Structural Evolution of the Neutron-Rich Calcium Isotopes

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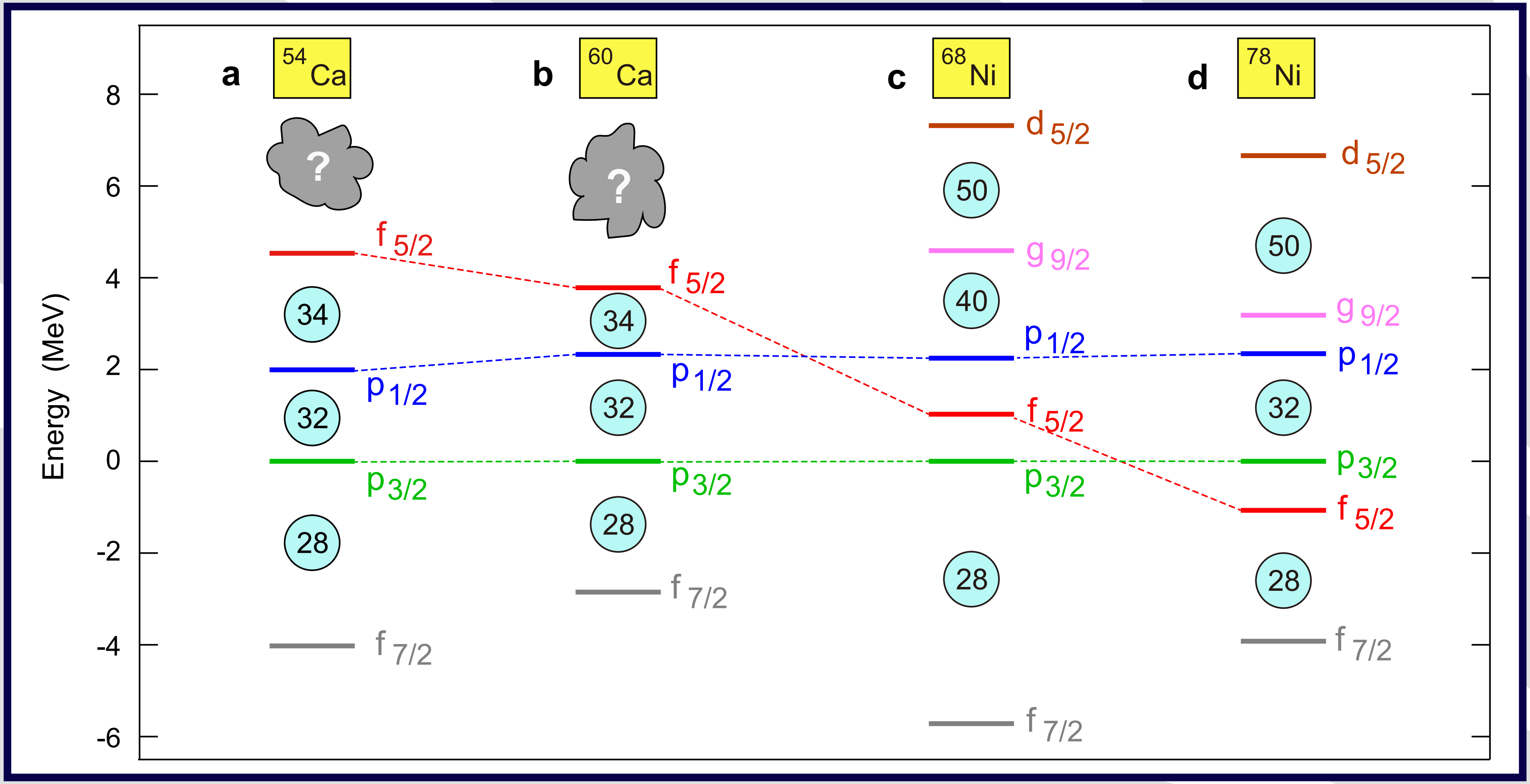
Outline

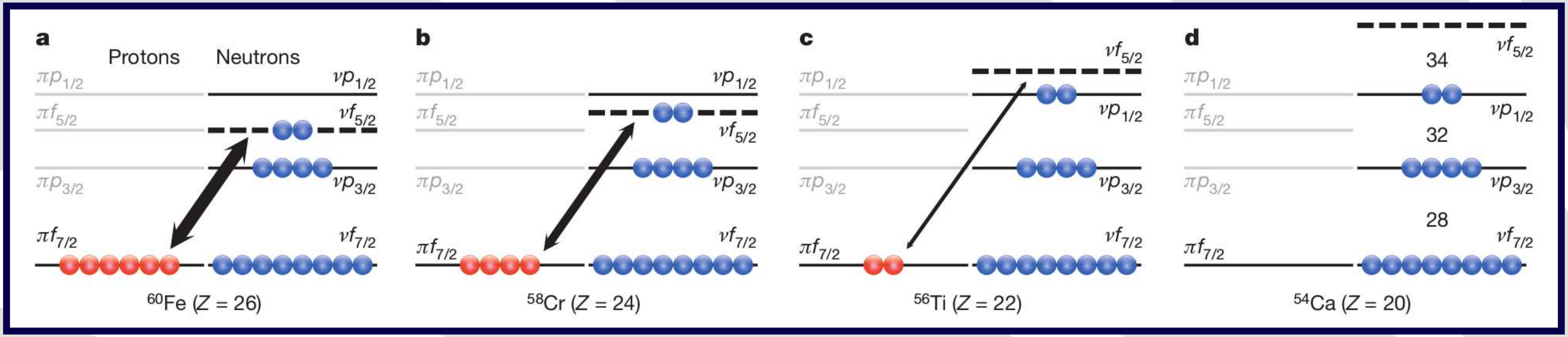
- Motivation
  - The $N = 32, 34, 40$ magic numbers
  - Evolution of neutron single particle energies
- Experimental description
  - RIBF, DALI2^{+}, MINOS, SAMURAI, NeuLAND/NEBULA
- Results
  - Detailed spectroscopy of ^{54}Ca from (p,pn) and (p,2p) reactions
  - First spectroscopy of ^{56,58}Ca from (p,2p) reactions
  - Neutron single particle states in ^{51,53,55}Ca
- Summary

