INSTITUTO GALEGO DE FÍSICA DE ALTAS ENERXÍAS

EXCELENCIA MARÍA DE MAEZTU

Probing the Structure of Neutron-Rich Carbon Isotopes through Transfer Reactions

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and the AT-TPC collaboration

(a) USC, (b) SUSTech

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Rede CIGUS Centros de investigación do Sistema Universitario de Galicia

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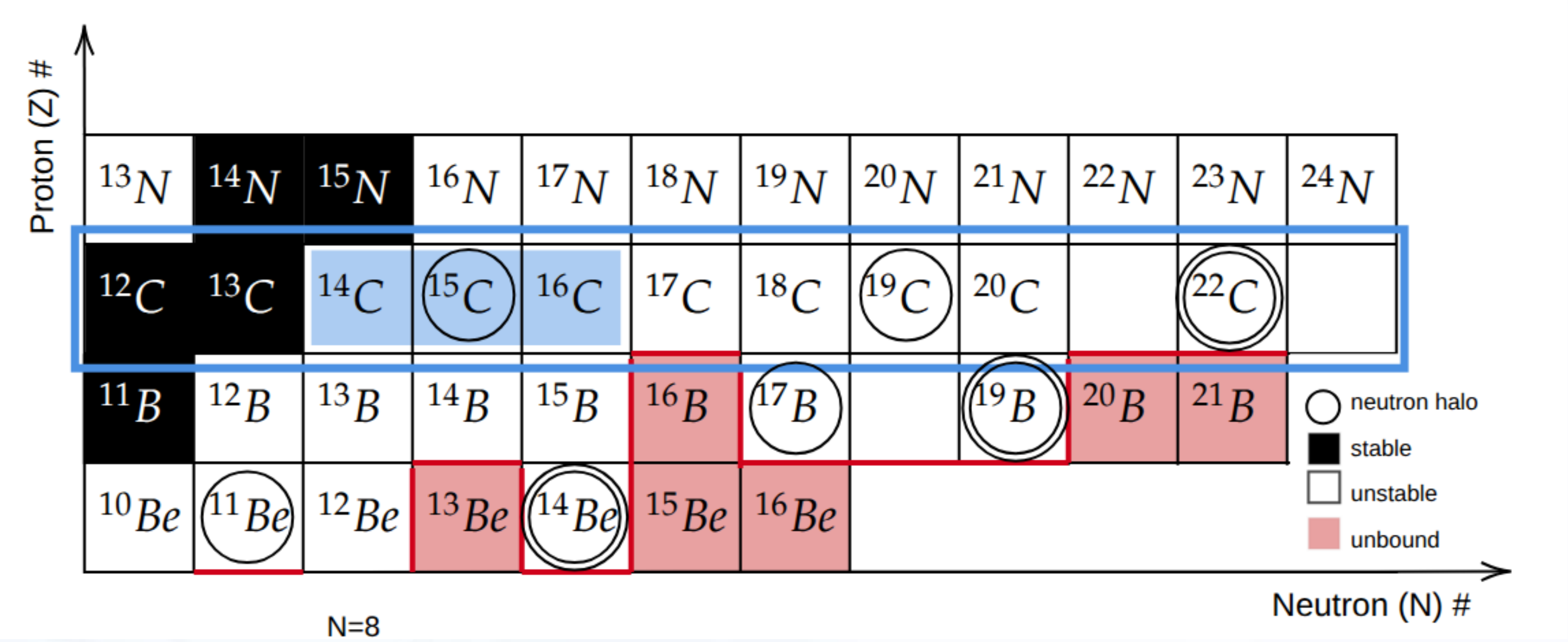
Xacobeo 2027

Neutron rich carbon isotopes



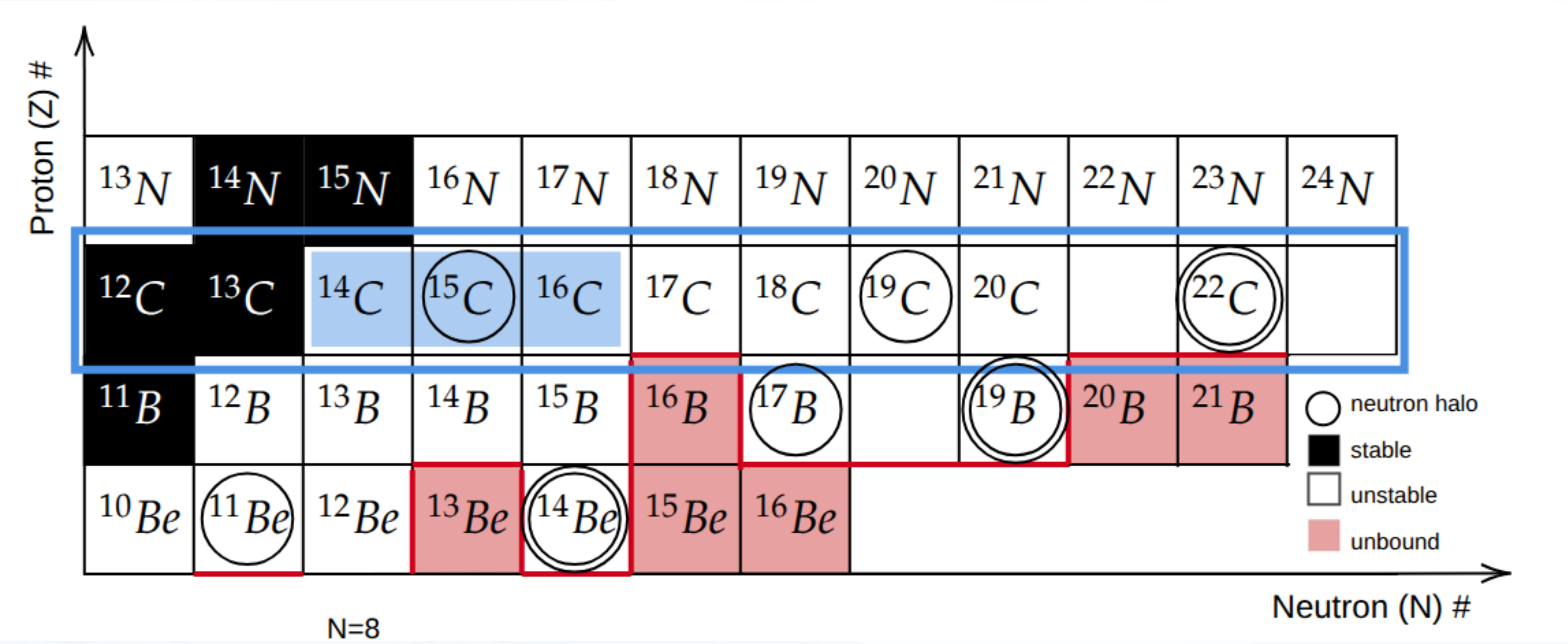
$$\Delta S = S_p - S_n \ [MeV]$$

^{13}C	12.59
^{14}C	12.65
^{15}C	19.86
^{16}C	18.30

Good test for N=8 shell gap weakening near the dripline

^{15}C as a loosely bound valence neutron system [computed from NNDC, *NuDat 3]*.

Neutron rich carbon isotopes



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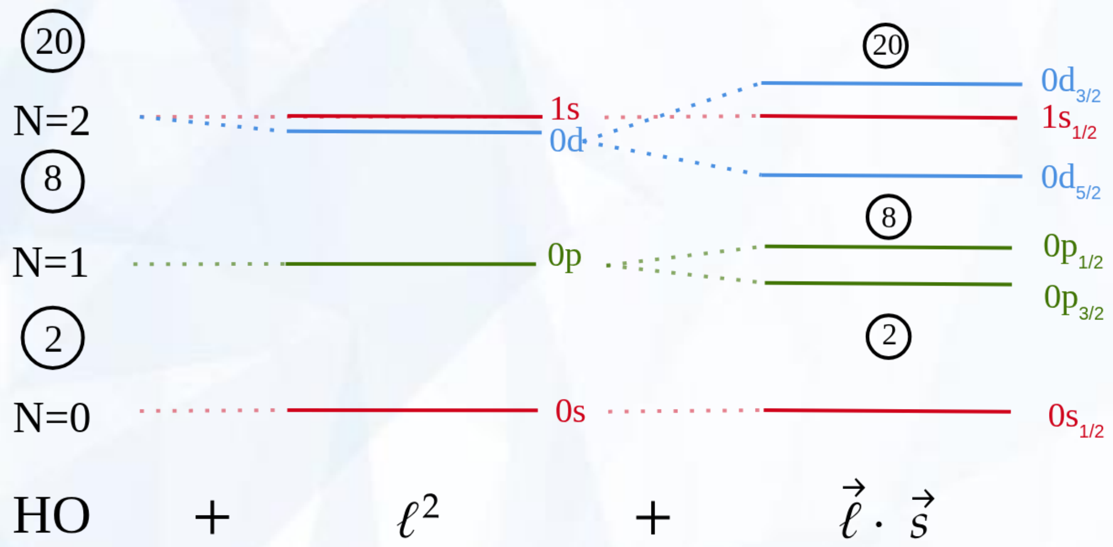
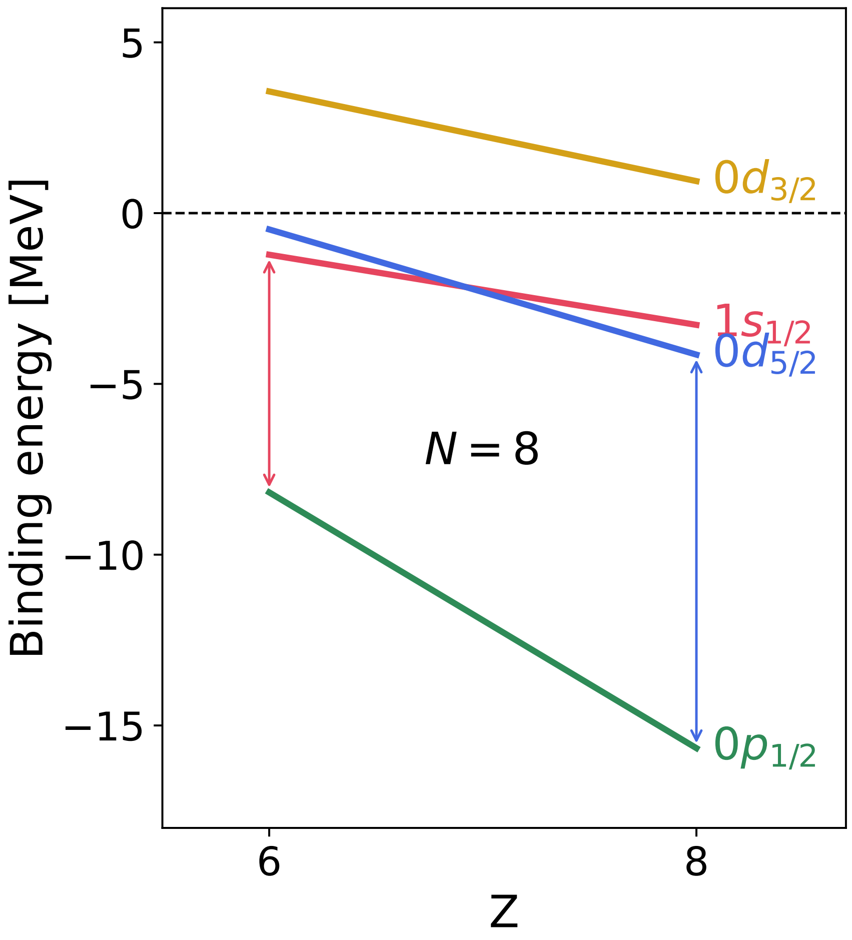
Good test for N=8 shell gap weakening near the dripline

