Exploring the possible bubble nucleus ^{46}Ar

Nuclear Saturation properties and shell structure

A saturated nuclear density ?

- Liquid-drop model dating back to 1929
- Saturated nuclear matter
- First evidence for a bubble in ^{34}Si
- Renewed interest in nuclear radii: large charge radii
- Shell structure <-> radii and bubbles


ARTICLES
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A proton density bubble in the doubly magic ^{34}Si nucleus

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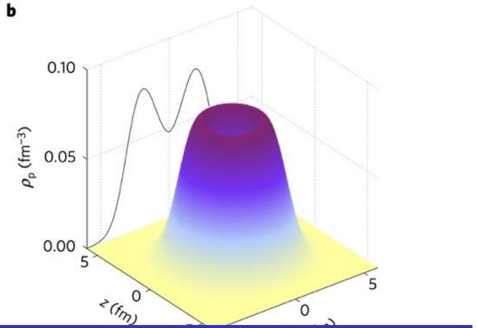
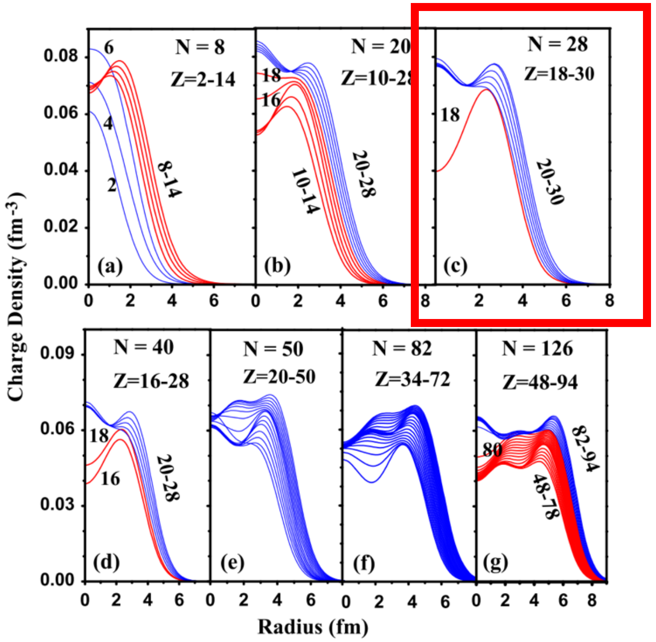
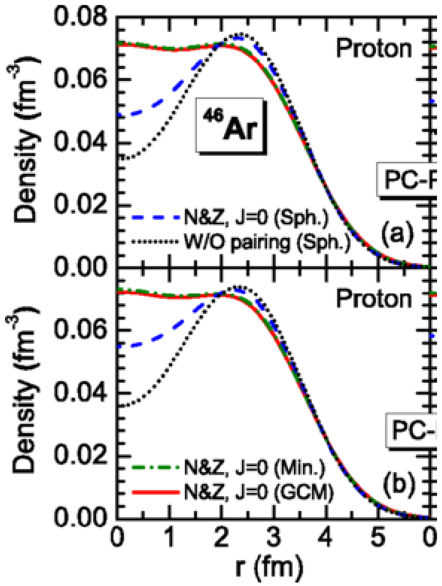




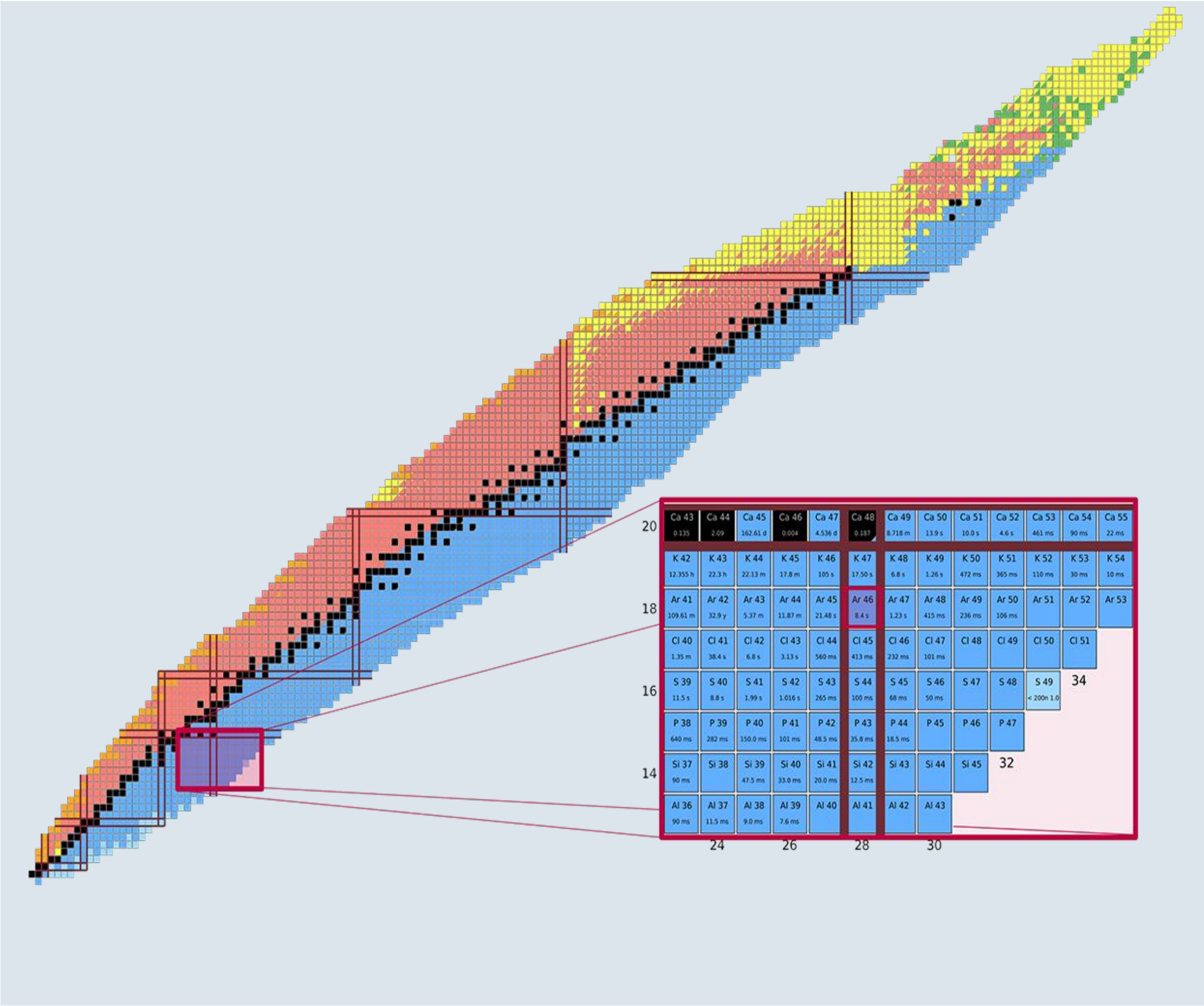
Physics Letters B 788 (2019) 1–6

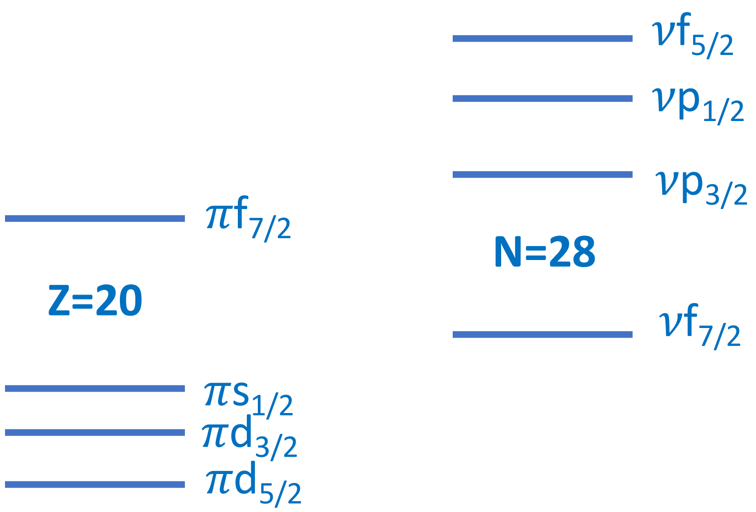


Phys. Rev. C **89**, 017304 (2014)

^{46}Ar: close to stability, but do we understand its structure ?

