The Shell Structure of the Neutron-Rich Calcium Isotopes

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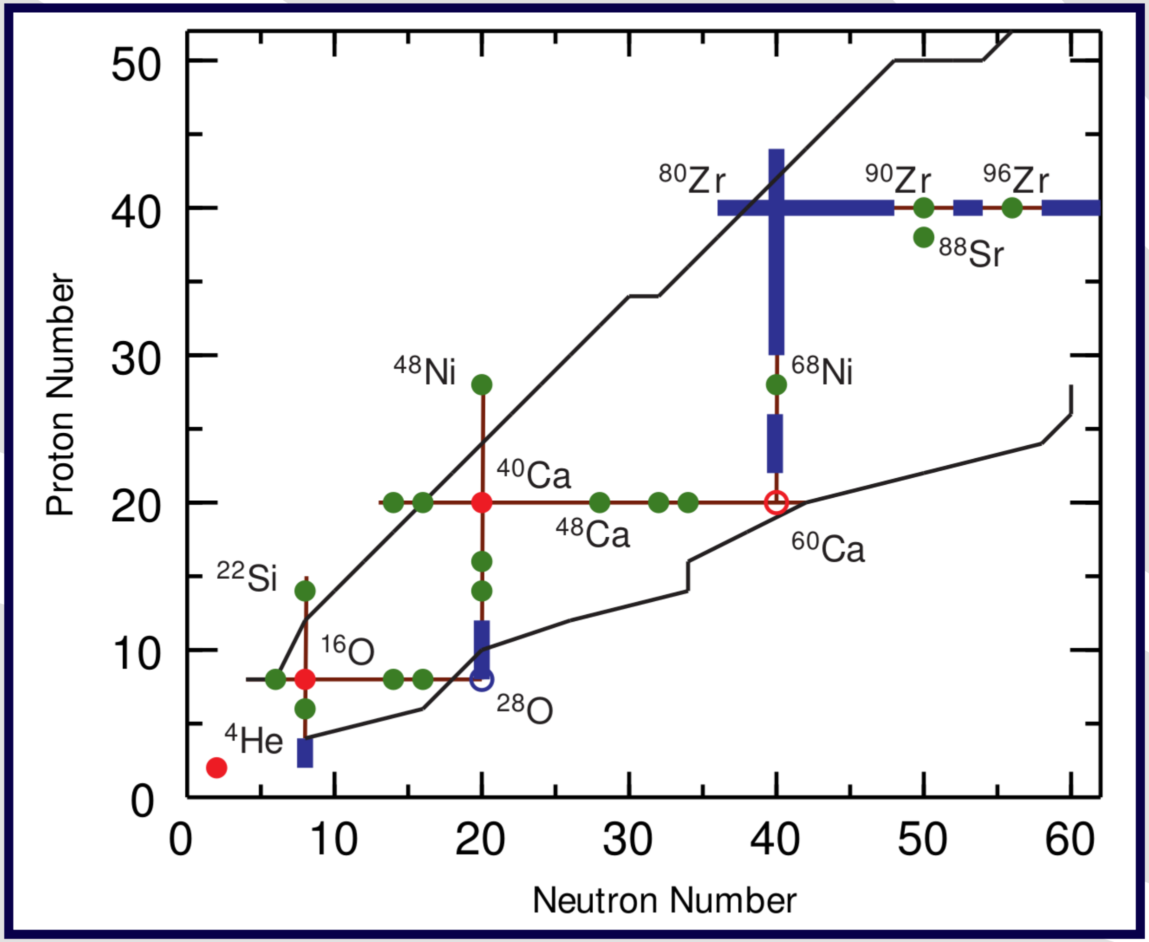
Outline

- Motivation
  - Potential new magic numbers $N = 32, 34, 40$
  - Evolution of neutron single particle energies
- In-beam γ-ray and invariant-mass spectroscopy at the RIBF
  - DALI2^{+}, MINOS, SAMURAI, NeuLAND/NEBULA
- Results
  - Detailed spectroscopy of ^{54}Ca from (p,pn) and (p,2p) reactions
  - First spectroscopy of ^{56,58}Ca from (p,2p) reactions
  - Neutron single particle states in $^{47–55}$Ca
- Summary

Doubly Magic Nuclei in Lower Half of Nuclear Chart

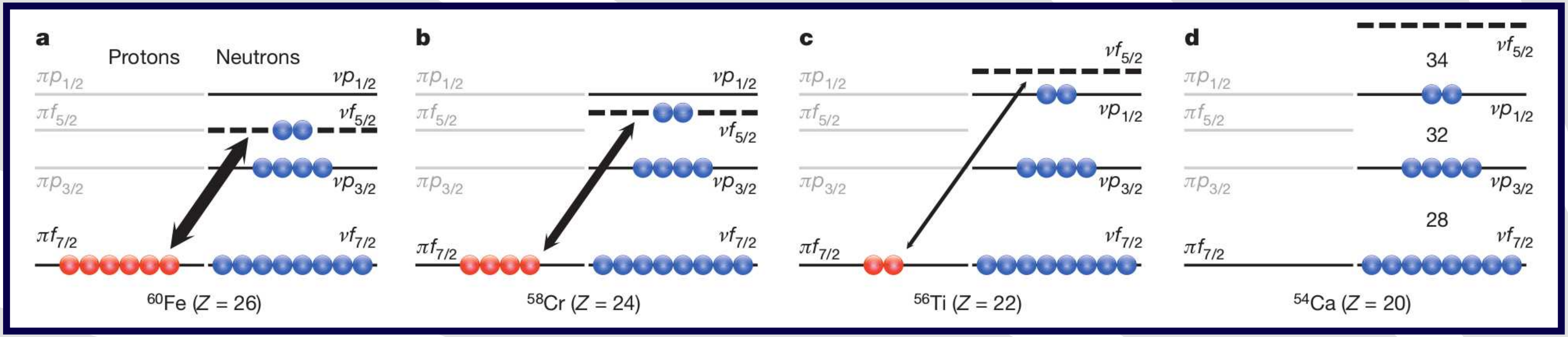


- Red: double-LS magic nuclei
- Green: doubly magic nuclei with j-orbital filling
- Black lines: UNEDF1 functional cross 1 MeV separation energy
- Blue lines: LS magic number broken

B. Alex Brown, Physics 4, 525 (2022).

Shell Evolution at $N = 32, 34$

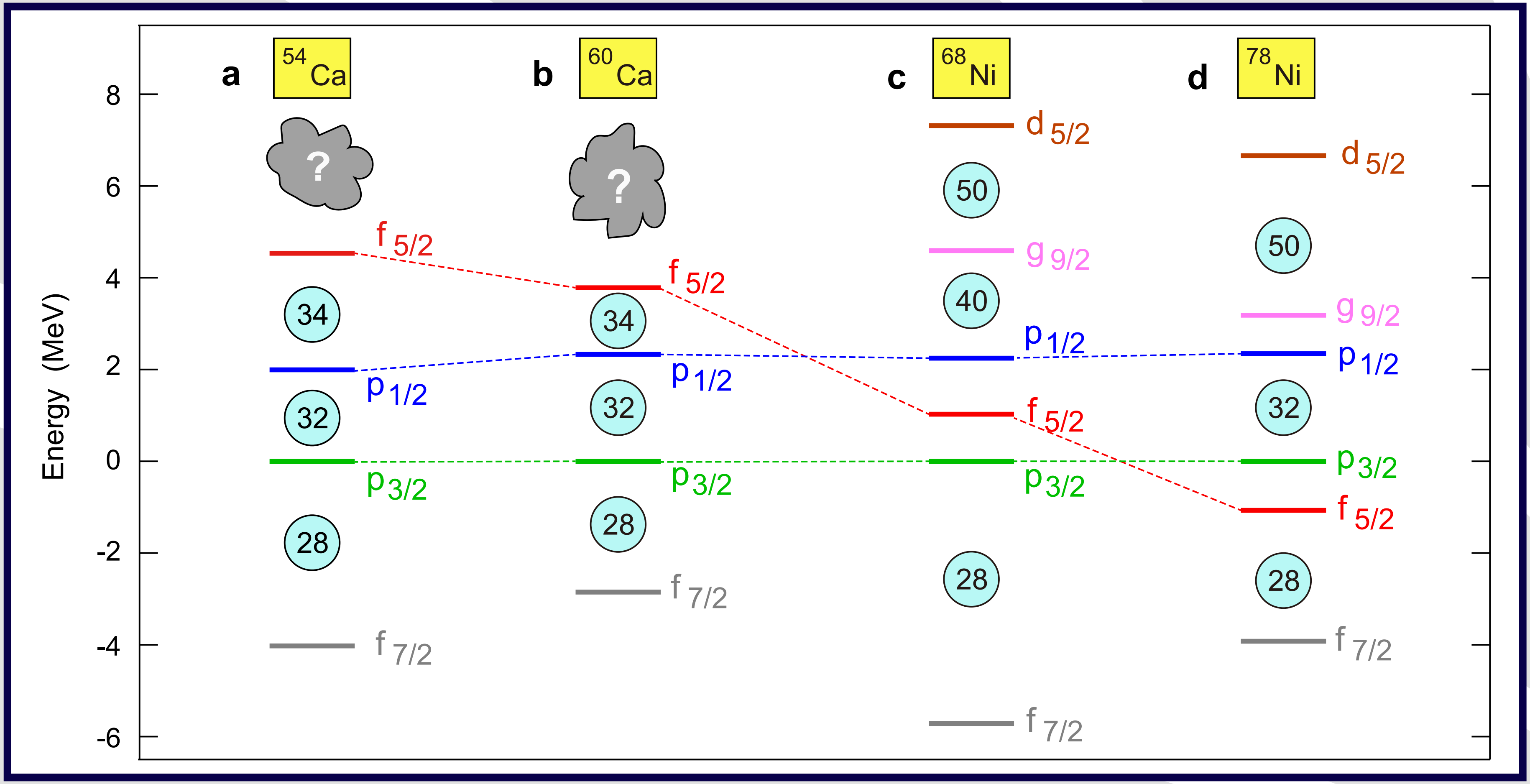
^{60}Fe, stable → ^{54}Ca, exotic



- Reduced attractive interaction between $\pi f_{7/2}$ and $\nu f_{5/2}$
- Possible development of new sub-shell closures at N = 32 and N = 34
- A single proton in $\pi f_{7/2}$ destroys $N = 34$ magicity!

D. Steppenbeck *et al.*, Nature 502, 207 (2013).
Prediction for $N = 34$ magic Number: T. Otsuka *et al.*, PRL 87, 082502 (2001).

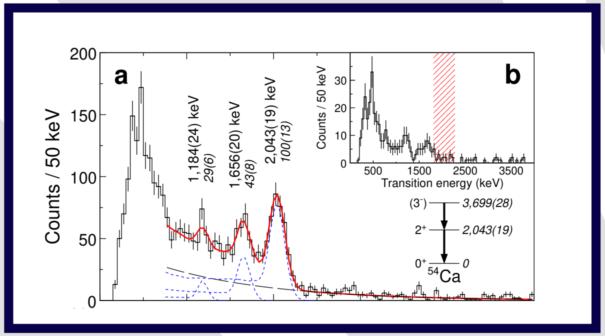
Effective Neutron Single Particle Energies

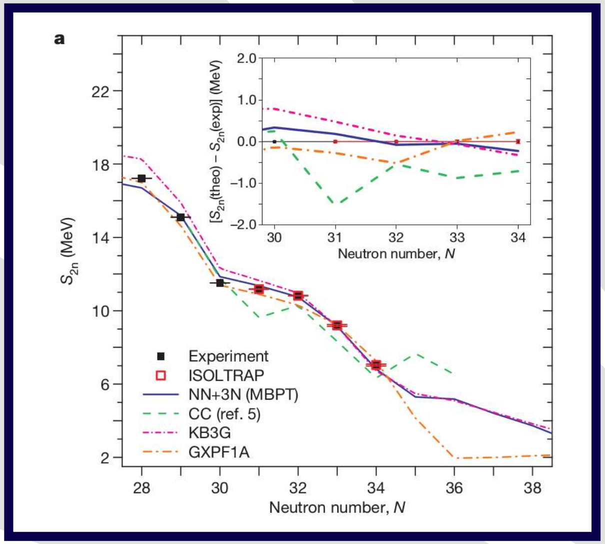


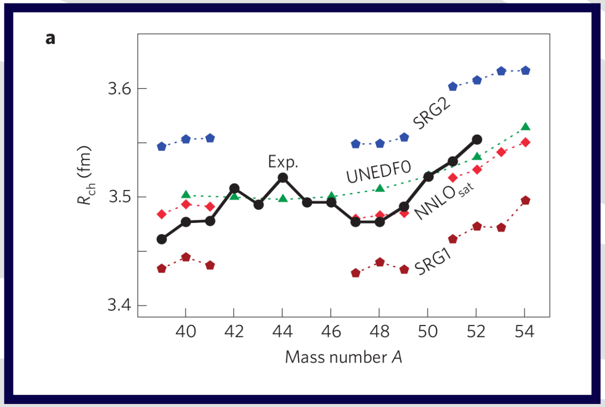
- Calculations with A3DA-t and A3DA-m Hamiltonian
- Influence of $d_{5/2}$ and $g_{9/2}$? Is $N = 40$ magic?
- How "magic" are $N = 32, 34$ in ^{52,54}Ca?
- Ca: Closed proton shell $\rightarrow$ Structure dominated by valence neutrons

Observations for Ca Isotopes

- Significant $N = 32, 34$ shell closures:
  - Large $E(2_1^+)$:
    ^{52}Ca: A. Huck *et al.*, PRC 31, 2226 (1985).
    ^{52}Ca: A. Gade *et al.*, PRC 74, 021302 (2006).
    ^{54}Ca: D. Steppenbeck *et al.*, Nature 502, 207 (2013).
  - Large shell gap Δ_{2n}:
    ^{54}Ca: F. Wienholtz *et al.*, Nature 498, 346 (2013).
    $^{55\text{–}57}$Ca: S. Michimasa *et al.*, PRL 121, 022506 (2018).
  - Small $0f_{5/2}$ occupation in g.s. of ^{54}Ca:
    S. Chen *et al.*, PRL 123, 142501 (2019).
- Large charge radii question $N = 32$ shell closure:
  ^{52}Ca: R.F. Garcia Ruiz *et al.*, Nature Physics 12, 596 (2016).
- First observation of ^{60}Ca:
  O. Tarasov *et al.*, PRL 121, 022501 (2018).



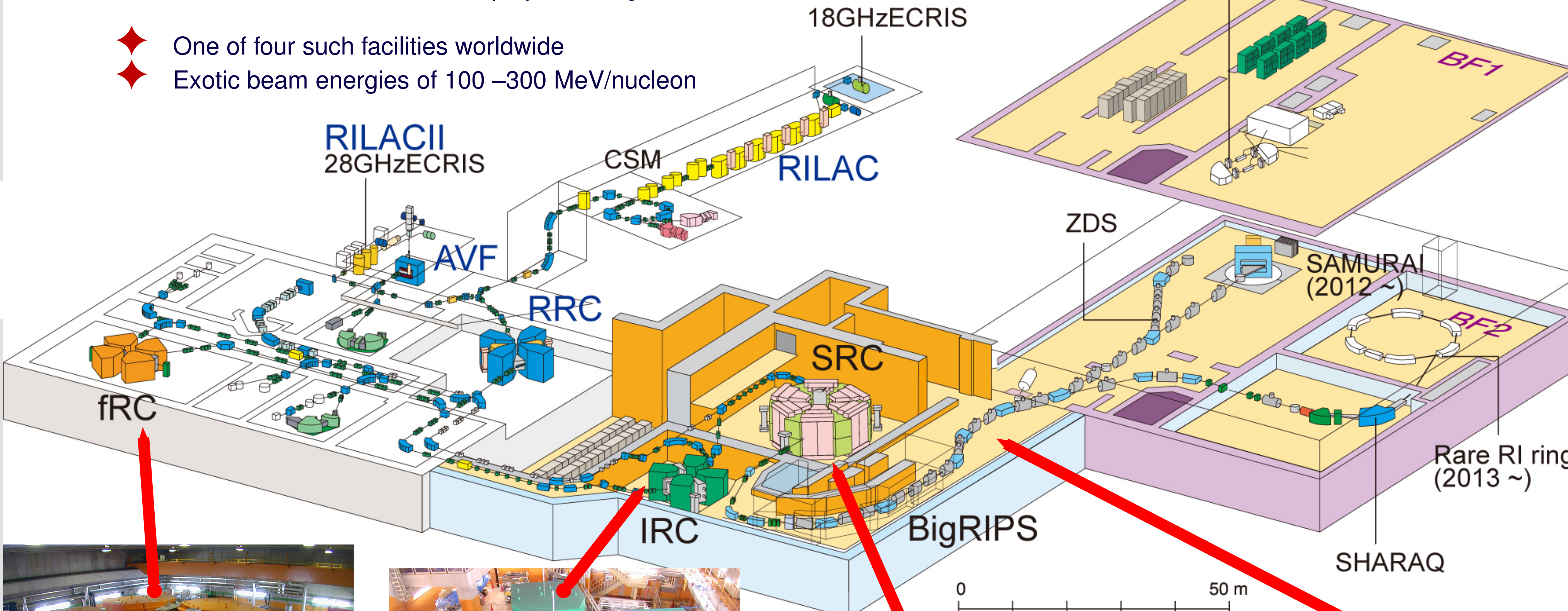


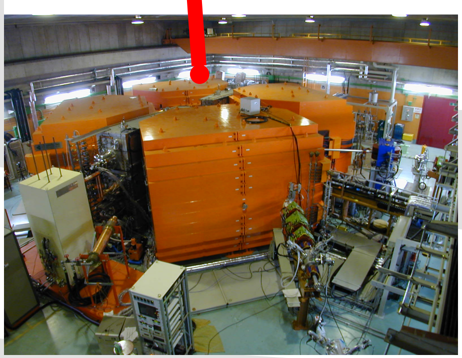


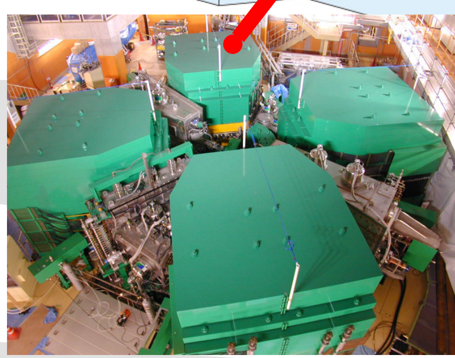
Experimental Setup

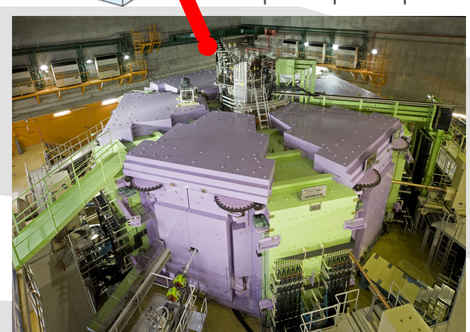
RIBF Overview

- Stable beams (^{70}Zn, ^{238}U, etc) up to 345 MeV/nucleon, 10^{12}–10^{13} pps
- Produce exotic nuclear beams via projectile fragmentation
  - One of four such facilities worldwide
  - Exotic beam energies of 100 –300 MeV/nucleon









