Nuclear structure at $N = 29$: The structure of ^{47}Ar and first spectroscopy of ^{45}S

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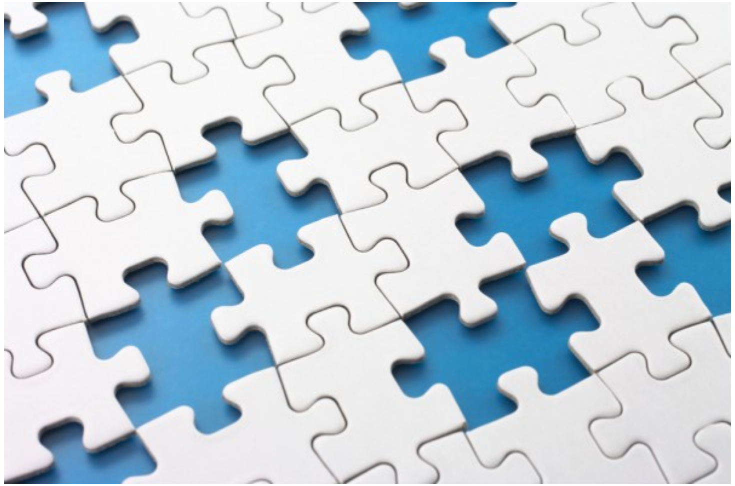
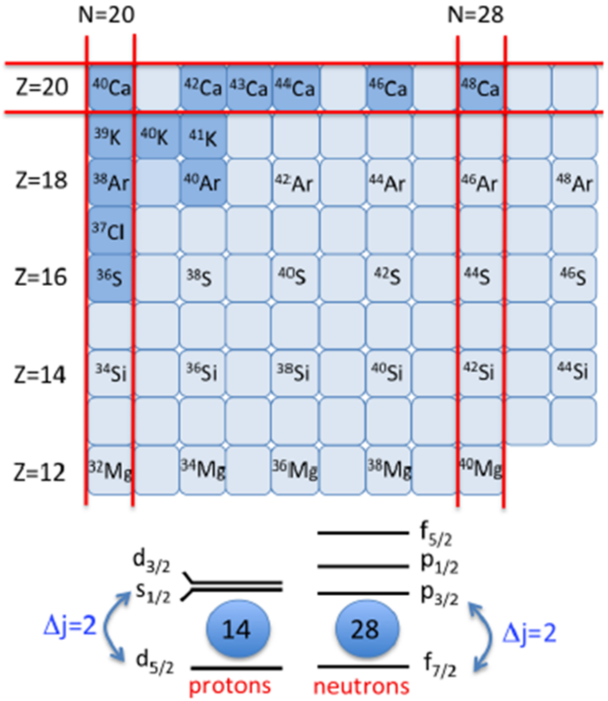
Outline

- Neutron-rich nuclei around *N=28* still interesting
  - ^{46}Ar: A puzzle
- Learning from *N=29* ^{47}Ar - A complementary approach
  - Single-neutron strength (pickup)
  - Proton-hole strength (knockout)
- First spectroscopy of ^{45}S
- Summary



N=28: Importance for understanding shell evolution

- N=28 is the first shell closure that requires the spin-orbit force
- Neutron-rich N=28 isotones near the dripline may come into reach soon for spectroscopy (explore continuum effects)
- The region around ^{42}Si has been a test bed for shell model (and DFT) to benchmark their implementation of the driving forces of shell evolution
  - Actions of the tensor force, reduced shell gap
  - Enhanced quadrupole correlations for orbitals with Δj=Δℓ=2
  - Recently: Some ab-initio type Hamiltonians need 3-body forces to describe N=28 ^{48}Ca

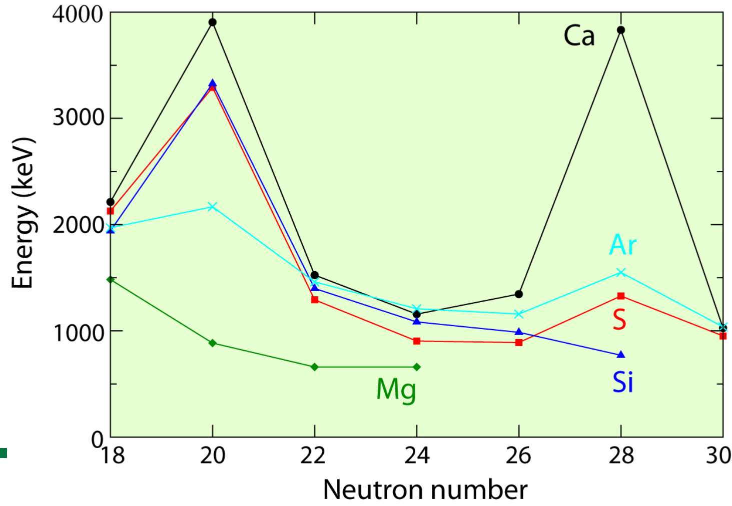


Why *N=28* is still interesting in neutron-rich nuclei

N=28

^{48}Ca	Doubly-magic
^{47}K	
^{46}Ar	Huh? Controversial
^{45}Cl	
^{44}S	Collective, shape coexistence proven (1997) and (2010)
^{43}P	
^{42}Si	Collective (2007)
^{40}Mg	Anybody? (Only proven to exist in 2007)