^{46}Ar: $-2p$ from ^{48}Ca



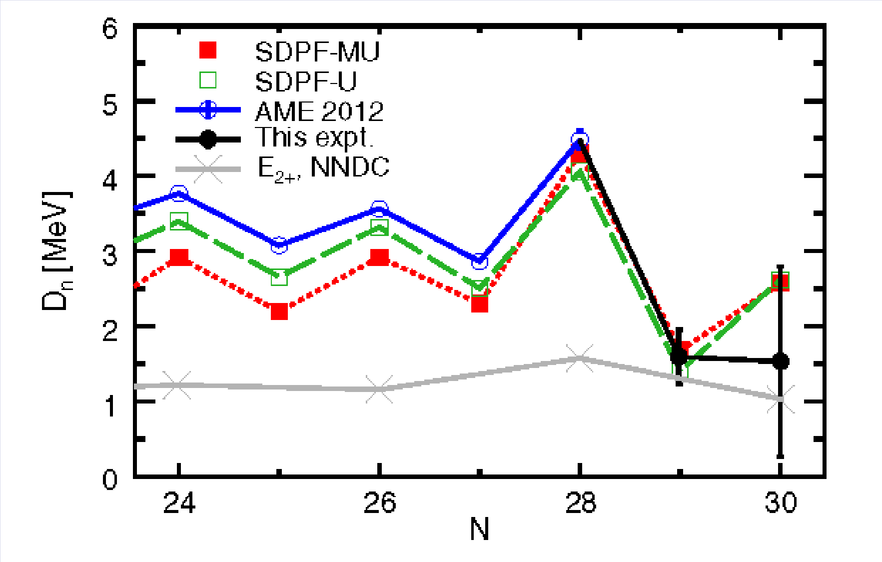


The N=28 shell closure

- The N=28 weakens below ^{48}Ca
- In ^{46}Ar almost one neutron in $p_{3/2}$
- Empirical shell-model Hamiltonians like SDPF-U reproduce the neutron observables very well

Do we understand physics at N=28, Z=18 ?

Neutron observables understood



Excellent theory for neutron-space related quantities:

- confirming N=28 shell closure in ^{46}Ar
- SDPF interaction describes valance-core neutrons interaction very well

Z. Meisel et al. PRL 114, 022501 (2015)

Large discrepancy in B(E2)

Large discrepancy with the measured B(E2) value at N=28:

problem with the proton E2 contribution ?

A. Gade et al., PRC 68, 014302 (2003)

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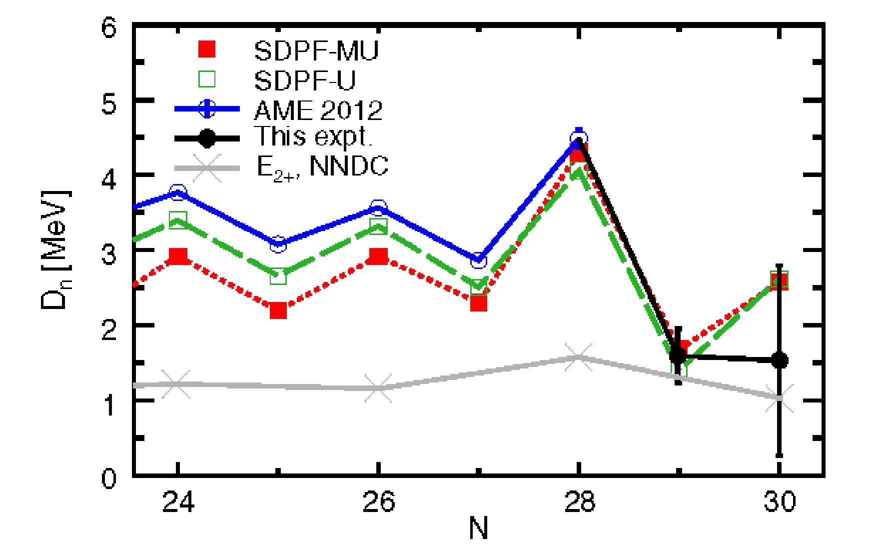
Do we understand physics at N=28 ?

Neutron observables understood



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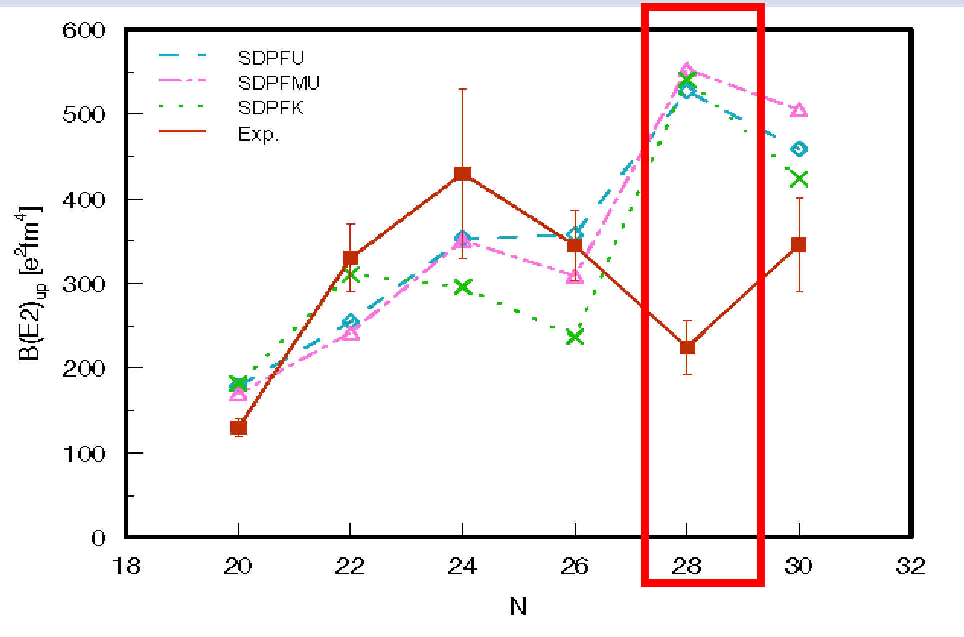

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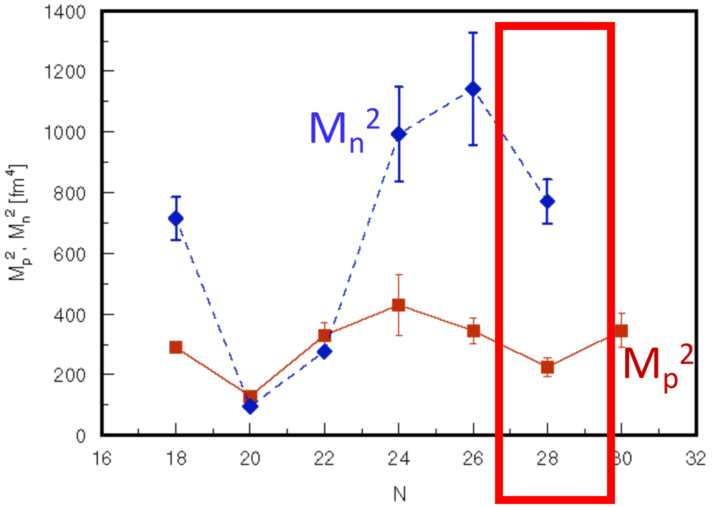
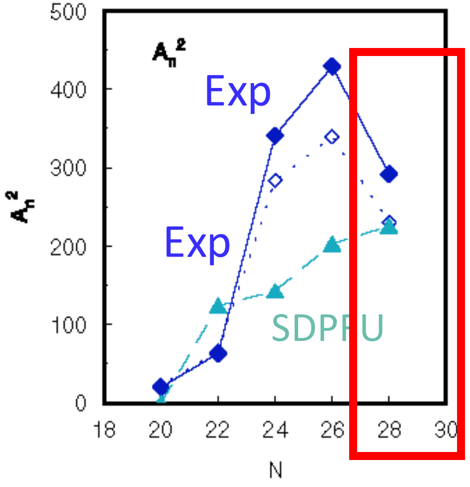
Problem with the predicted proton wave function (?)