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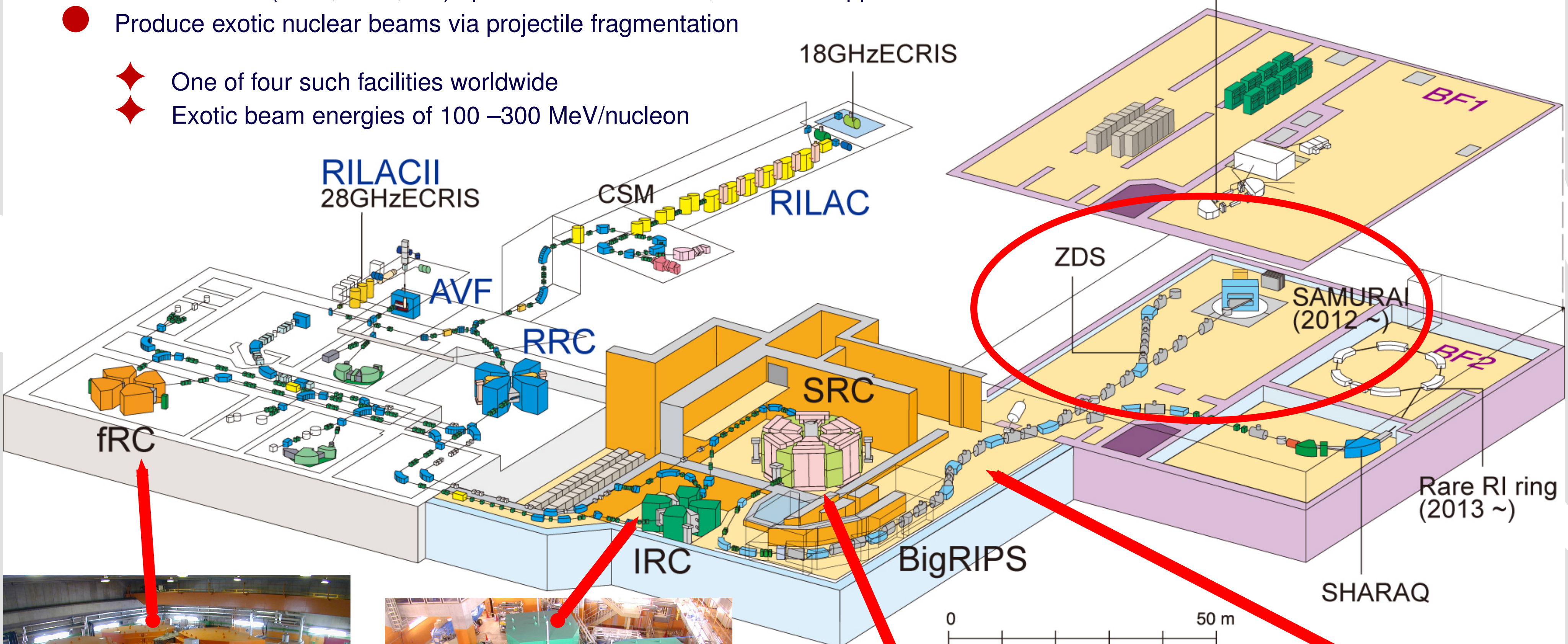
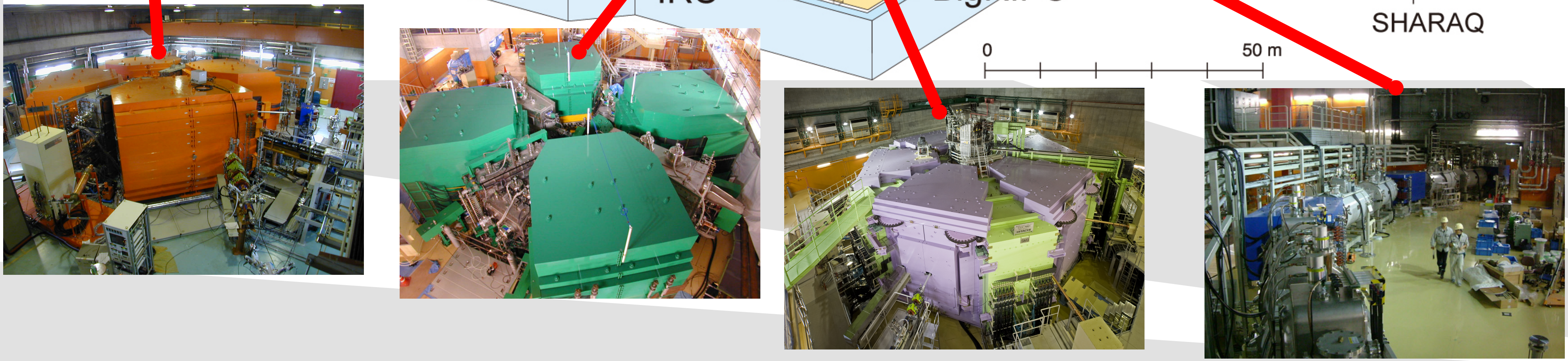
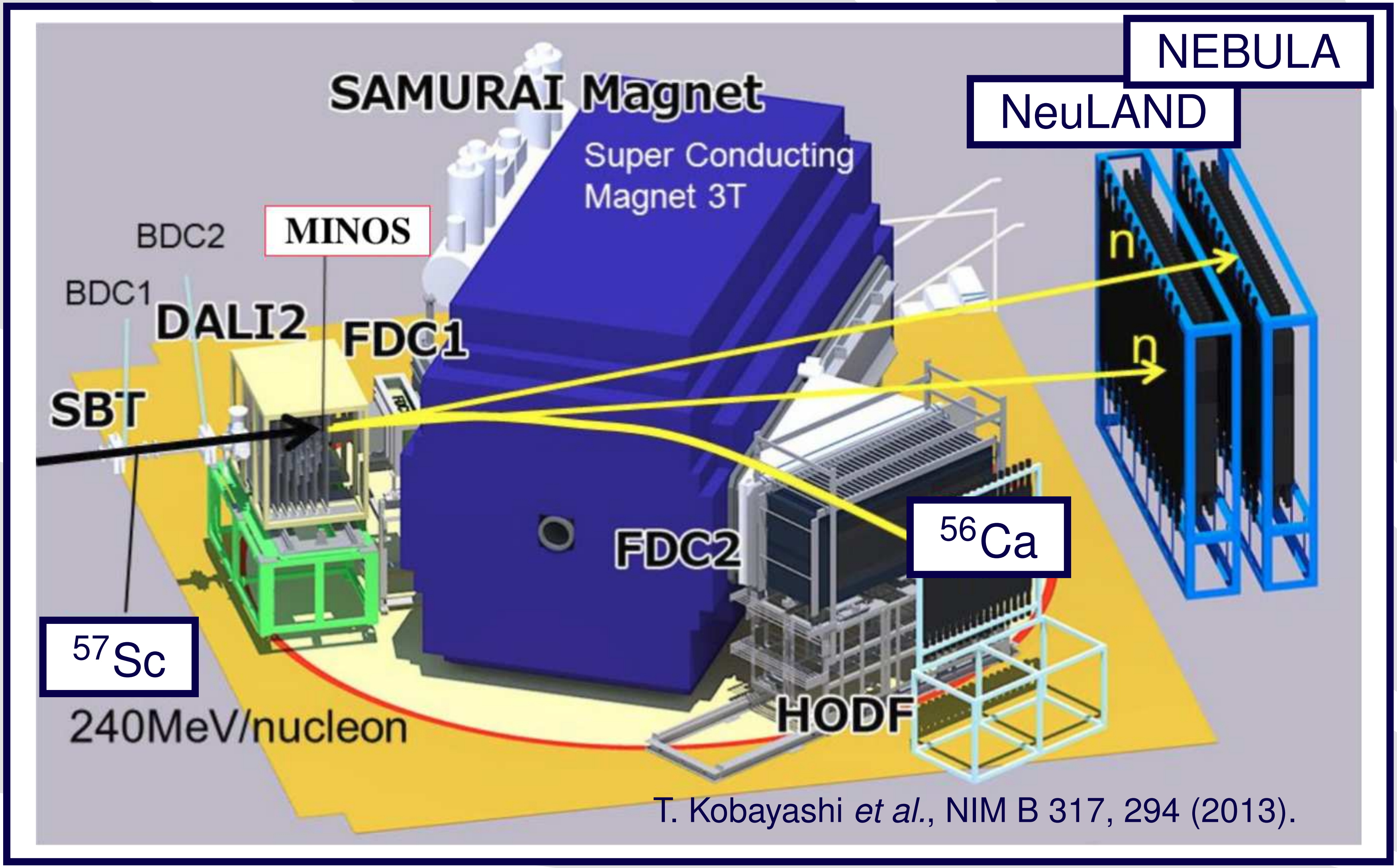


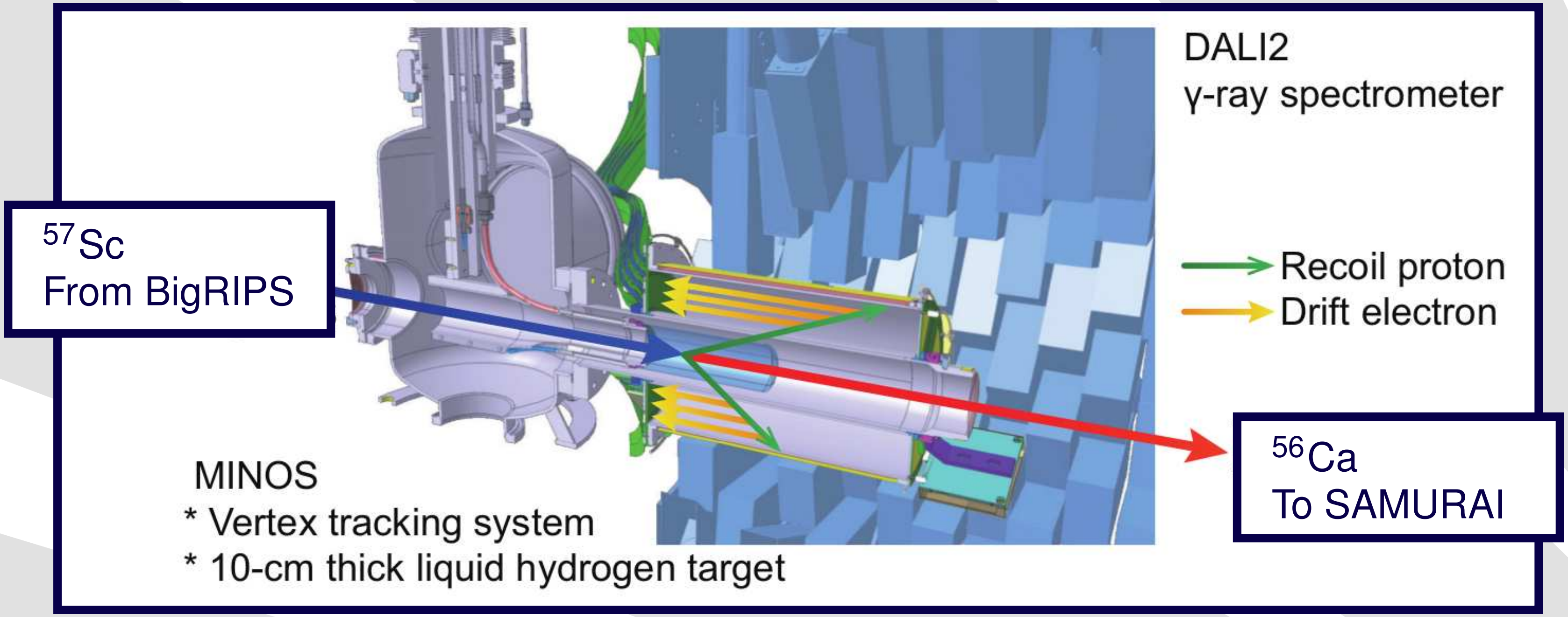


Shell Evolution And Search for Two-plus energies At RIBF (SEASTAR) with SAMURAI



- Large acceptance spectrometer
  - Simultaneous measurement of $^{51–58}$Ca within single experiment
  - Bound states with DALI2^{+}, unbound states with NeuLAND and NEBULA

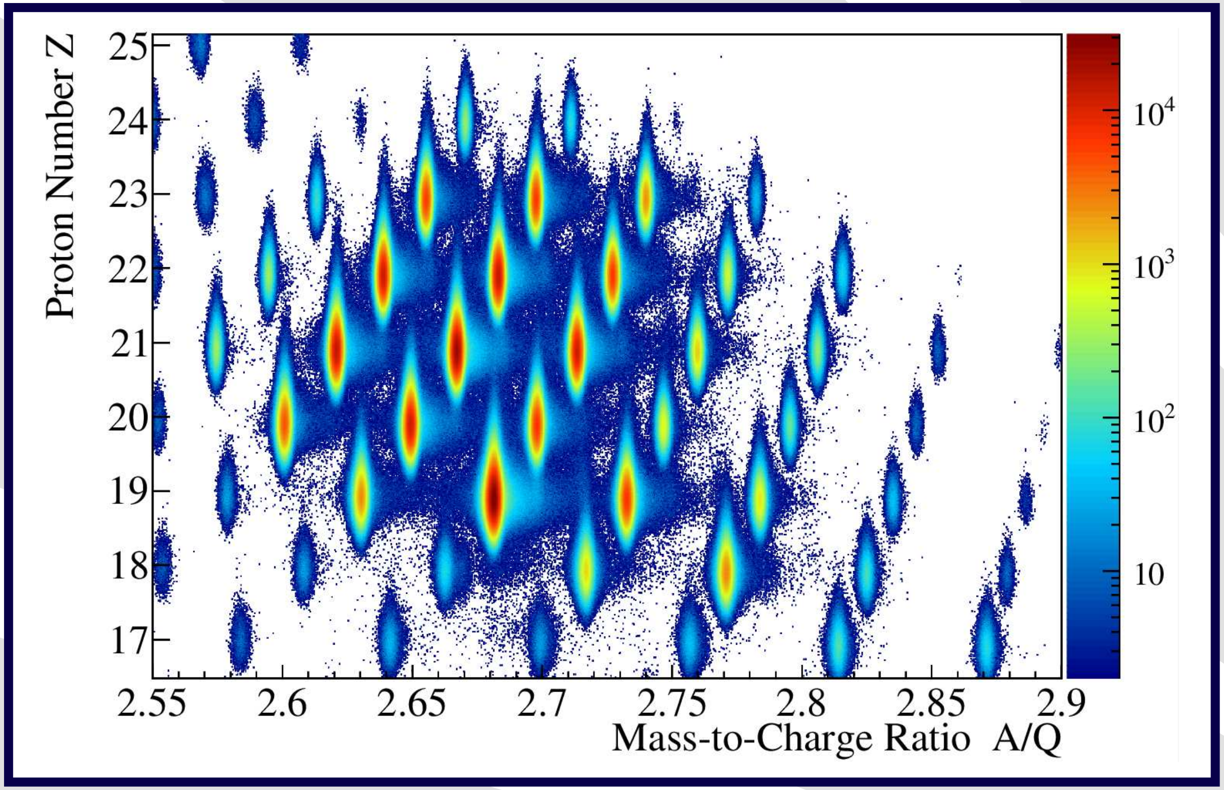
In-Beam Gamma-Ray Spectroscopy With a Liquid Hydrogen Target



- MINOS, **M**ag**I**c **N**umbers **O**ff **S**tability
  - up to 1 g/cm^2 (150 mm) liquid hydrogen target, velocity $\beta \approx 0.6$
  - Position sensitive TPC, vertex position reconstruction with ≈5 mm (FWHM)
  - Higher resolution, higher luminosity, “cleaner” probe than solid targets
  - Resurgance of quasi-free scattering $(p, 2p)$ (p, pn) as spectroscopic tool
- DALI2$^+$, **D**etector **A**rray for **L**ow **I**ntensity γ rays 2$^+$
  - 226 NaI(TI) detectors, large solid angle coverage
  - 10 % resolution 35 % efficiency at 1 MeV

MINOS: A. Obertelli *et al.*, EPJA 50, 8 (2014), DALI2$^+$: S. Takeuchi *et al.*, NIMA 763, 596 (2014).

SEASTAR III at SAMURAI Particle Identification



- ^{70}Zn primary beam, 345 MeV/nucleon, 240 pnA, 8 days
- Secondary beam at 240 MeV/nucleon, $\delta p/p = \pm 3\%$
- **ONE unique setting**
- Total beam intensity: 200 pps
- ^{53}K: 0.8 pps, ^{57}Sc: 13.6 pps, ^{59}Sc: 0.3 pps, ^{63}V: 3 pps

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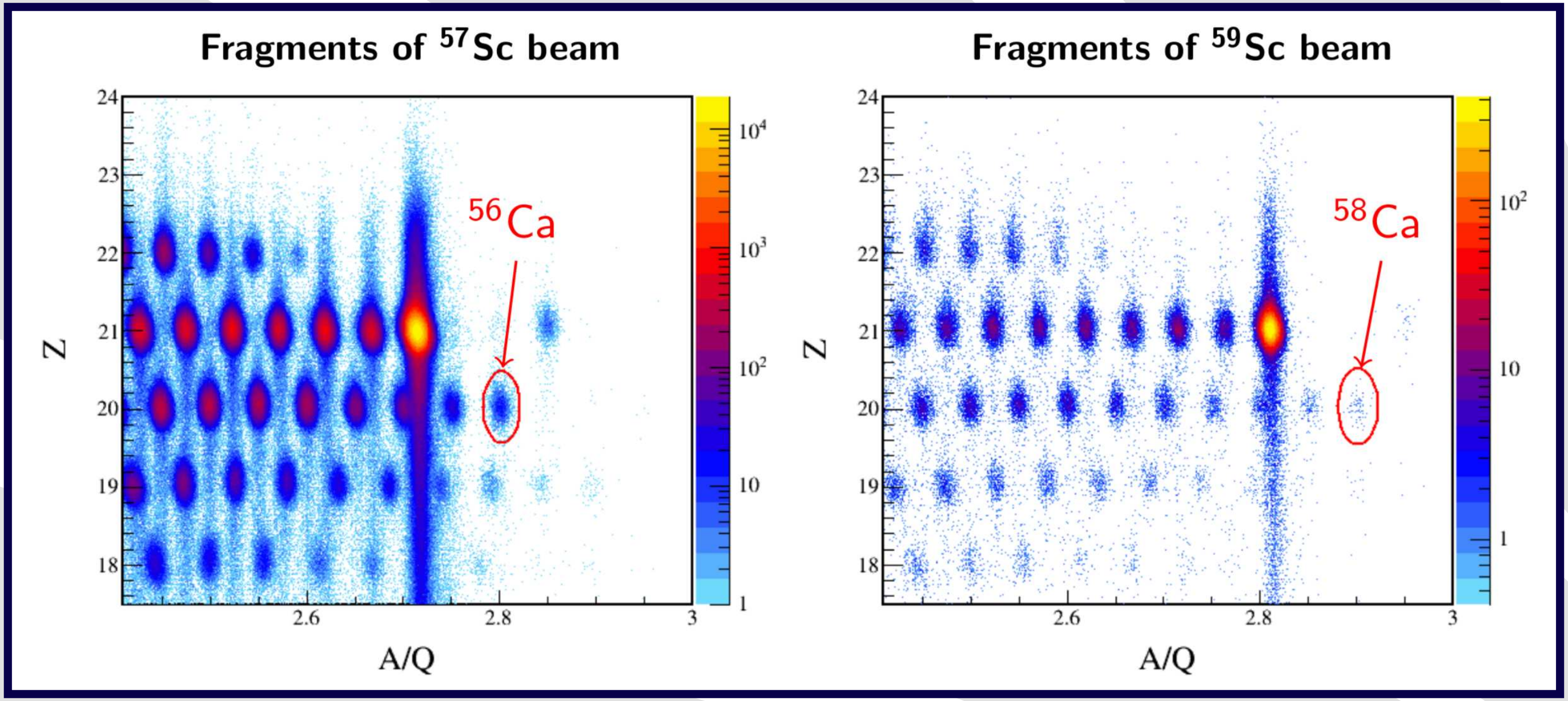