Sensitive probe of shell evolution and emerging halo/skin structures

^{15}C as a loosely bound valence neutron system [computed from NNDC, *NuDat 3]*.

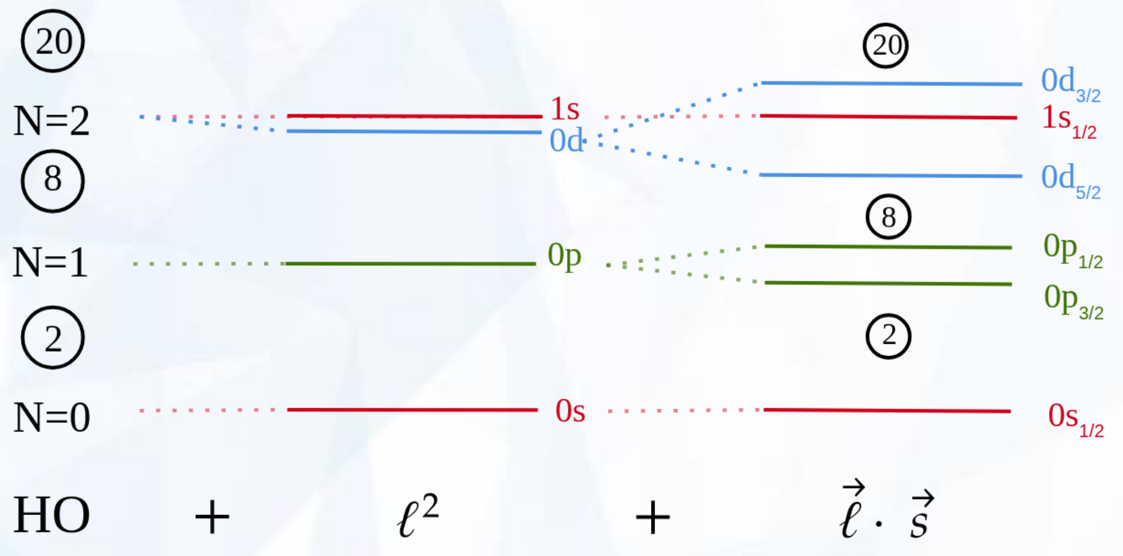
N=8 gap evolution

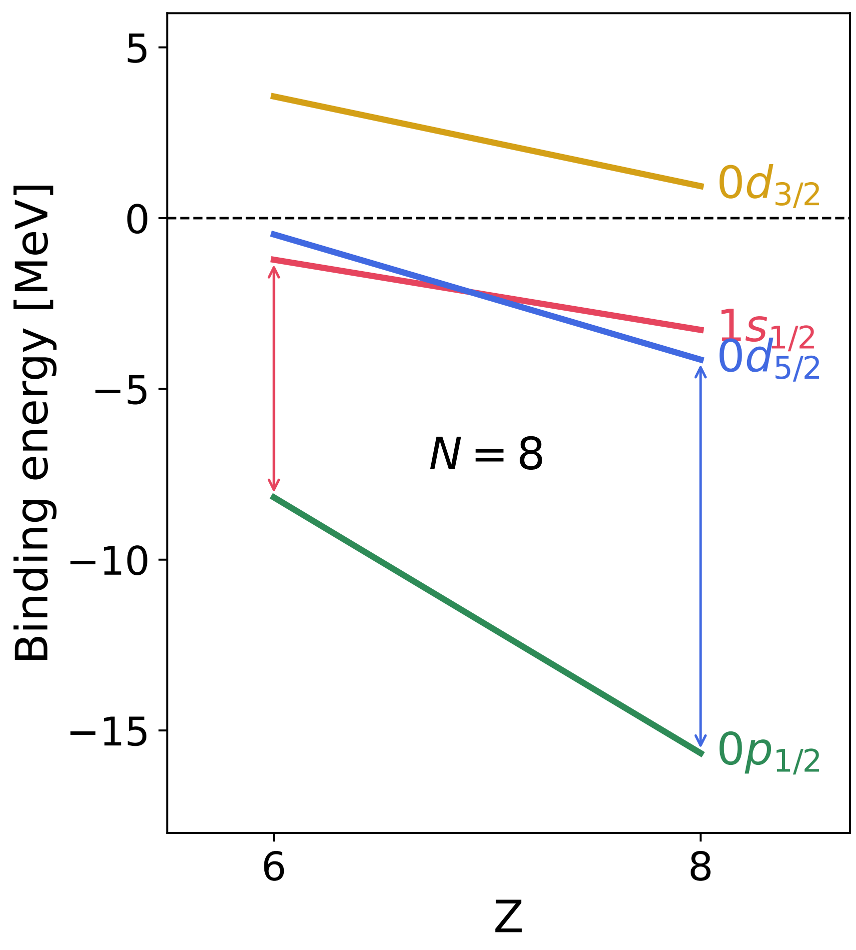




Adapted from O. Sorlin and M.-G. Porquet, Prog. Part. Nucl. Phys. 61 (2008) 602–673.

N=8 gap evolution





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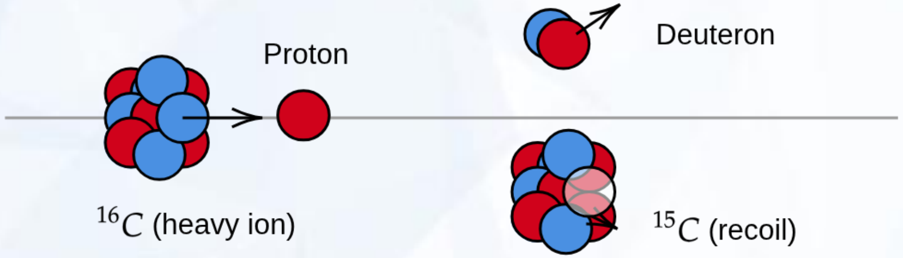
Inversion of the $0d_{5/2}$ -$1s_{1/2}$ orbitals: as protons empty $\pi 0p_{1/2}$ from O→C, the $\pi p_{1/2}$-$\nu d_{5/2}$ tensor force weakens.

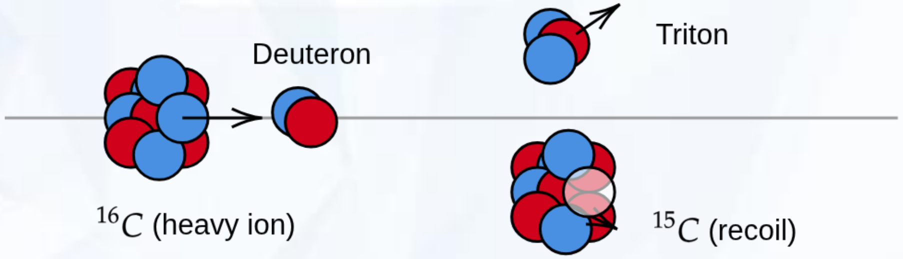
^{15}C is an established **one-neutron halo:**

- Weakly bound: $S_n(^{15}C)$=1.218 MeV, can extend far from the core.
- GS is $1/2^+$: ℓ=0, the wavefunction can extend further than the nuclear surface (no centrifugal barrier).