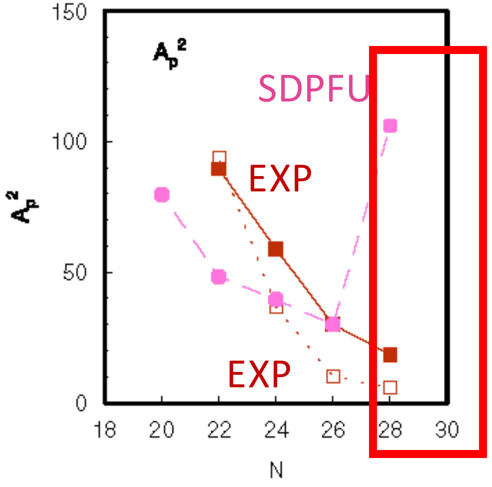
A. Gade et al., PRC 68, 014302 (2003)

S. Calinescu et al., PRC 93, 044333 (2016)

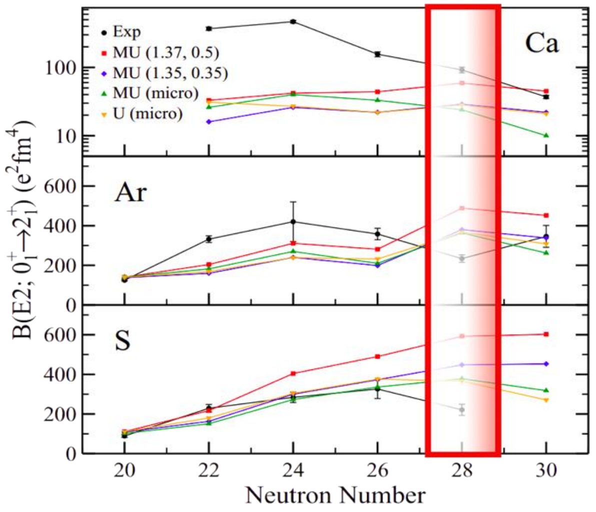
L. A. Riley et al., PRC 72, 024311 (2005)







- Similar discrepancy in ^{44}S, located −2p with respect to ^{46}Ar
- Intermediate-energy Coulomb excitation measurements in agreement with the SDPF-U results up to ^{42}S
- Effect of polarization charges on B(E 2) calculations is found not sufficient to justify the discrepancy in ^{46}Ar and ^{44}S



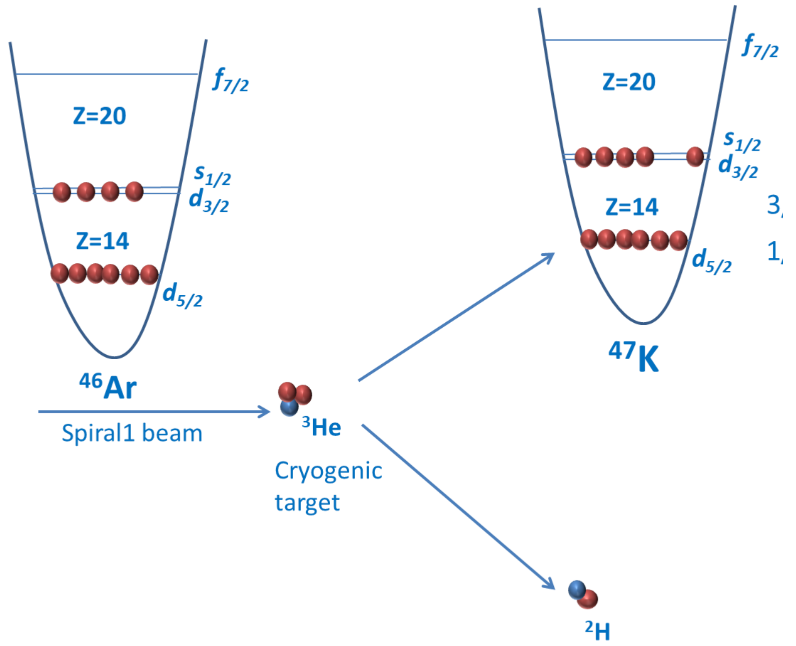
B. Longfellow et al., PRC 103, 054309 (2021)

Need to probe the proton wave function predicted by SDPF:

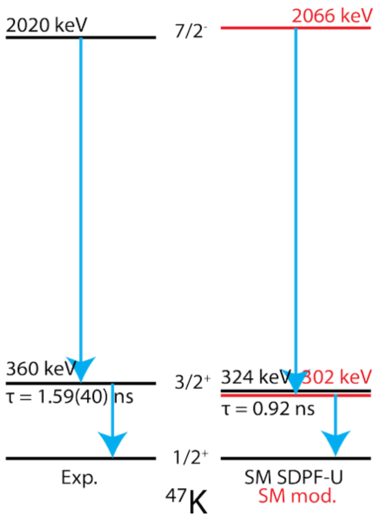
Example: $\pi s_{1/2}$ almost full or empty in ^{46}Ar to decrease B(E2) to exp. value

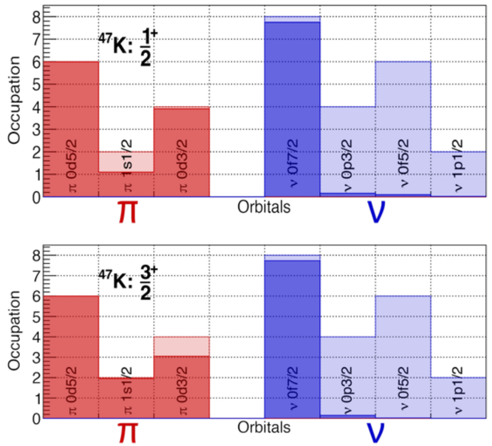
Smaller effect from N=28 quenching:with $\nu p_{3/2}$ almost full, B(E2)$_{up}$ in ^{46}Ar still ~ 350 e^2fm^4

Direct proton transfer in inverse kinematics



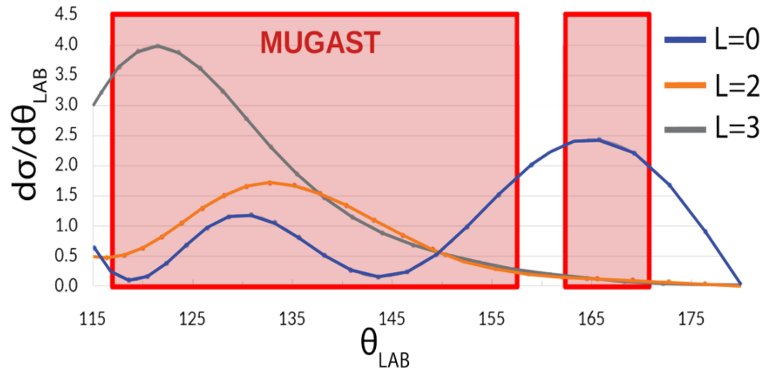
Direct proton-adding reaction to probe the ^{46}Ar ground state wave function