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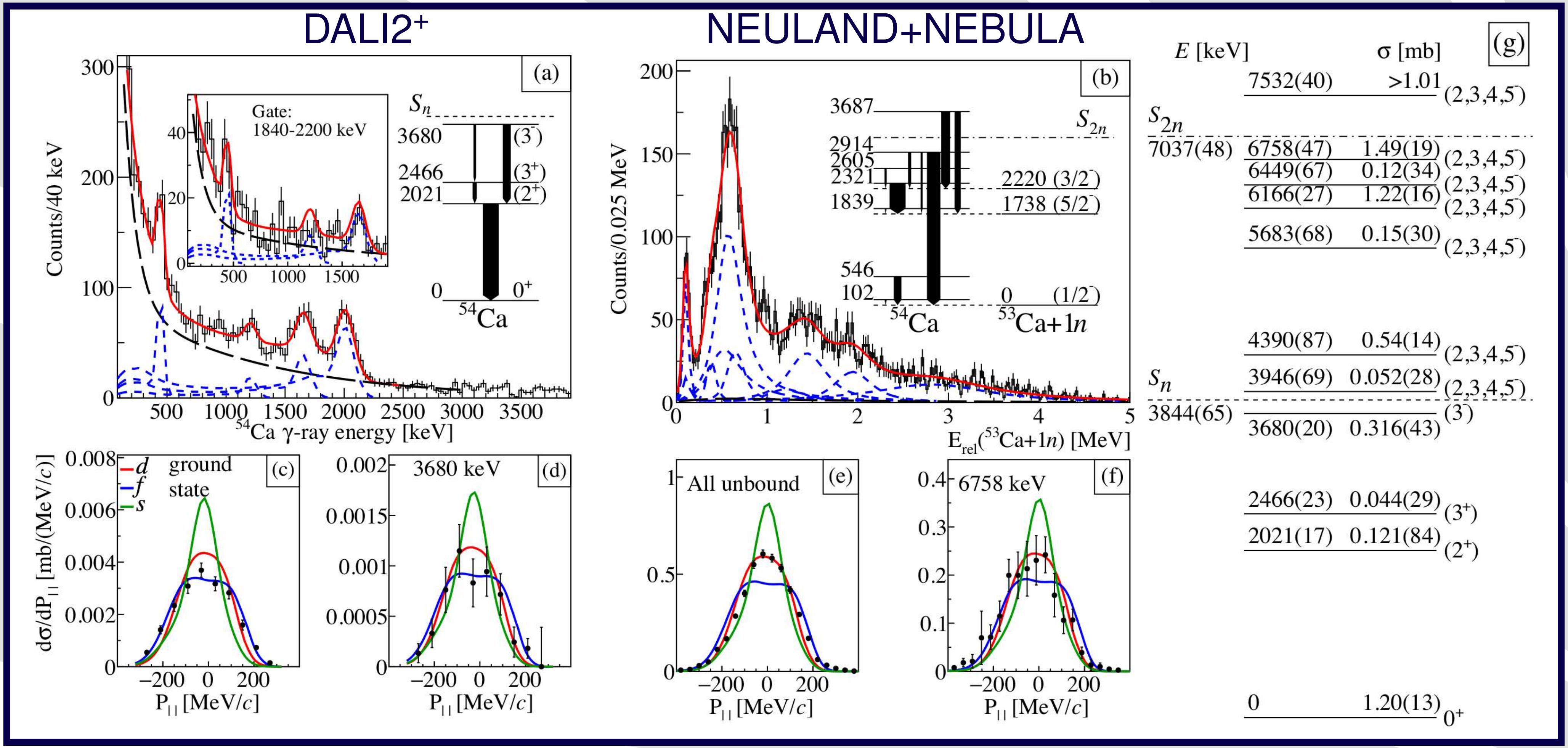
Detailed Spectroscopy of ^{54}Ca

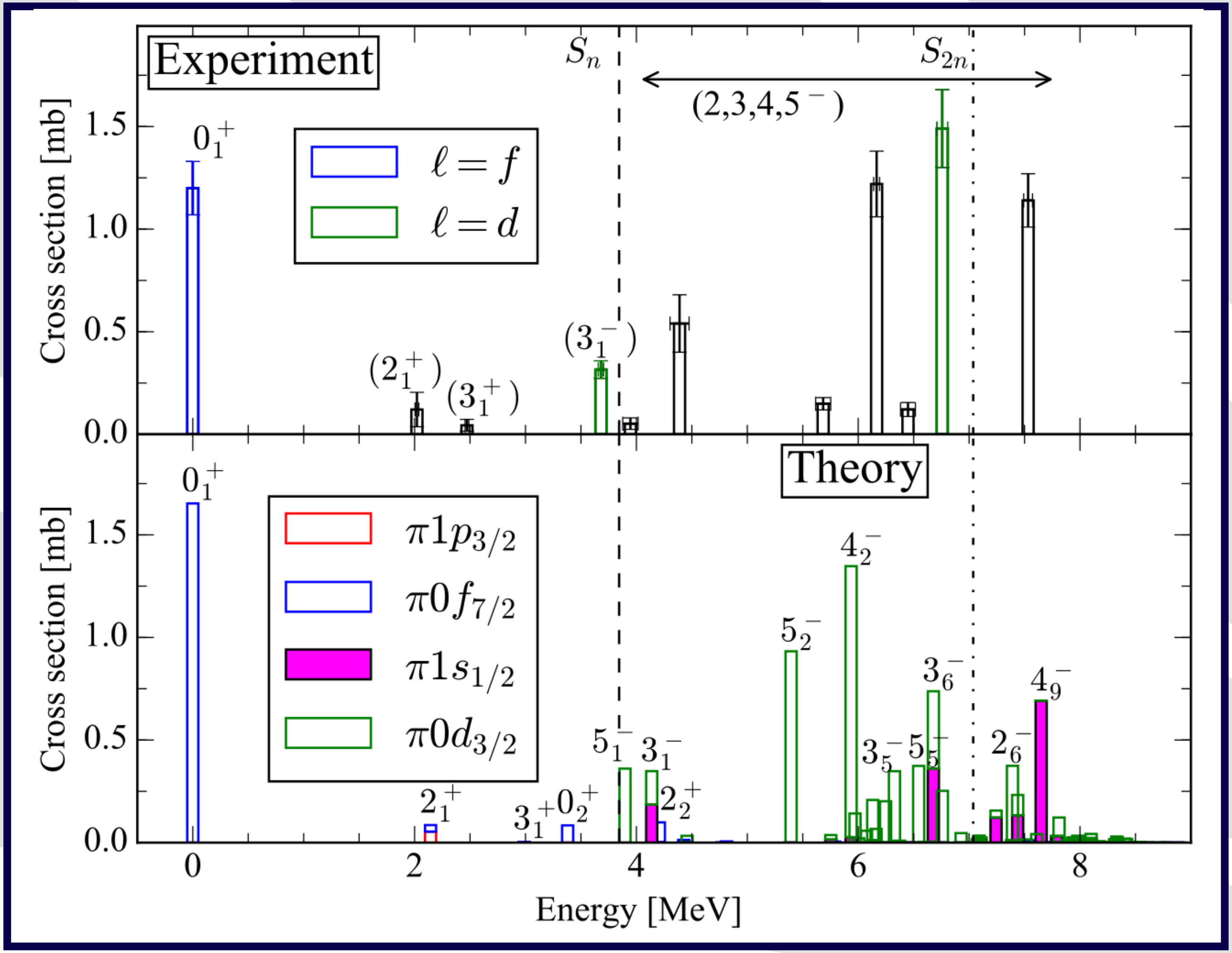
Detailed Spectroscopy of ^{54}Ca from ^{55}Sc(p,2p)^{54}Ca and ^{55}Ca(p,pn)^{54}Ca

^{55}Sc(p,2p)^{54}Ca case:



First Spectroscopy of ^{54}Ca: D. Steppenbeck, S. Takeuchi *et al.*, Nature 502, 207 (2013).
This work: F. Browne, S. Chen *et al.*, PRL 126, 252501 (2021).
Theory: GXPF1Br interaction in full $sd-pf-gds$ model space, DWIA for σ_{sp} and $P_{||}$

Detailed Spectroscopy of ^{54}Ca from ^{55}Sc(p,2p)^{54}Ca and ^{55}Ca(p,pn)^{54}Ca



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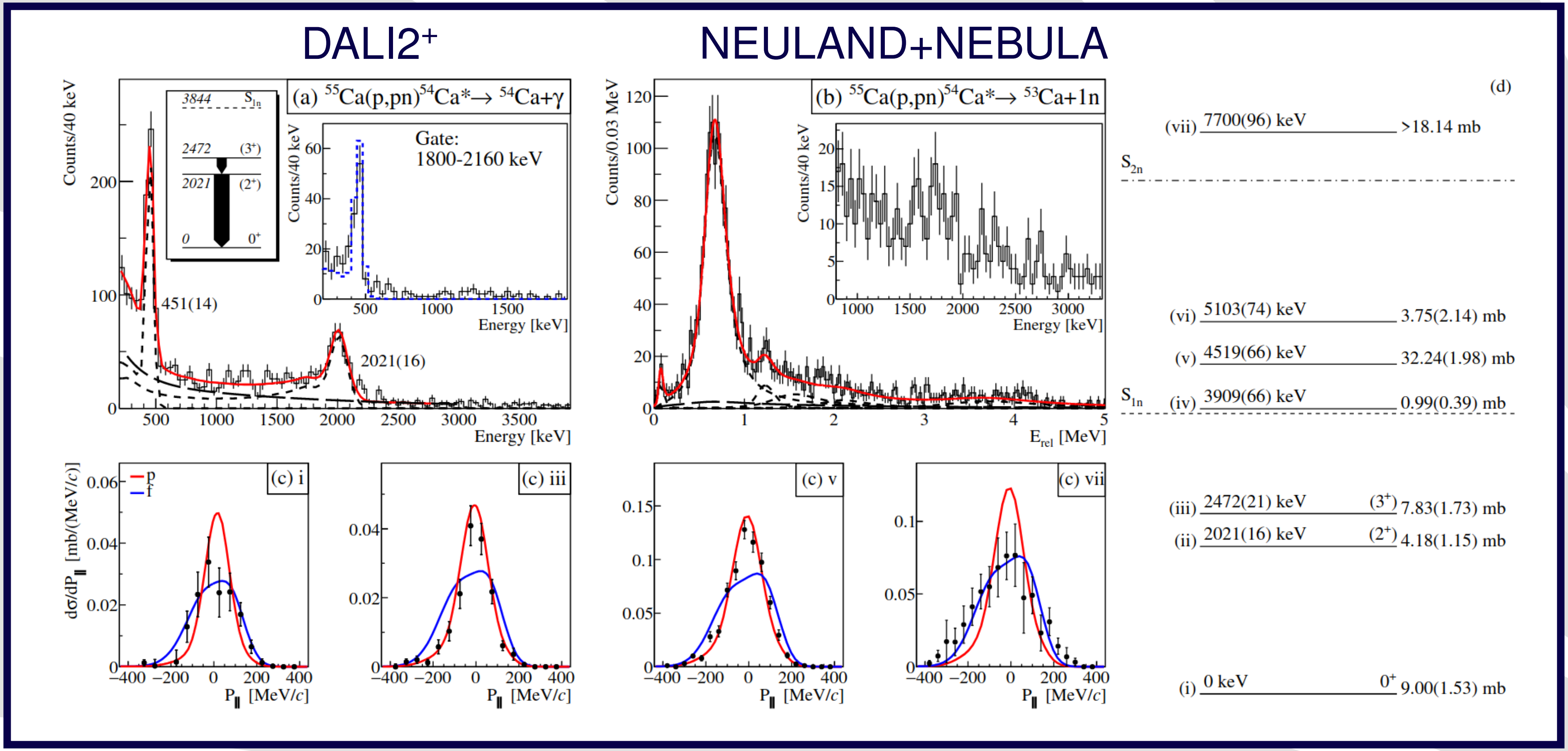
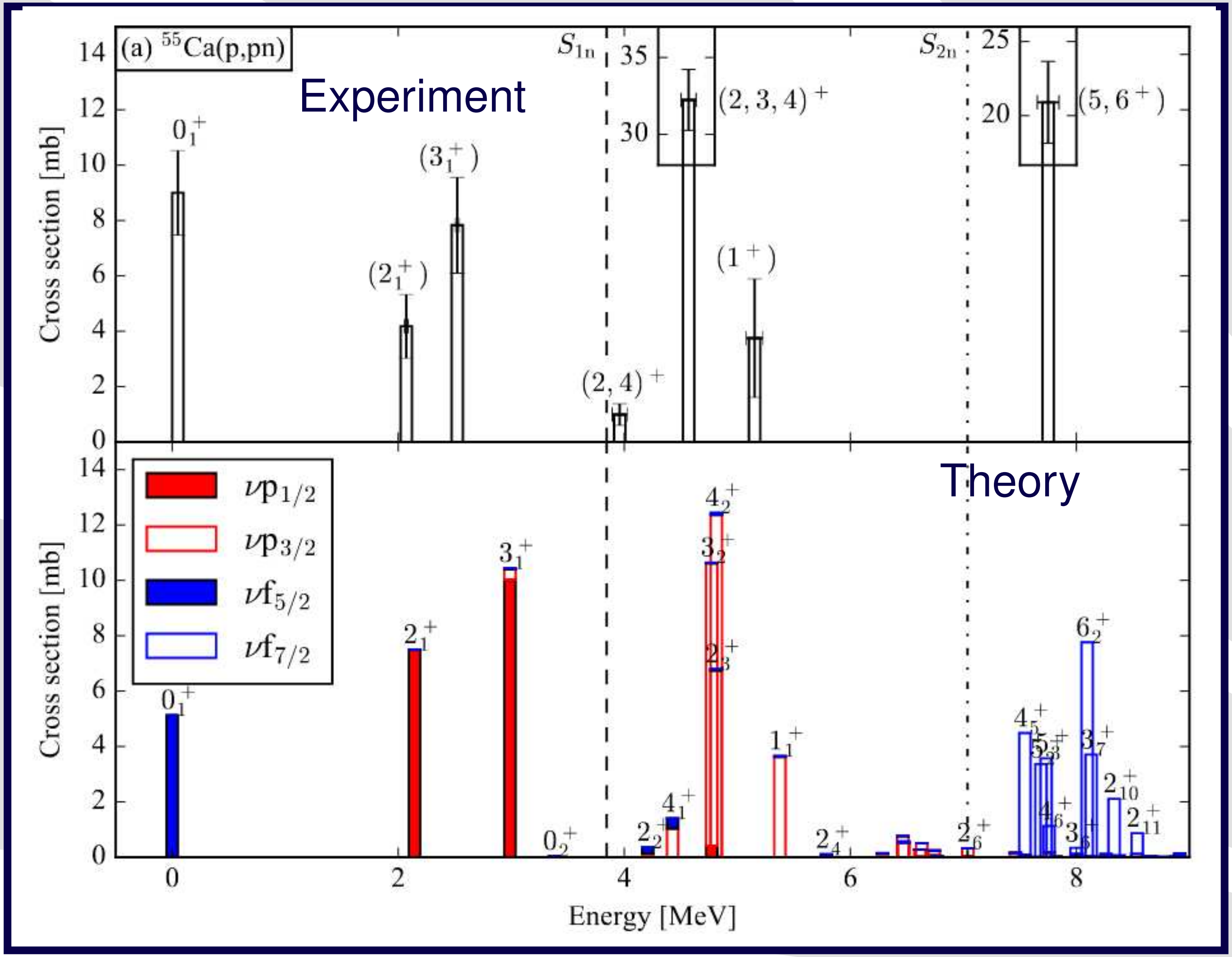
Detailed Spectroscopy of ^{54}Ca from ^{55}Sc(p,2p)^{54}Ca and ^{55}Ca(p,pn)^{54}Ca

^{55}Ca(p,pn)^{54}Ca case:



F. Browne, S. Chen *et al.*, to be published.
Theory: GXPF1Br interaction in full $sd-pf-gds$ model space, DWIA for σ_{sp} and $P_{||}$

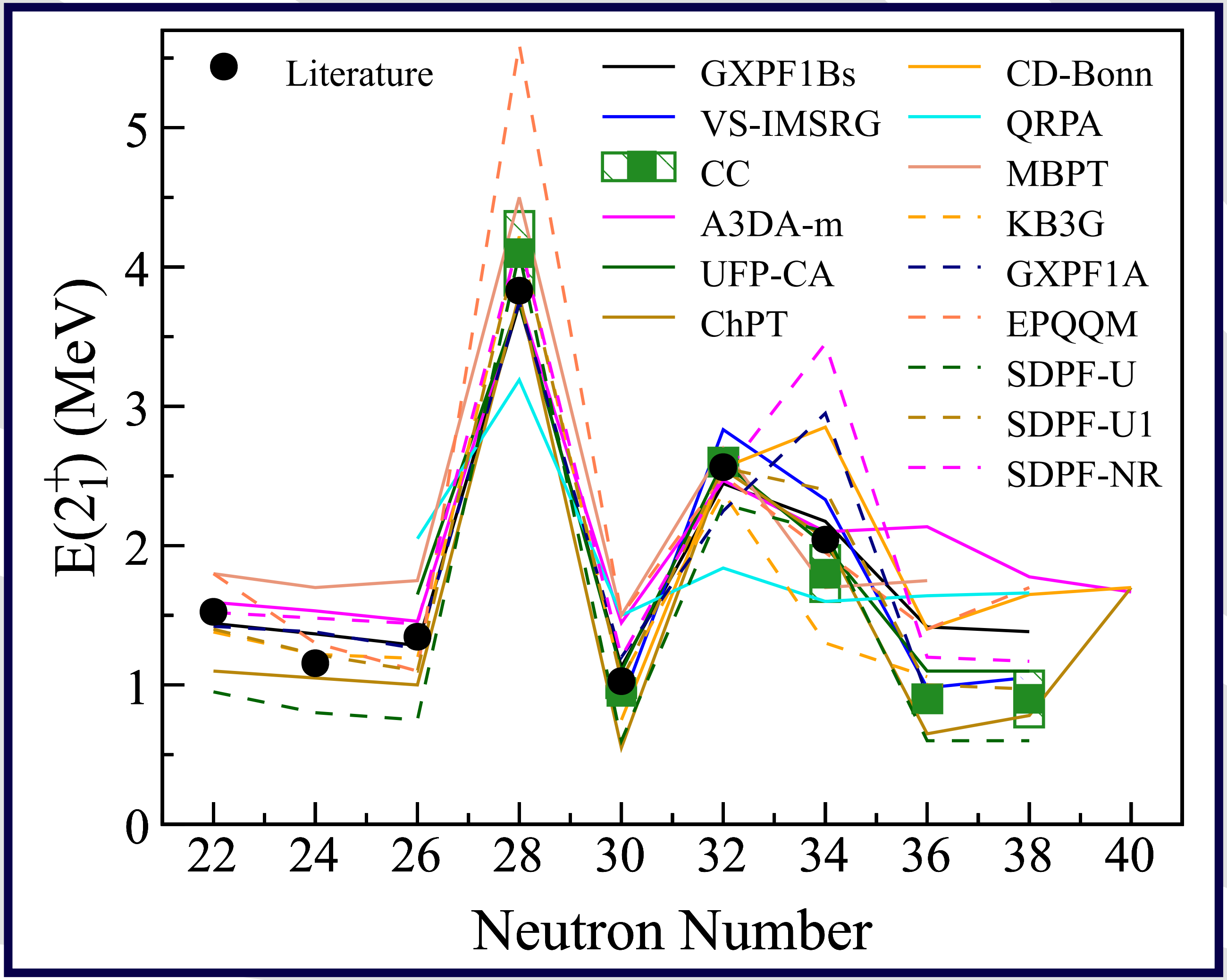
Detailed Spectroscopy of ^{54}Ca from ^{55}Sc(p,2p)^{54}Ca and ^{55}Ca(p,pn)^{54}Ca