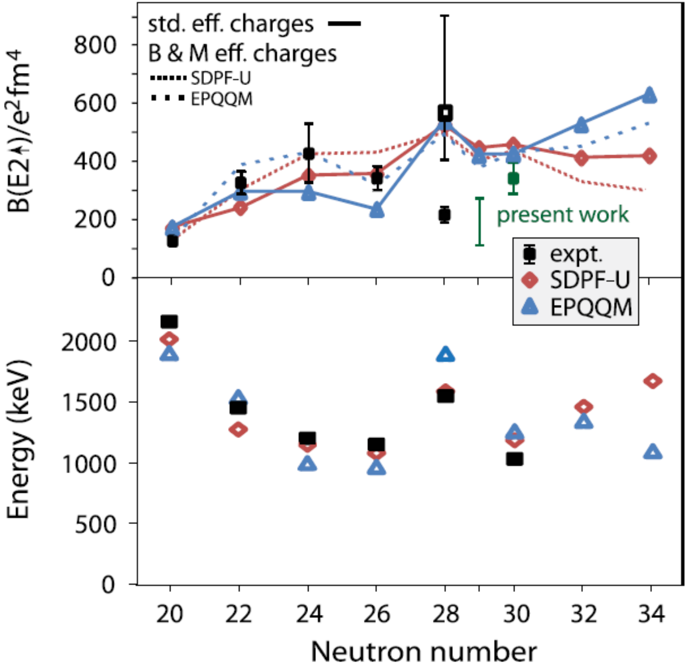
- Region of rapid shell evolution
- Collectivity of ^{46}Ar is not described by shell model – puzzling deviation
- In my view – ^{46}Ar is a key nucleus on the path from doubly-magic ^{48}Ca to deformed ^{42}Si that theory has to get right if the details of shell evolution are claimed to be understood and implemented in the shell model



A brief history – Collectivity of ^{46}Ar

Observed for the first time in 1974 produced in a ^{48}Ca(^{6}Li,^{8}B) transfer experiment

- 1996: $B(E2)_{up}$=196(39) e^2fm^4 (NSCL Coulex)
- 2003: $B(E2)_{up}$=218(31) e^2fm^4 (NSCL Coulex)
- Shell model: factor of 2.5 higher than the above
- DFT (DD-PCI): $B(E2)_{up}$= 200 e^2fm^4
- 2010: $B(E2)_{up}$=570^{+335}_{-160} e^2fm^4 (INFN lifetime)
- Shell model claims victory … or agreement
- 2012: ^{47}Ar (2^+ x $p_{3/2}$) multiplet B(E2) consistent with low B(E2):
- 2016: $B(E2)_{up}$=232(19)e^2fm^4 (GANIL Coulex)



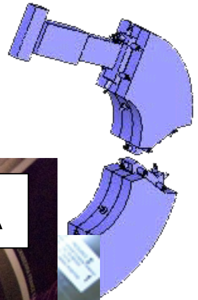
H. Scheit et al., PRL 77, 3967 (1996)
A. Gade *et al.*, PRC 68, 014302 (2003)
Z. P. Li et al., PRC 84, 054304 (2011)
D. Mengoni et al., PRC 82, 024308 (2010)
R. Winkler et al., PRL 108, 182501 (2012)
S. Calinescu et al., PRC 93, 044333 (2016)

^{46}Ar has been poked with different probes

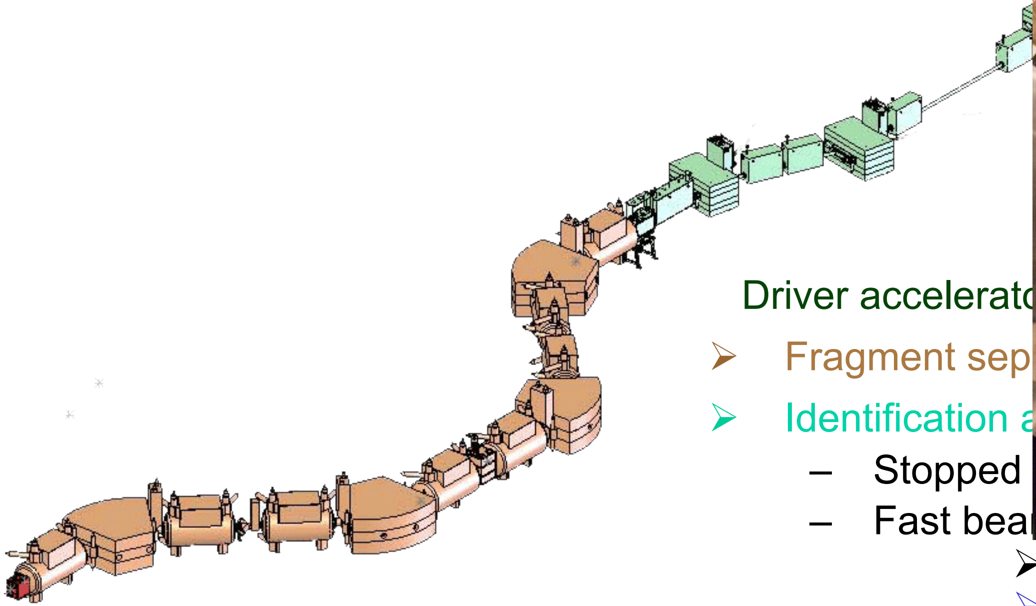
- ^{46}Ar one-neutron knockout to ^{45}Ar was done → $C^2S=0.2(2)$ for $p_{3/2}$ orbital found to be small, indicating that the N=28 shell gap is intact
  A. Gade et al., PRC 71, 051301(R) (2005)
- Thick-target inelastic proton scattering → no surprise, ratio of M_n/M_p neutron/proton matrix elements shows slight n dominance over N/Z
  L. A. Riley et al., PRC 72, 024311 (2005)
- Masses (or separation energies) agree with shell model Z. Meisel et al., PRL 114, 022501 (2015)
- ^{46}Ar from (t,p) broadly consistent with SDPF-U
  K. Nowak, K. Wimmer et al., PRC 93, 044335 (2016)

