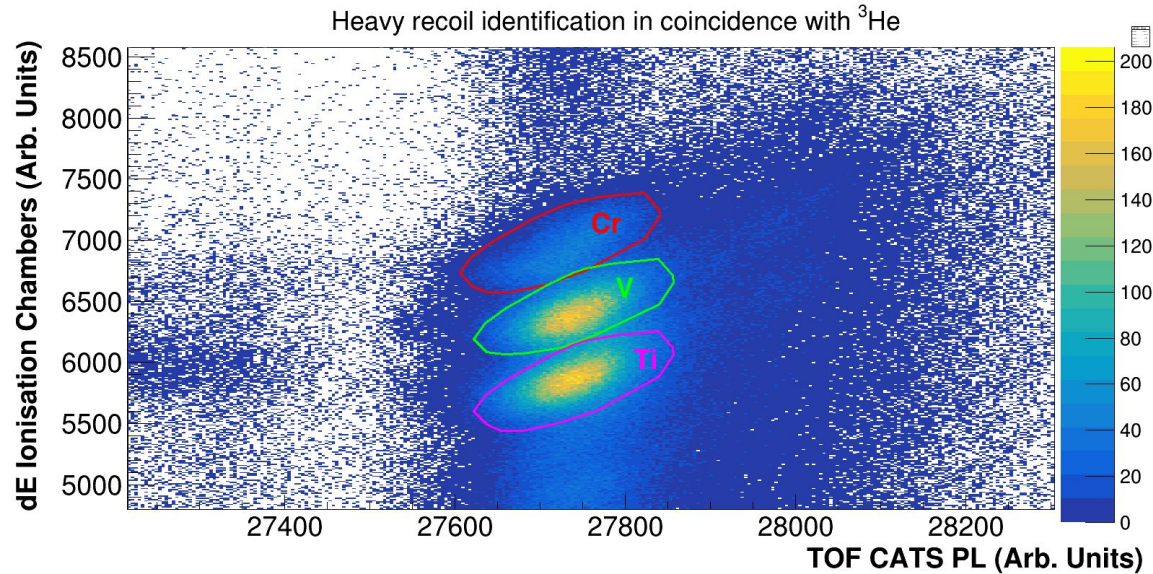
- Crystal segmentation for better position sensitivity (Doppler correction)

Data analysis

The background is a solid orange color. It features several decorative elements: two overlapping circles (one white, one dark blue) in the top right corner, two overlapping circles (one white, one dark blue) in the bottom left corner, and two thin dark blue arcs, one in the top right and one in the bottom left, framing the central text.

ZDD identification

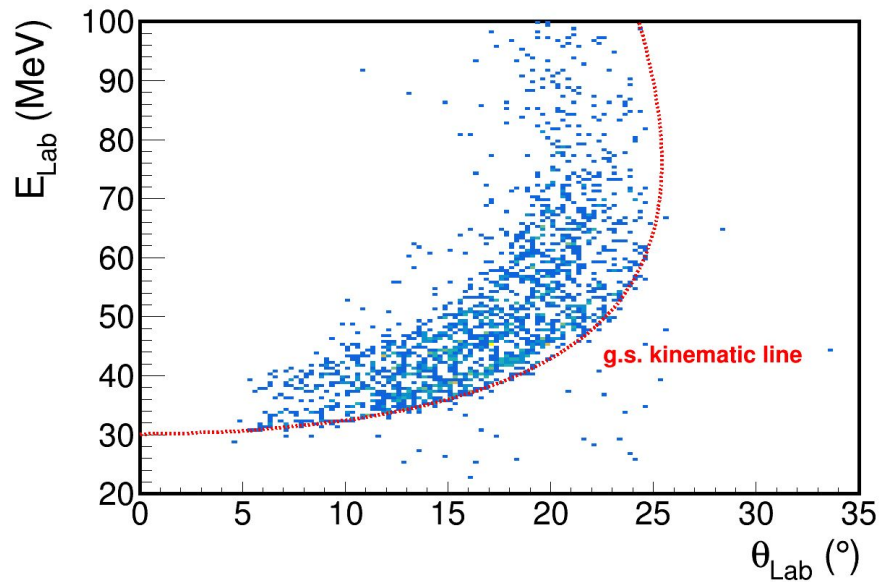
- Identification performed with deltaE/TOF (TOF CATS PL)
- Typical nuclei used in our analysis are Cr, V and Ti