F. Browne, S. Chen *et al.*, to be published.
Theory: GXPF1Br interaction in full $sd-pf-gds$ model space, DWIA for σ_{sp} and $P_{||}$

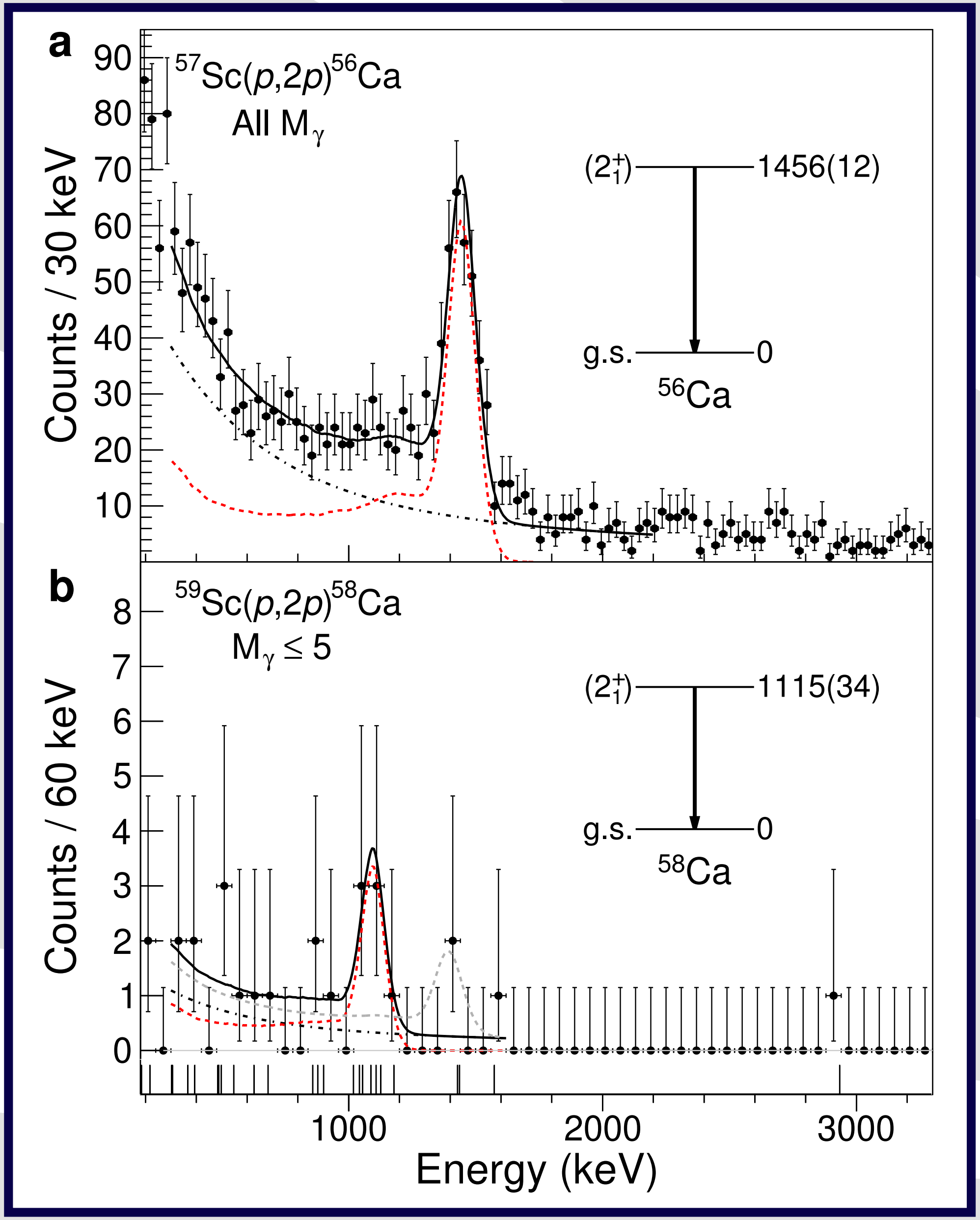
First Spectroscopy of $^{56,58}Ca$

$E(2_1^+)$ Predictions in N-Rich Calcium Isotopes



- Various theoretical predictions, signifying the importance of the Ca isotopes
- No consensus for $E(2_1^+)$ at $N = 36, 38$ for ^{56,58}Ca
  - ✦ predictions between 0.5–2 MeV, flat trend

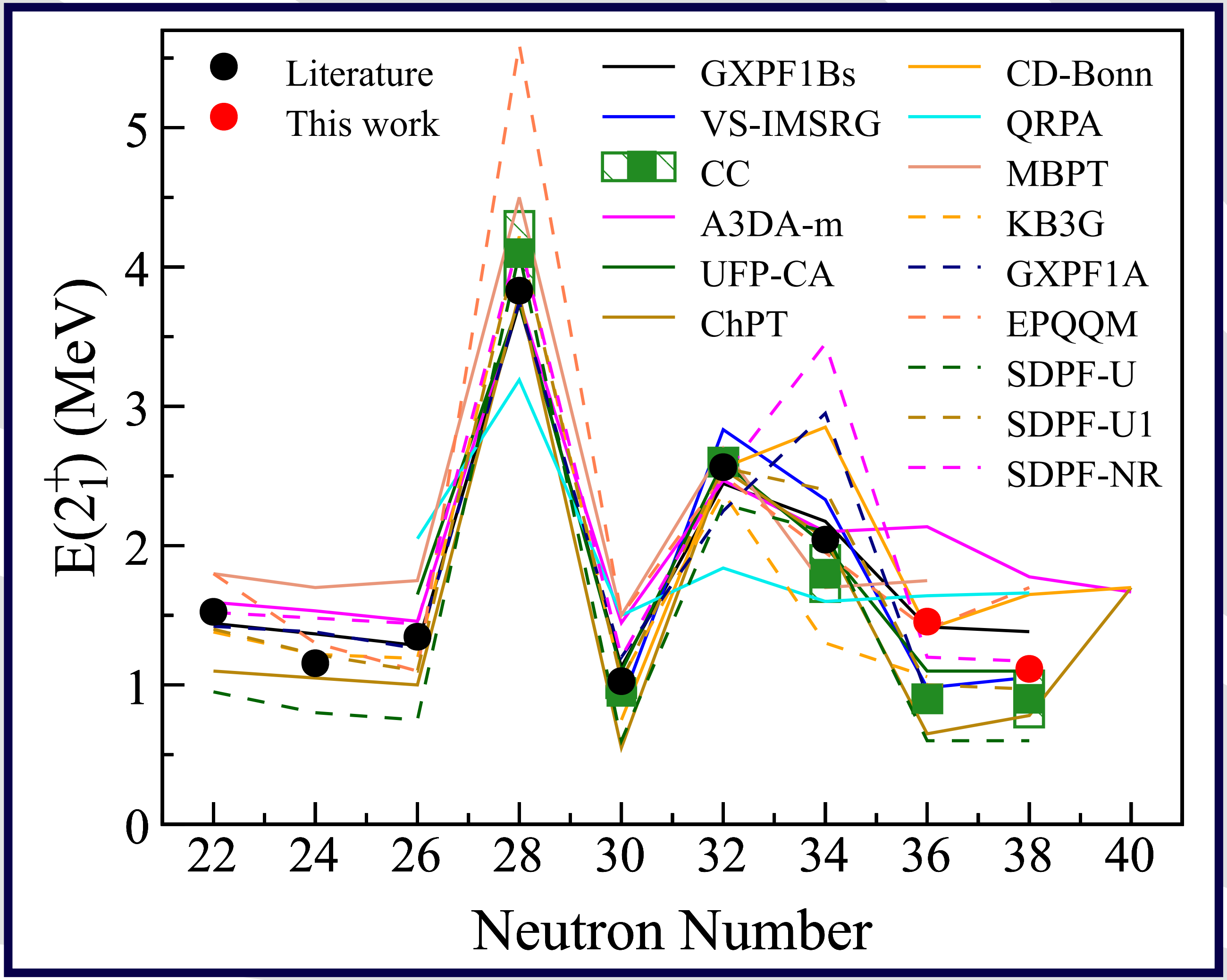
$E(2_1^+)$ *in* ^{56,58}*Ca*



- 13.6 particles/s for ^{57}Sc
- 0.3 particles/s for ^{59}Sc
- $E(2_1^+)$ differ by ≈ 340 keV
- ^{58}Ca at the limit of feasibility
  - S.L = 2.8 σ for $E(2_1^+)$
- particle hole symmetry of $0f_{5/2}$
  - if $N = 40$ closed, constant energy expected
  - (doubly)-magic ^{60}Ca disfavored

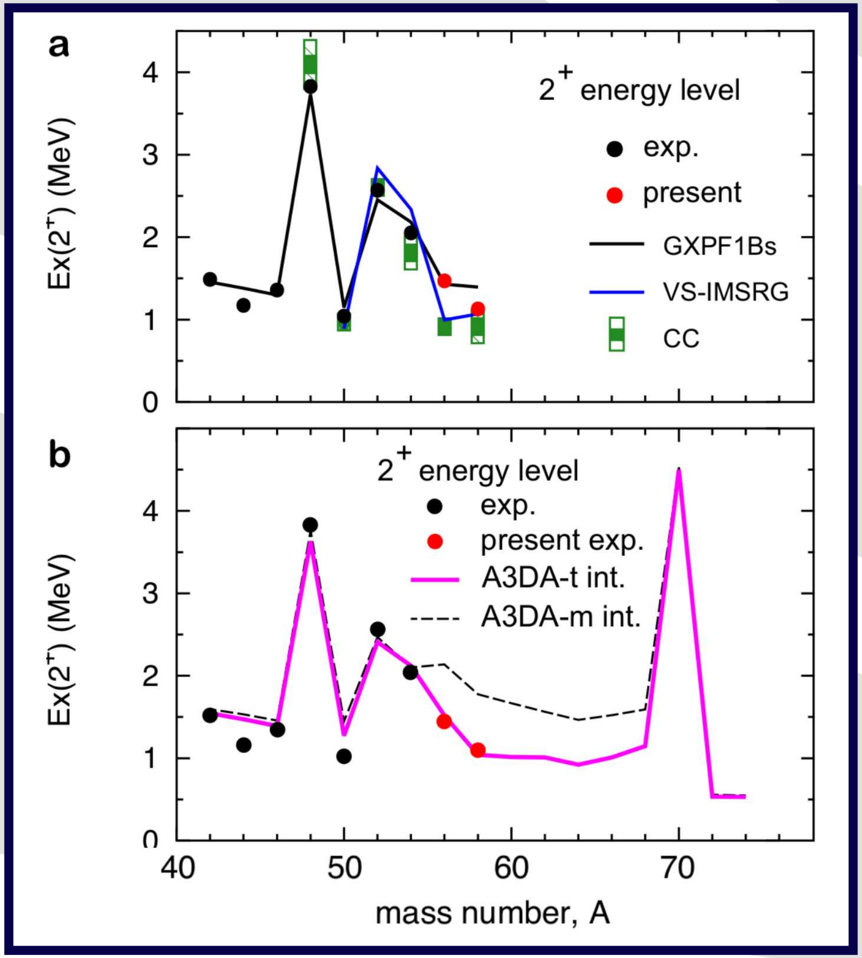
S. Chen, F. Browne *et al.*, PLB 843 138025 (2023).

$E(2_1^+)$ *Predictions in N-Rich Calcium Isotopes*



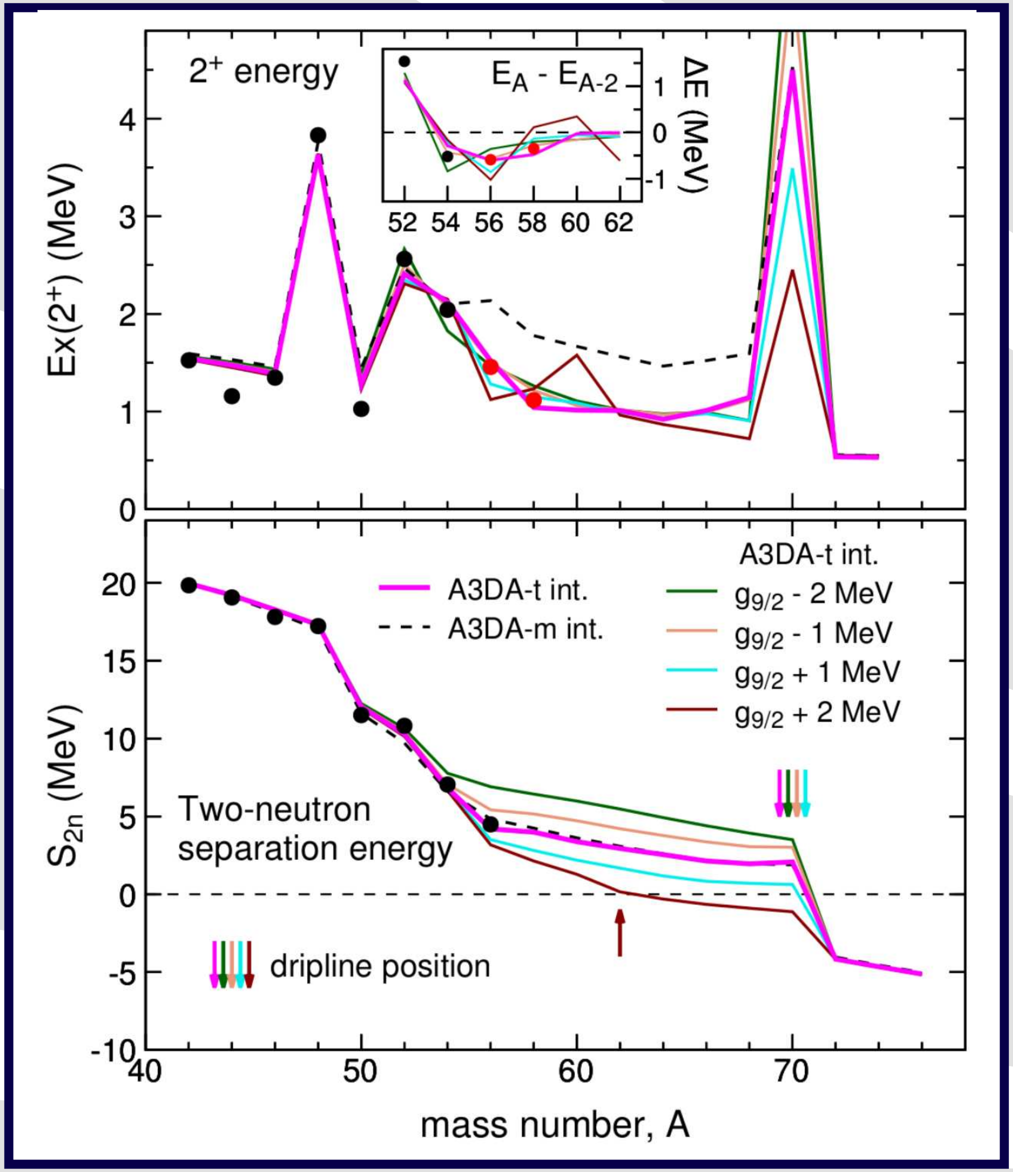
- Downward slope not reproduced by most theories
  - Usually $N = 40$ shell closure
- Need to confirm $E(2_1^+)$ indication for ^{58}Ca, final proof by spectroscopy of ^{60}Ca

First Spectroscopy of ^{56,58}Ca



- GXPF1Bs:
  Shell-model
  neutron pf shell
- VS-IMSRG:
  Valence-space in-medium similarity renormalization group
  1.8/2.0 (EM) interaction
  neutron pf shell
- CC: Coupled-cluster theory
  Two-particle removed/attached equation-of-motion (2PR/2PA-EOM)
- A3DA-t: Revision of A3DA-m interaction fitted to existing $E(2_1^+)$ and S_{2n} data
  Neutron $pf - g_{9/2}d_{5/2}$ orbitals