One-neutron transfer reactions



$$^{16}C + p \to d + {}^{15}C$$



$$^{16}C + d \to t + {}^{15}C$$

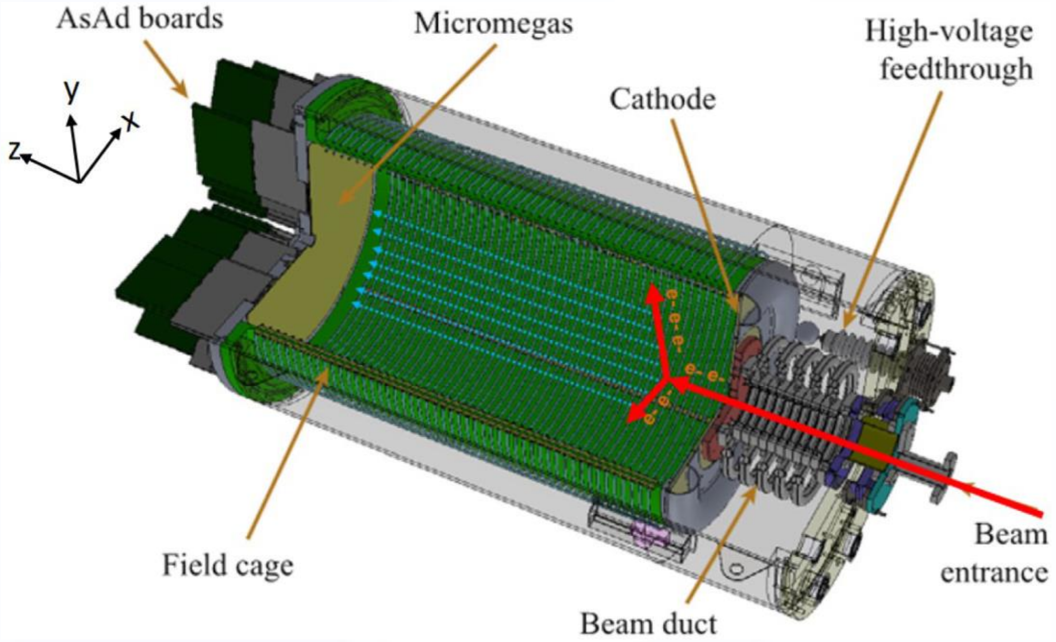
Neutron-transfer reactions → direct probes of single-particle structure & shell evolution

- Populate the $1/2^+$ GS and $5/2^+$ excited state of ^{15}C separately → a direct test of the $0d_{5/2}$-$1s_{1/2}$ inversion
- (p,d) and (d,t) on ^{16}C remove a neutron, probing p-shell hole states in ^{15}C

Extracted observable: C^2S — quantifies occupancy of a given orbital, and the purity/cross-shell admixture of the ^{16}C ground state $\langle ^{16}C(gs) | ^{15}C(gs) \otimes \nu(1s_{1/2}) \rangle$

ATTPC: Active Target Time Projection Chamber

- Designed for **low-intensity exotic beams in inverse kinematics.**



J.S. Randhawa et al. NIMP Res. A. Volume **948** (2019)

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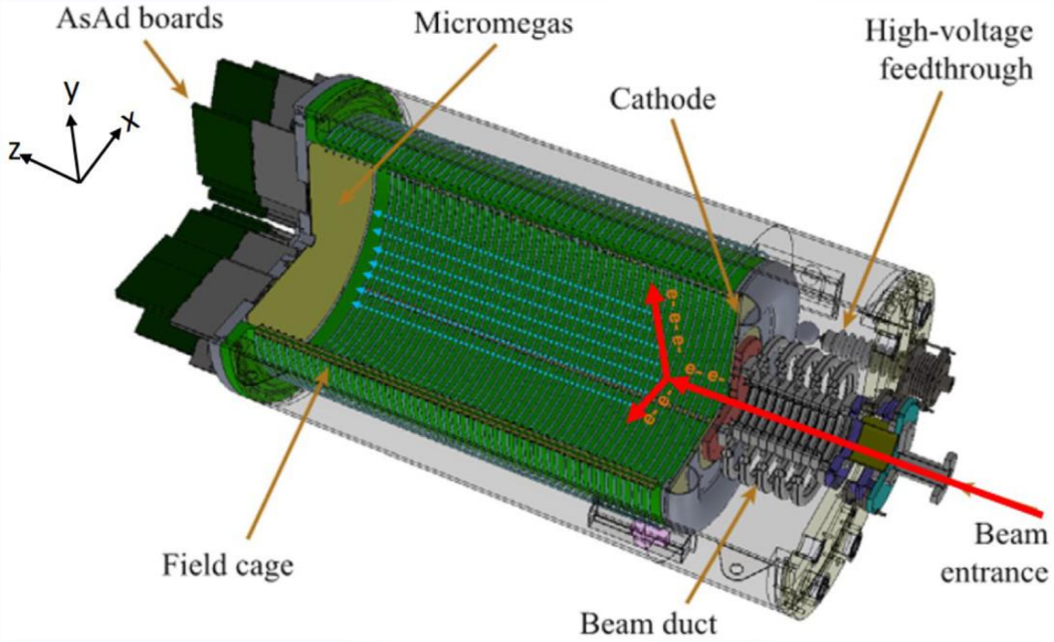

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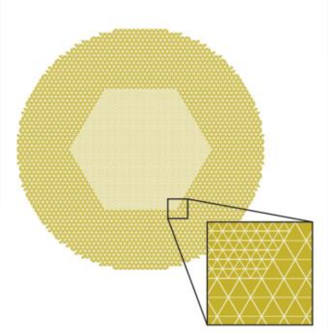


J. Bradt et al. NIMP Res A. Volume **875** (2017) 65-79

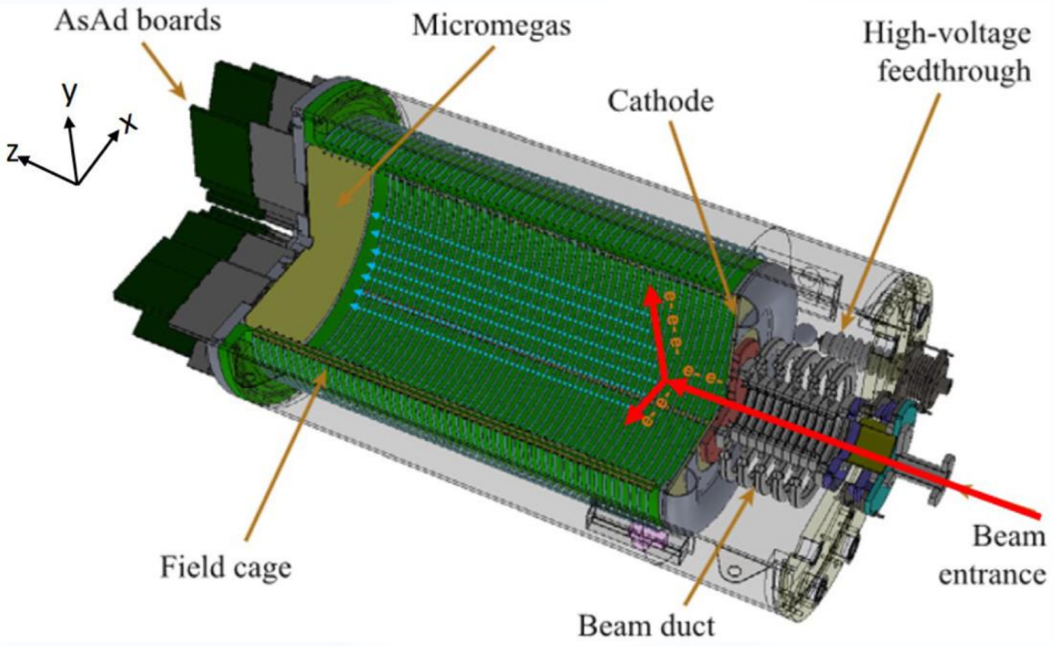
ATTPC: Active Target Time Projection Chamber

- Designed for **low-intensity exotic beams in inverse kinematics.**

- **Thick target:** high luminosity and broad acceptance
- **Pad plane with high granularity:** 10k pads, finer near the vertex

- **Scattering angle & momentum** - from track reconstruction in *B*-field
- **Missing mass method** – reveals bound & unbound recoil states

1° angular resolution
3% FWHM energy resolution



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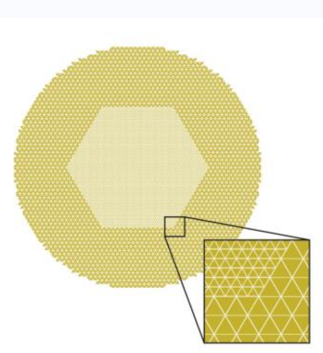