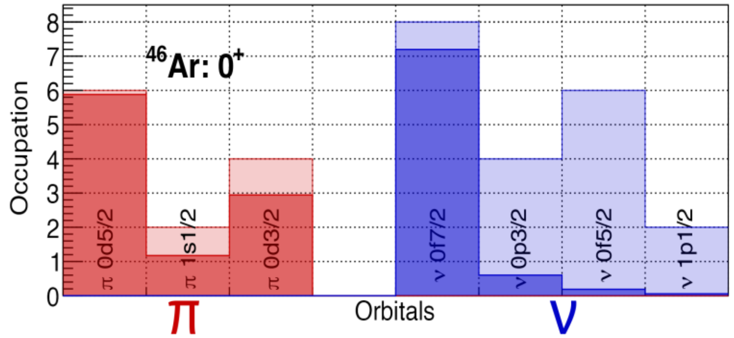
[Banks, S. et al., Nucl. Phys. A 437 2 (1985)]

d laboratory angular distribution

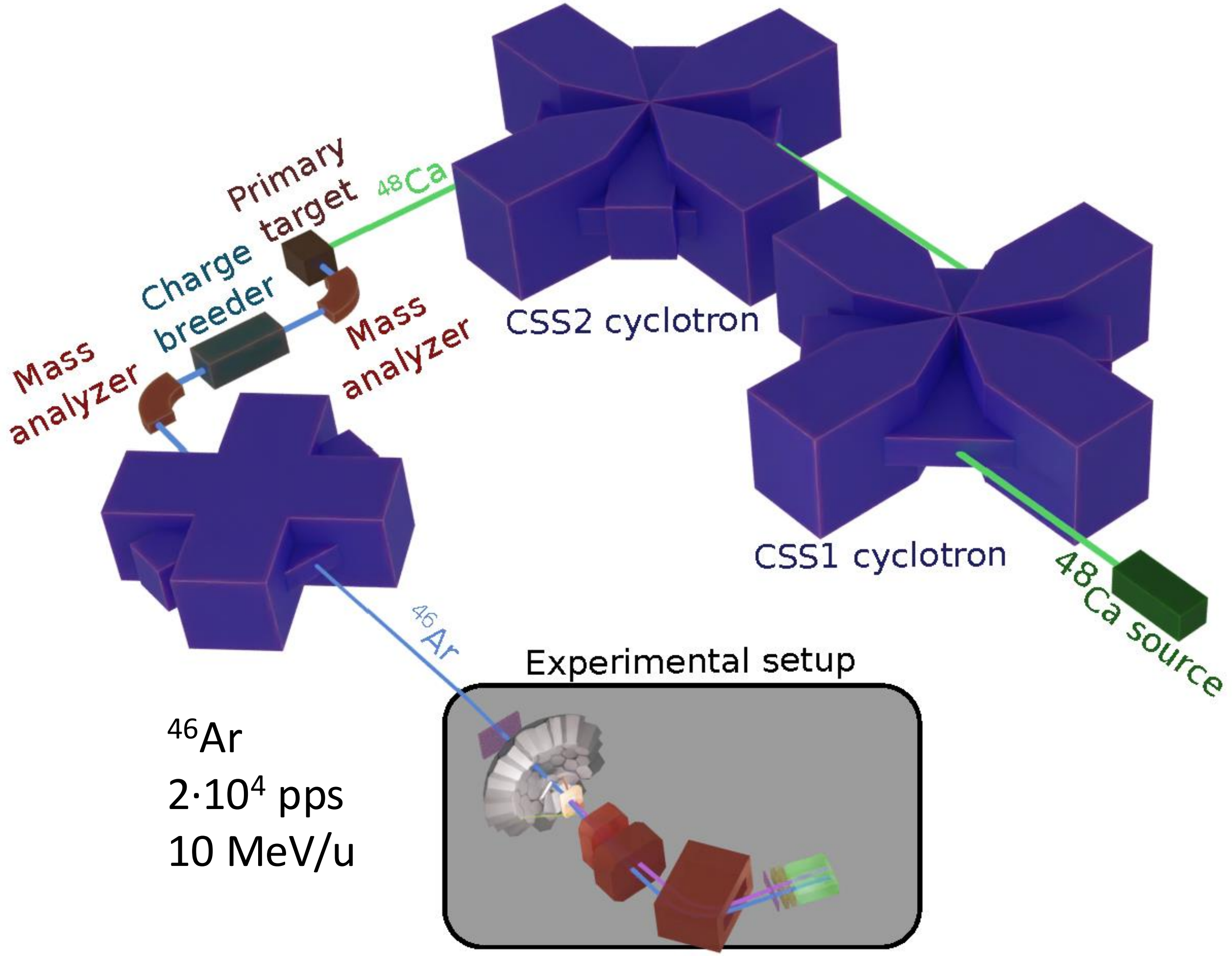


High sensitivity to the transferred wave's L

^{46}Ar predicted wave function



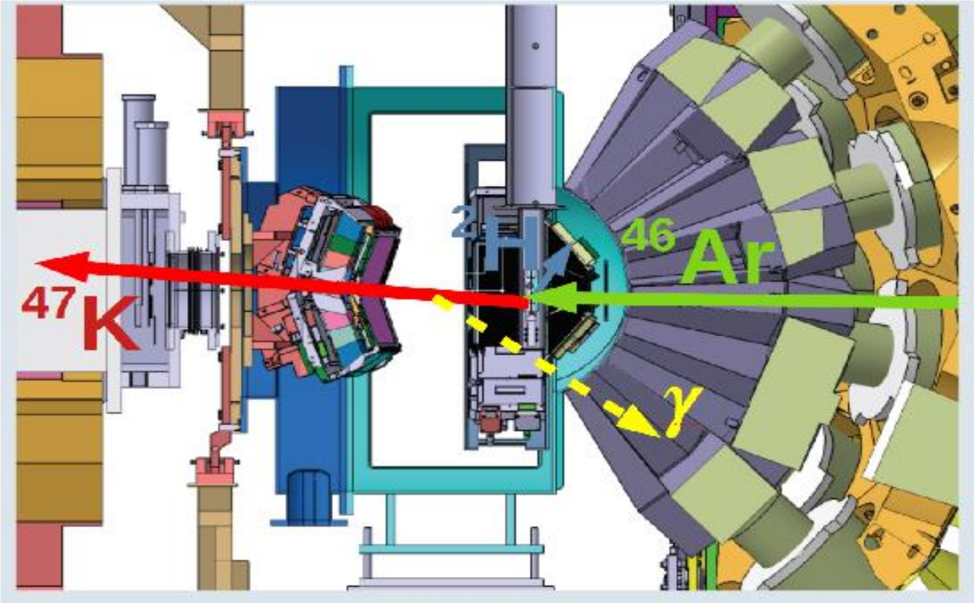
Direct proton transfer in inverse kinematics
@ GANIL Spiral 1