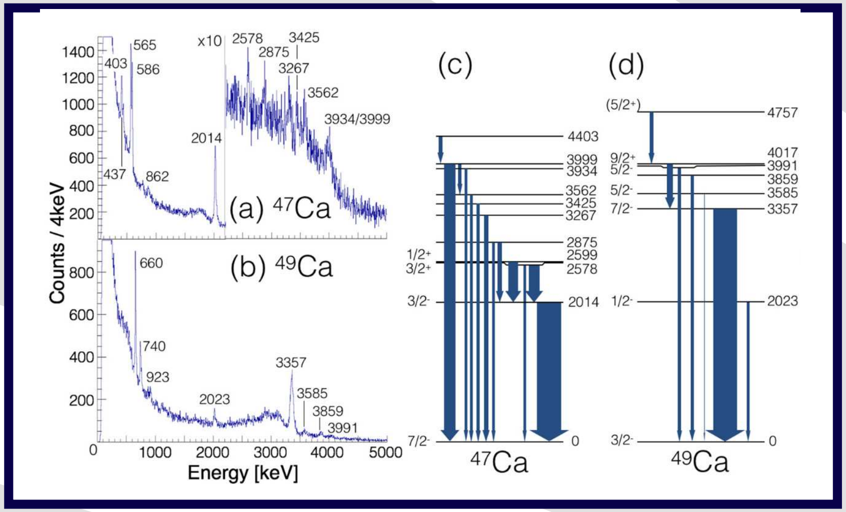
First Spectroscopy of ^{56,58}Ca

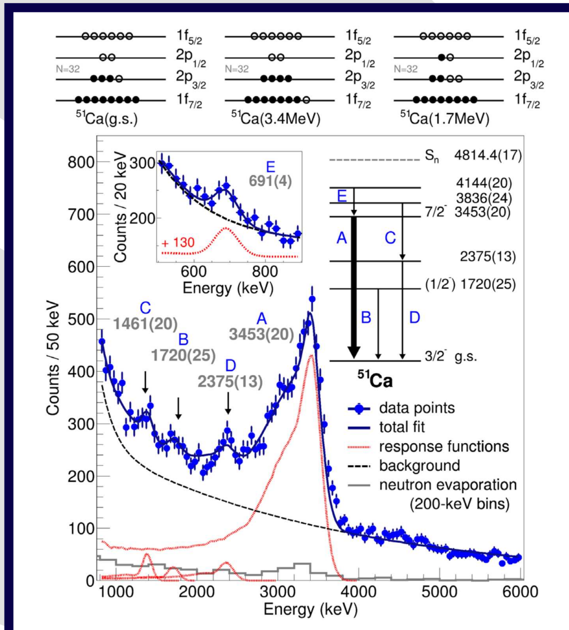


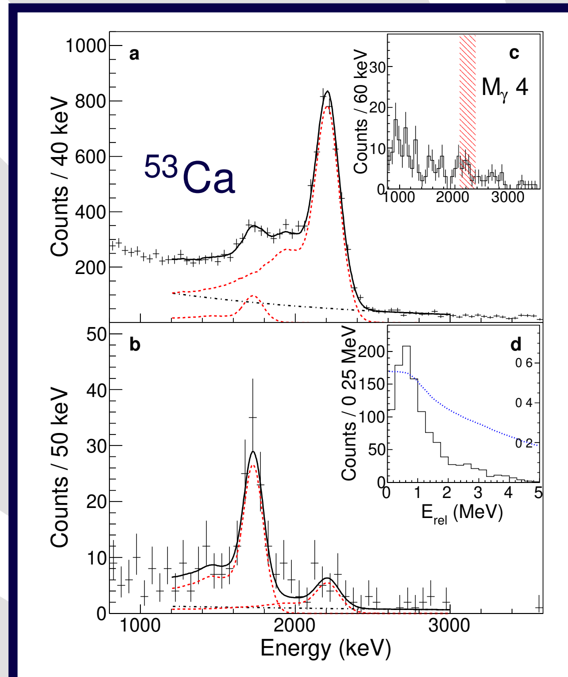
- Predictions with A3DA-T Hamiltonian
- Sensitivity of the neutron $0g_{9/2}$ SPE
  $\rightarrow$ variation of up to ± 2 MeV
  - ✦ Positive shifts of $0g_{9/2}$ SPE
    $\rightarrow$ low $E(2_1^+)$ and S_{2n} of ^{56}Ca
    $\rightarrow$ Doubly magic ^{60}Ca
  - ✦ Negative shifts of $0g_{9/2}$ SPE
    $\rightarrow$ quenching of $N = 34$ shell gap
    $\rightarrow$ Contradiction with observation
  - ✦ No shift of $0g_{9/2}$ SPE
    $\rightarrow$ No doubly magic ^{60}Ca
    $\rightarrow$ Positive S_{2n} up to ^{70}Ca

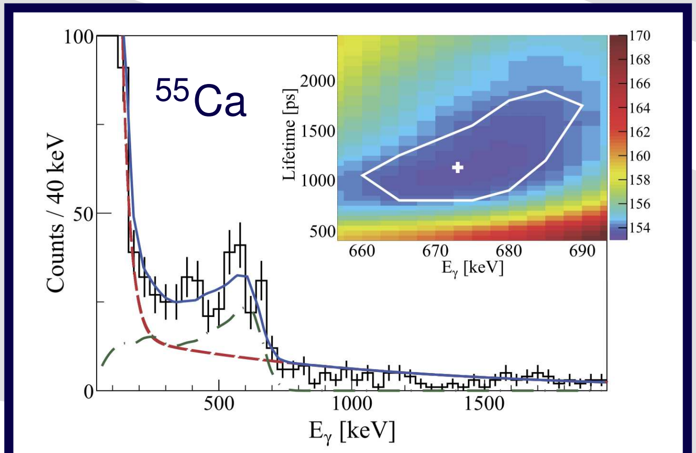
Structure of Neutron-Rich Odd Ca Isotopes

Bound Excited States in ^{49,51,53,55}Ca from One-Neutron Knockout





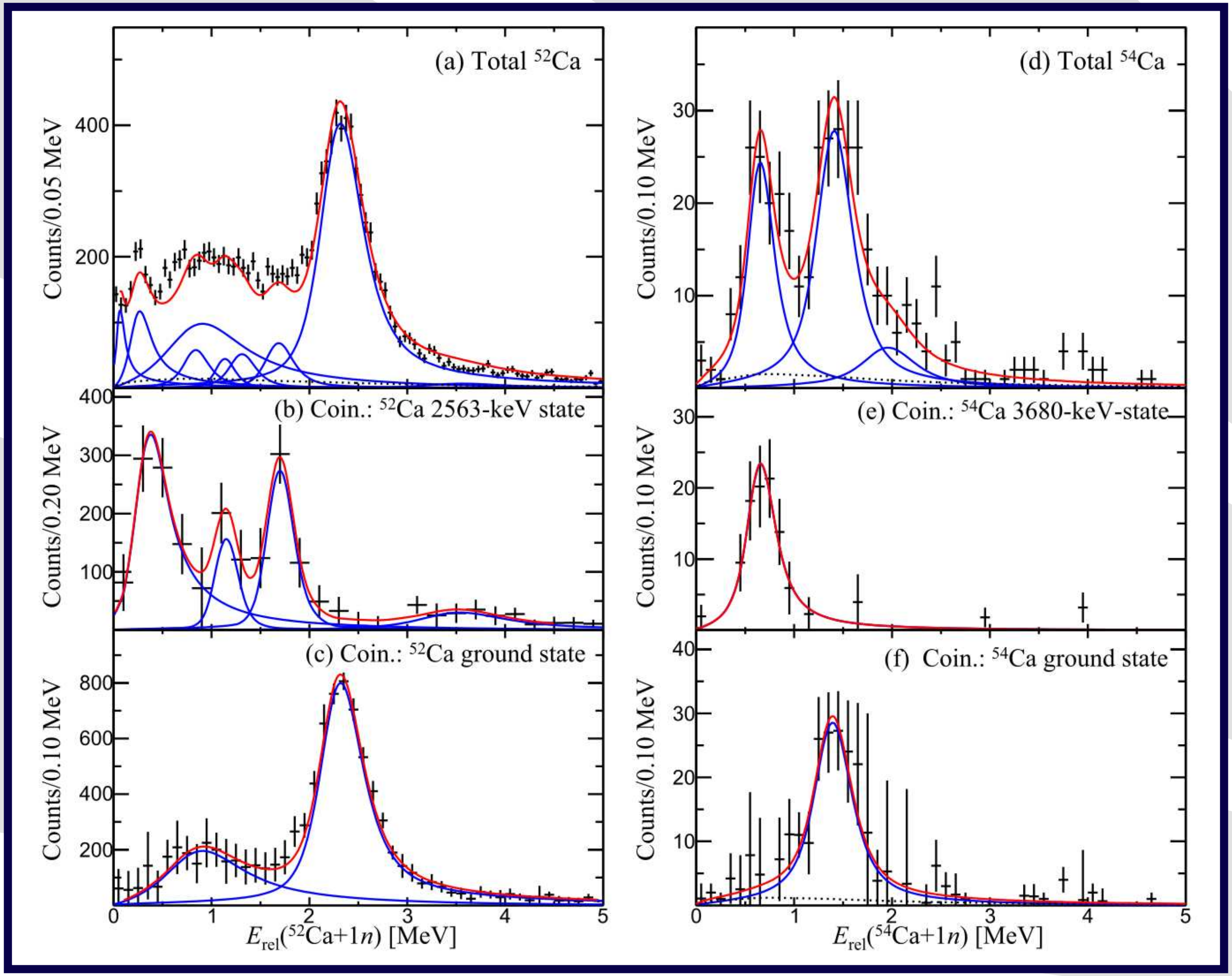


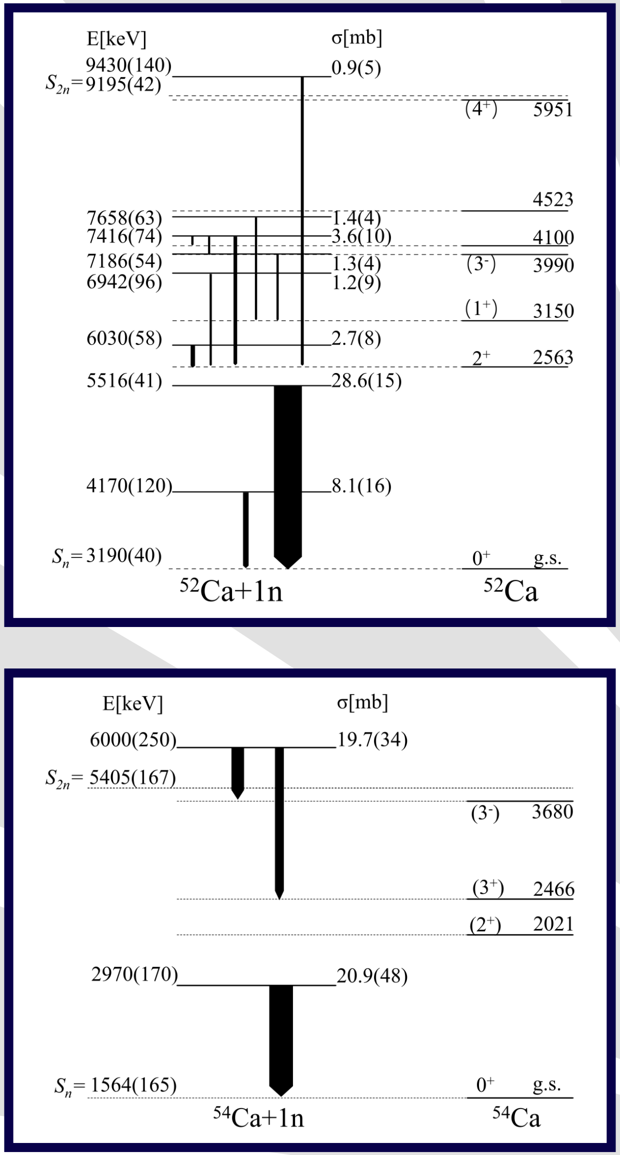


^{47,49}Ca: H. Crawford *et al.*, PRC 95, 064317 (2017).
^{51}Ca: M. Enciu *et al.*, PRL 129, 262501 (2022).
^{53}Ca: S. Chen *et al.*, PRL 123, 142501 (2019).
^{55}Ca: T. Koiwai *et al.*, 827, 136953 (2022).

- Few bound excited states for $A > 50$
- Spectroscopic strengths for $0f_{7/2}, 0f_{5/2}, 1p_{3/2}, 0p_{1/2}$
- Very little fragmentation

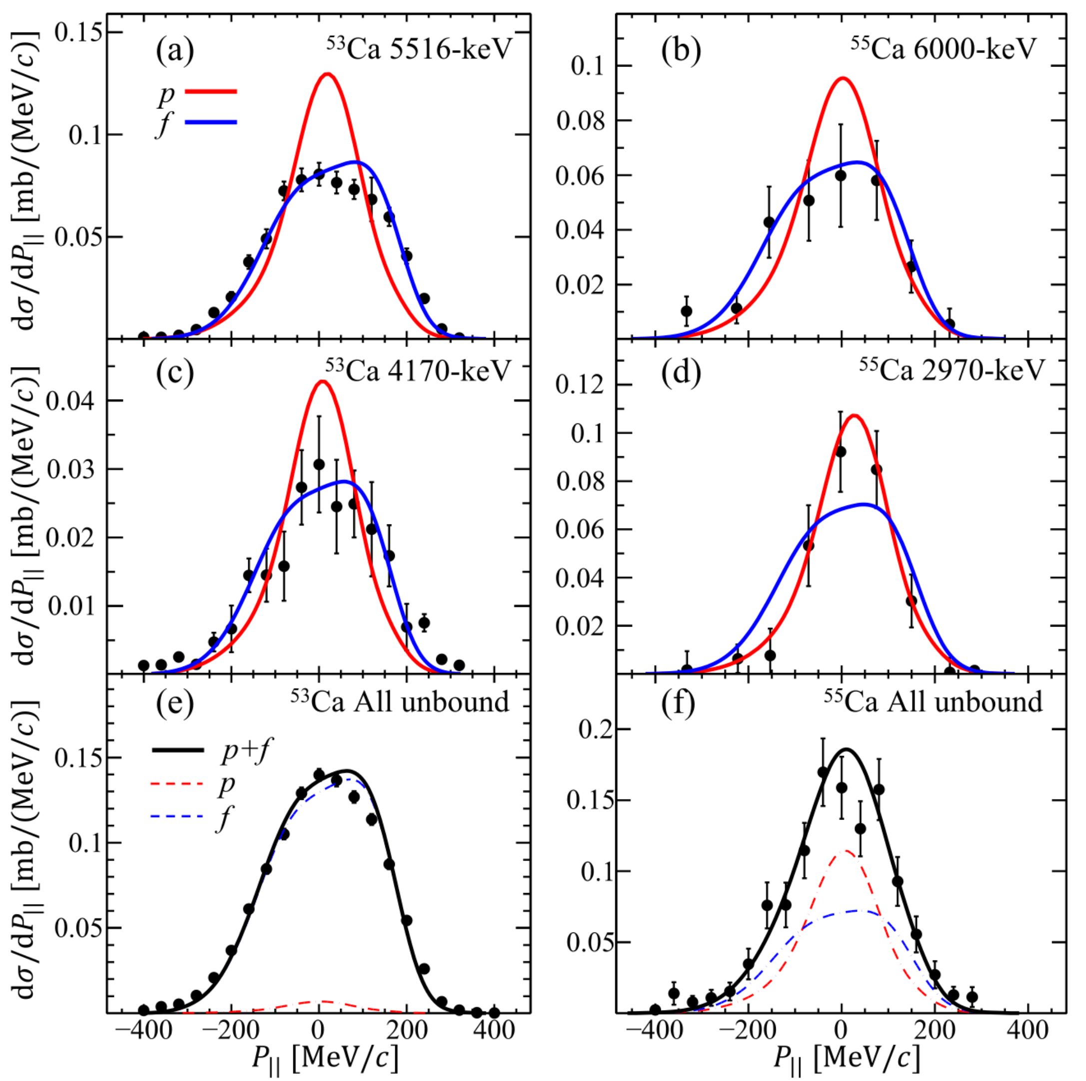
Unbound States in ^{53,55}Ca Following the ^{54,56}Ca(p,pn)^{53,55}Ca Reaction