Effective Neutron Single Particle Energies



- ESPE 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

Shell Evolution at $N = 32, 34$

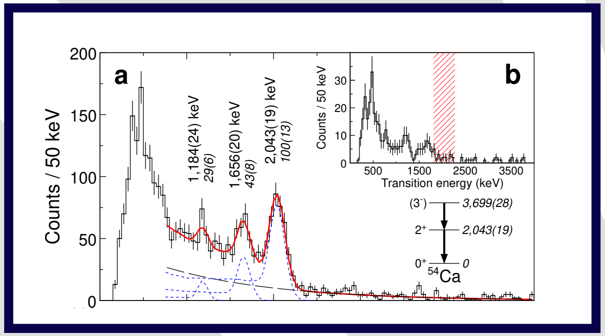


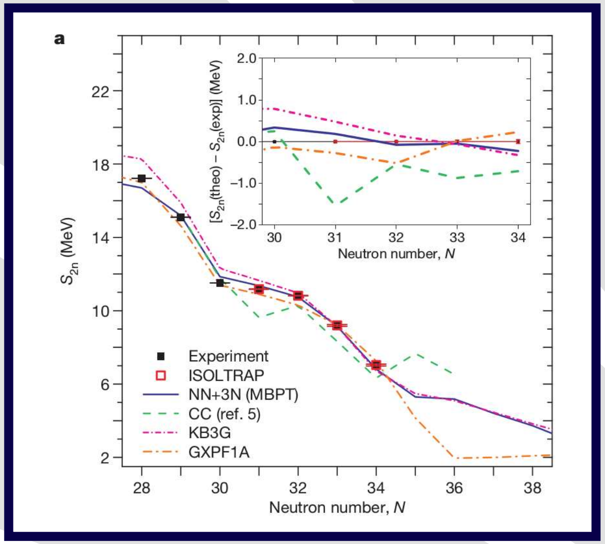
- Reduced attractive interaction between $\pi f_{7/2}$ and $\nu f_{5/2}$
- Possible development of new sub-shell closures at N = 32 and N = 34
- Observation of $N = 32$ sub-shell closure for ^{52}Ca, ^{54}Ti
- A single proton in $\pi f_{7/2}$ destroys $N = 34$ magicity!

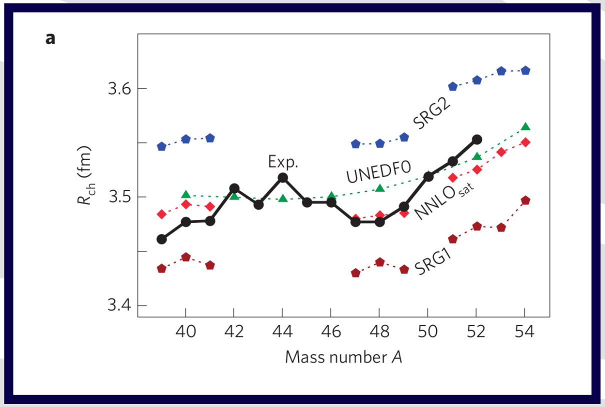
D. Steppenbeck et al., Nature 502, 207 (2013).
Prediction for $N = 34$ magic Number: T. Otsuka et al., PRL 87, 082502 (2001).

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).