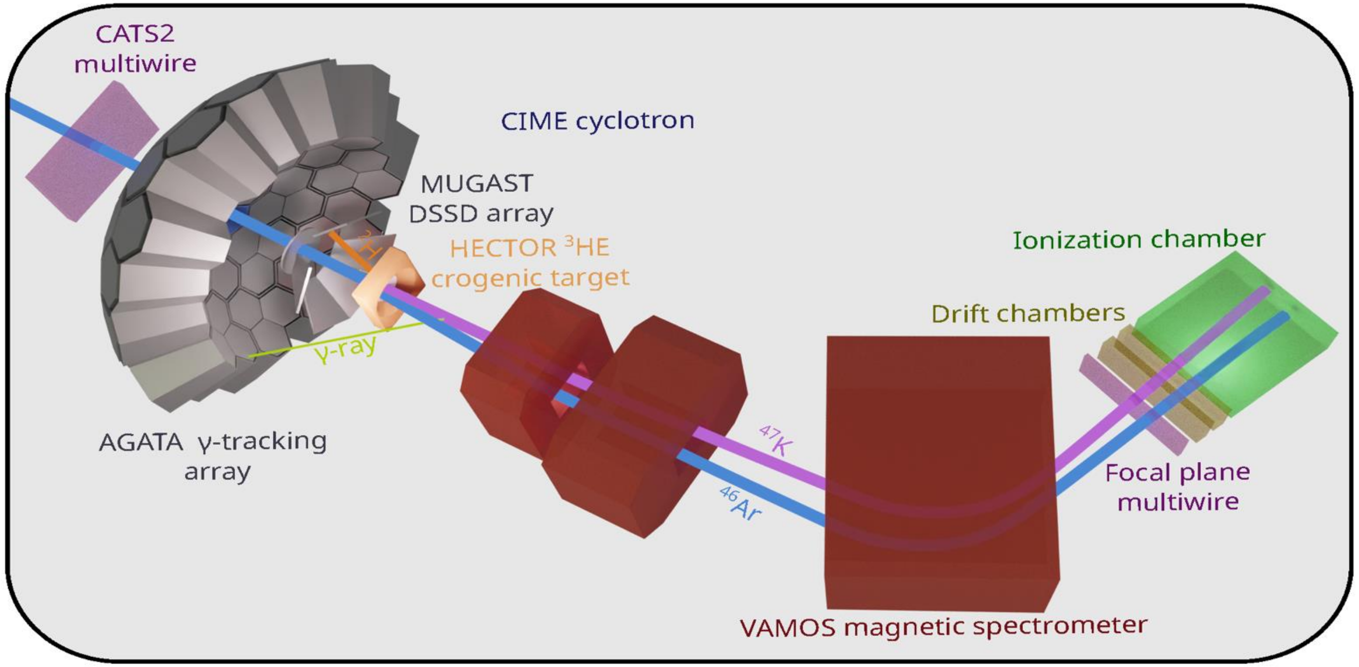


^{48}Ca
60 MeV/u
300-600 W

^{46}Ar
$2{\cdot}10^4$ pps
10 MeV/u

AGATA-MUGAST-VAMOS-HeCTOR



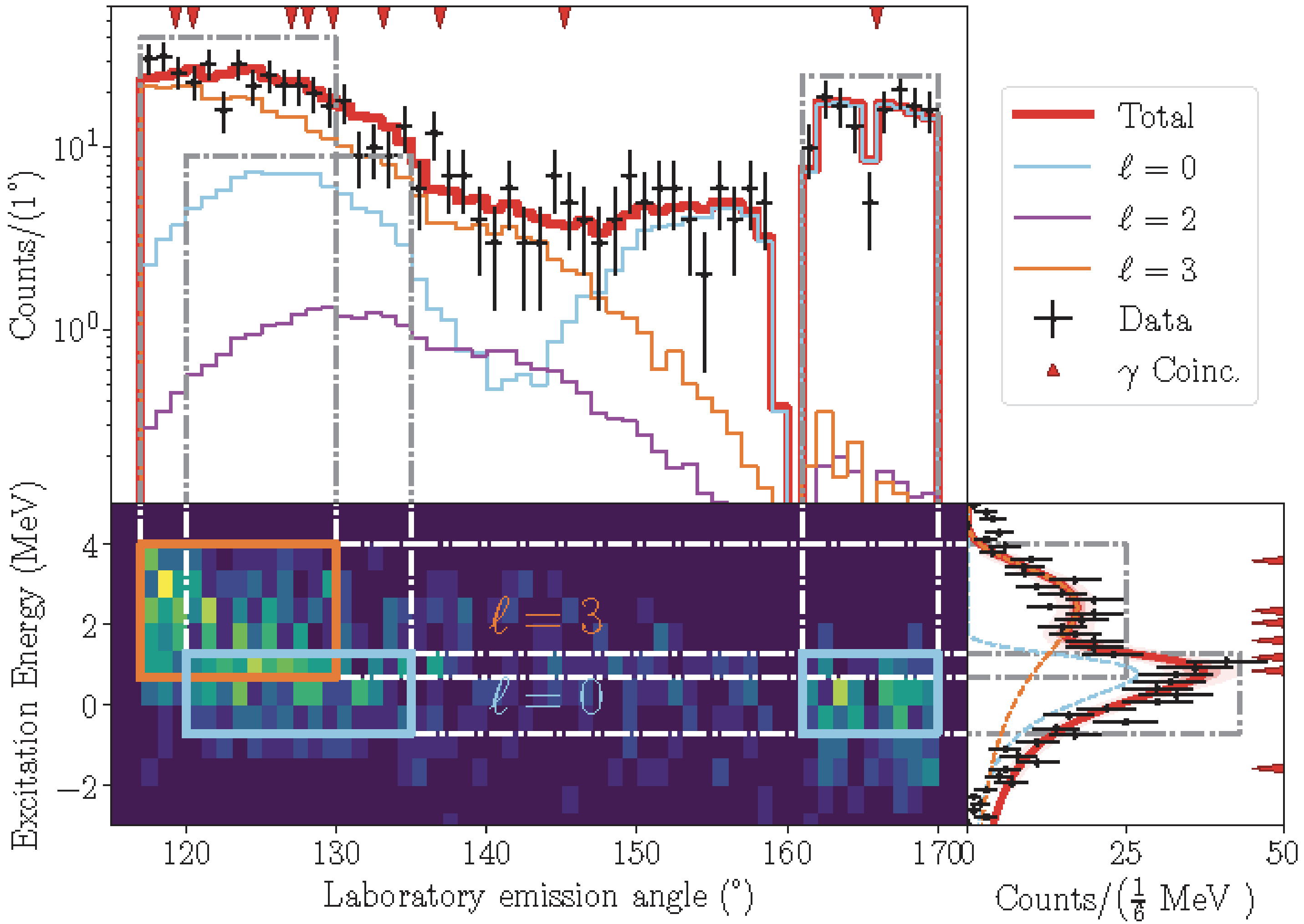


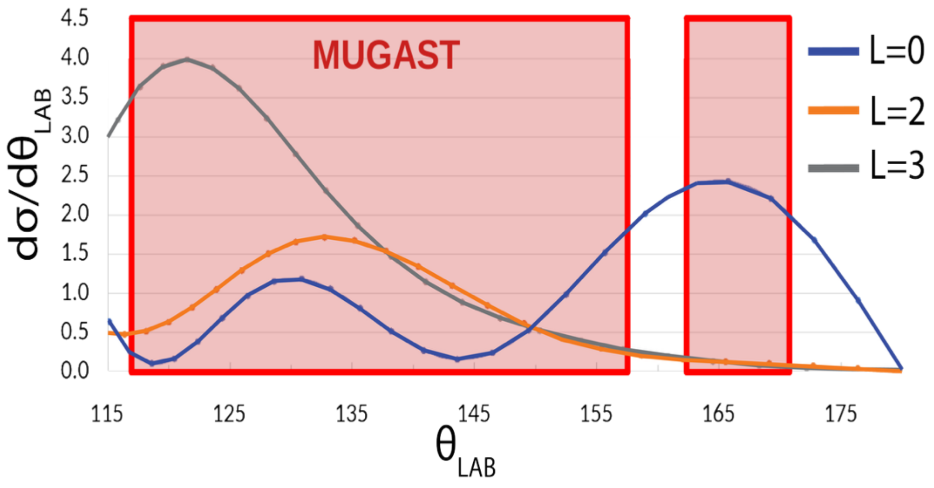
[1] F.Galtarossa et al., NIM A 165830 (2021)

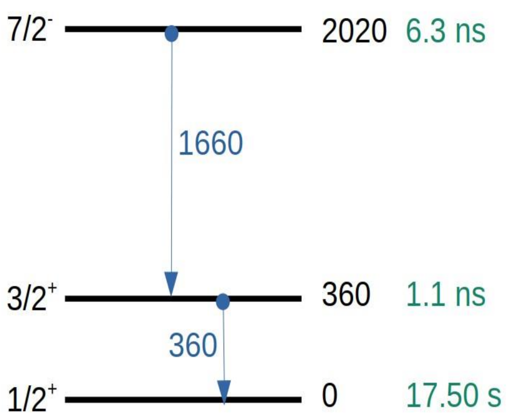
Setup for a complete measurement of reaction-related observables