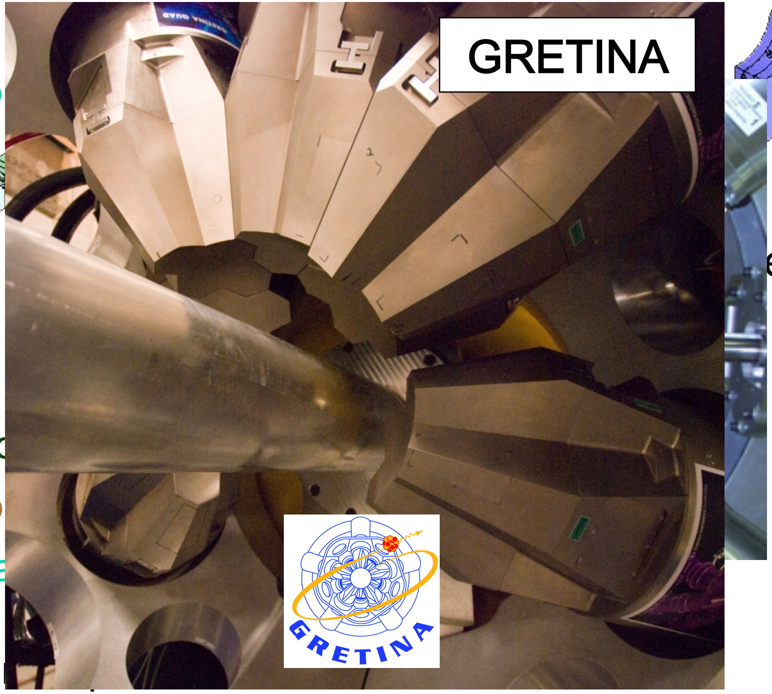
Experimental Scheme

Reaction product identification
S800 spectrograph



Identification and beam transpo





et

Driver accelerato

- Fragment sep
- Identification a
  - Stopped
  - Fast bea
- Secondary reaction
- Reaction product identification

Single-particle structure at *N* = *29*: The structure of ^{47}Ar from complementary probes

One-nucleon pickup at NSCL beam energies

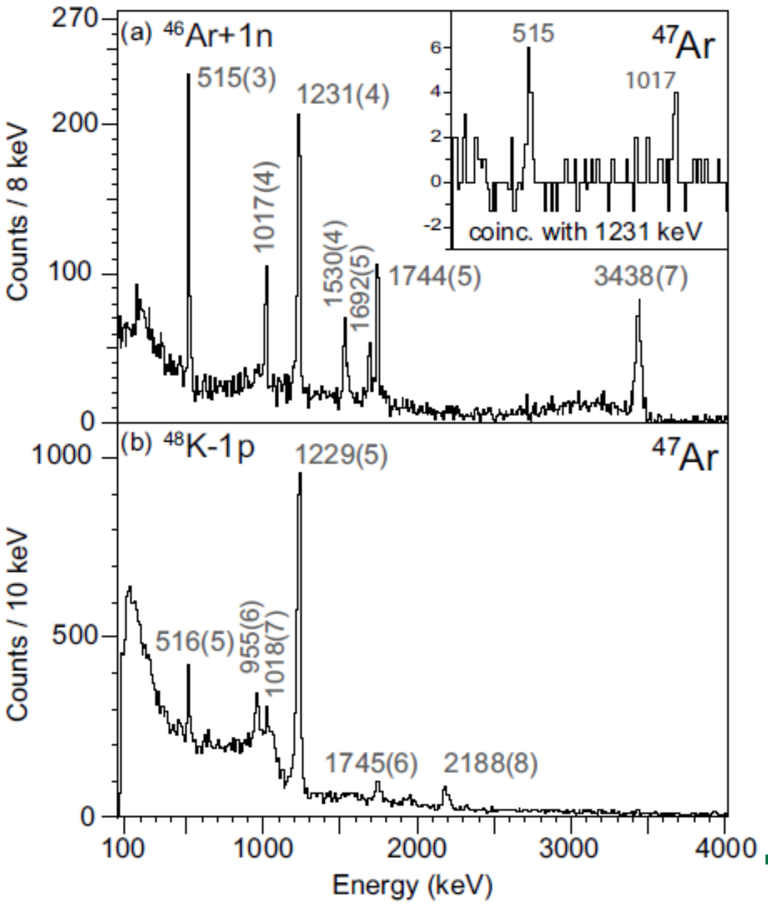
- Selectively populates single-particle states with high orbital angular momentum
- Complements knockout reactions

A. Gade, J. A. Tostevin *et al.*, PRC 93, 054315 (2016) and references within

One-nucleon knockout at NSCL beam energies

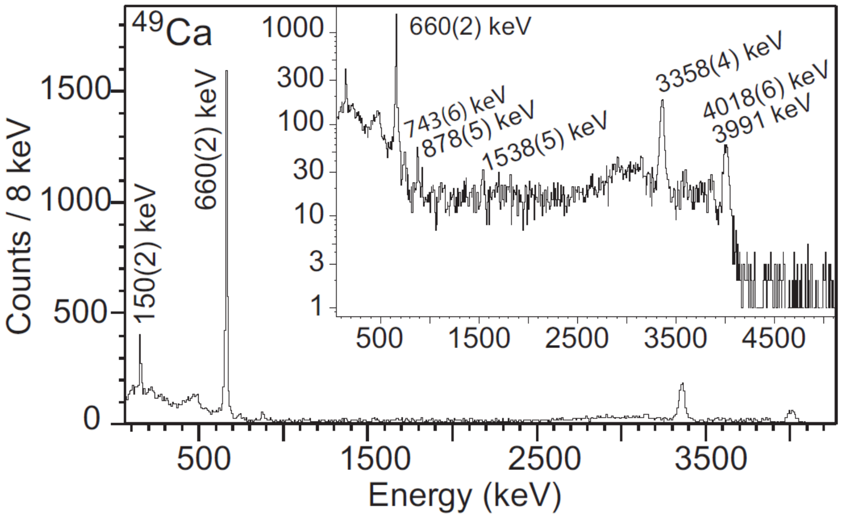
- Selectively populates single-hole states relative to the projectile ground state
- Cross sections: Quantify the wavefunction overlap of the projectile ground state and the final state in the knockout residue