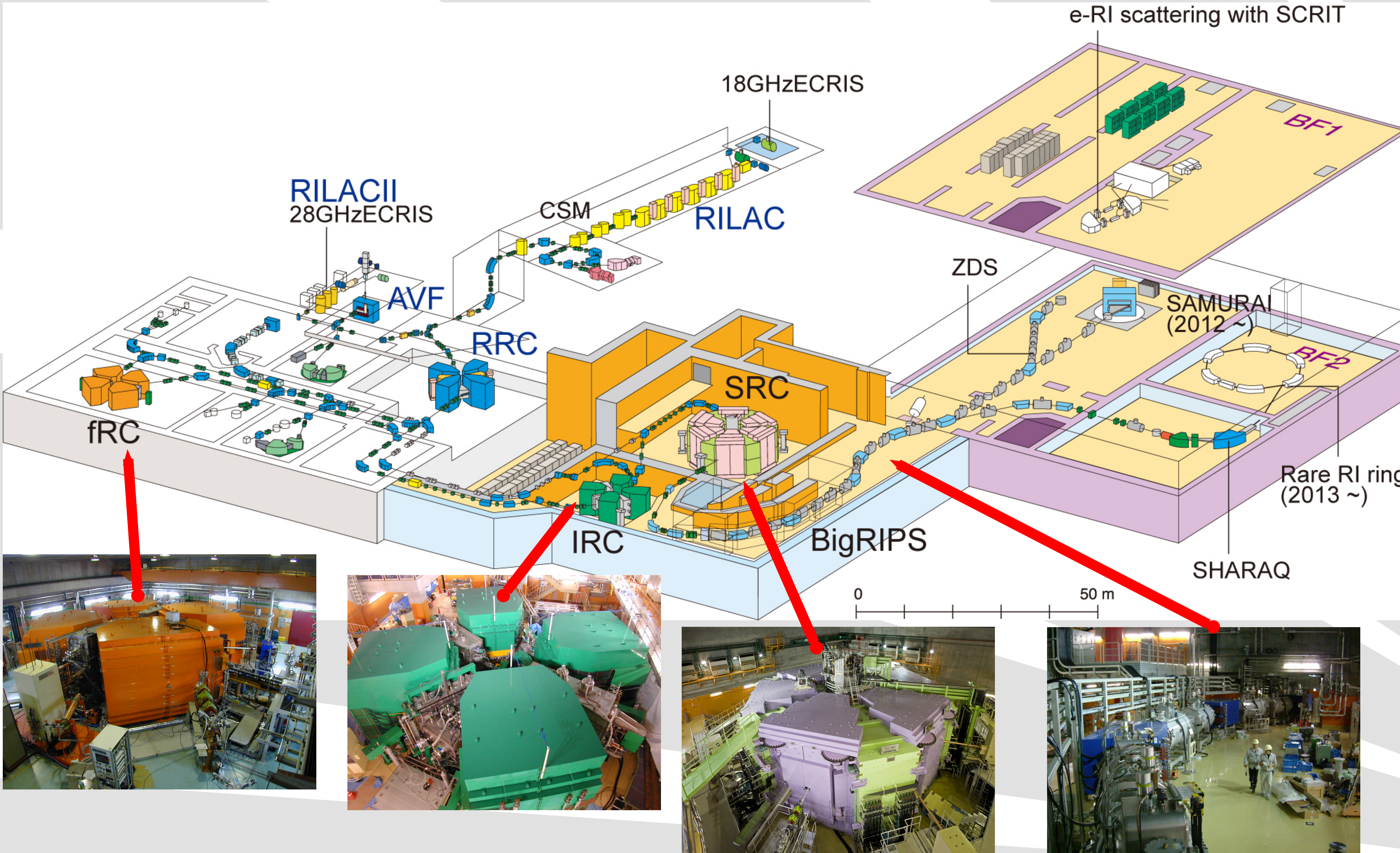




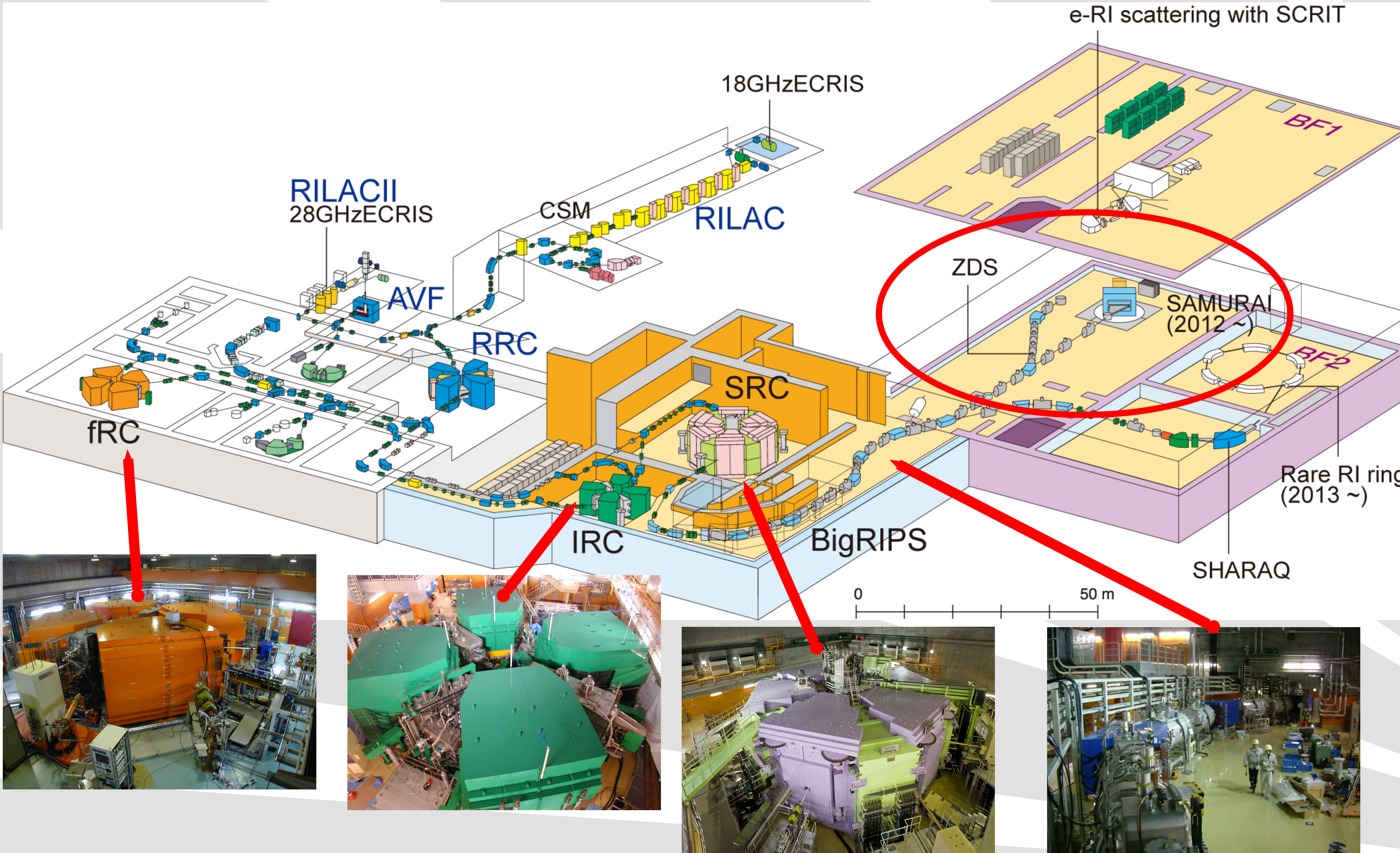


Experimental Setup

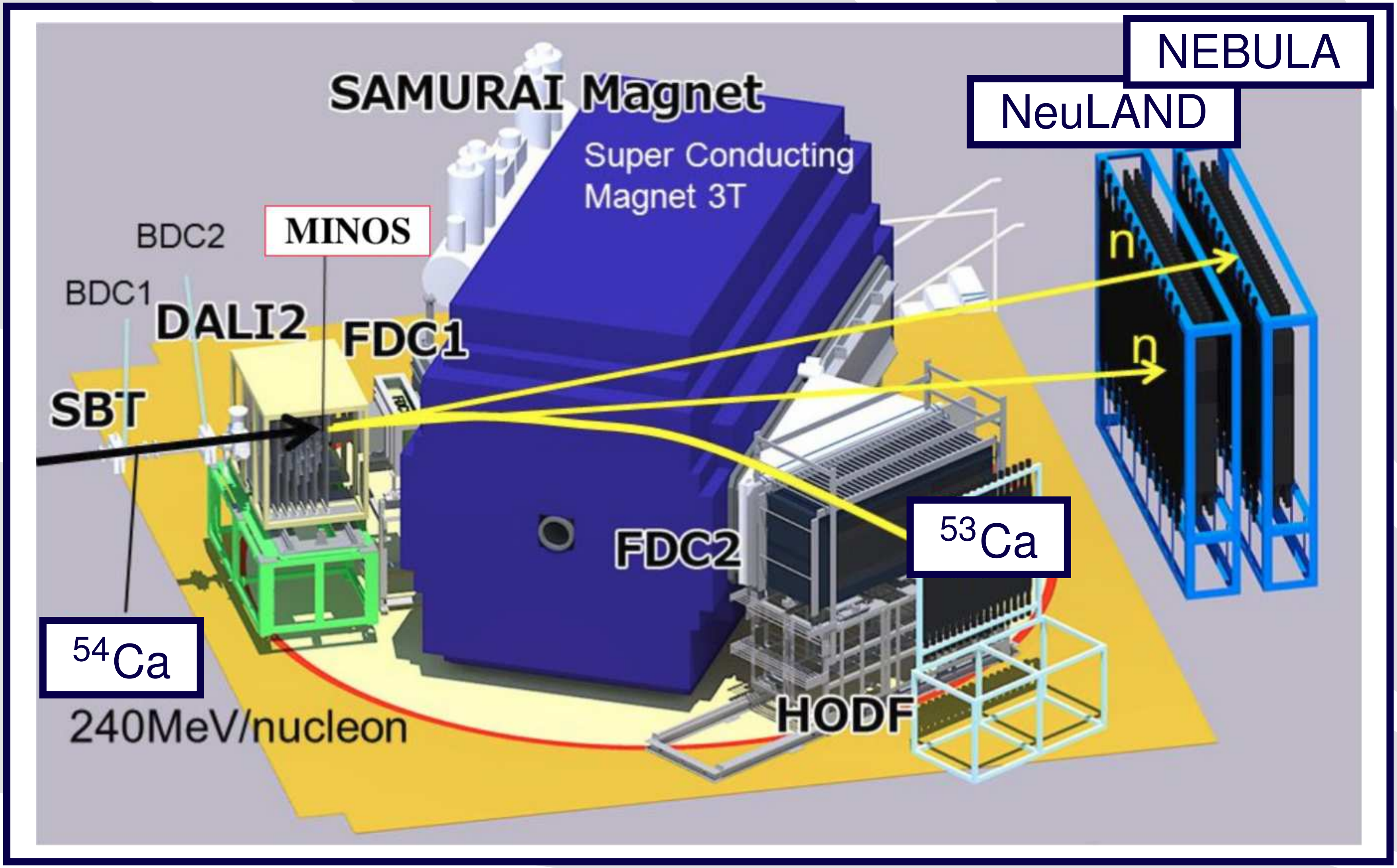
RIBF Overview



RIBF Overview

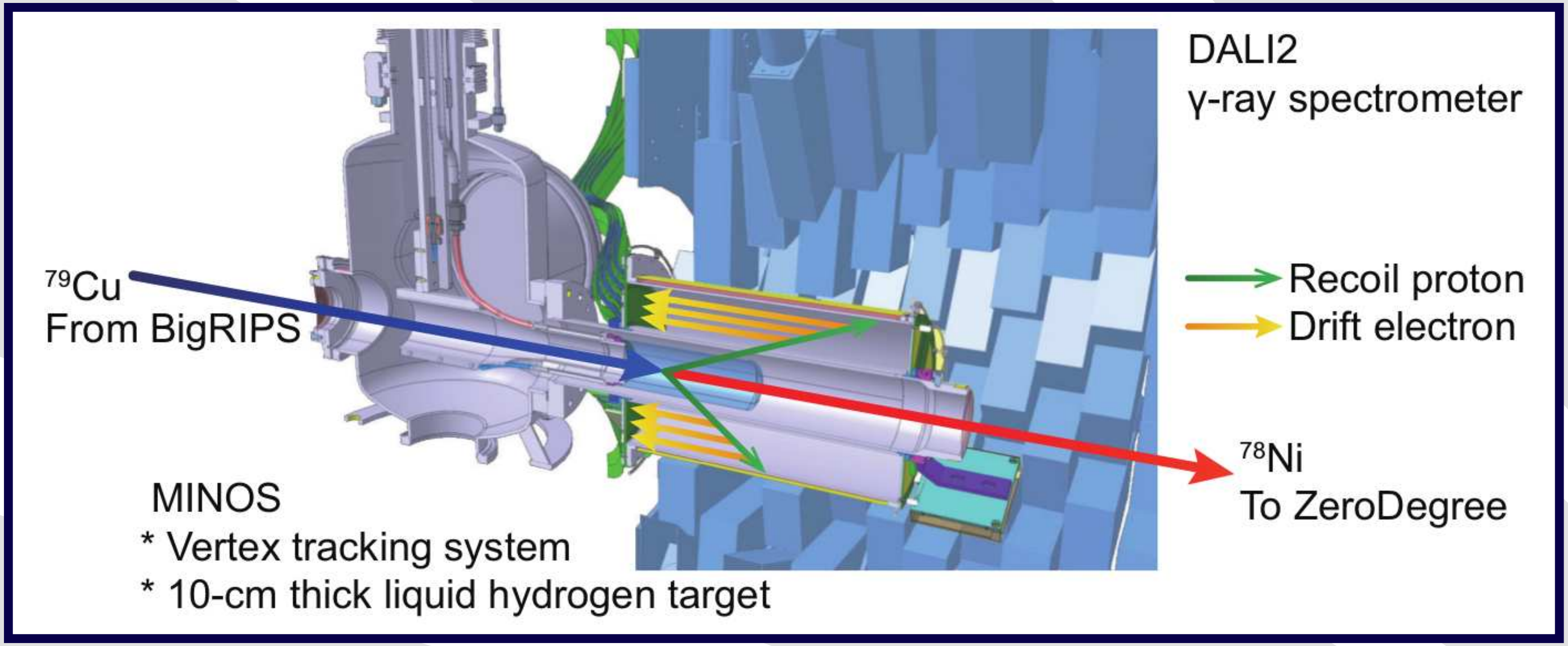


Shell Evolution And Search for Two-plus energies At RIBF (SEASTAR) at SAMURAI



- Large acceptance
  - Simultaneous $E(2_1^+)$ measurement of ^{52}Ar, ^{56,58}Ca, and ^{62}Ti
  - Many other isotopes within acceptance