- HeCTOr: Cryogenic (6 K) ^{3}He target, 3 mm thick – 1 mg/cm^{2}
- AGATA: γ-ray tracking array, 40 crystals, 10% efficiency
- MUGAST: array of high-granularity DSSD detectors for light ejectiles
- VAMOS: mass spectrometer
- CATS2: beam tracking gas detectors

Data analysis: angular distributions



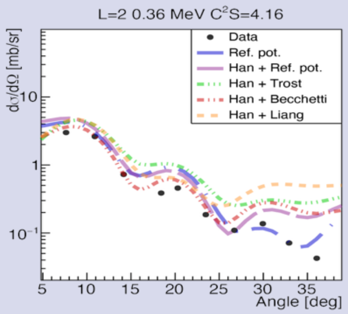


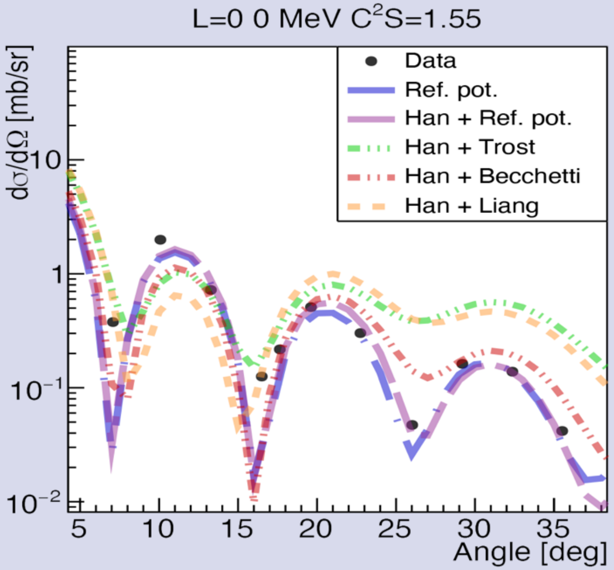


Results

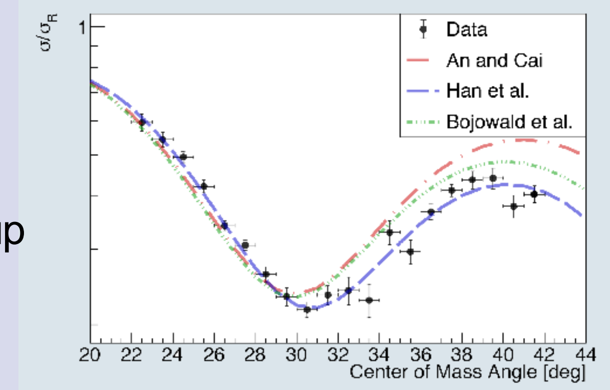
Particle spectra from MUGAST-VAMOS coinc.

- Optical potential tested on ^{48}Ca(d, ^{3}He)^{47}K data





- Elastic scattering of the ^{47}K(d,d)^{47}K reaction @ 7.52 MeV/u: tested on recent data acquired with the same setup [Paxman, C. and the e793s collaboration. Priv. Comm]



Spectroscopic factors

The SM (SDPF-U) fails the comparison with experimental data in terms of C^2S.

$C^2S[L]/C^2S[L=0]$	$3/2^+$ state	$7/2^-$ state
SDPF-U	0.63	2.6
Experiment	$0.10^{+0.11}_{-0.10}$	$1.10^{+0.18}_{-0.15}$

- **$\pi s_{1/2}$ empty, $\pi d_{3/2}$ full !**
- The proton WF of the g.s. of ^{46}Ar is not correctly described

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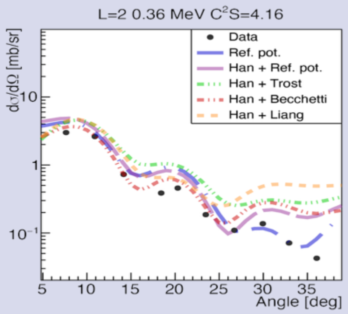

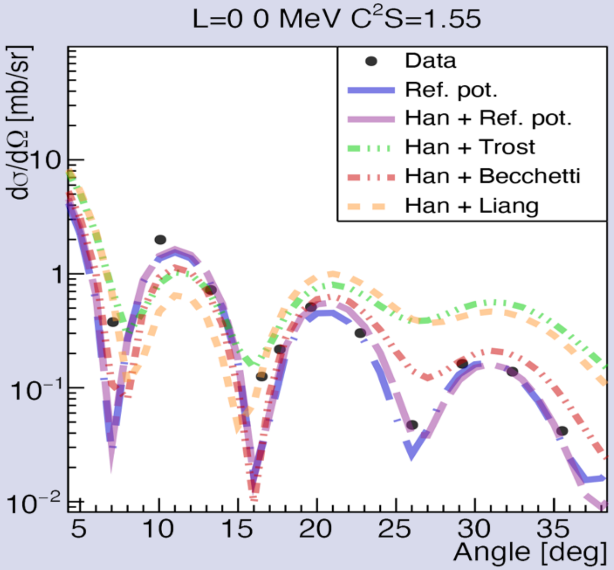

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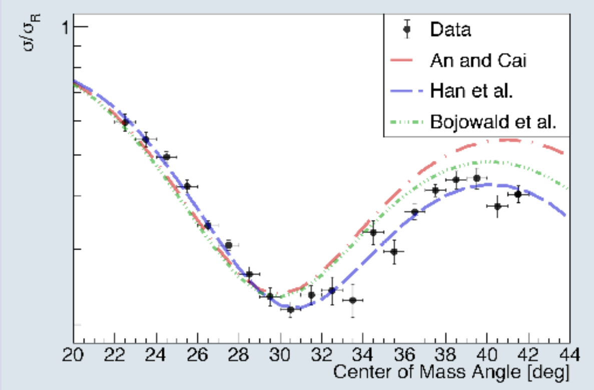

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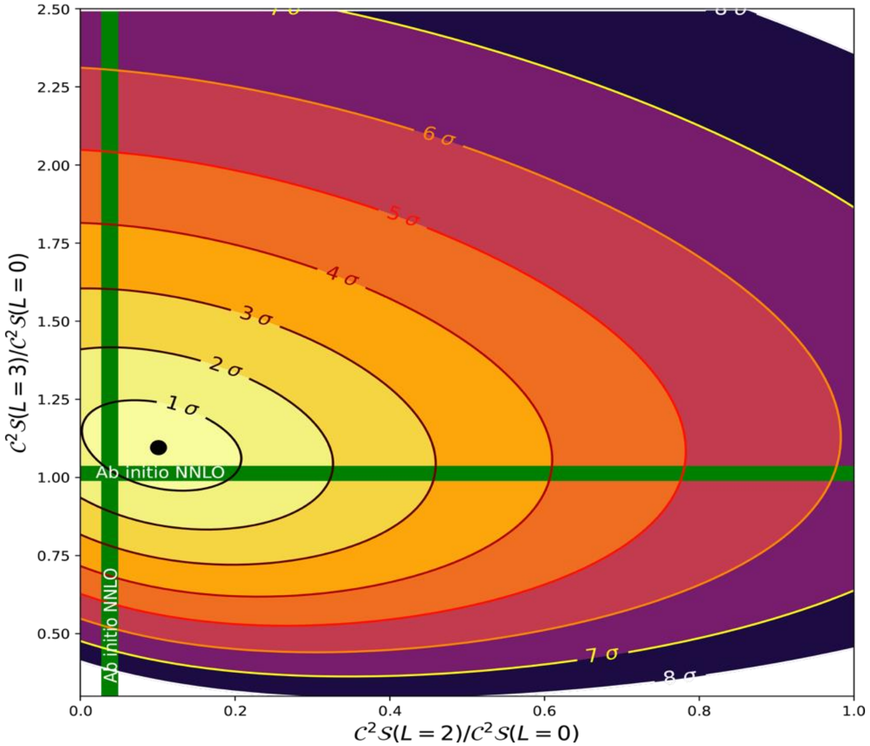
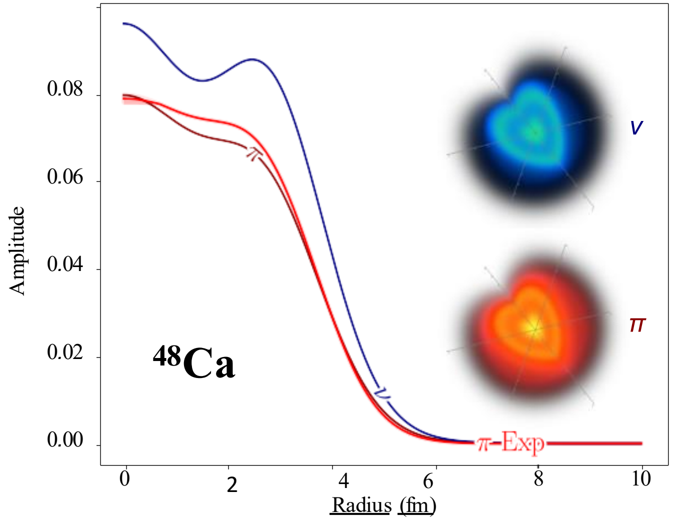
Ab-initio model NNLO$_{sat}$: shell structure