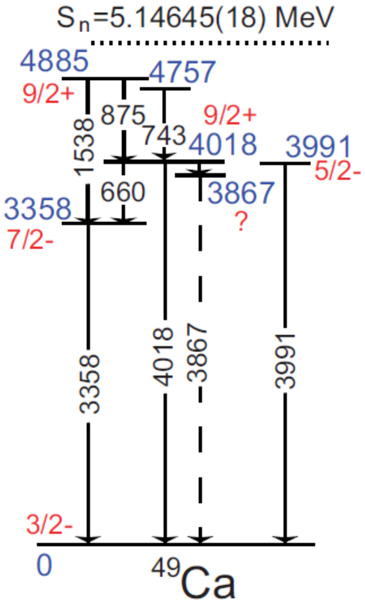
P.G. Hansen and J. A. Tostevin, ARNPS 53, 219 (2003)
A. Gade *et al.*, Phys. Rev. C 77, 044306 (2008)



Diversion: Fast-beam γ-ray one-neutron pickup reactions – neutron $g_{9/2}$ spectroscopic strength in ^{49}Ca

- Pioneered at NSCL with γ-ray tagging
- Clean spectra through high-ℓ selectivity – only *ℓ=3* and *ℓ=4* states are populated (60 MeV/u)
- Fast-beam γ-ray tagging and thick C targets allow for measurements at a few 1000 projectiles/s
- One-neutron pickup from ^{48}Ca to ^{49}Ca provides a sensitive benchmark for shell model and identifies $g_{9/2}$ strength that now can be included in the largest-scale calculations



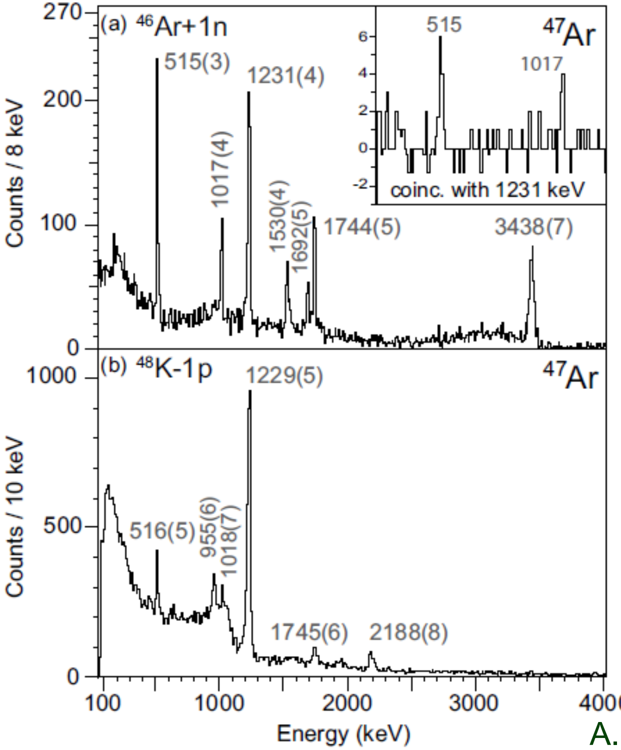


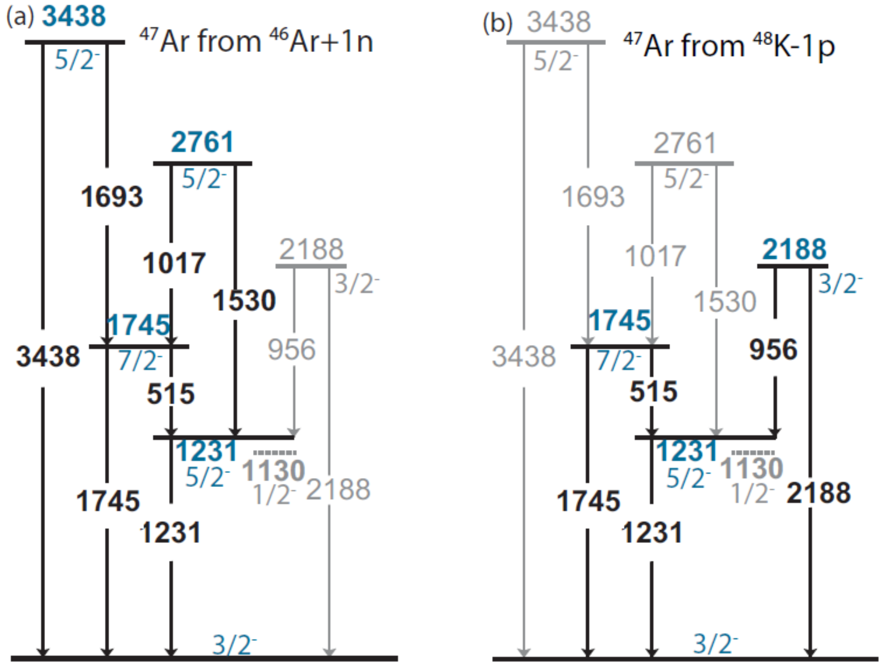
FYI: Nature of the $9/2^+$ state: core-coupled $(^{48}\mathrm{Ca}(3^-) \times p_{3/2})^{9/2}$ and a small $g_{9/2}$ component

A. Gade, J. A. Tostevin *et al.*, PRC 93, 031601(R) (2016)

Single-particle structure at *N = 29*: The structure of ^{47}Ar from complementary probes