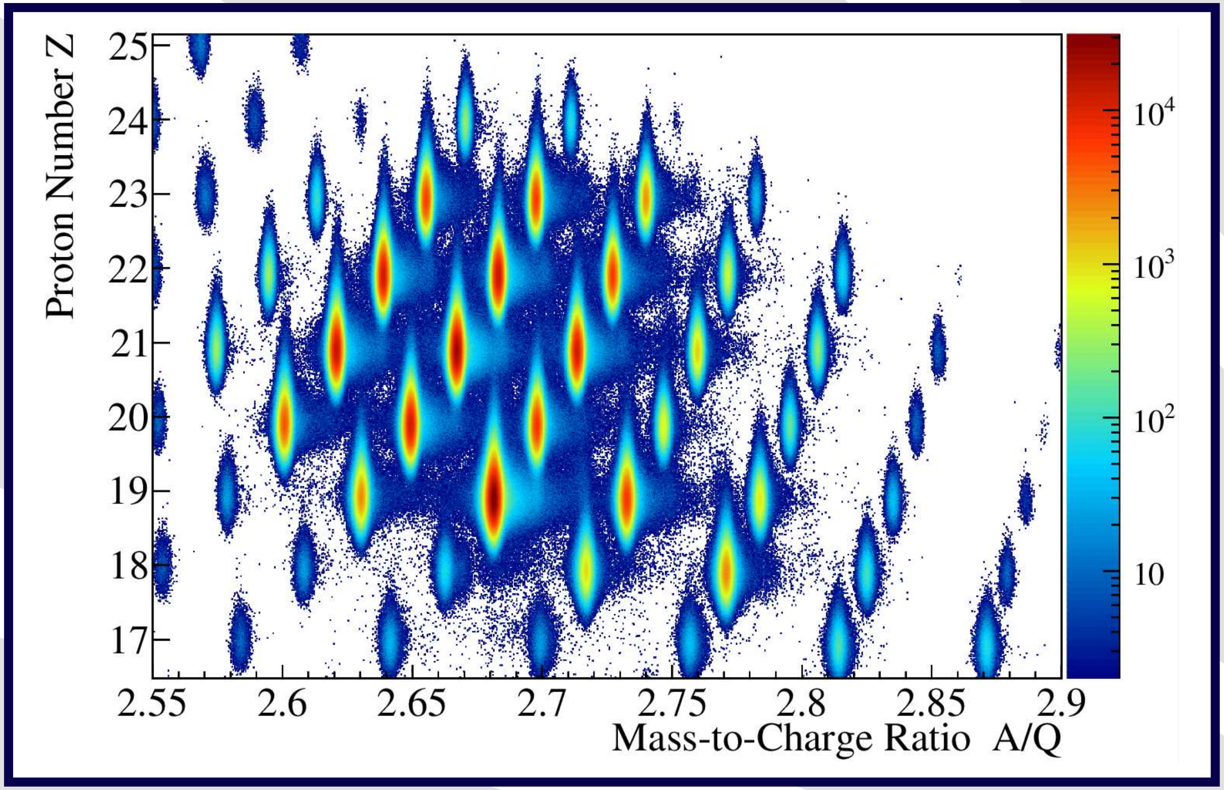
In-Beam Gamma-Ray Spectroscopy With a Liquid Hydrogen Target



- MINOS, MagIc Numbers Off Stability
  - 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)
- DALI2$^+$
  - 186 (226) NaI(Tl) detectors, large solid angle coverage
  - 7 % intrinsic resolution at 1 MeV, 10(11) % at 100(250) MeV/nucleon
  - 35 % efficiency at 1 MeV with add-back

A. Obertelli et al., EPJA 50, 8 (2014), 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

SEASTAR III at SAMURAI
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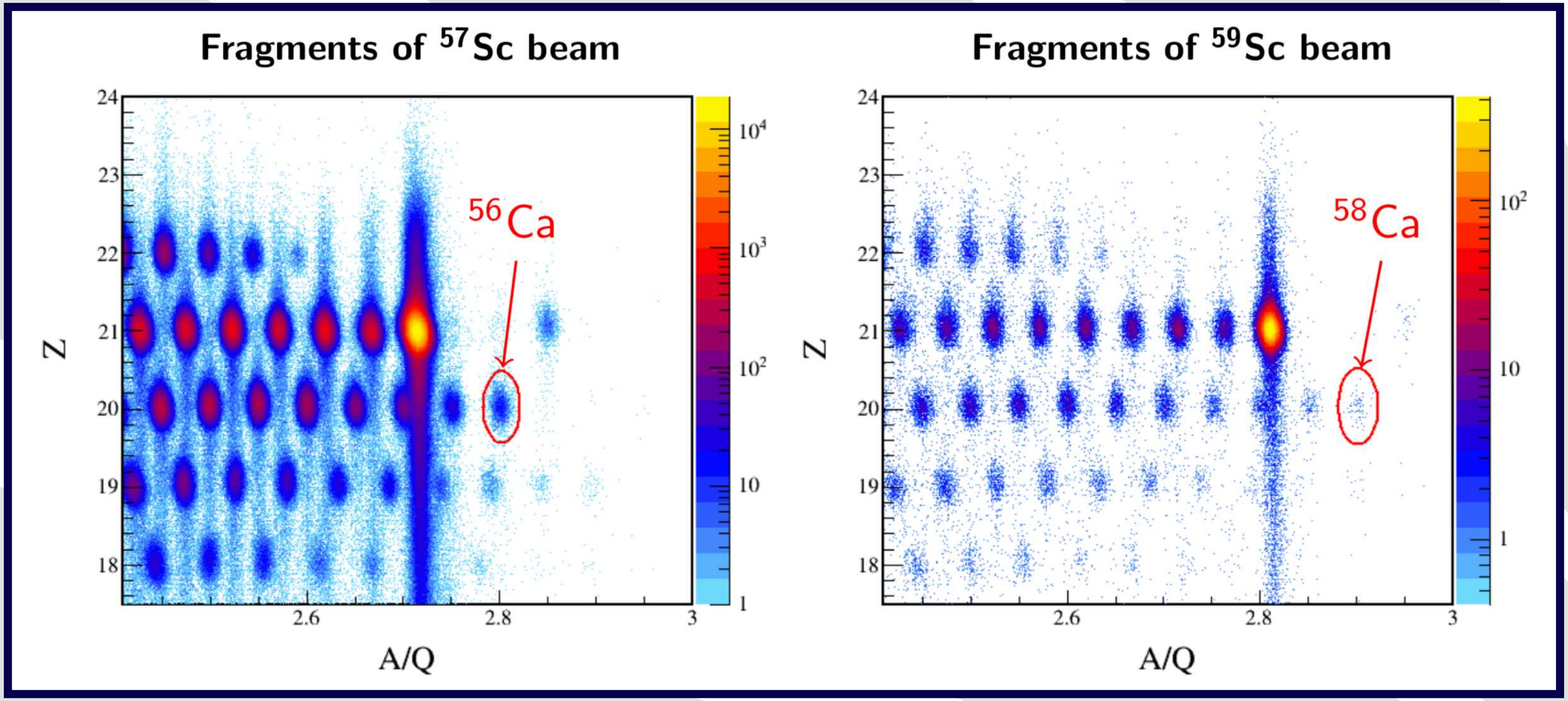