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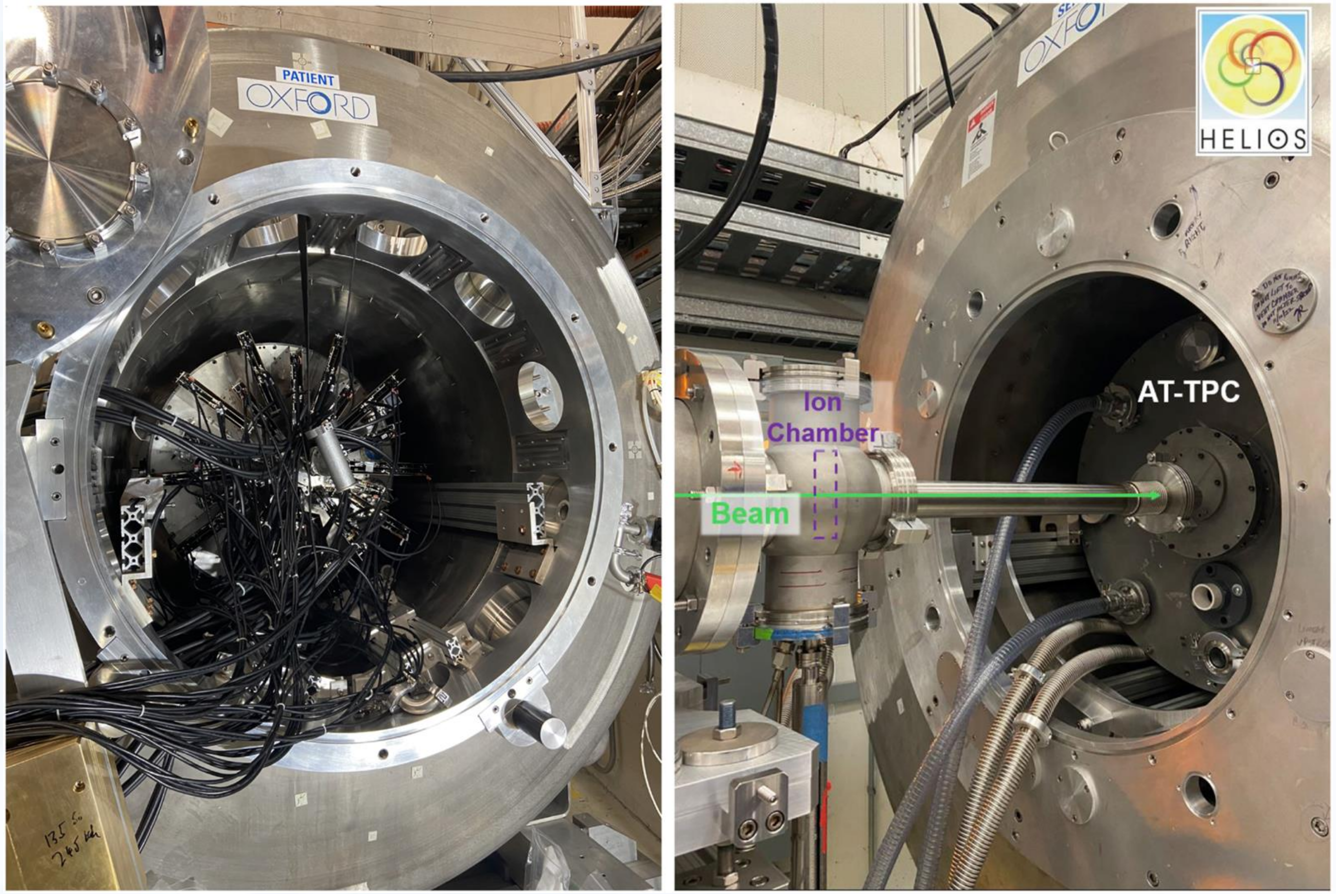
ATTPC transfer reaction program @ANL



Left panel: Downstream end of the AT-TPC. Right panel: Upstream end of the AT-TPC coupled to RAISOR through an ion chamber

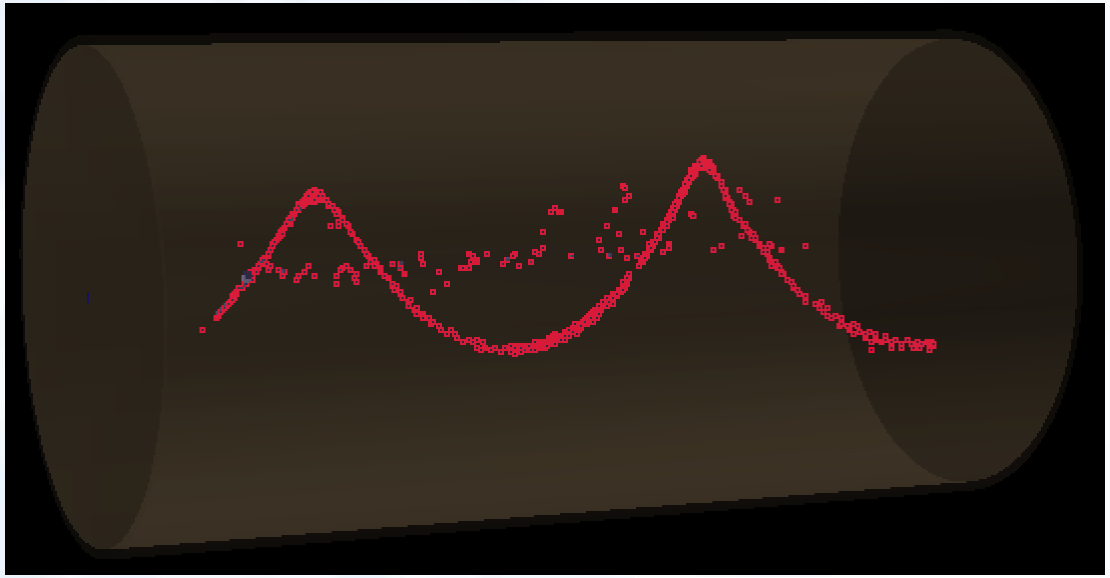
a1975 — $^{16}C(p,d)^{15}C$ & $^{16}C(d,t)^{15}C$ neutron pickup reactions

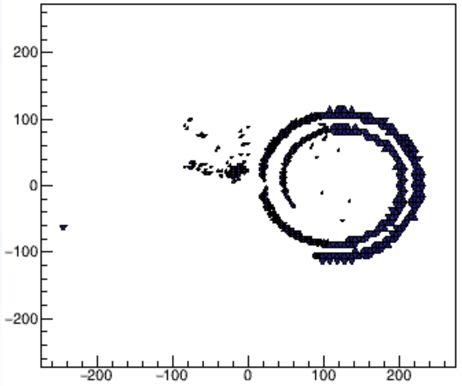
- H_2 / D_2 pressure @300 Torr
- HELIOS @2.85 T
- Beam intensity: $2 \cdot 10^3$ pps
- E_{beam} (^{16}C)= 196 ± 2 MeV (measured upstream of IC)