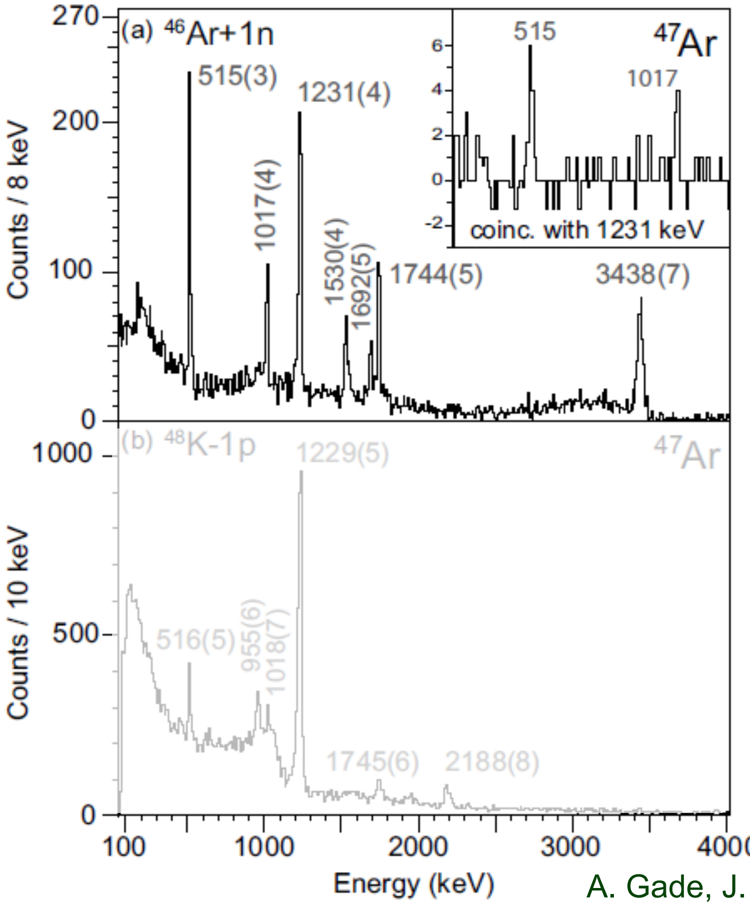
- Reactions populate complementary states – identify different configuration in the comparison to theory





- Complementary reaction probe neutron and proton particle/hole configurations
- Consistent with L. Gaudefroy et al., PRL 97, 092501 (2006)

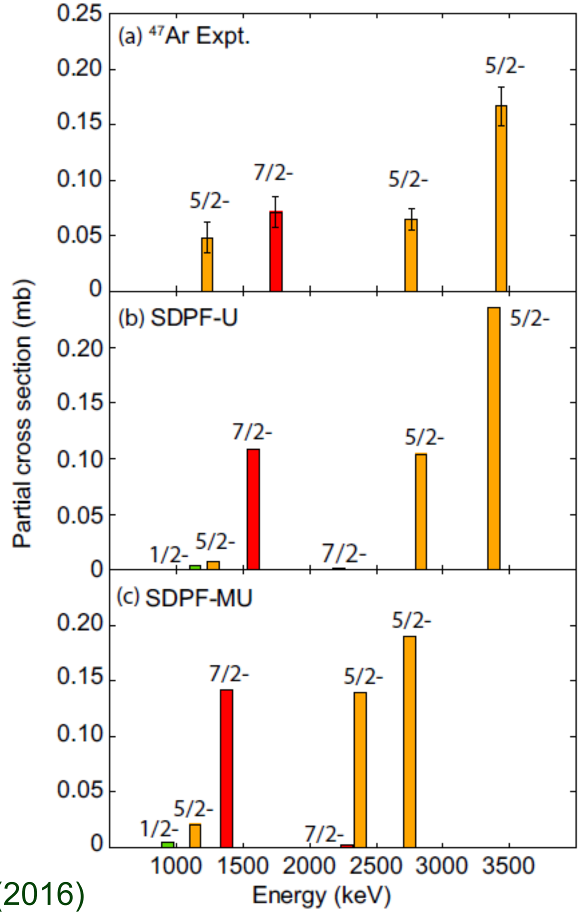
Single-particle structure at N = 29: The structure of ^{47}Ar from complementary spectroscopy ^{12}C(^{46}Ar,^{47}Ar+γ)X



67 MeV/u ^{46}Ar beam at 3 10^5 pps ($\Delta p/p$=0.25%) on a 149 mg/cm^2 glassy carbon target

From efficiency corrected peak areas corrected for indirect feeding, partial cross sections can be deduced and compared to theory.

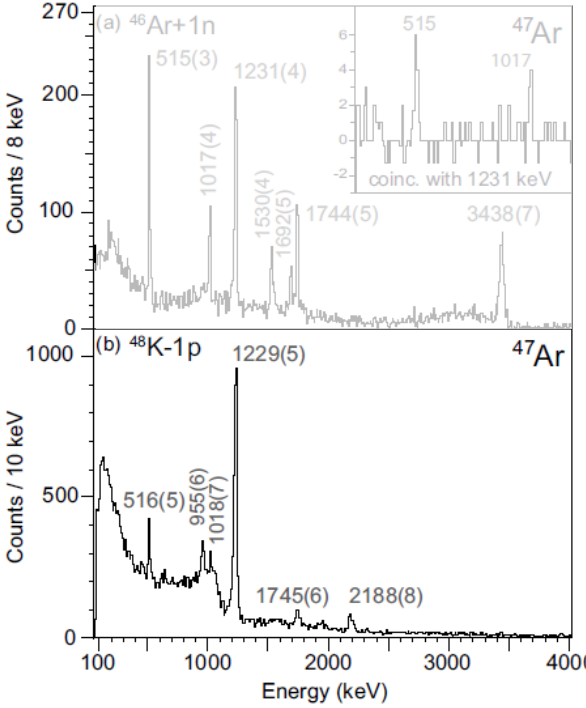
Theory = Reaction model x structure model