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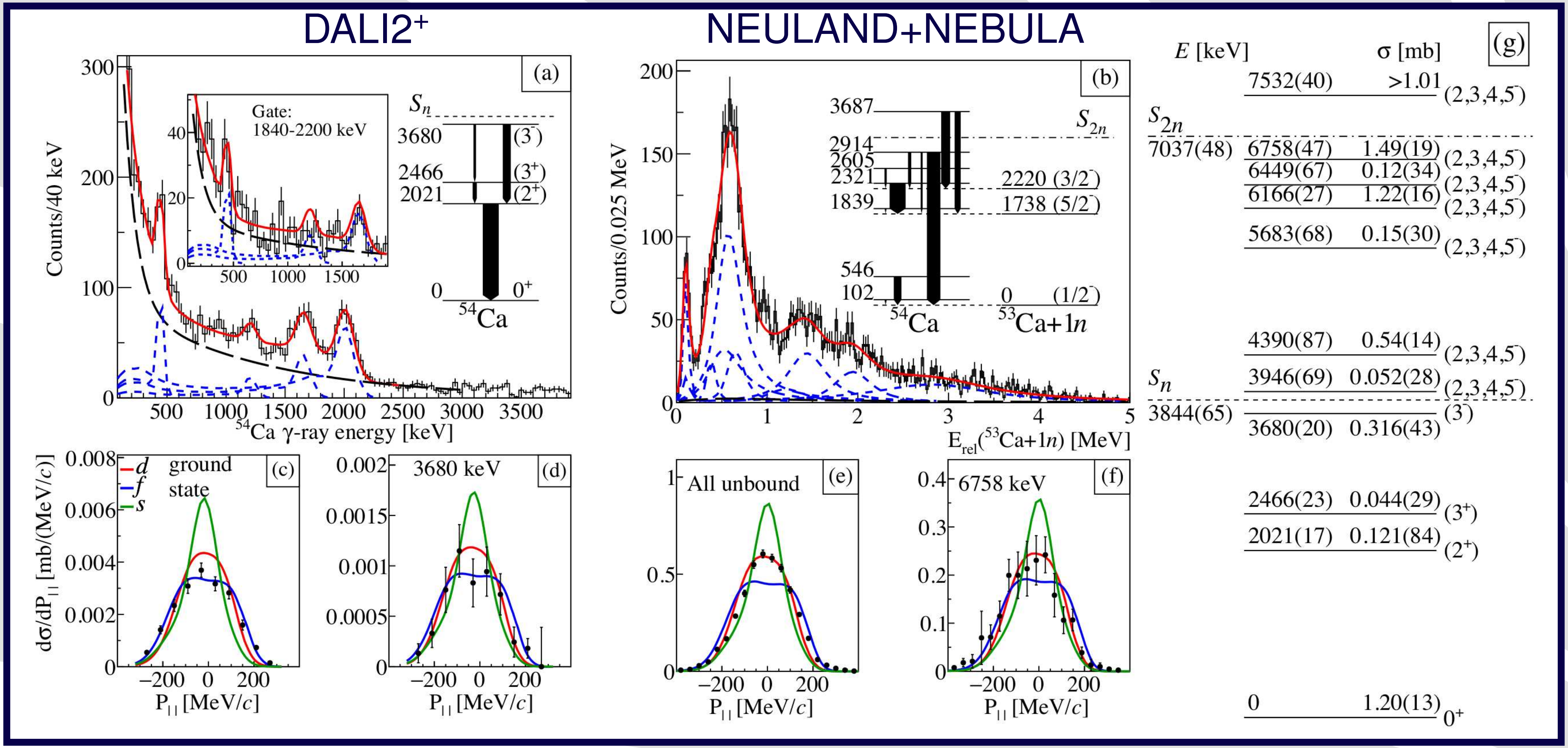
Detailed Spectroscopy of ^{54}Ca

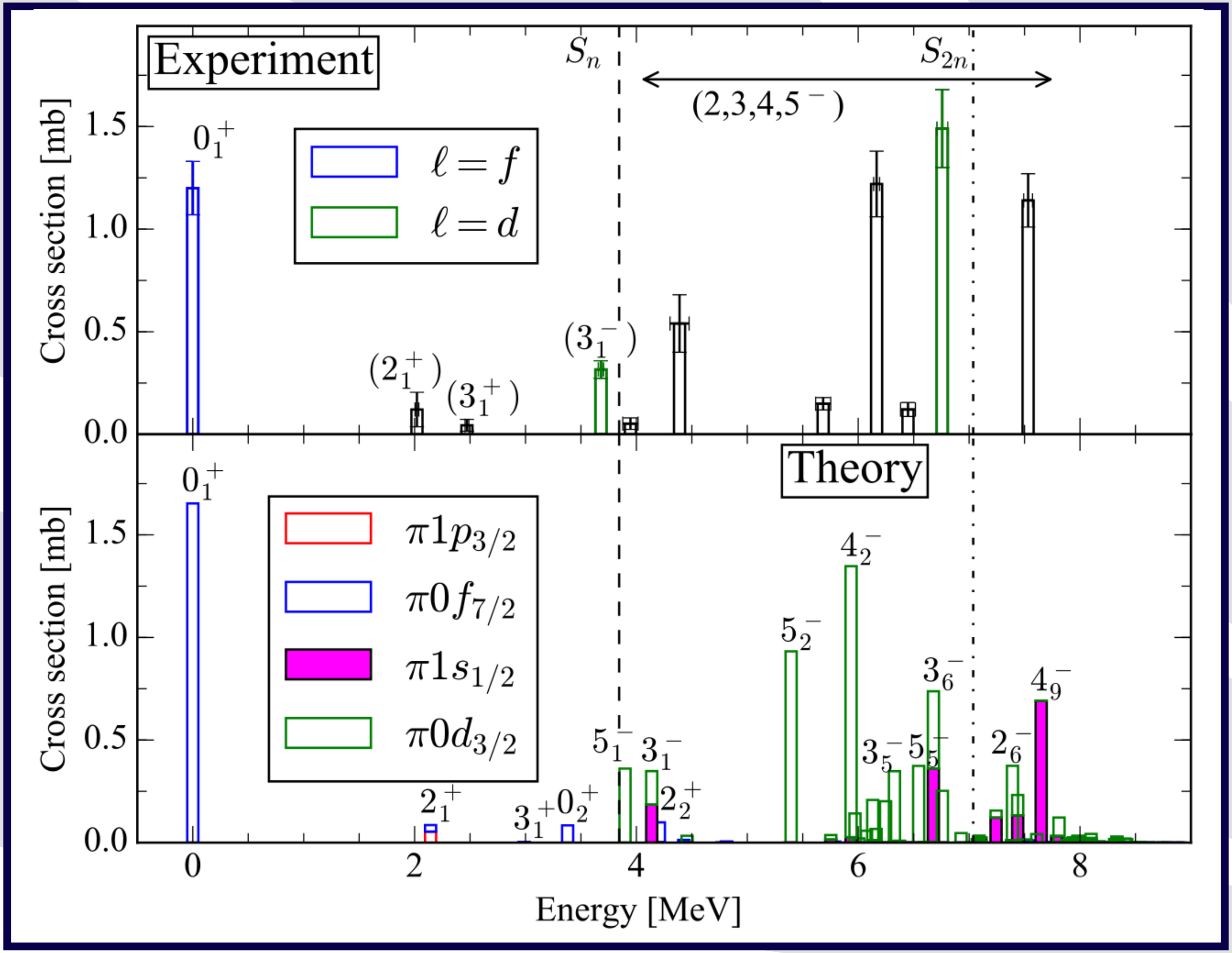
Detailed Spectroscopy of ^{54}Ca from ^{55}Sc(p,2p)^{54}Ca and ^{55}Ca(p,pn)^{54}Ca