Y. Ayyad et al., Frontiers in Physics, 10.3389/fphy.2025.1539148

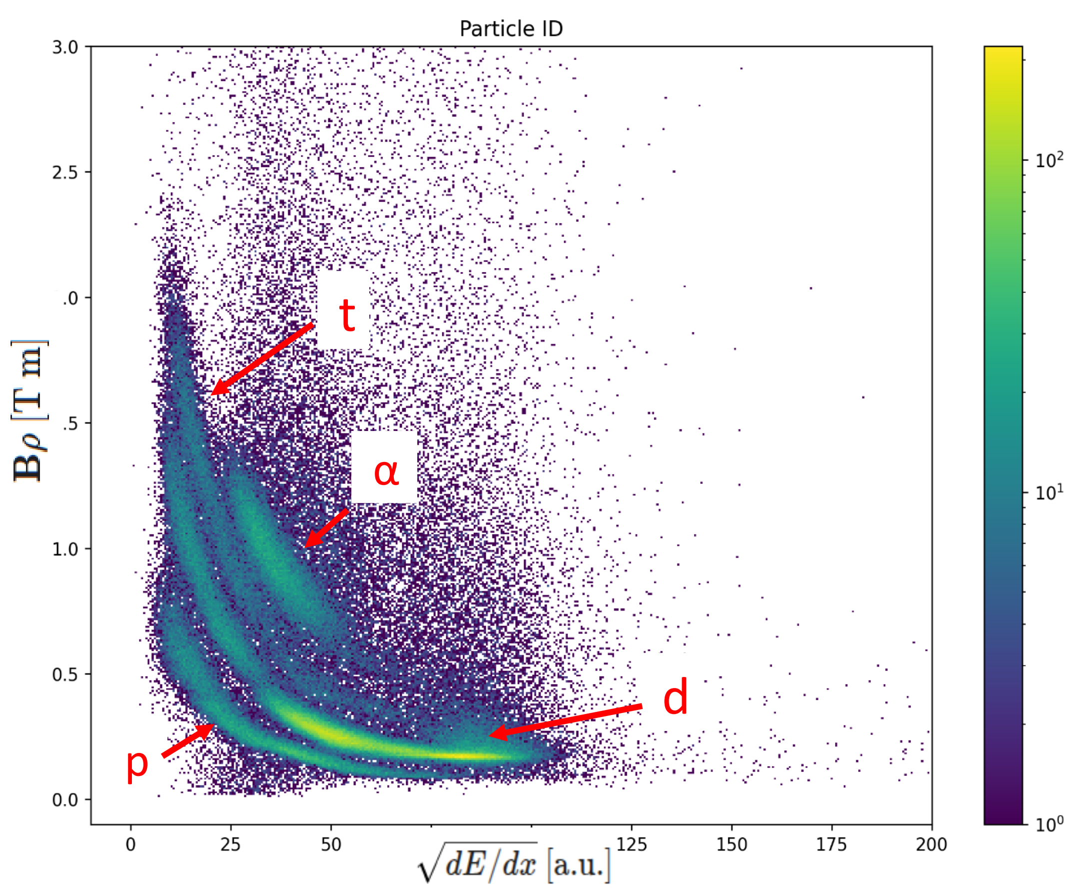
Argonne NATIONAL LABORATORY

a1975 experiment





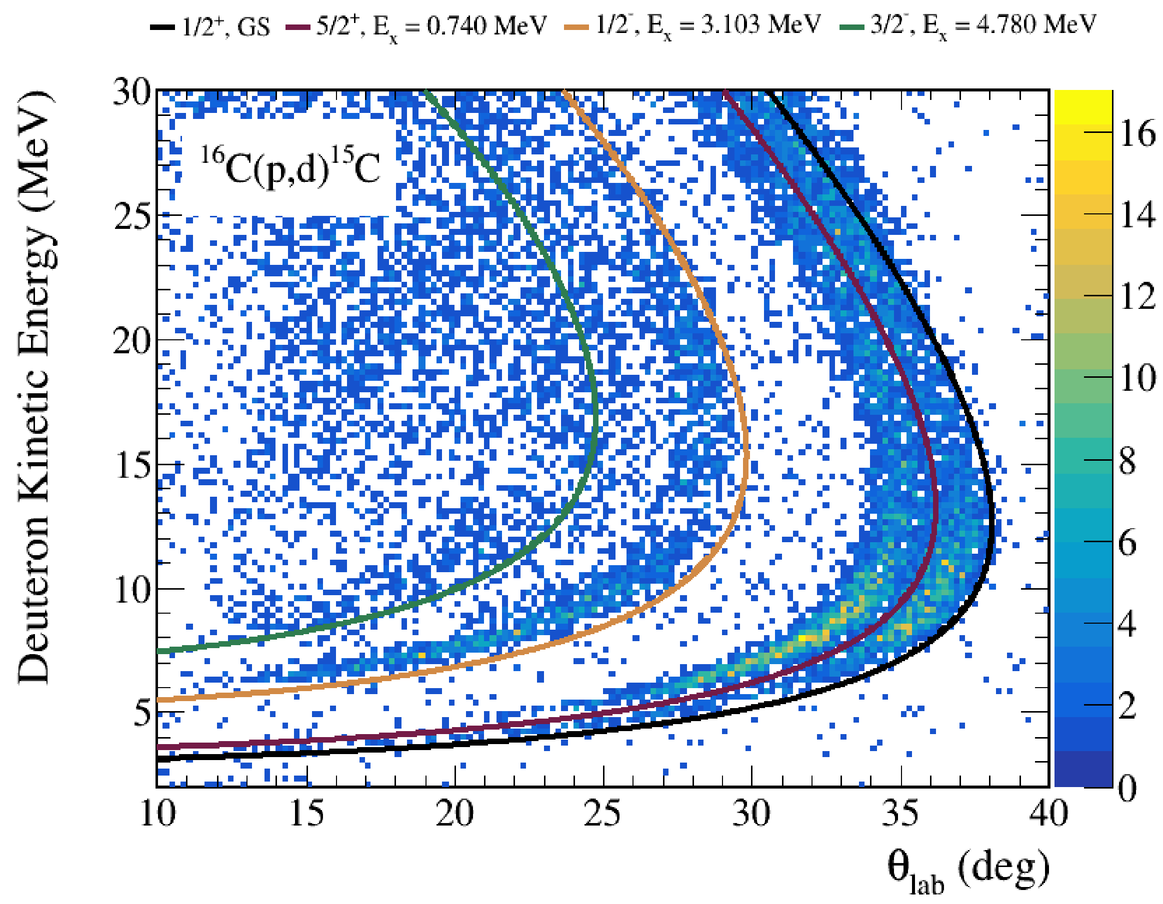
3D point cloud in the chamber volume — x,y from pad position, z reconstructed from drift time