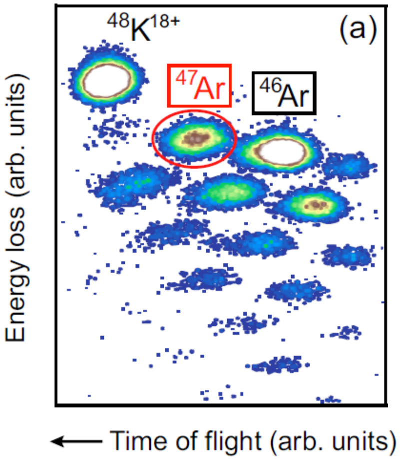


A. Gade, J. A. Tostevin *et al.*, PRC 93, 054315 (2016)

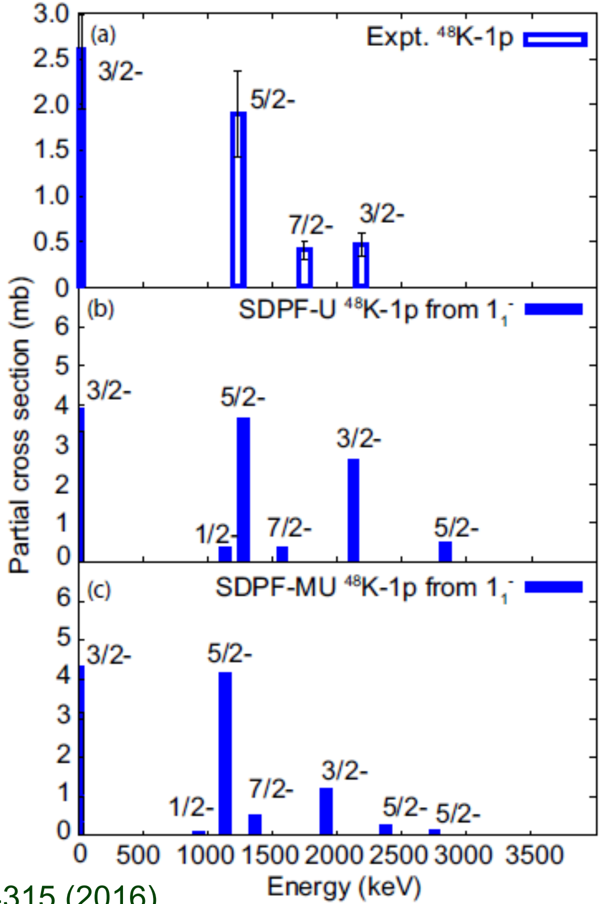
Single-particle structure at *N = 29*: The structure of ^{47}Ar from comprehensive spectroscopy ^{9}Be(^{48}K,^{47}Ar+γ)

- Complementary reaction: One-proton knockout from ^{48}K probes the single-proton structure of ^{47}Ar relative to ^{48}K. A 1^- ground-state spin assignment from ISOLDE laser spectroscopy (K. Kreim 2014)



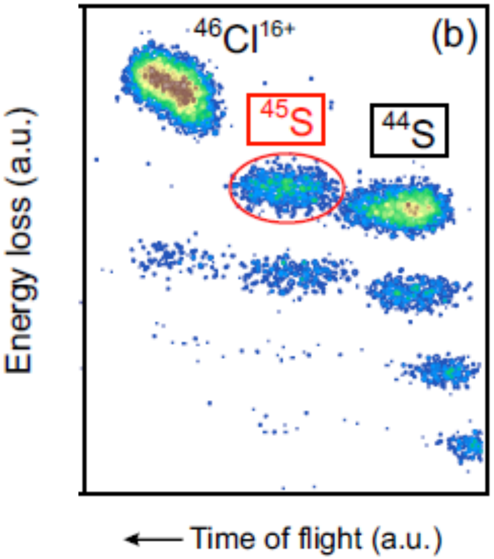


87.5 MeV/u ^{48}K beam at 1.1 x 10^5 pps (Δp/p=0.5%) on a 376 mg/cm^2 ^{9}Be target

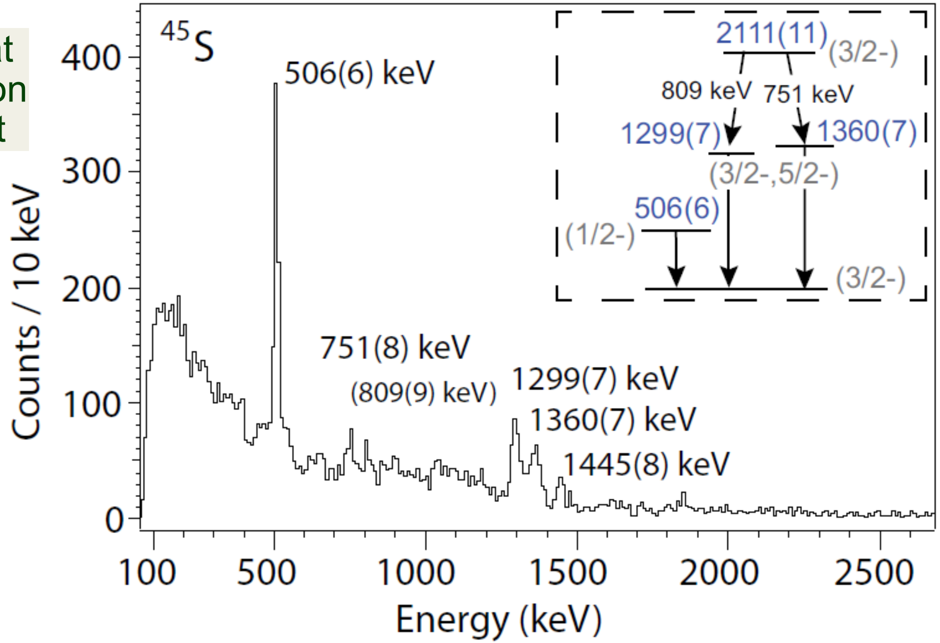


A. Gade, J. A. Tostevin *et al.*, PRC 93, 054315 (2016)

Single-particle structure at $N = 29$: New frontiers – first spectroscopy of ^{45}S