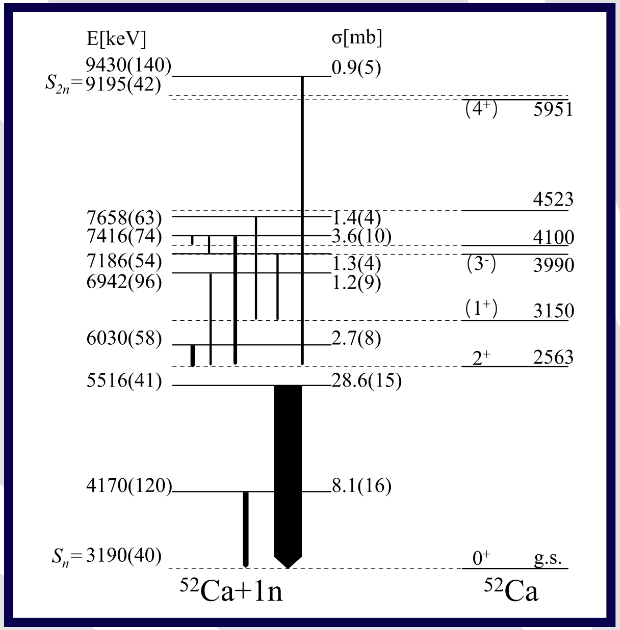


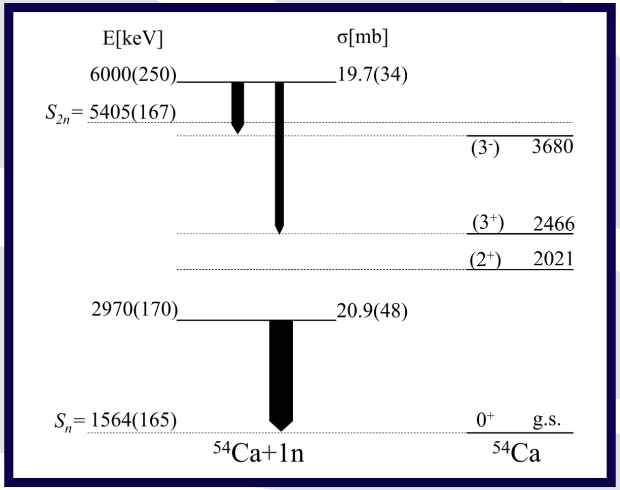


^{53}Ca ^{55}Ca

Unbound States in ^{53,55}Ca Following the ^{54,56}Ca(p,pn)^{53,55}Ca Reaction



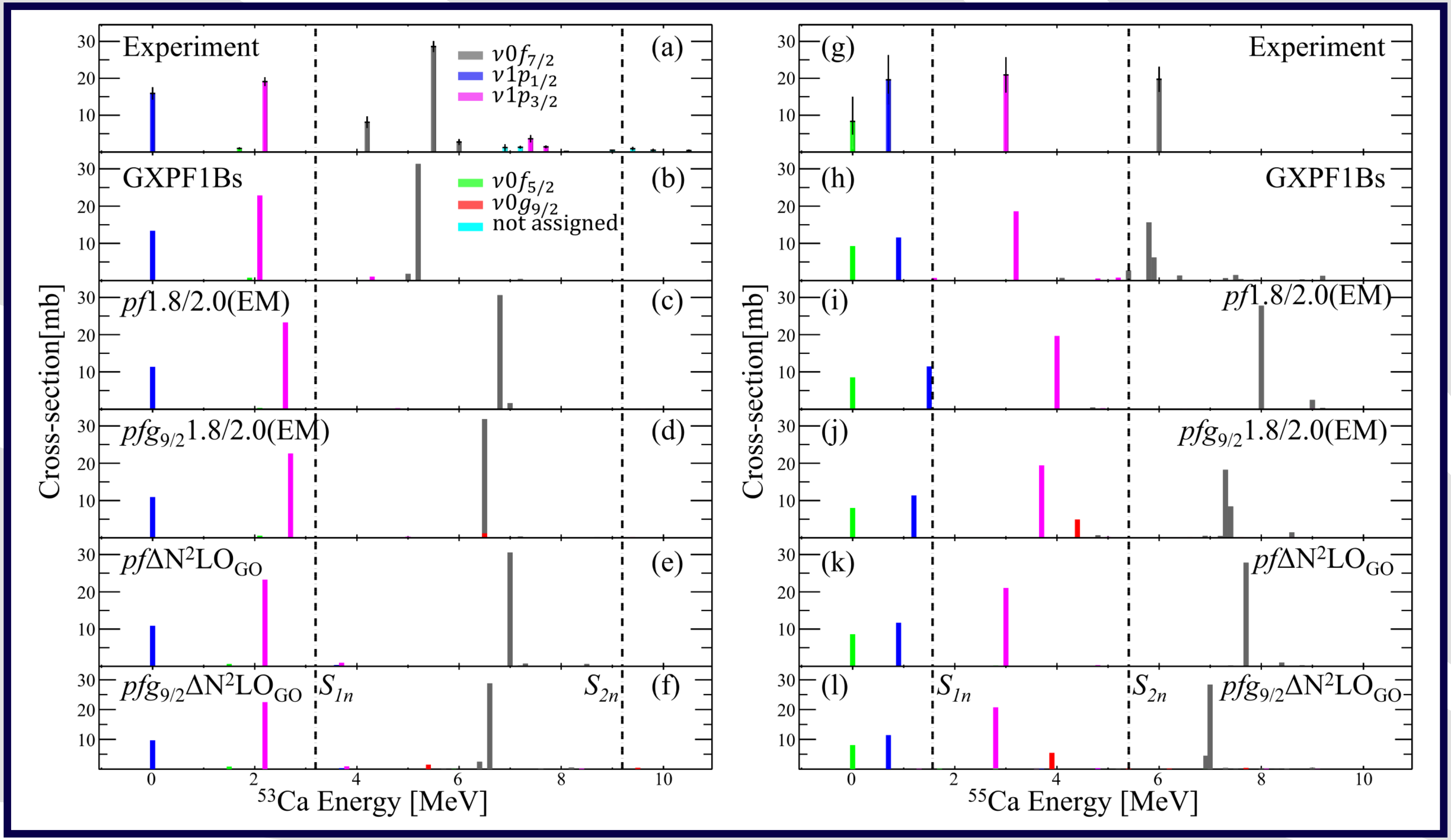




^{53}Ca ^{55}Ca

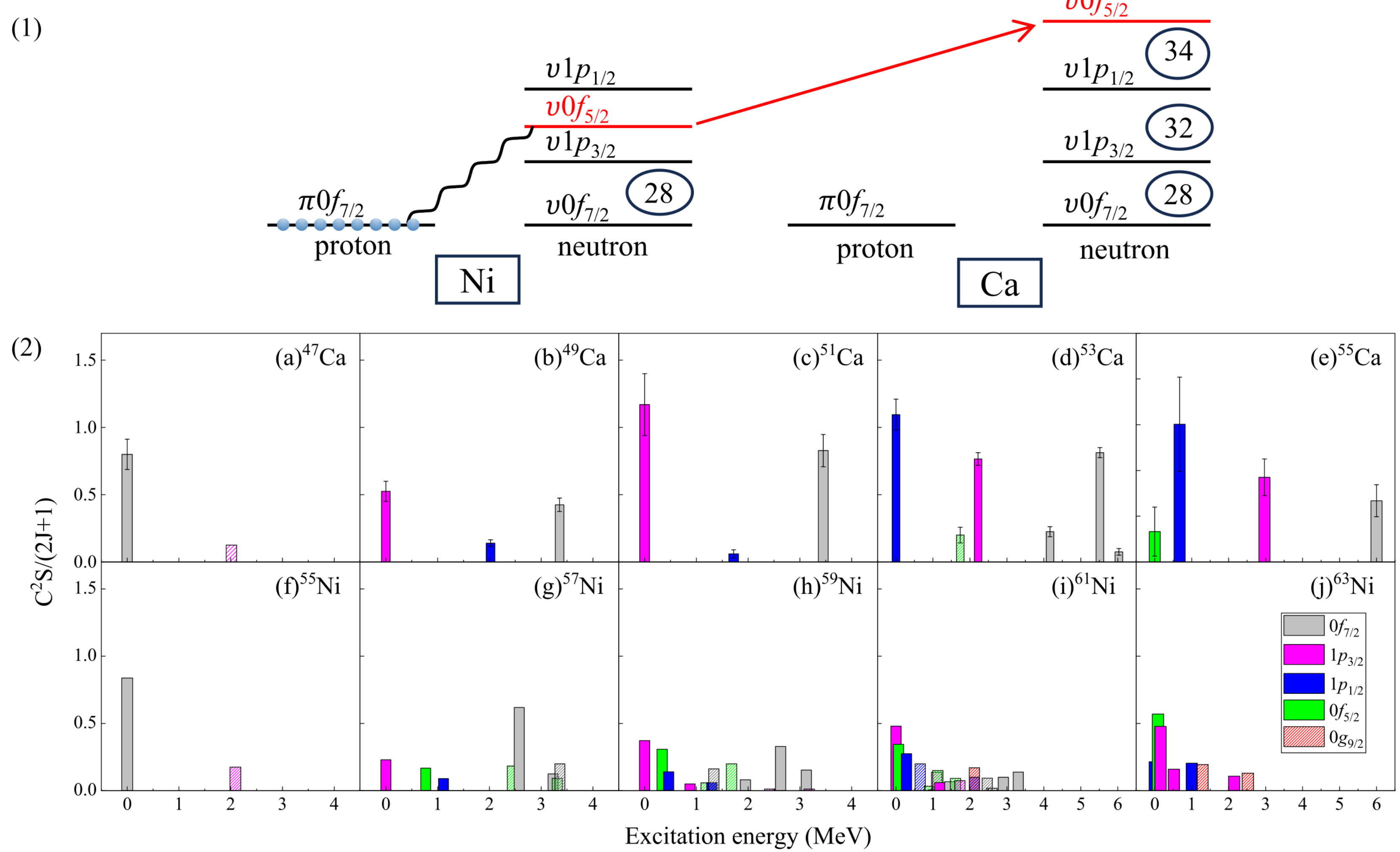
P. Li, J. Lee *et al.*, PLB 855, 138828 (2024).

Spectroscopic Strengths Distribution Following ^{54,56}Ca(p,pn)^{53,55}Ca Reaction



- Theoretical predictions: nuclear structural model + DWIA framework
- SM using GXPF1Bs interaction
- VS-IMSRG employing chiral NN+3N: 1.8/2.0 (EM), N^{2}LO
- Bound states in ^{53}Ca: S. Chen *et al.*, PRL 123, 142501 (2019).
- Bound states in ^{55}Ca: T. Koiwai, K. Wimmer *et al.*, PLB 827, 136953 (2022).

Experimental C^2S Distributions: Nickel vs. Calcium Isotopes



- ^{47,49}Ca: 1n-knockout, H.L. Crawford *et al.*, PRC 95, 064317 (2017).
- ^{55}Ni: (p, d), A. Sanetullaev *et al.*, PLB 736, 137 (2014).
- ^{57,59,61,63}Ni: (p, d) or (^{3}He, α), J.P. Schiffer *et al.*, PRC 87, 034306 (2013).

Summary

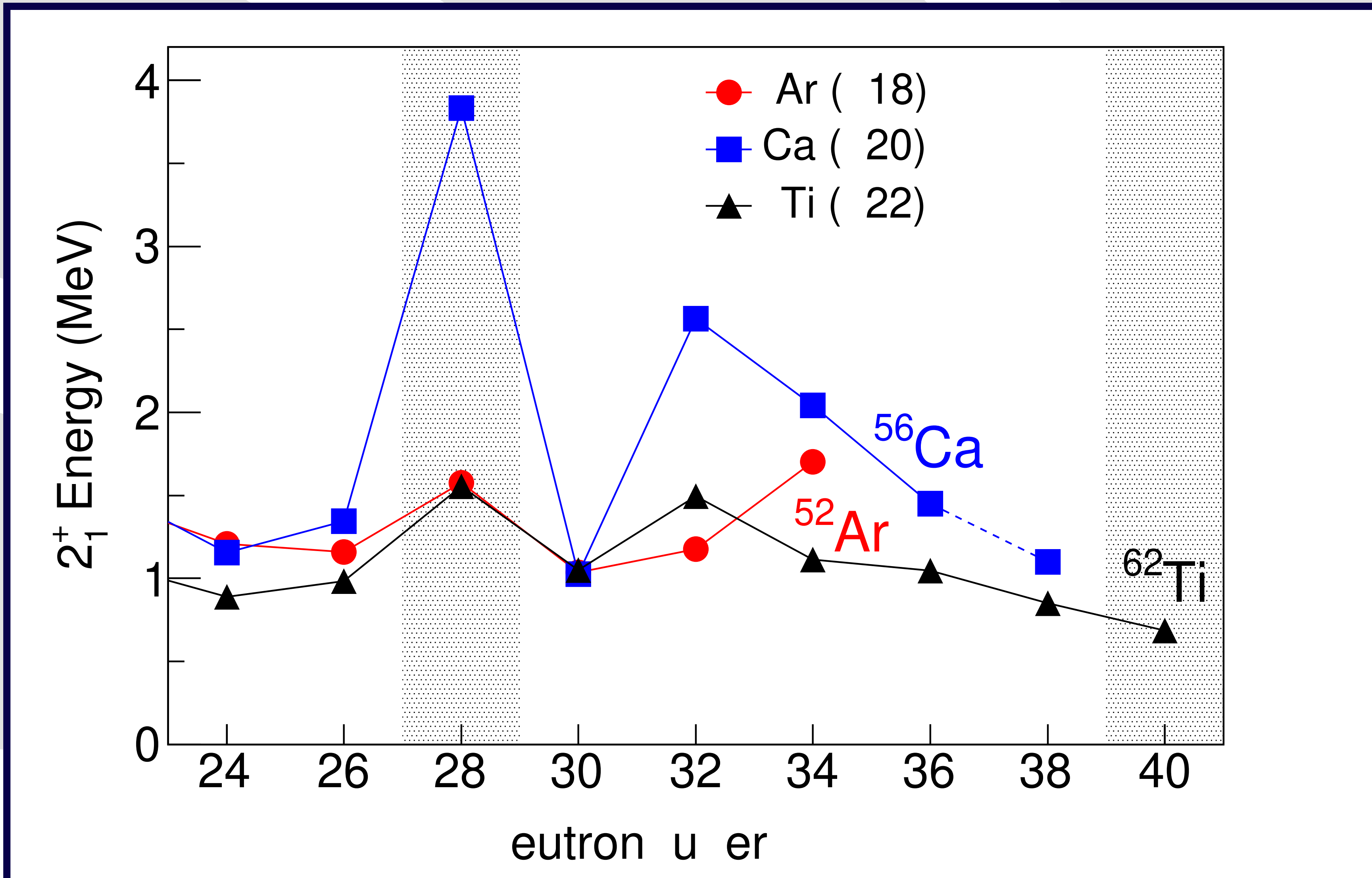
Summary

- Ca isotopes ideal benchmark for nuclear structure and reaction theories
- Obtained comprehensive data set
  - Spectroscopy of $^{51\text{–}58}$Ca
  - Many other isotopes
- $N = 32, 34$ magic numbers
  - $N = 32, 34$ shell closures as strong as $N = 28$
- Approaching ^{60}Ca
  - $E(2_1^+)$ in Ca isotopes challenge theory
- Single particle strengths
  - Very simple picture in Ca isotopes
  - No, or very little, fragmentation
  - Obtained complete picture for $0f_{7/2}$, $1p_{3/2}$, $1p_{1/2}$, and $0f_{5/2}$ SPE up to ^{55}Ca

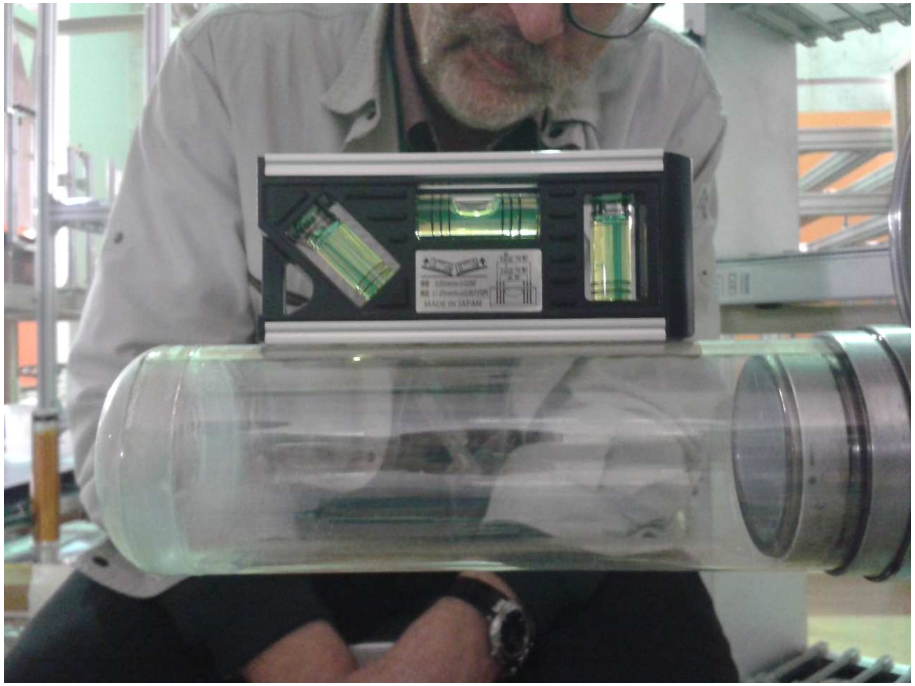
Thank You!

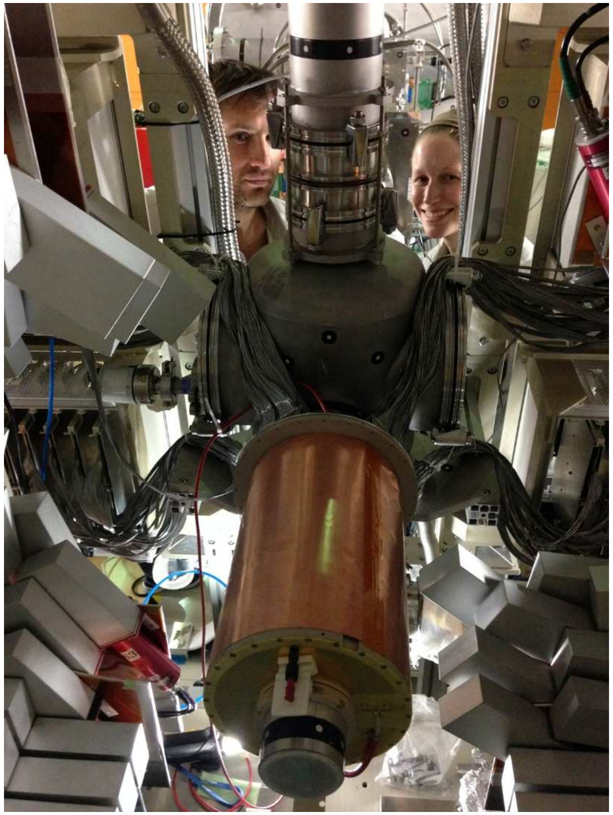
Backup slides

$E(2_1^+)$ *Systematics*

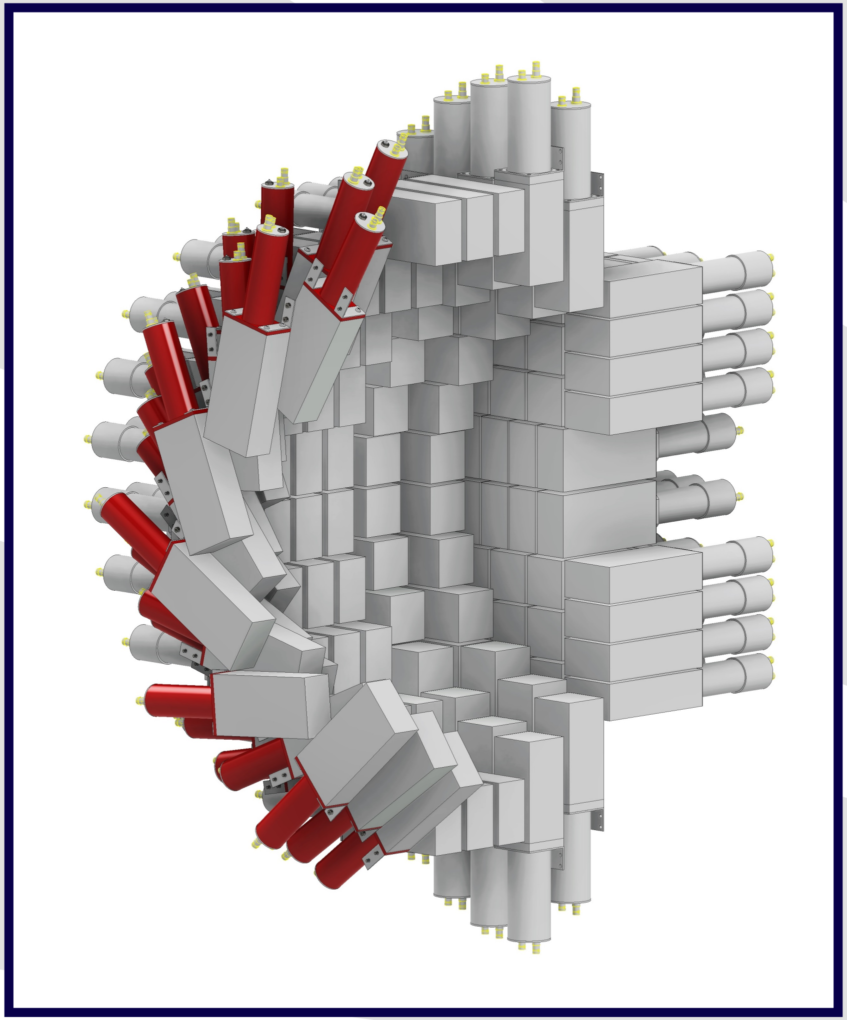


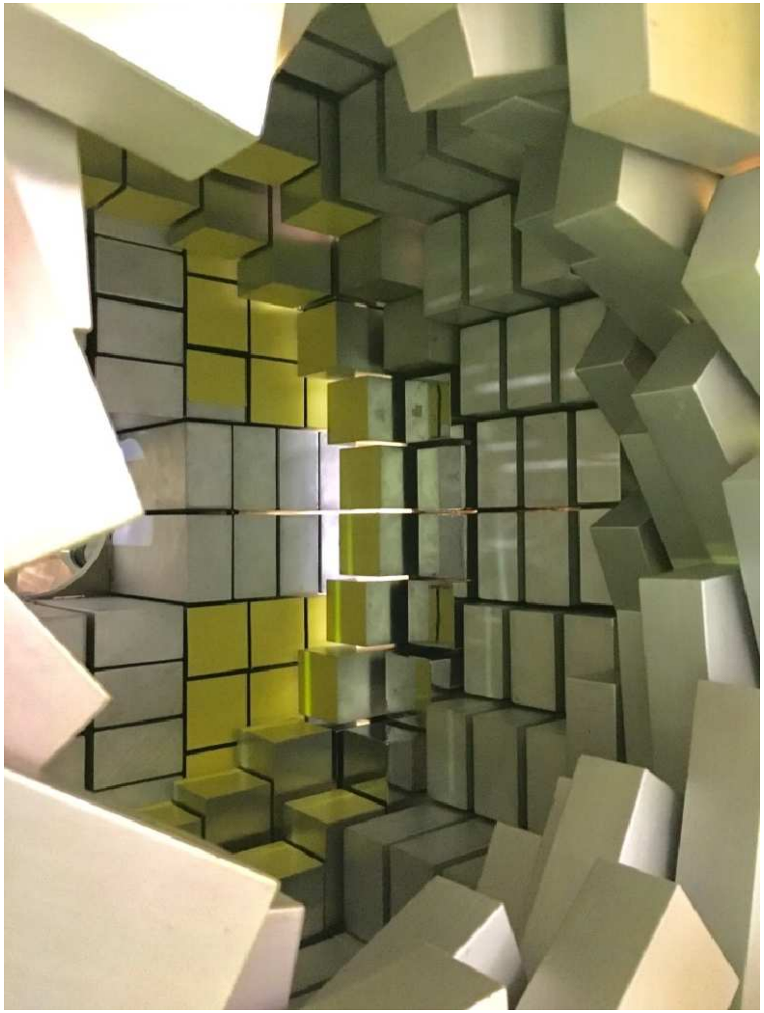
MINOS Target and TPC





DALI2^{+} (Since 2017)