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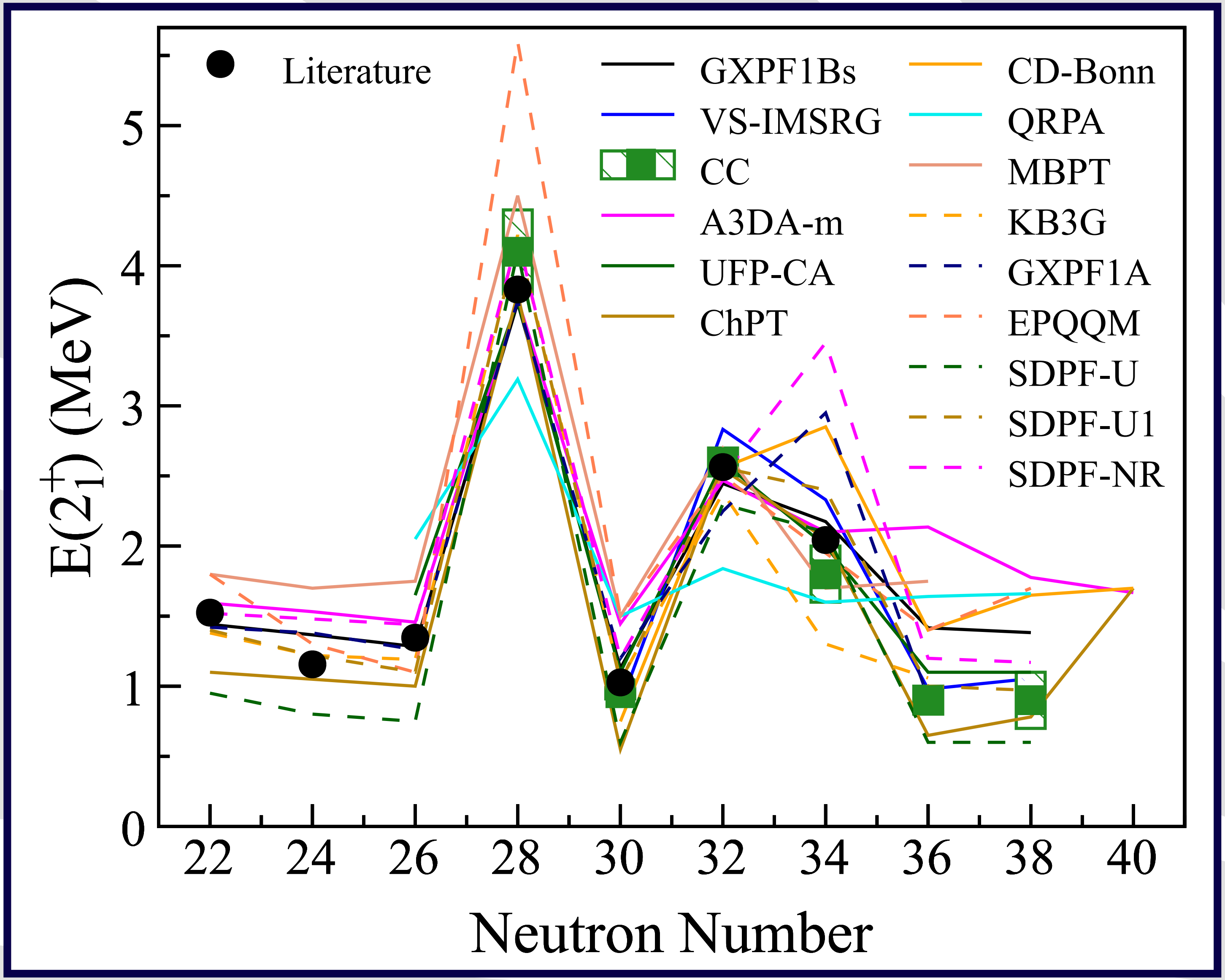
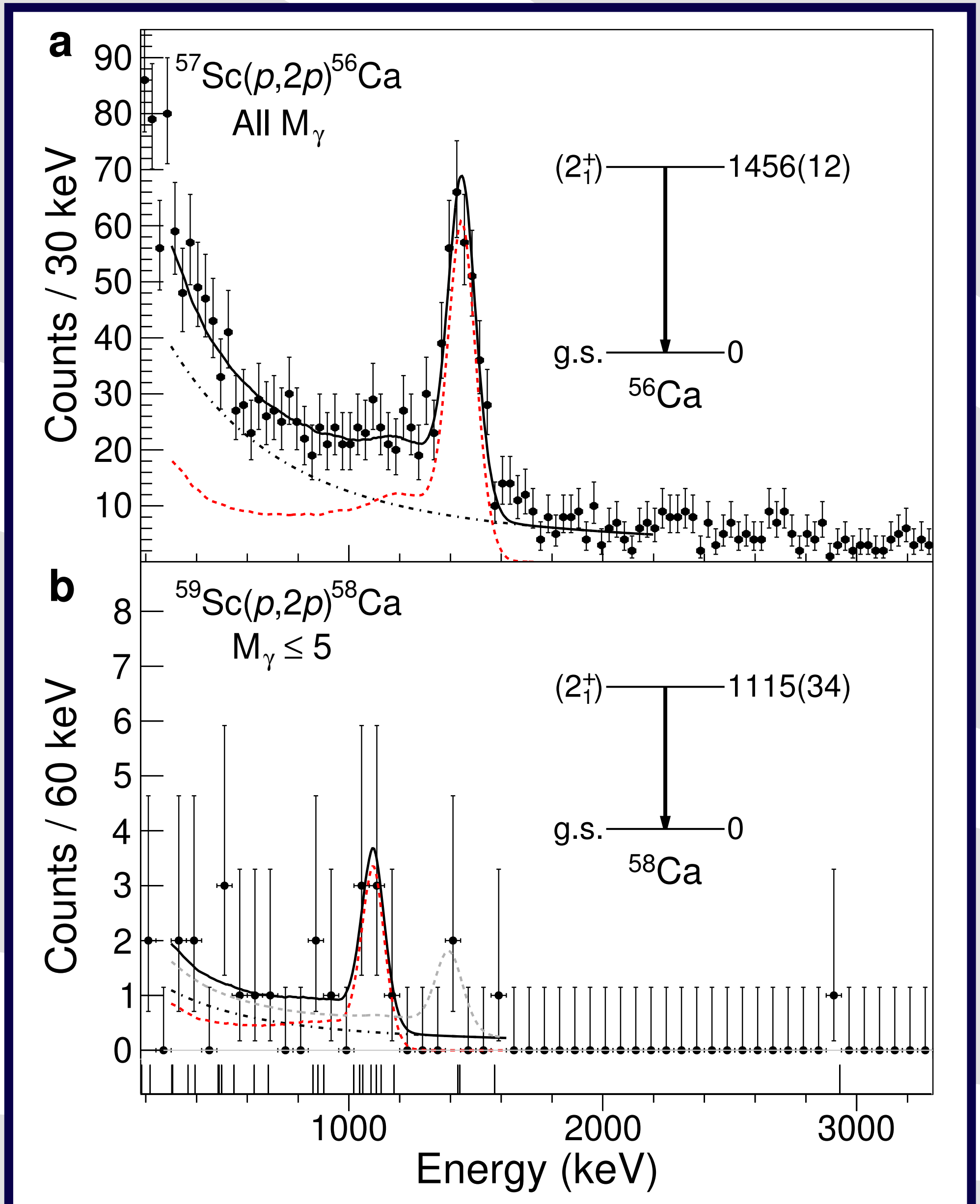
First Spectroscopy of $^{56,58}Ca$