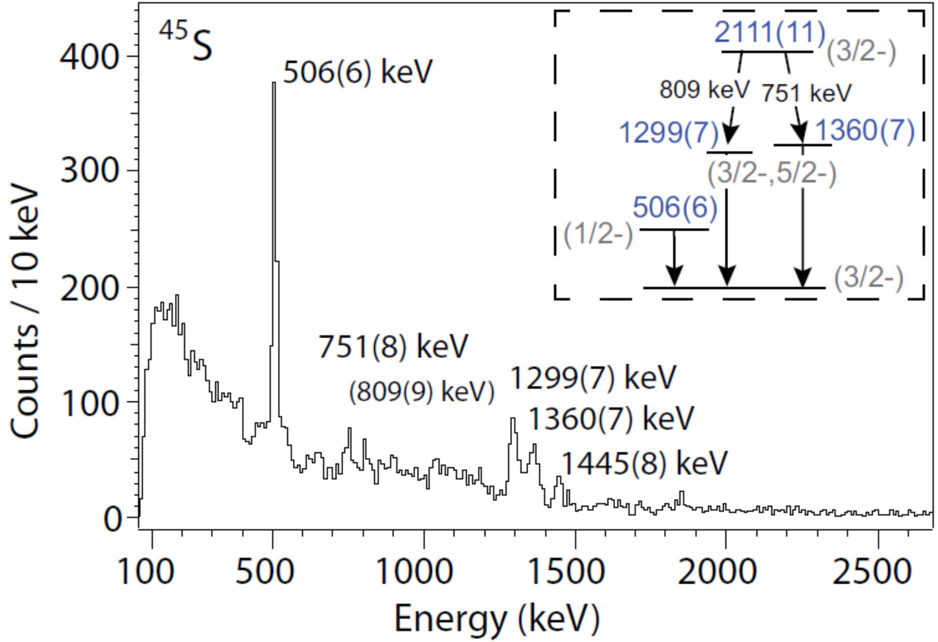


86.6 MeV/u ^{46}Cl beam at 6 x 10^3 pps ($\Delta p/p$=2%) on a 376 mg/cm^2 ^9Be target



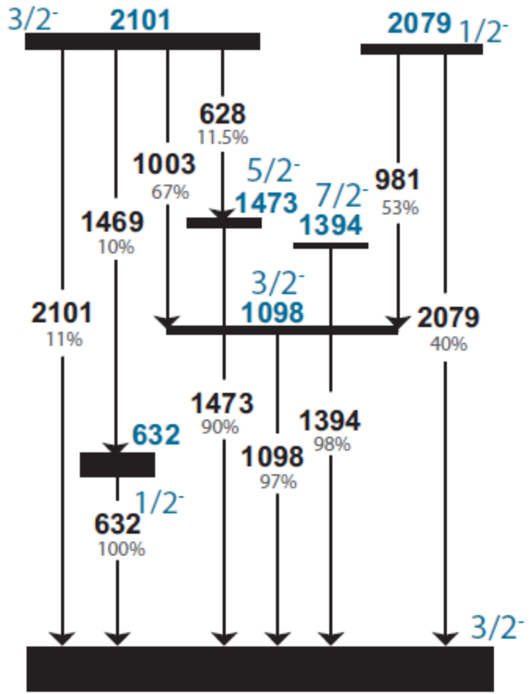
- One-proton removal from ^{46}Cl enabled the first spectroscopy of ^{45}S
- The ground state of ^{46}Cl is not known and so the one-proton knockout cannot be analyzed as for the ^{48}K-1p reaction

Single-particle structure at *N = 29*: New frontiers – first spectroscopy of ^{45}S



^{45}S from ^{46}Cl-1p

SDPF-U with 1^- ^{46}Cl g.s.



- Assuming a 1^- ground state for ^{46}Cl, the level scheme on the right is predicted to be observed for ^{45}S assuming large-scale shell model with the SDPF-U effective interaction

Summary

- Neutron-rich nuclei with *N=28* show a rich structure with magicity at ^{48}Ca, shape-coexistence at ^{44}S, high collectivity at ^{42}Si, and a puzzle at ^{46}Ar
- Complementary nucleon-adding and removing direct reactions enable the identification of proton-hole and neutron-particle states in ^{47}Ar, relative to ^{48}K and ^{46}Ar, respectively
- ^{48}K-1p and ^{46}Ar+1n spectroscopic strengths compare well to shell model with SDPF-U and SDPF-MU Hamiltonians – no hint on what is going on at ^{46}Ar and the failure of both effective interactions to describe its collectivity
- South of ^{47}Ar, performed first spectroscopy of ^{45}S
- The challenge remains to explain the shell evolution from ^{48}Ca to ^{42}Si, including a proper account of the quadrupole collectivity in ^{46}Ar