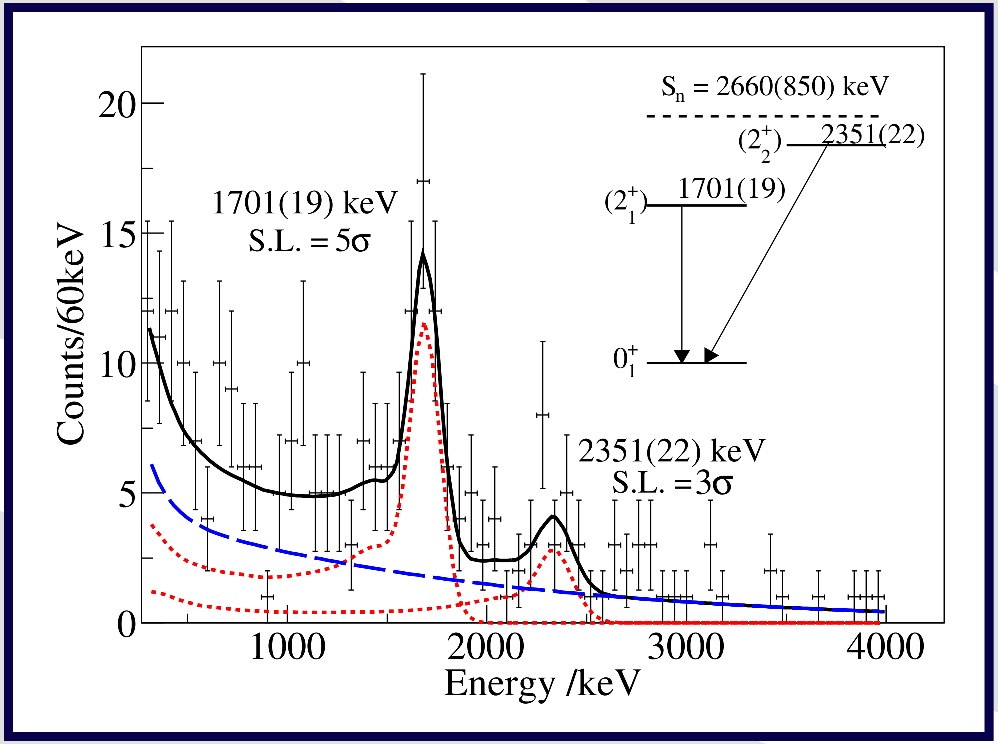


- 226 NaI(Tl) detectors (60 detectors from HKU)
- ≈36 % FEP efficiency, 9 % resolution (FWHM) for 1 MeV γ ray at 100 MeV/nucleon
- Experiments with solid targets and liquid hydrogen

S. Takeuchi *et al.*, NIMA 763, 596 (2014).

$N = 34$ gap "South" of ^{54}Ca

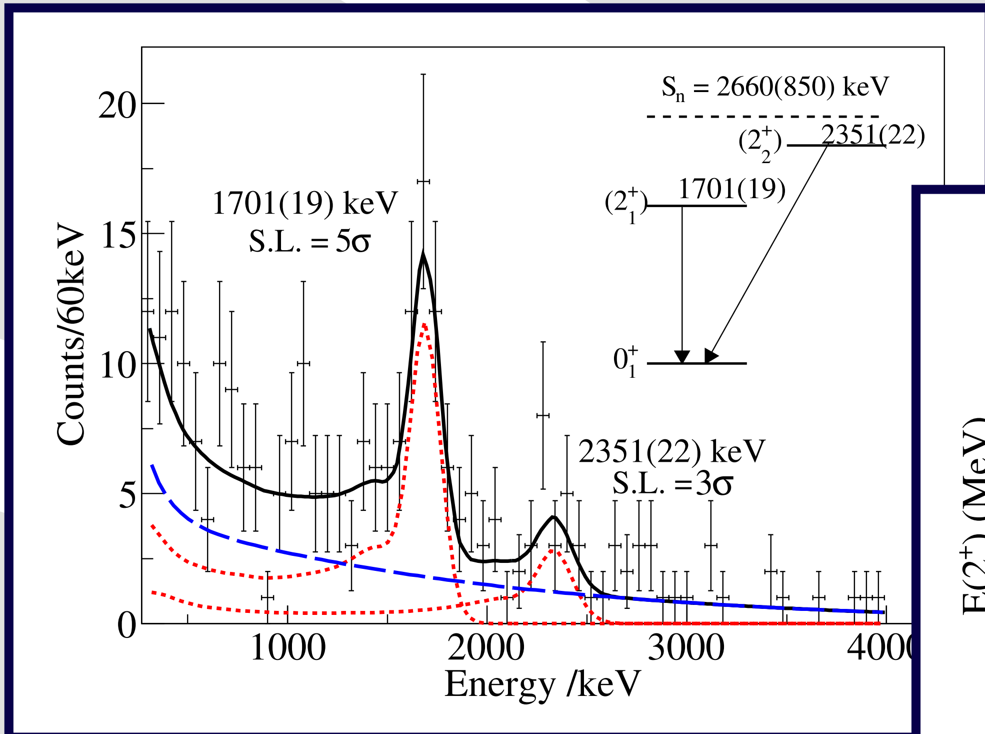
^{53}K(p,2p)^{52}Ar

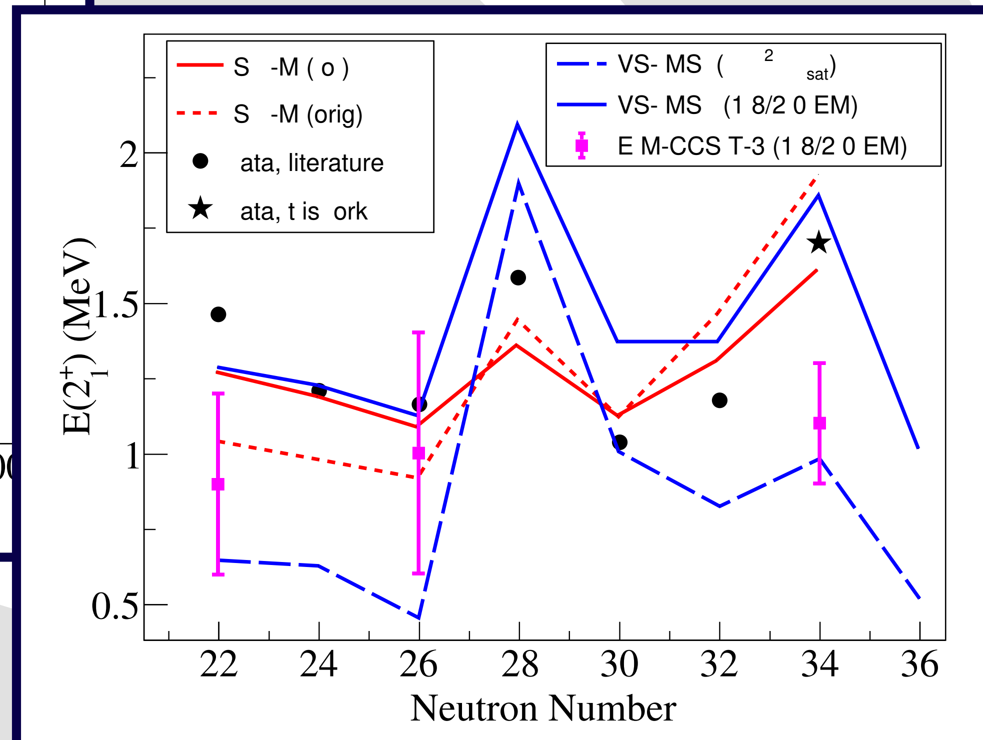


- Largest $E(2_1^+)$ in Ar isotopes beyond N = 20

H. Liu, A. Obertelli *et al.*, PRL 122, 072502 (2019).

$N = 34$ gap "South" of ^{54}Ca
^{53}K(p,2p)^{52}Ar



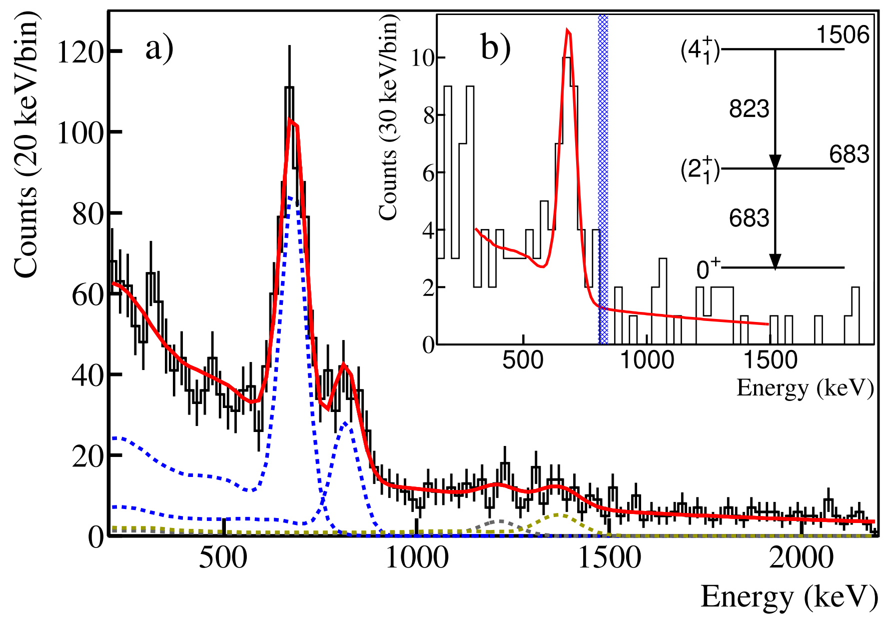


- Largest $E(2^+_1)$ in Ar isotopes beyond N = 20

SDPF-MU (orig): Y. Utsuno *et al.*, PRC 86, 051301(R) (2012).
SDPF-MU (mod): D. Steppenbeck *et al.*, PRL 114, 252501 (2015).
VS-IMSRG: J.D. Holt, R.Stroberg *et al.*
EOM-CCSDT-3: G. Hagen, T. D. Morris *et al.*

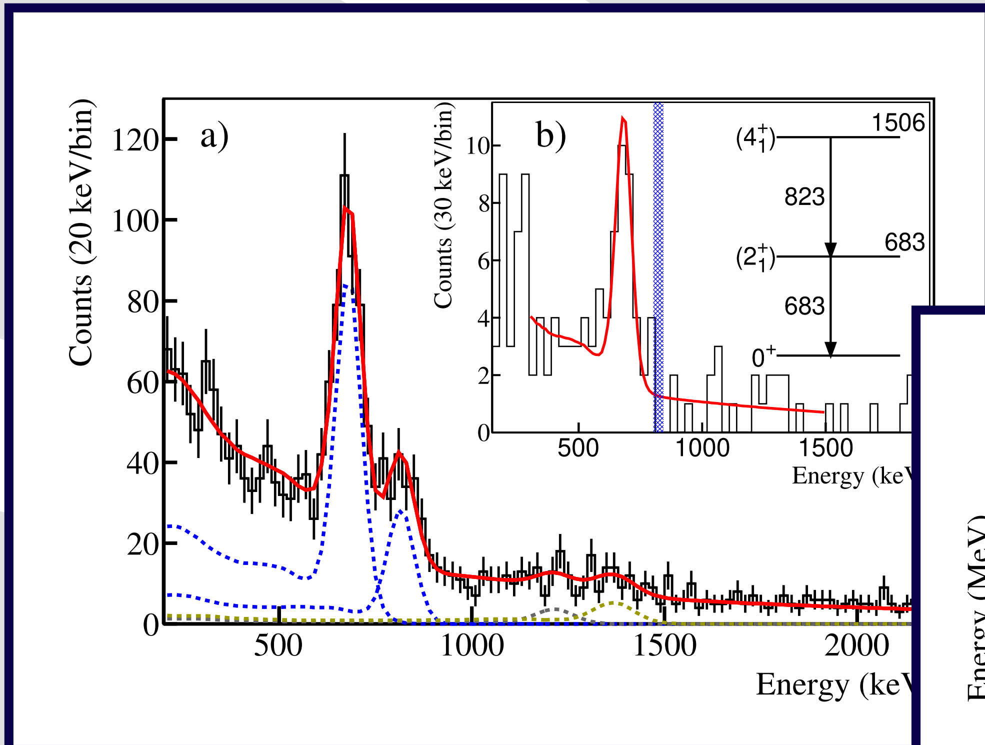
H. Liu, A. Obertelli *et al.*, PRL 122, 072502 (2019).

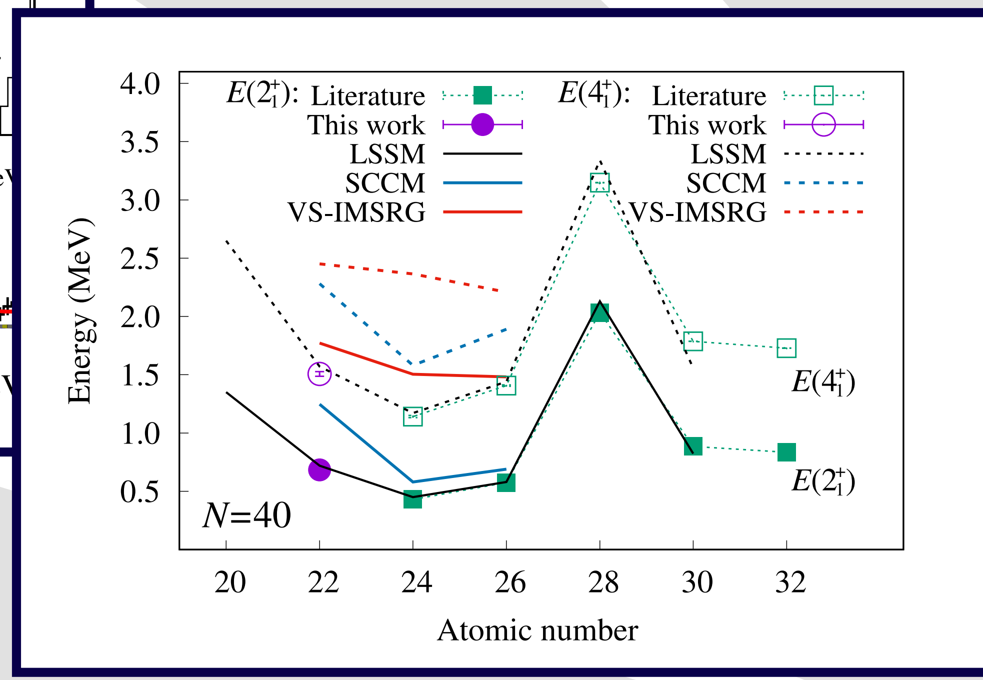
$N = 40$ Structure towards ^{60}Ca: ^{63}V(p,2p)^{62}Ti



M.L. Cortés, W. Rodriguez *et al.*, Phys. Lett. B 800, 135071 (2020).

N = 40 Structure towards ^{60}Ca: ^{63}V(p,2p)^{62}Ti

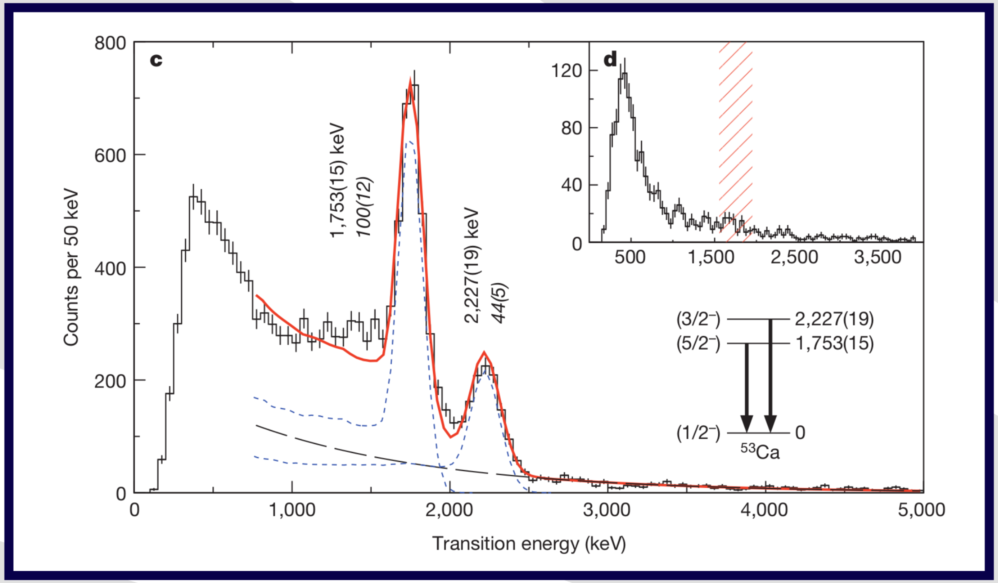




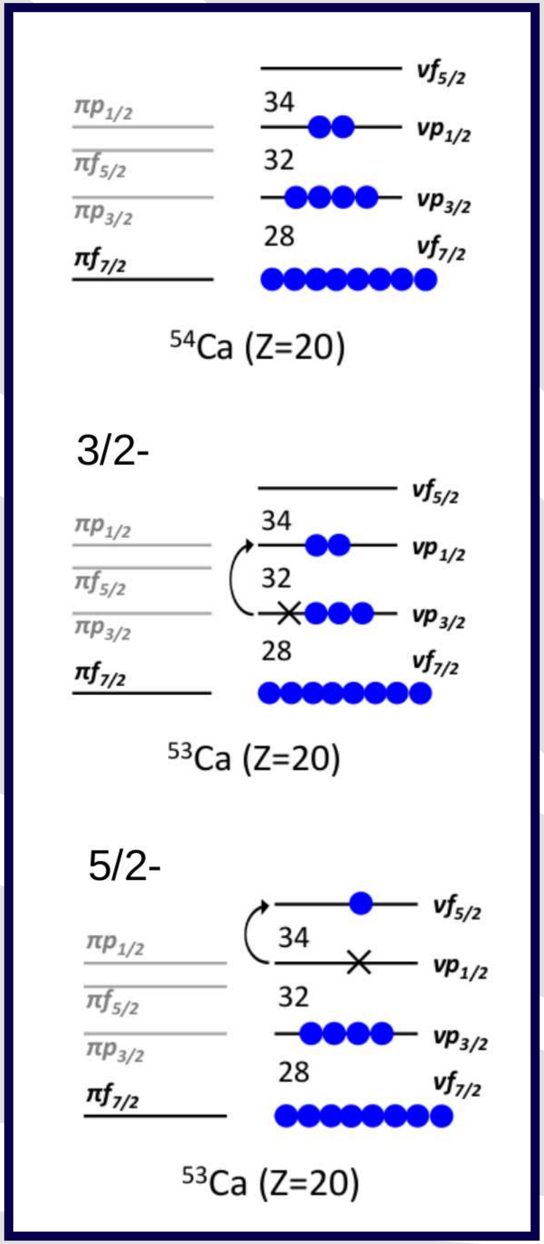
LNPS: S. Lenzi, F. Nowacki, A. Proves, K. Sieja
VS-IM-SRG: J.D. Holt, J. Menéndez, A. Schwenk, J. Simonis, S.R. Stroberg
SCCM: T. Rodriguez

M.L. Cortés, W. Rodriguez *et al.*, Phys. Lett. B 800, 135071 (2020).