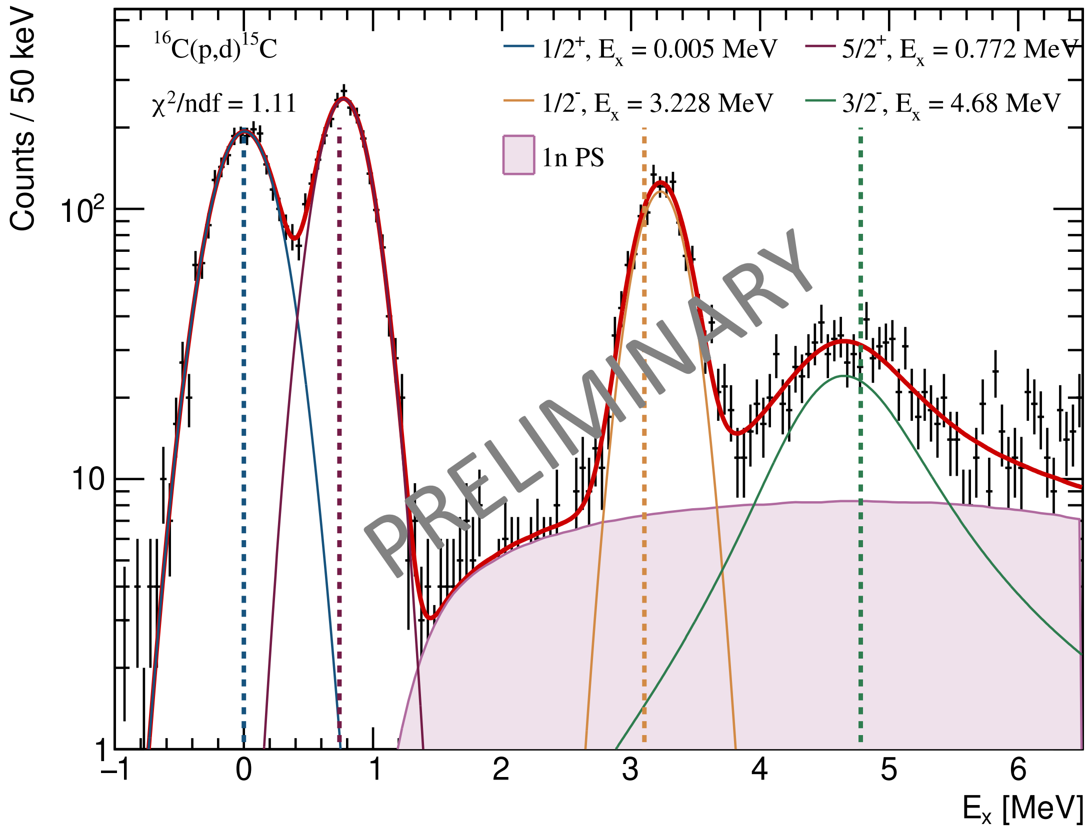


Particle identification (Bρ vs. √(dE/dx)) for ^{16}C(p,d) case

$^{16}C(p, d)^{15}C$

2 bound + 2 unbound states: S_n= 1218.1 keV

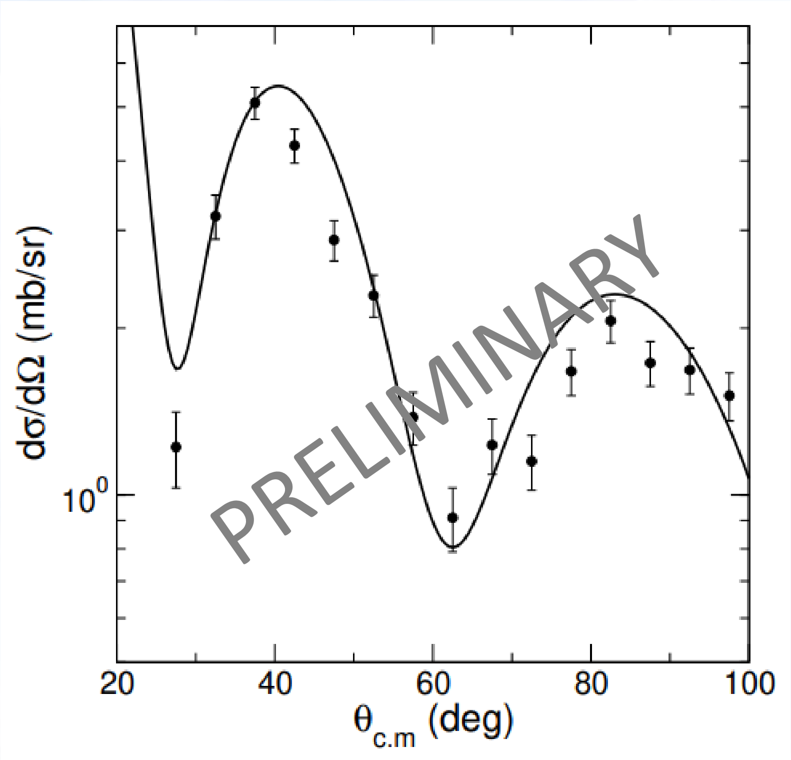




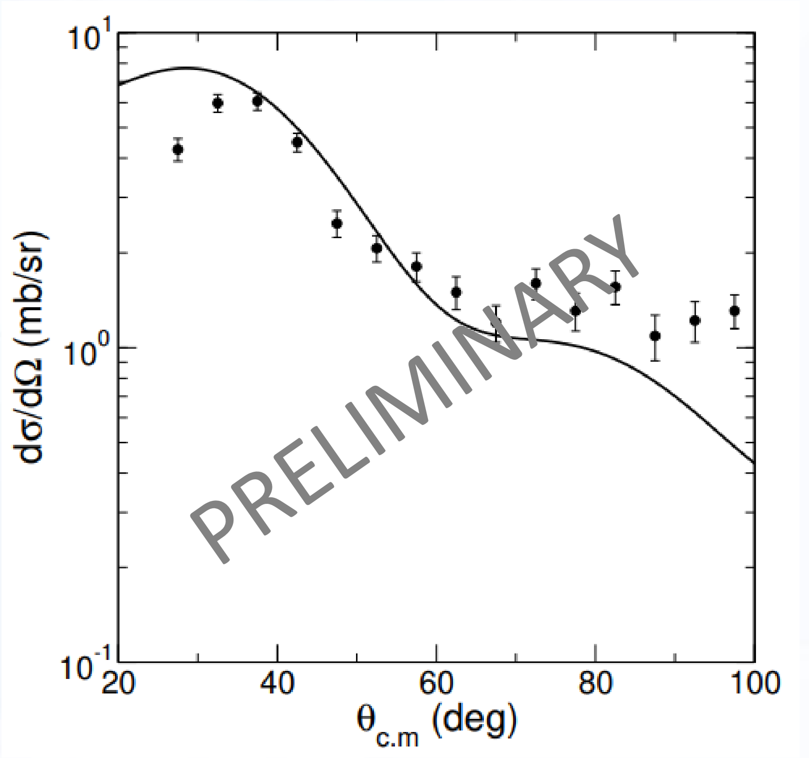
σ = 188 ± 4 keV

$^{16}C(p, d)$ cross sections

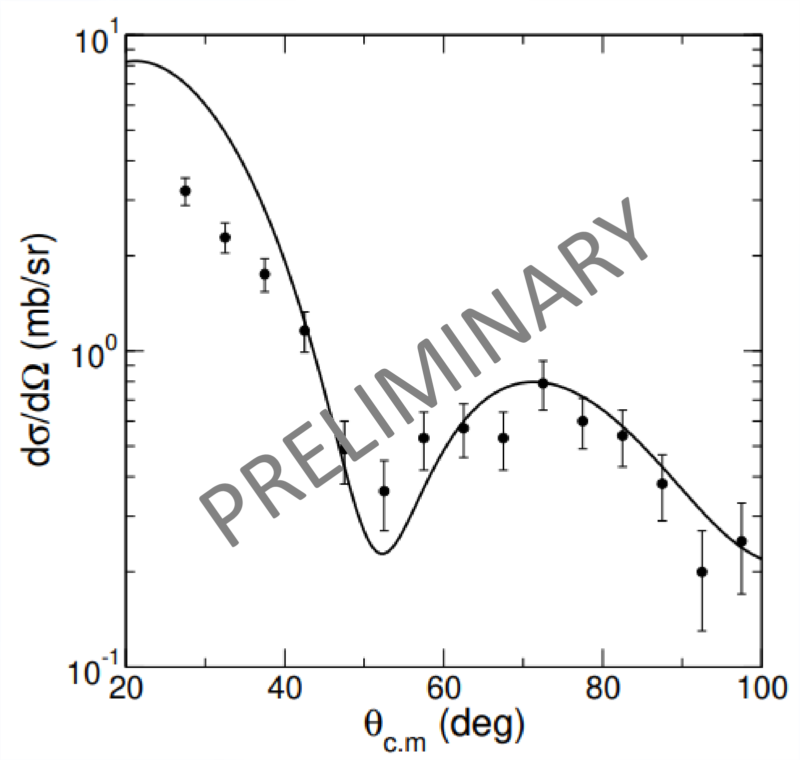
CRC calculations *[Comput. Phys. Rep. 7, 167 (1988)]*
Outgoing channel: Daenick et al. *[Phys. Rev. C 21, 2253 (1980)]*
(Not done yet for the 4th state)



Ground state: $1s_{1/2}$



1st excited state: $1d_{5/2}$@740 keV

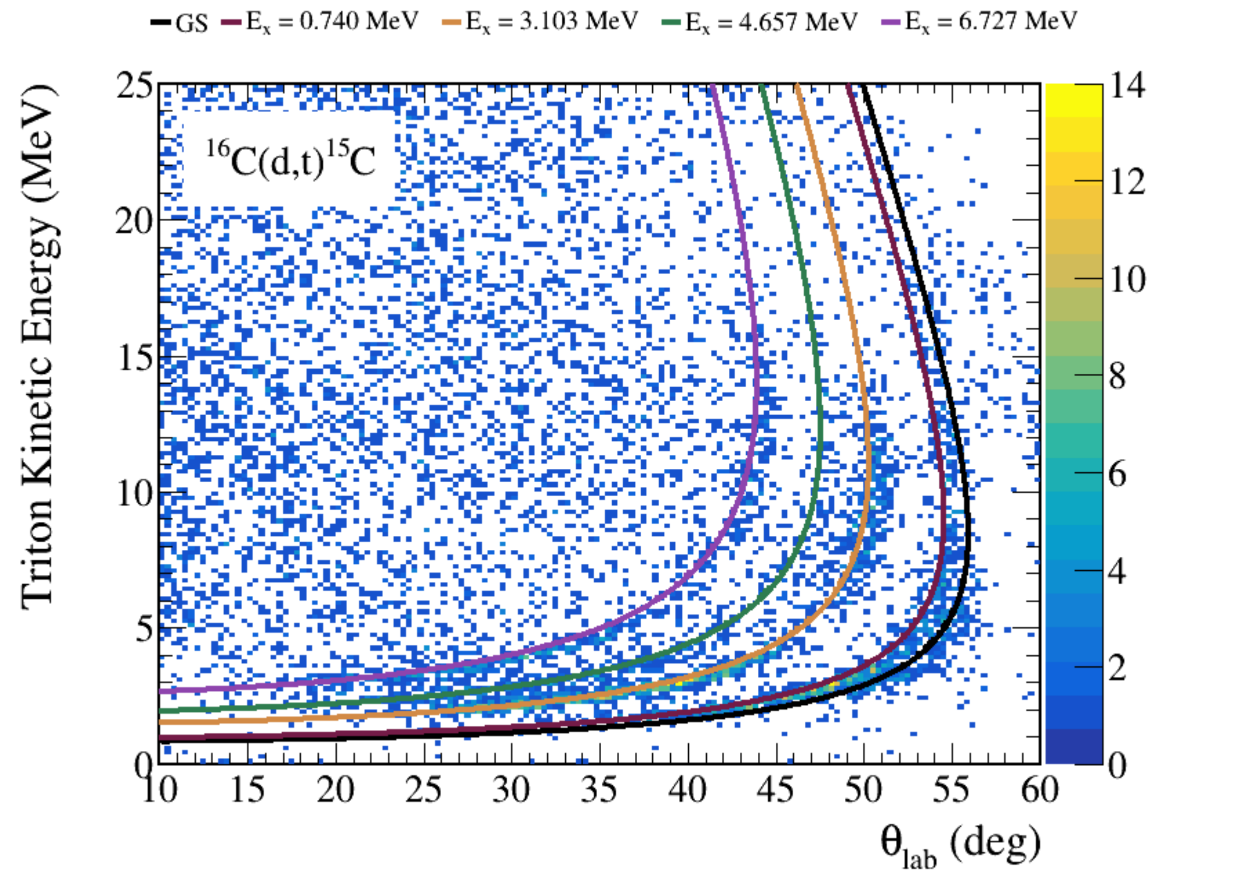


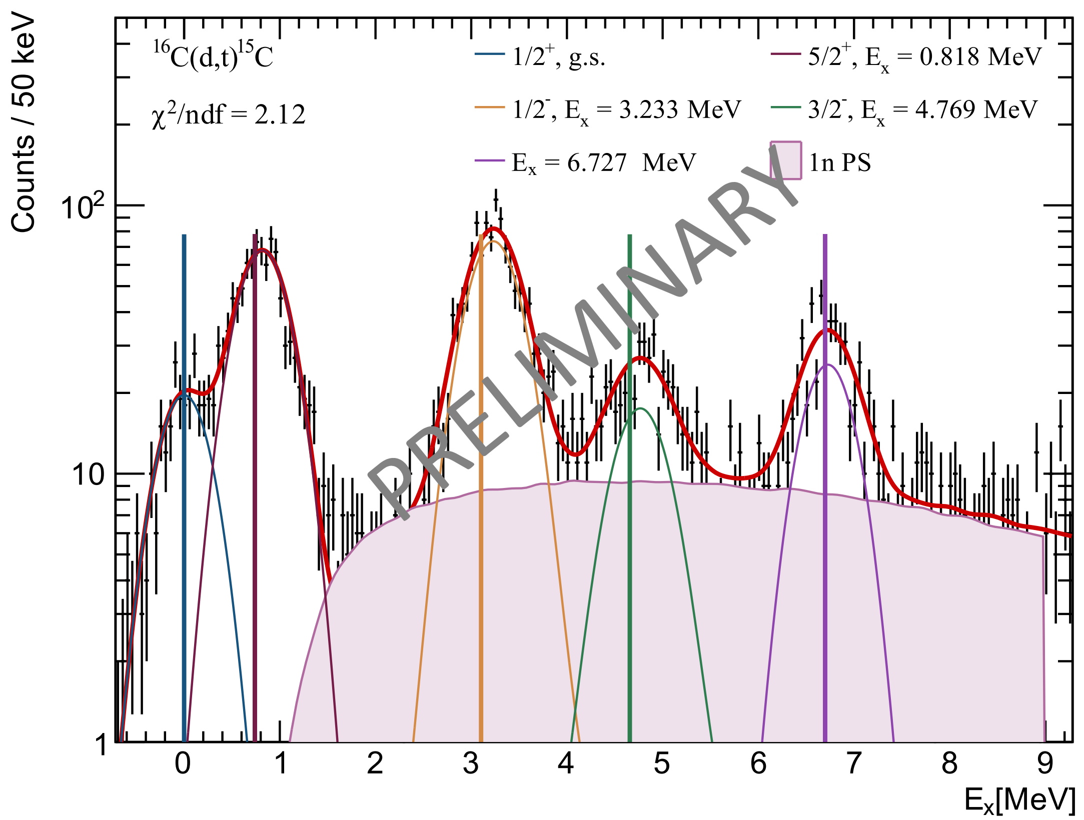
2nd excited state: $1p_{1/2}$@3.1 MeV (unbound)

Theoretical calculations performed by Nicholas Keeley (nicholas.keeley@ncbj.gov.pl)