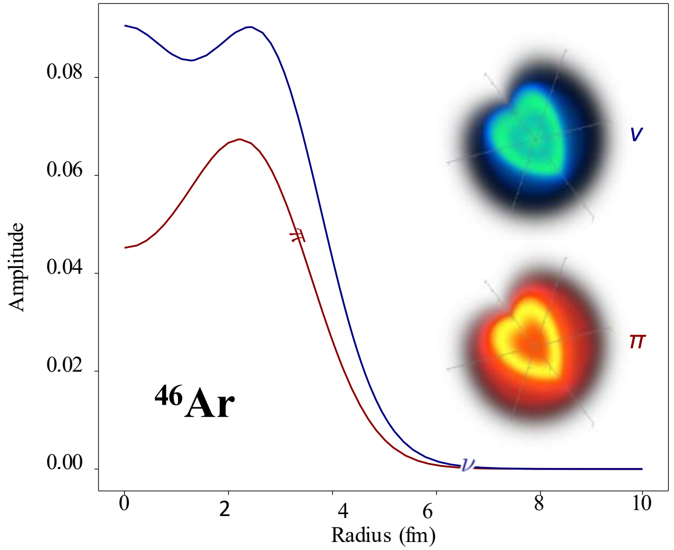
Ab-initio calculations

- Ab-initio calculations with the NNLOsat in ADC2 and ADC3 (C. Barbieri, S. Brolli, V. Somà)
- NNLO$_{SAT}$ chosen because of its capability of reproducing radii (cross check with the NNLO$_{lnl}$ in ADC2)
- 14 harmonic oscillator shells and $\hbar\Omega$=22 MeV to optimize the convergence of binding energies
- BE and charge radii well in agreement with ^{48}Ca and ^{46}Ar data
- **SF in ^{46}Ar in agreement with data**

	^{48}Ca	^{46}Ar
BE exp. (MeV)	416	386.70
BE NNLO$_{sat}$ (MeV)	414.67	384.18
r_{ch} exp. (fm)	3.4771 (20)	
r_{ch} NNLO$_{sat}$ (fm)	3.478	







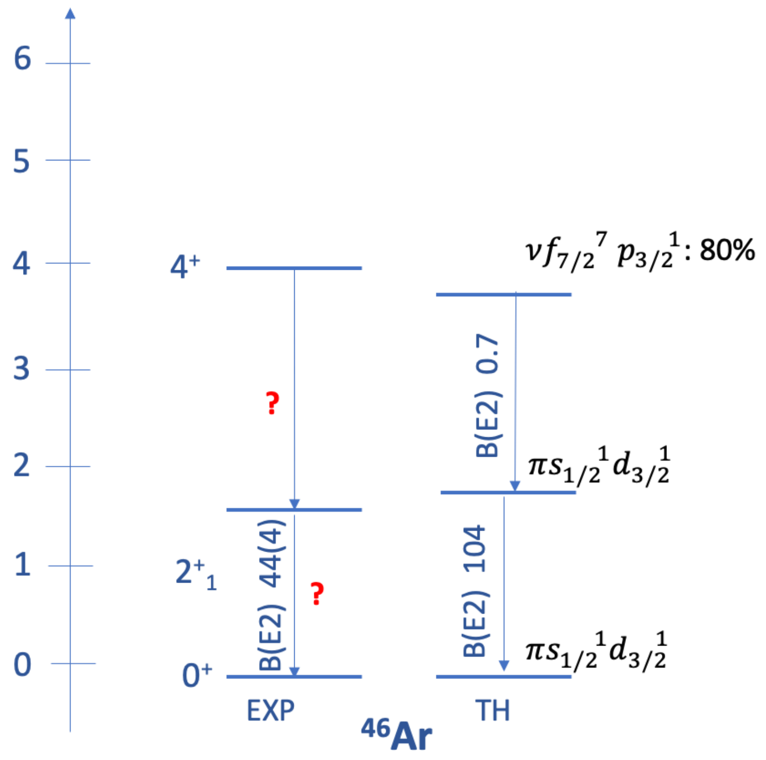
And the B(E2) ?

B(E2) puzzle solved ?

- Naive considerations: by closing the $d_{3/2}$ shell the restricted proton space will return a small B(E2) –> confirmed by SM calculations
- Mapping the NNLOsat χEFT Hamiltonian into the effective mean-field orbits generated by SCGF ADC(3)
  Phys. Rev. C 100, 024,317 (2019)
- The Hamiltonian was then diagonalized, with Antoine adjusting SP energies to reproduce experimental ^{46}Ar, ^{47}K level schemes:
  $B(E2, 2^+ \rightarrow 0^+) = 30\ e^2fm^4$

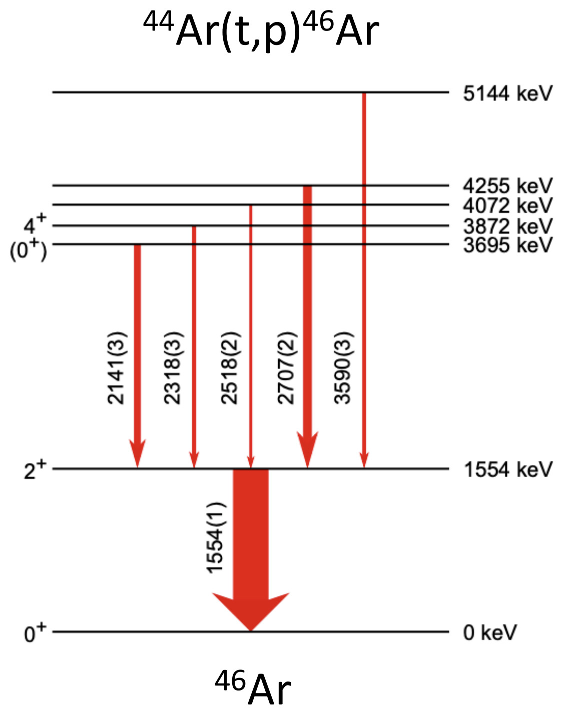
One question arises: if ^{46}Ar is magic, how can we justify a 2^+ at only 1.6 MeV ? Where is SDPF-U shell model (so) wrong ?