Partners in Crime …

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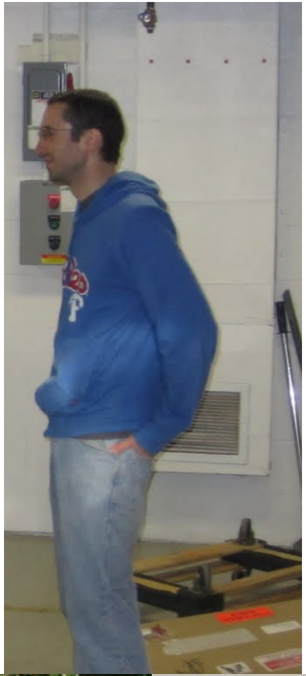
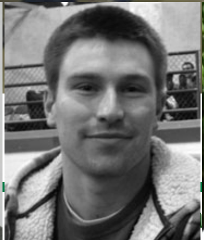
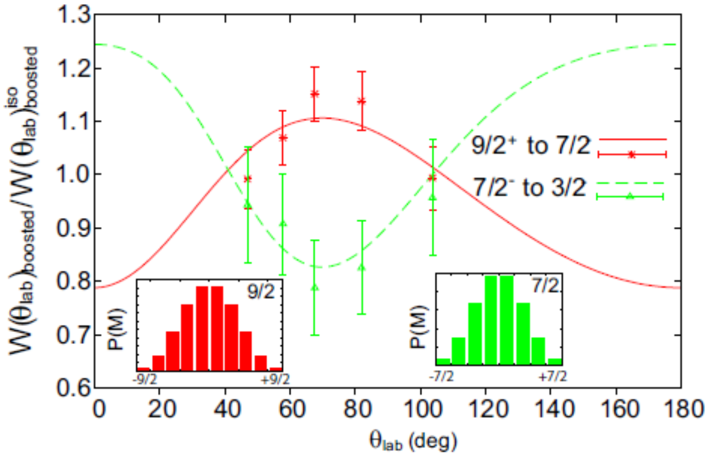
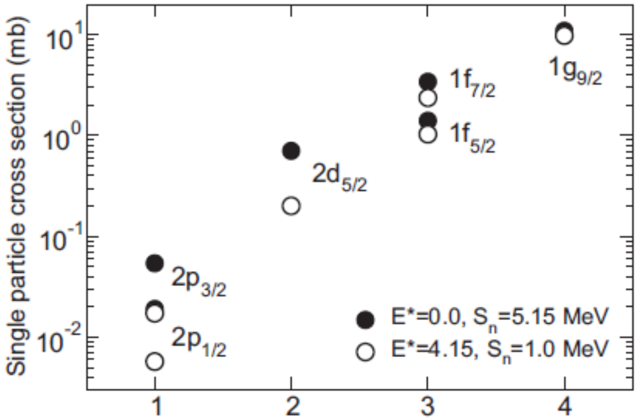




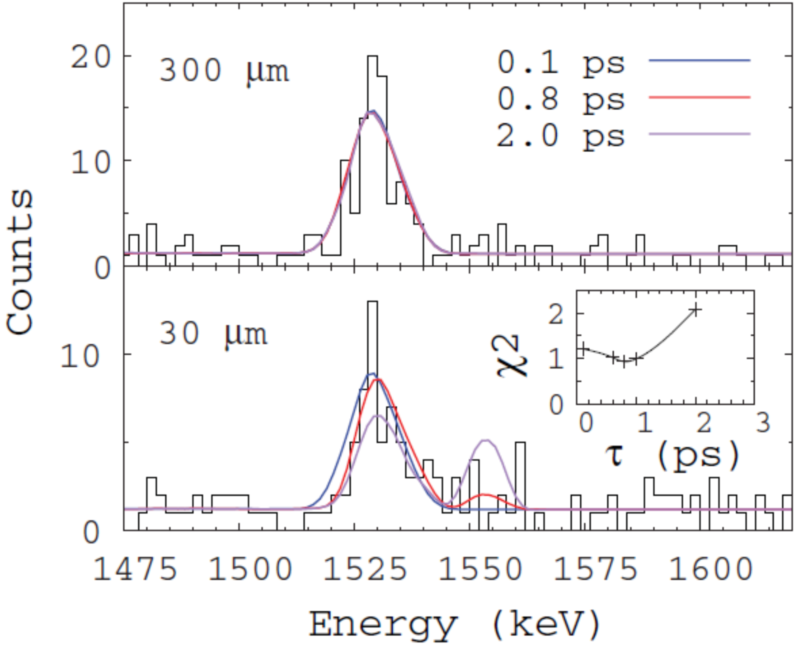
Pickup reaction theory (J. A. Tostevin)

- ^{12}C-induced pickup calculated in (post-form) DWBA (FRESCO)
- Transfer calculated as ^{48}Ca(^{12}C, ^{11}C(I^{π}))^{49}Ca(J^{π}) with incoherent sum over I=3/2- (g.s), 1/2- (2 MeV), 3/2- (4.8 MeV) for ^{11}C with C^2S from (e,e'p)
- Distorting potential in entrance and exit channel from double folding with effective NN interaction by Ray (like in knockout)
- Bound-state geometries of the neutron in the ^{12}C inital and ^{49}Ca final state guided by HF like in knockout

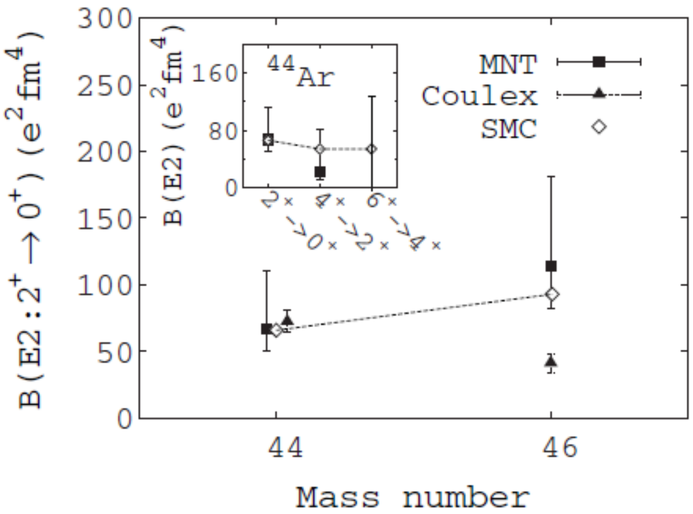




Lifetime measurement



- Marginal statistics
- Shell model (SDPF-U with e_p/e_n=1.5/0.5) agrees



- Plunger measurement, uses intensity ratios of peaks stemming from emission before or after a degrader