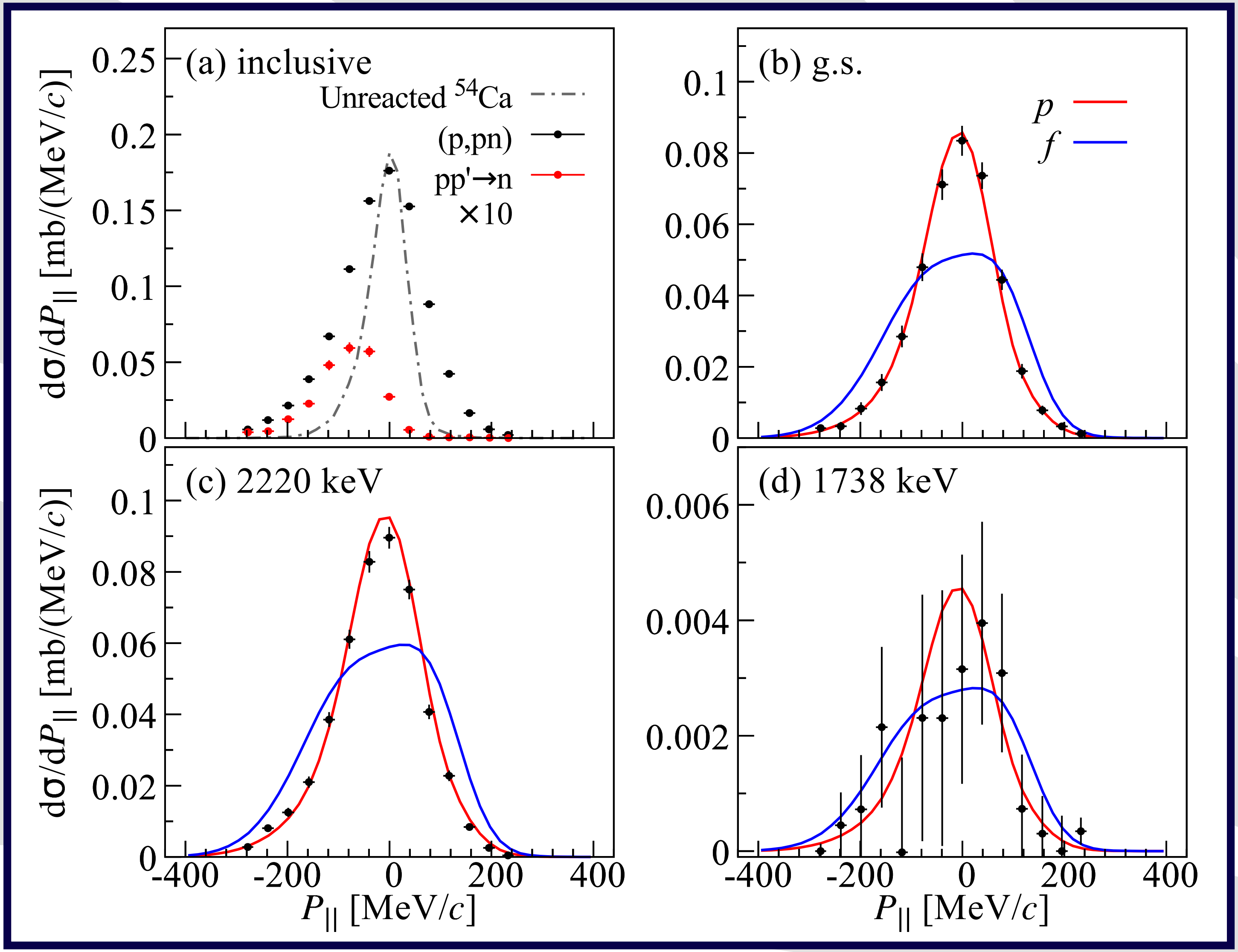
Testing the Robustness of N = 34: Spectroscopy of ^{53}Ca from ^{54}Ca(p,pn)^{53}Ca



- E_x = 2220 keV via β decay.
  F. Perrot *et al.*, PRC 74, 014313 (2006).
- ^{53}Ca not directly populated
  Be(^{55}Sc,^{53}Ca+γ)
  D. Steppenbeck *et al.*, Nature 502, 207 (2013).
- Use direct reaction ^{54}Ca(p,pn)^{53}Ca
  - Direct probe of g.s. wave function of ^{54}Ca
    - Cross sections → SFs
    - Only one strong 2220 keV transition → shell closure at N = 34

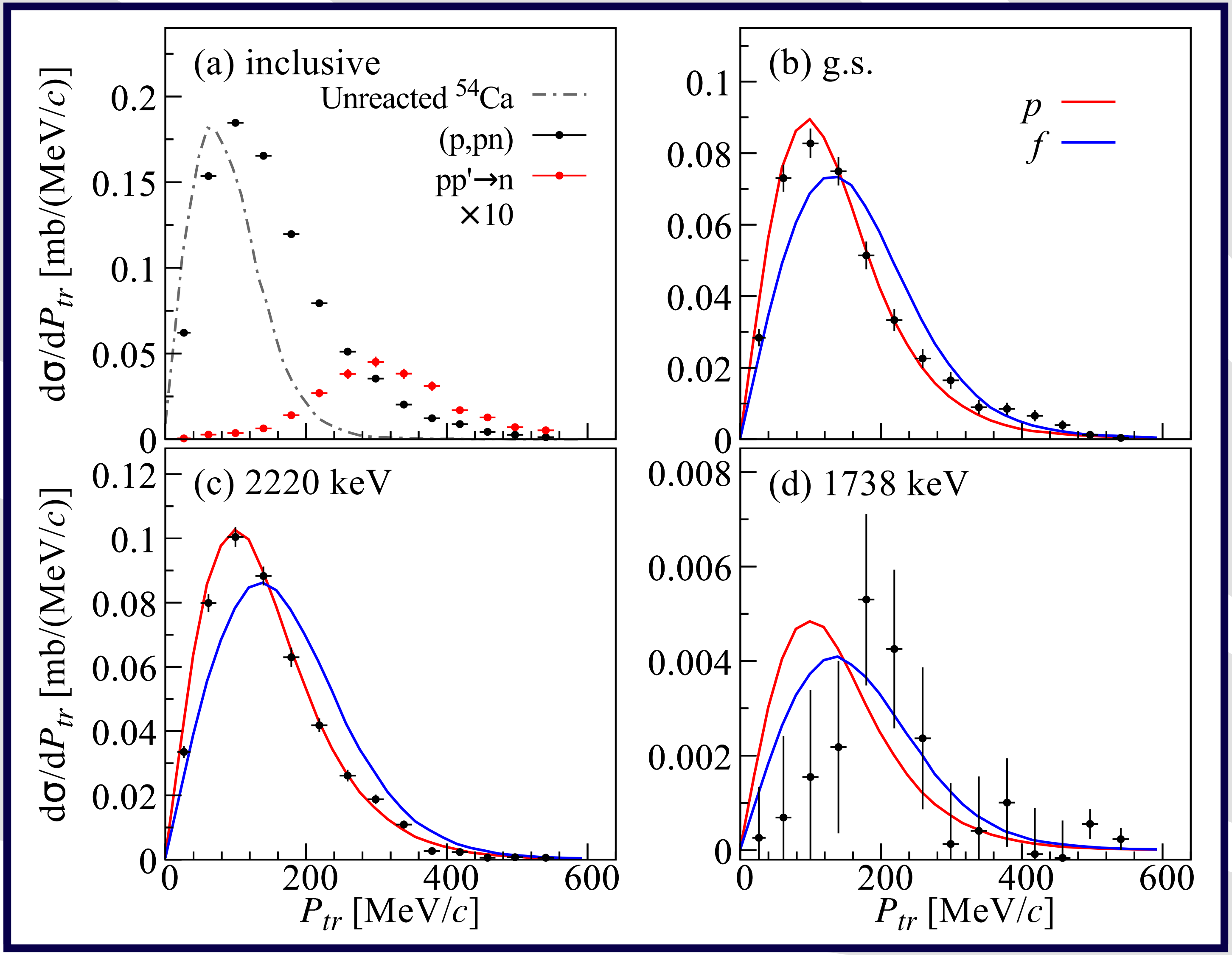


$^{54}Ca(p,pn)^{53}Ca$ Momentum Distributions



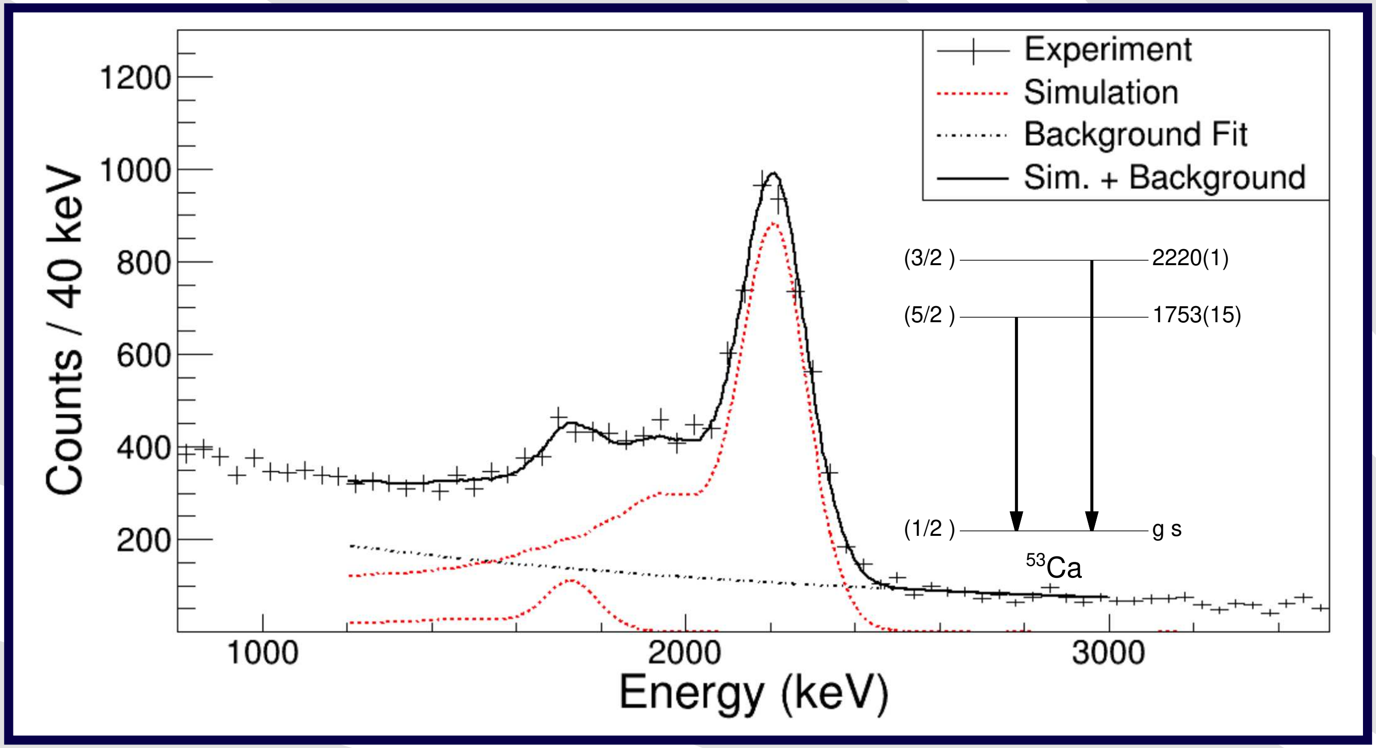
DWIA: Y. Chazono, K. Ogata, K. Yoshida *et al.*
S. Chen, J. Lee *et al.*, PRL 123, 142501 (2019).

$^{54}Ca(p,pn)^{53}Ca$ Momentum Distributions



DWIA: Y. Chazono, K. Ogata, K. Yoshida *et al.*
S. Chen, J. Lee *et al.*, PRL 123, 142501 (2019).

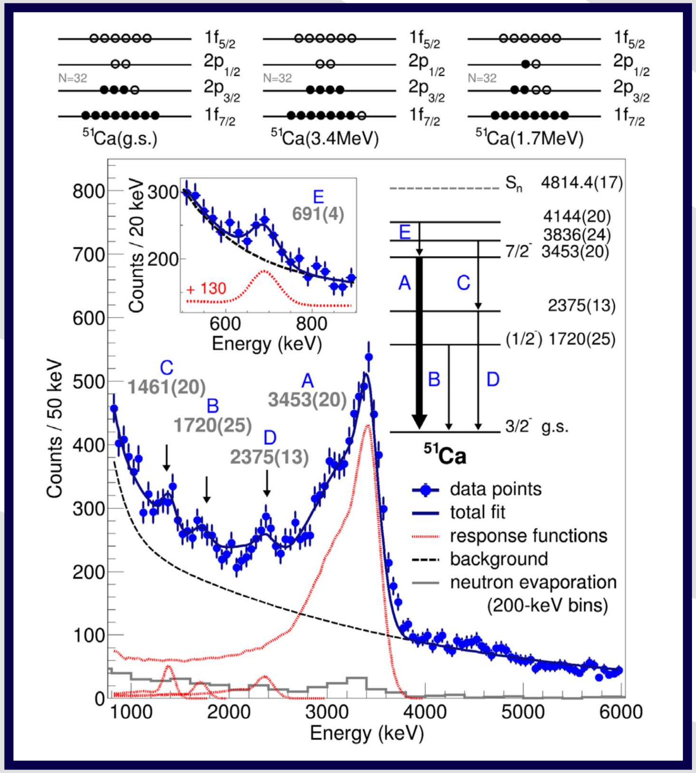
Spectroscopy of ^{53}Ca from the ^{54}Ca(p,pn)^{53}Ca Reaction

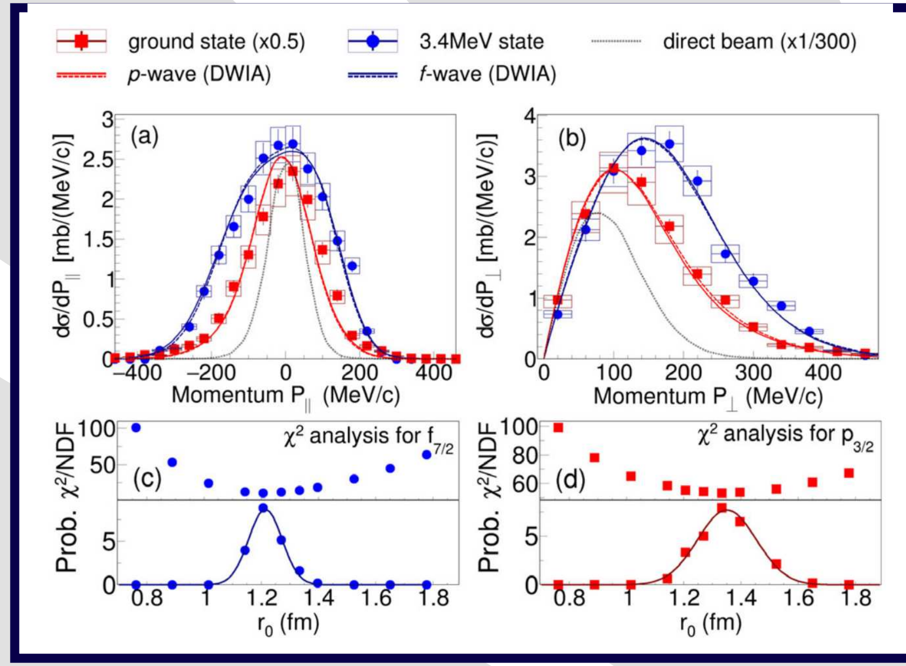


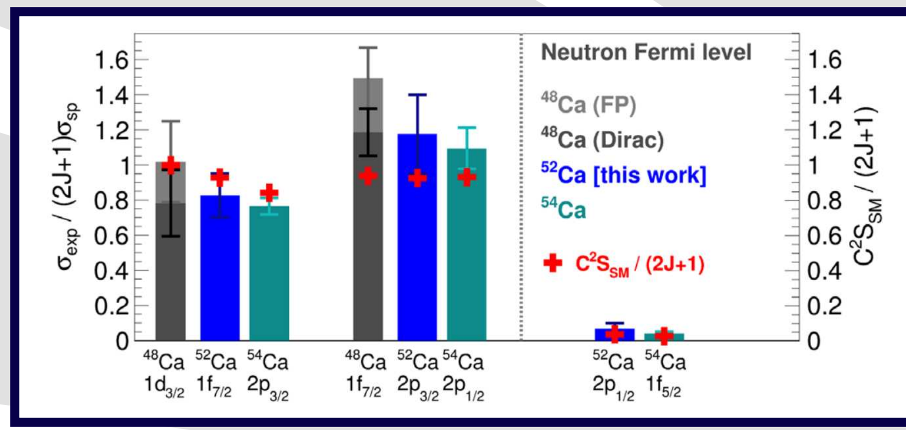
	J^π	-1n	Exp $\sigma_{\text{-1}n}$(mb)	DWIA σ_{sp}(mb)	GXPF1Bs E$_x$(keV)	GXPF1Bs C^2S	GXPF1Bs $\sigma^{\text{th}}_{\text{-1}n}$	*NN + 3N* (lnl) E$_x$(keV)	*NN + 3N* (lnl) C^2S	*NN + 3N* (lnl) $\sigma^{\text{th}}_{\text{-1}n}$
g.s.	1/2$^-$	$p_{1/2}$	15.9(17)	7.27	0	1.82	13.2	0	1.56	11.3
2220(13)	3/2$^-$	$p_{3/2}$	19.1(12)	6.24	2061	3.55	22.2	2635	3.12	18.5
1738(17)	5/2$^-$	$f_{5/2}$	1.0(3)	4.19	1934	0.19	0.8	1950	0.01	0.1
Inclusive			36.0(12)				36.2			29.9

GXPF1Bs: T. Otsuka, Y. Utsuno *et al.*
NN+3N (lnl): V. Soma, C. Barbieri *et al.*
DWIA: Y. Chazono, K. Ogata, K. Yoshida *et al.*
S. Chen, J. Lee *et al.*, PRL 123, 142501 (2019).

The ^{52}Ca(p,pn)^{51}Ca Reaction: Extended $1p_{3/2}$ Orbital and the N = 32 Shell Closure







- J. Bonnard *et al.*, PRL 116, 212501 (2016): 0.7 fm size difference between $1p_{3/2}$ and $0f_{7/2}$
- Experimentally deduced 0.61(23) fm
- Level energies known from M. Rejmund *et al.* PRC 76, 021304(R) (2007)
- 0.6(3) mbarn cross section to state at 1720 keV

M. Enciu, H. Liu *et al.*, PRL 129, 262501 (2022).