^{45}Ar(d,p)^{46}Ar to probe the neutron content of the 2^+ state



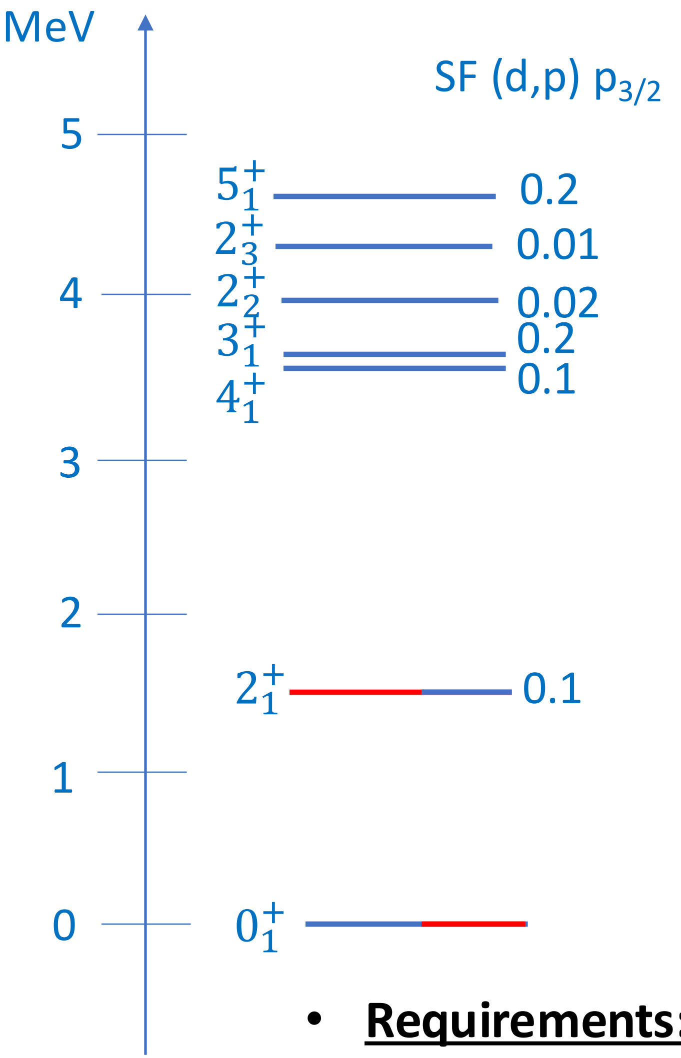
Possible neutron wave function

- 2^+ is an a priori proton state, but if $\pi d_{3/2}$ is closed it should come above 2 MeV
- N=28 core breaking $\nu f_{7/2}$-$p_{3/2}$ contributions are possible
- We propose to investigate this state via ^{45}Ar(d,p)^{46}Ar
- We will get a multiplet of states ν $f_{7/2}$-$p_{3/2}$: 2^+…5^+



K.Nowak et al., Phys. Rev. C **93**, 044335 (2016)

SDPF-U 4p-4h: how well does it describe the N=28 breaking ?



Experimental details $^{45}Ar(d,p)^{46}Ar$

- AGATA-GRIT (backwards) : γ rays necessary to disentangle the multiplet !
- VAMOS to distinguish fusion on CD_2 (10^5 Hz on focal plane ?)
- We will check the excited state neutron content prediction from different Hamiltonians

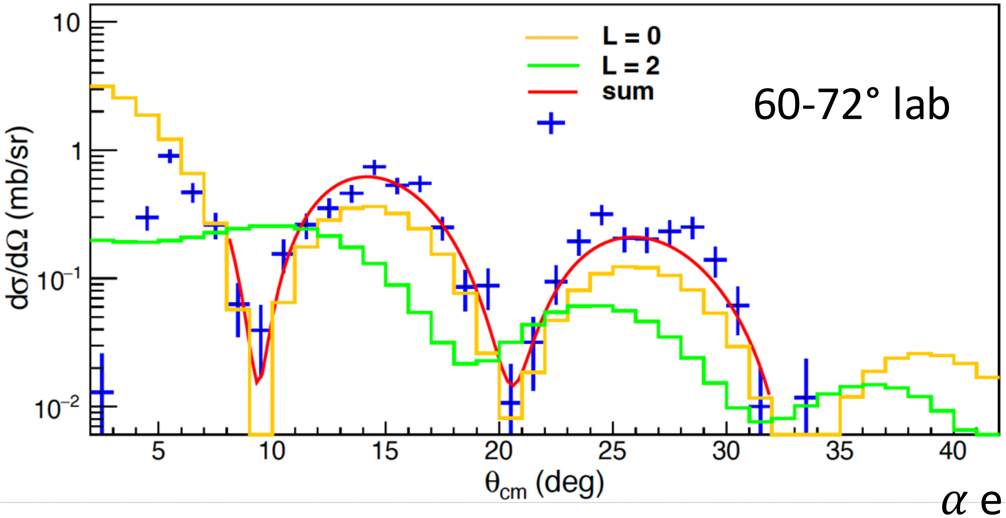
Reac/day (5^+)(σ_{sp}=10 mbarn)= 2000

Reac/day (2^+_3)(σ_{sp}=10 mbarn)= 100

Reac/day (2^+_1)(σ_{sp}=10 mbarn)= 1000

- **Requirements: ^{45}Ar, ~ 1.5 10^5 pps, ~ 8-10 MeV/u, AGATA-GRIT(backwards)-VAMOS at zero degree (^{45}Ar @ 10^6 pps would be desirable !)**

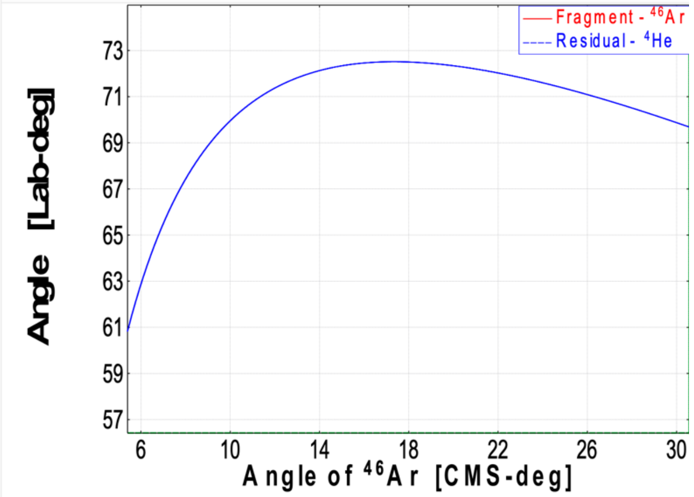
$^{47}K(t,\alpha)^{46}Ar$ to probe the proton content of the 2^+ state

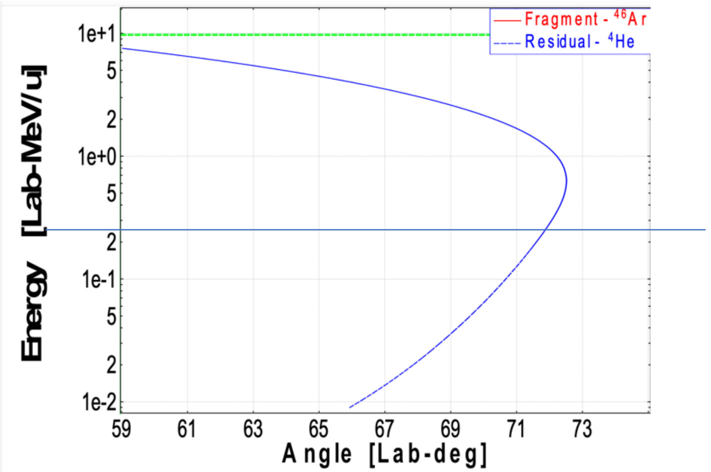


Possible proton wave function

- 2^+ is an a priori proton state, should be strongly populated by (t,α)
- $1/2^+$ gs in ^{47}K: $\pi s_{1/2} \otimes 1/2^+ : 0^+$
- $1/2^+$ gs in ^{47}K: $\pi d_{3/2} \otimes 1/2^+ : 0^+,2^+$
- $1/2^+$ gs in ^{47}K: $\pi d_{5/2} \otimes 1/2^+ : 0^+,2^+,3^+$
- ~ 200 reac/day

α energy out of Ti^3H target





- **Requirements: ^{47}K, ~ 10^6 pps, ~ 10 MeV/u, AGATA-GRIT(backwards)-VAMOS at zero degree**

THANK YOU FOR YOUR ATTENTION !