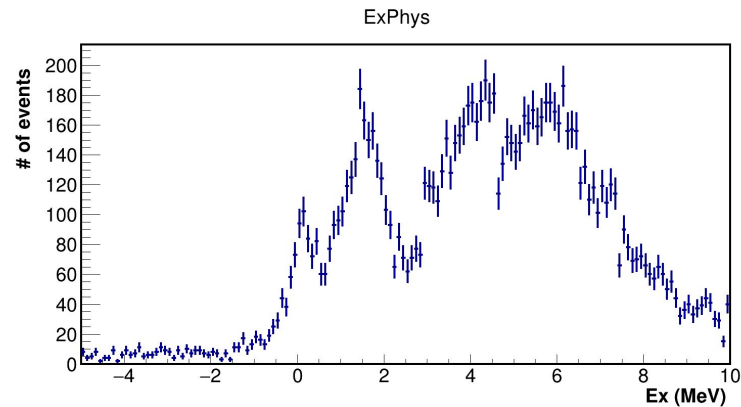
ZDD Identification in dE/TOF with CUTS used in the analysis

MUST2 kinematics

(p,³He) kinematic line



⁴⁶V Excitation Energy (all gates applied)

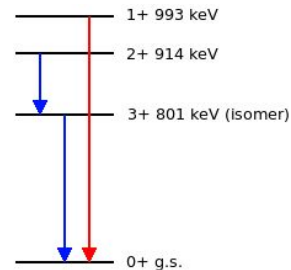
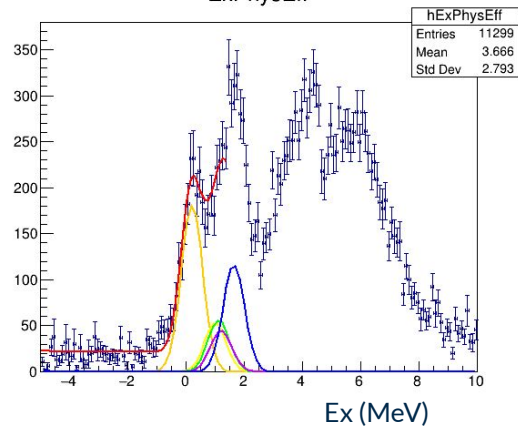