$^{16}C(d, t)^{15}C$

2 bound + 3 unbound states: S_n= 1218.1 keV

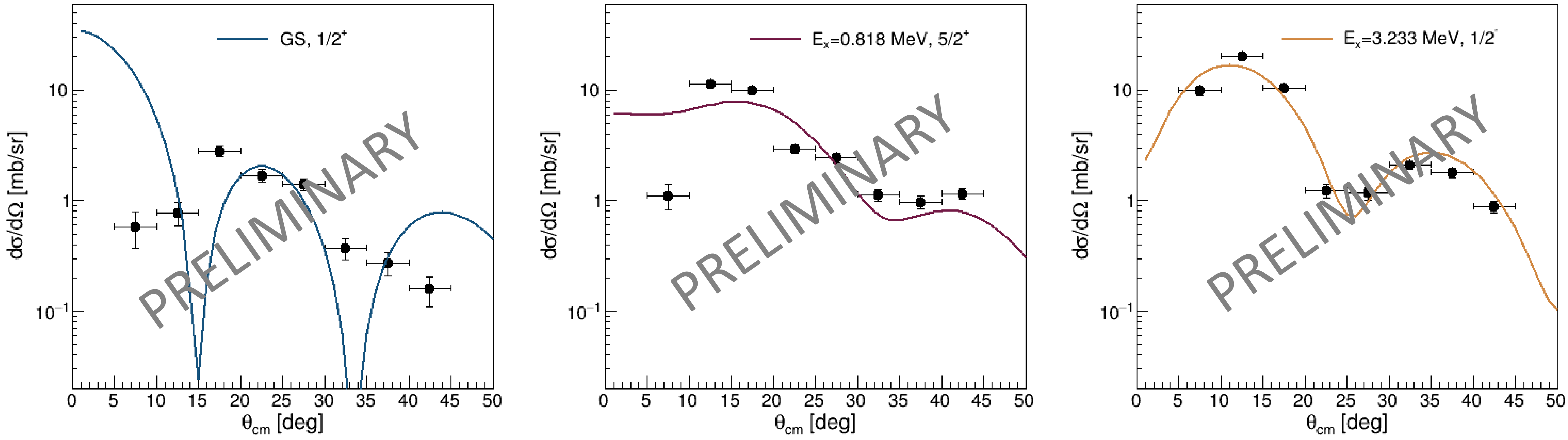




σ = 270 ± 11 keV

^{16}C(d, t) cross sections

Incident channel: Daehnick et al. *[Phys. Rev. C 21, 2253 (1980)]*
Outgoing channel: Becchetti-Greenlees mass-3 *[Phys. Rev. 182, 1190]*
Overlap <^{16}C|^{15}C+n>: Woods-Saxon [Phys. Rev. 95, 577–578 (1954)]



Quasi-bound state approximation

$^{16}C(d, t)$ cross sections

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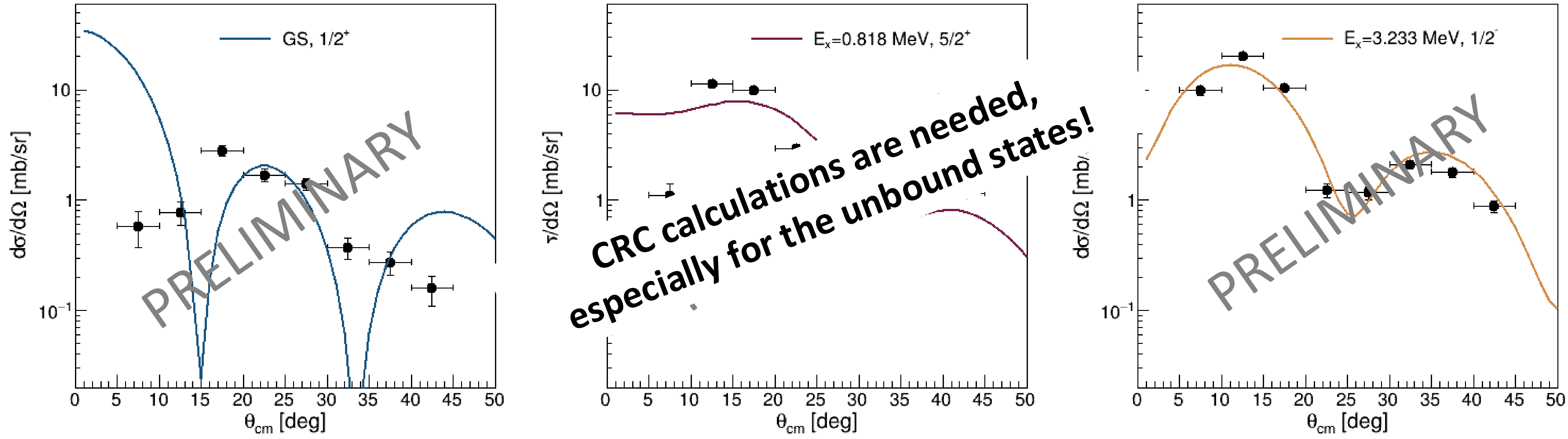
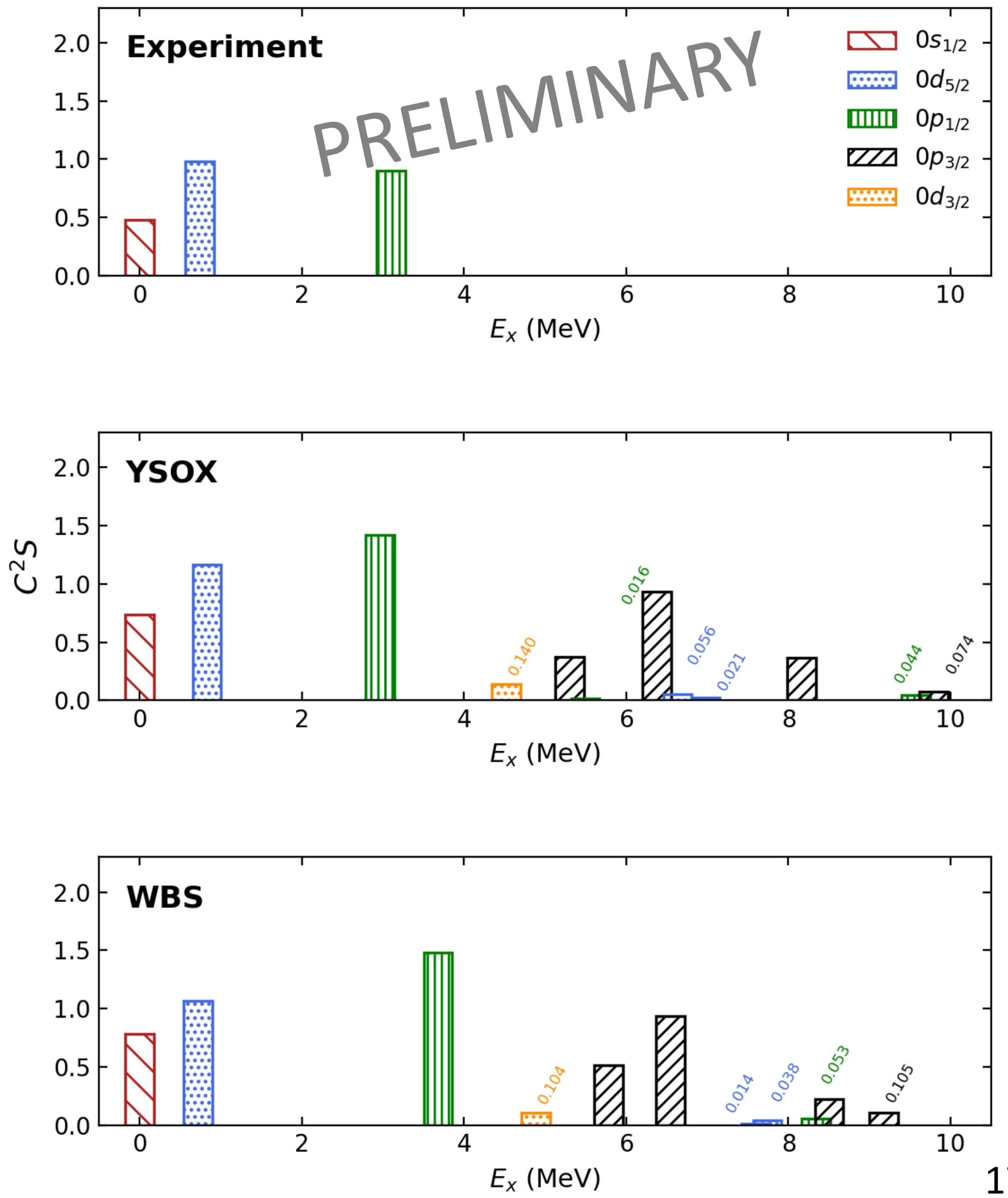


Quasi-bound state approximation

SM calculations

YSOX: its T=0 tensor term ($\pi p_{1/2} - \nu d_{5/2}$) and inclusion of $2\hbar\omega$ cross-shell excitations better reproduce the fragmentation in ^{15}C. *Phys. Rev. C 85, 064324 (2012)*



SM calculations performed by: J. Chen (chenjie@sustech.edu.cn)

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- **Bound states (Ex < 1 MeV)**

Benchmark the absolute $0s_{1/2}$ and $0d_{5/2}$ spectroscopic strengths.