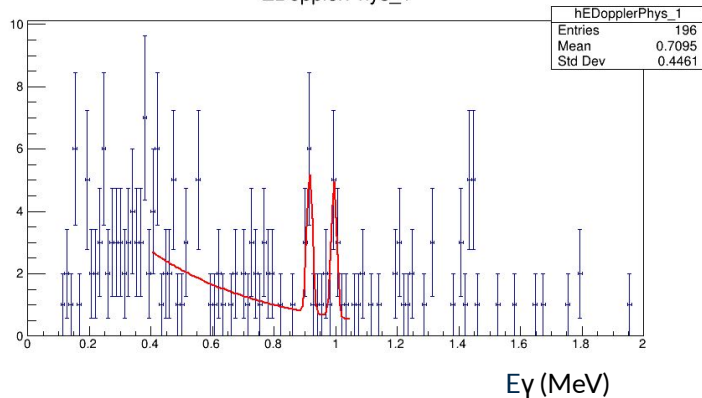
Preliminary results

Fitting experimental data

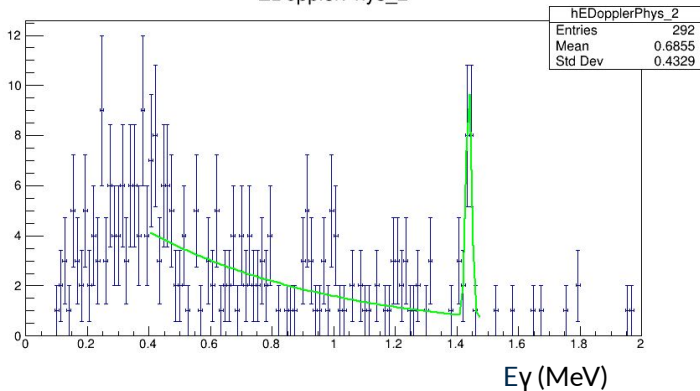
ExPhysEff



EDopplerPhys_1

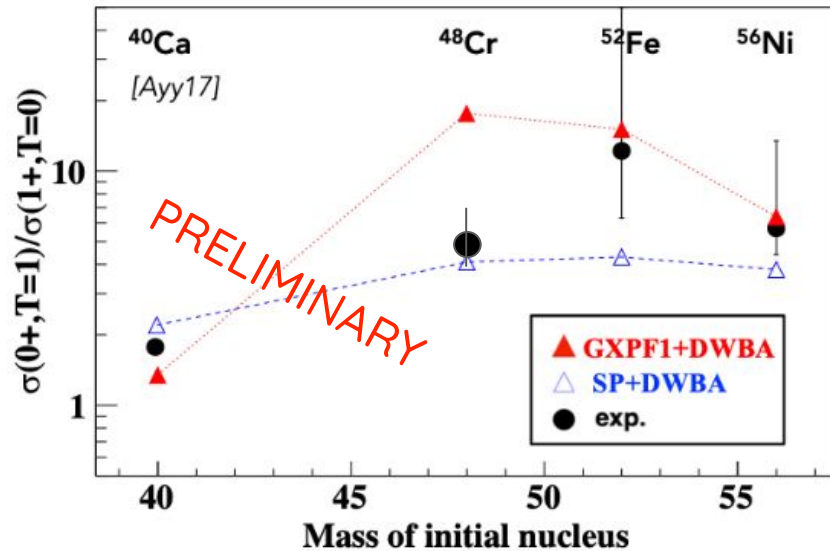


EDopplerPhys_2



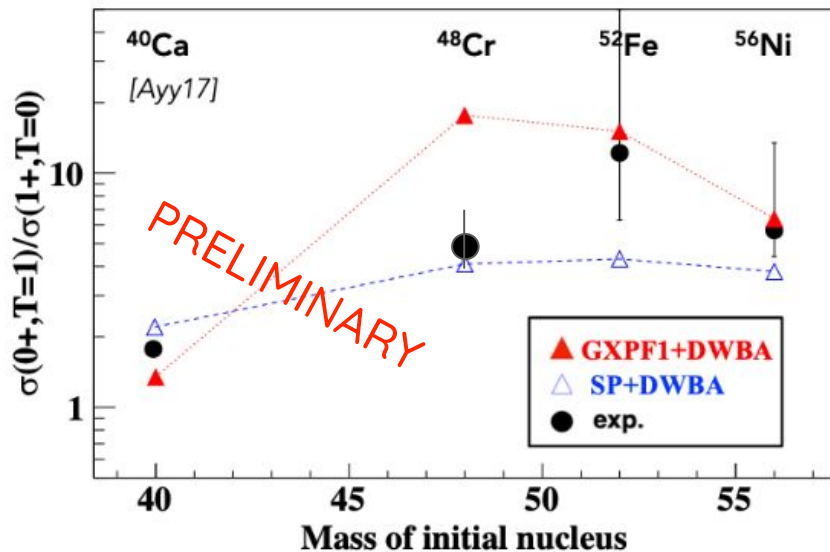
Pairing preliminary results

Cross section ratio



Pairing preliminary results

Cross section ratio



Preliminary absolute cross sections

$\sigma(T=1) \text{ } ^{48}\text{Cr}(p, ^3\text{He}) ^{46}\text{V}$: 69.4(24) μb
 $\sigma(T=0) \text{ } ^{48}\text{Cr}(p, ^3\text{He}) ^{46}\text{V}$: 13.3(39) μb

PRELIMINARY

	$\sigma(0+, T=1) (\mu\text{b})$	$\sigma(1+, T=0) (\mu\text{b})$	Ratio
$^{56}\text{Ni}(p, ^3\text{He}) ^{54}\text{Co}$			
this work	$109^{stat}_{\pm 5} {}^{sys}_{\pm 10}$	$17^{stat}_{\pm 7} {}^{sys}_{\pm 2}$	$6.3^{+3.1}_{-2.1}$
SP	73	19	3.8
GXPF1	136	21	6.4
$^{52}\text{Fe}(p, ^3\text{He}) ^{50}\text{Mn}$			
this work	$145^{stat}_{\pm 12} {}^{sys}_{\pm 15}$	$16^{+29}_{-16} {}^{sys}_{\pm 2}$	$9.1^{+\infty}_{-3.7}$
SP	69	16	4.3
GXPF1	257	17	15.1