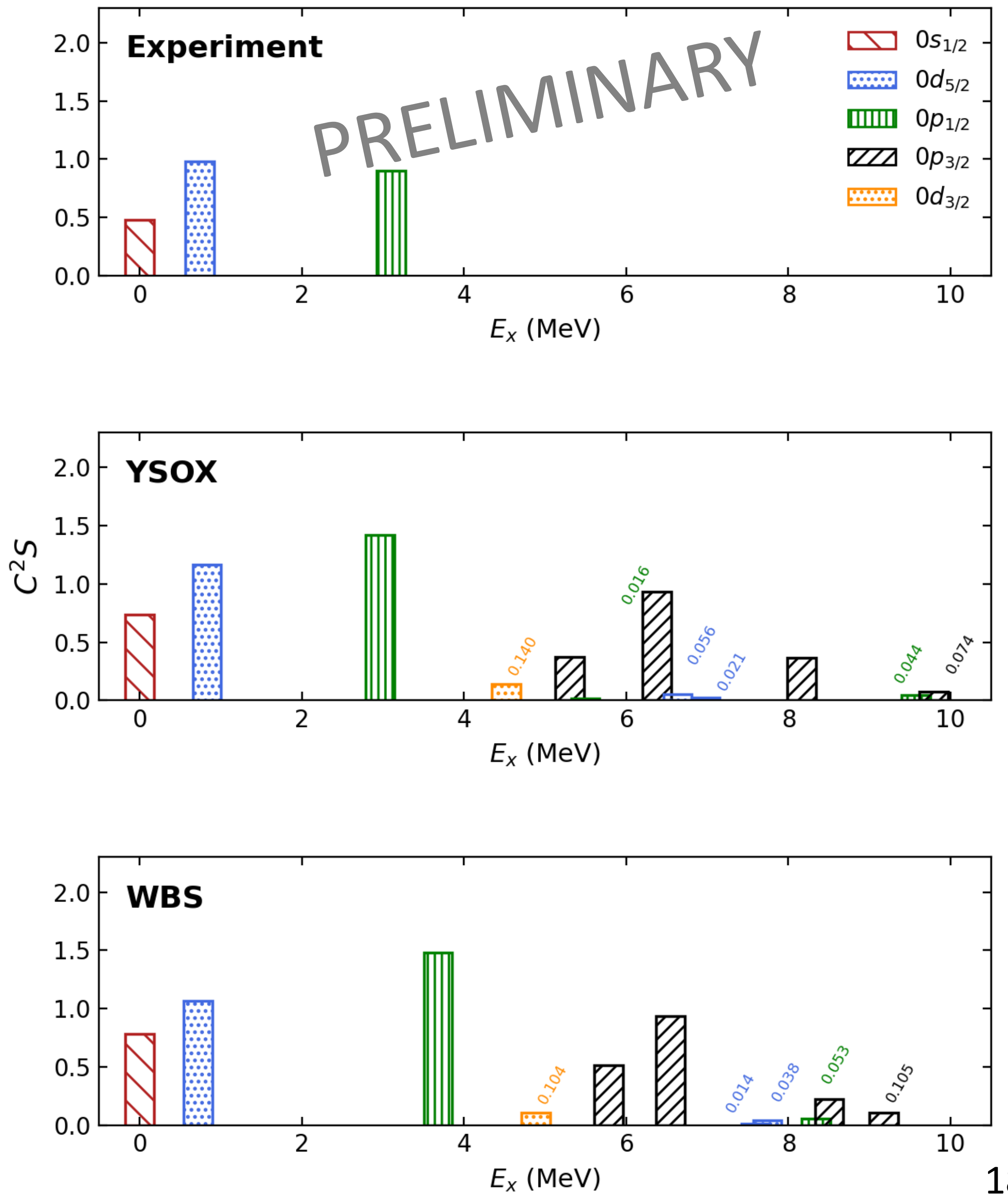
- **Negative-Parity States (> 3 MeV)**

Configurations with a $(sd)^2\,(0p)^{-1}$ structure relative to a ^{14}C core.

- **Cross-Shell Excitations (4.5 - 7 MeV)**

Fragmented positive-parity strength → active (2p-2h) mixing, driven by ⟨pp|V|sd sd⟩.

SM calculations performed by: J. Chen (chenjie@sustech.edu.cn)



Spectroscopic factors

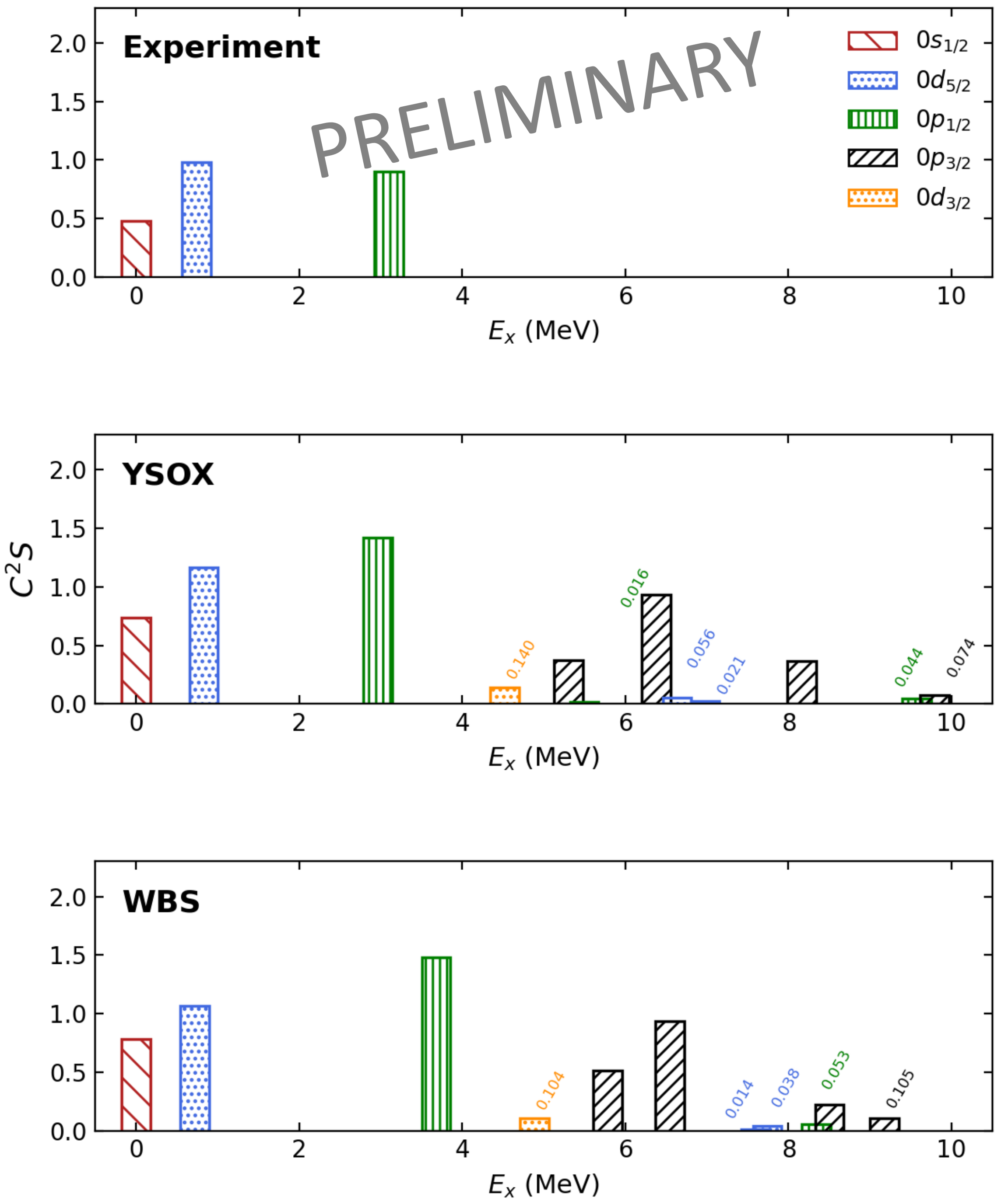
$$\left(\frac{d\sigma}{d\Omega}\right)^{exp} = C^2S \times \left(\frac{d\sigma}{d\Omega}\right)^{sp}$$

We can compare the C^2S^{exp} with C^2S^{th} computing the quenching factor, R_s, for both theoretical models.

$$R_s = \frac{C^2S^{exp}}{C^2S^{th}}$$

J^π	E_x^{exp} (MeV)	C^2S^{YSOX}	R_s^{YSOX}
$1/2^+$	0.00	0.7341	0.6541
$5/2^+$	0.74	1.1666	0.8436
$1/2^-$	3.10	1.4218	0.6334

SM calculations performed by: J. Chen (chenjie@sustech.edu.cn)



Summary and outlook

Status & Next Steps

- **a1975 analysis:** Finalizing spectroscopic factors and cross-sections; paper in preparation.
- **Broader Program:** Ongoing analysis of two-neutron transfer $^{16}C(p, t)^{14}C$.
- Preliminary quantifying the quenching factor R_s against shell model predictions.

Physics Outlook

- Combining (p, d) and (d, t) datasets to tightly constrain orbital occupancies in ^{15}C.
- Compare with the future CRC calculations for the missing states.
- Compare with previous measurements.

THANK YOU

Acknowledgments to the AT-TPC collaboration:

[1]Ahn, T., [2]Anthony, A., [3]Avila, M., [4]Bazin, D., [5]Beceiro-Novo, S., [3]Bhatt, K., [6]Cabo, C., [7]Furuno, T., [8]Guimarães, V.,[3,9] Hall-Smith, A., [4]Hunt, C., [10]Jayatissa, H.,[11]Kawabata, T., [3]Kay, B. P., [5]Kumi, H., [6]Lois-Fuentes, J., [6]López-González, J. M.,[12] Macchiavelli, A. , [4]McCann, G., [4,13]Mittig, W., [3]Mueller-Gatermann, C., [6]Muñoz, A., [5]Regueira, D., [11]Sakajo, S., [6]Santamaría, C., [4,13]Serikow, Z., [4,13]Tang, T., [3]Tolstukhin, I., [13]Turi, N., [3]Watwood, N., [4]Zamora, J. C.

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[3]Argonne National Laboratory (ANL)
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[5]Universidade da Coruña (UDC)
[6]Universidade de Santiago de Compostela (USC)
[7]University of Fukui
[8]University of São Paulo
[9]University of York (UoY)
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[11]Osaka University
[12]Oak Ridge National Laboratory (ORNL)
[13]Michigan State University (MSU)

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