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



$E(2_1^+)$ in ^{56,58}Ca from ^{57}Sc(p,2p)^{56}Ca and ^{59}Sc(p,2p)^{58}Ca

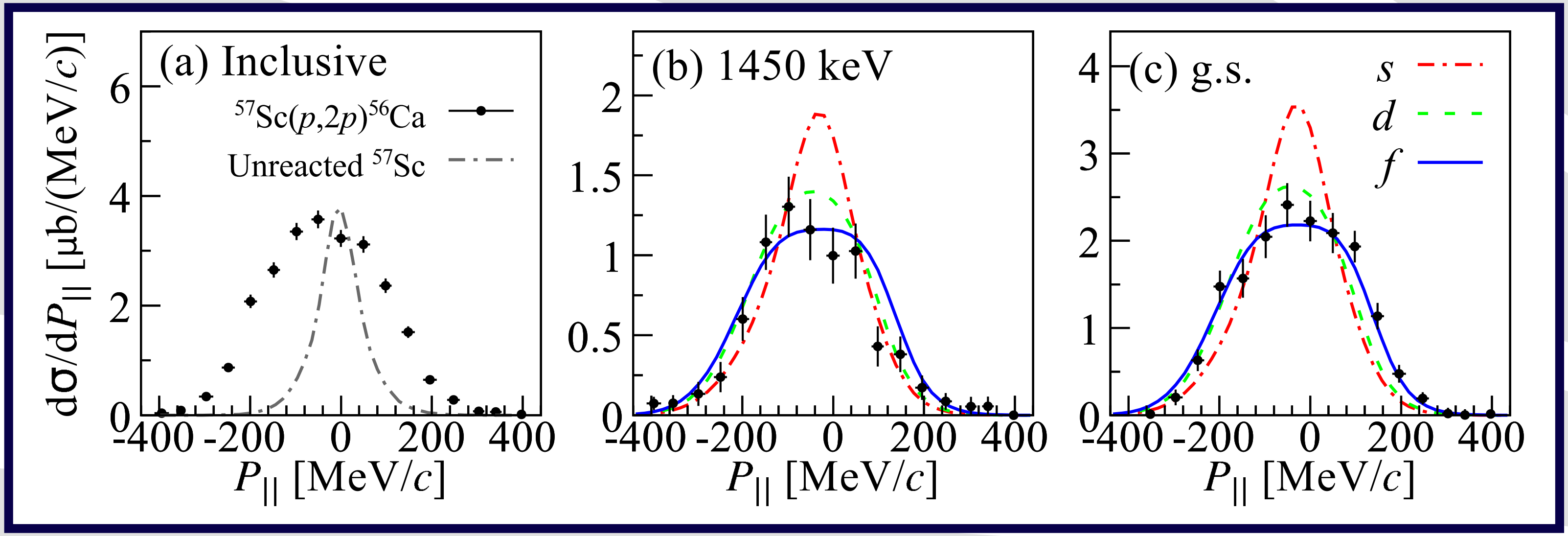


- 13.6 particles/s for ^{57}Sc
- 0.3 particles/s for ^{59}Sc
- $E(2_1^+)$ differ by ≈ 440 keV
- S.L = 2.8 σ for $E(2_1^+)$ of ^{58}Ca
- particle hole symmetry of $0f_{5/2}$
  - if $N = 40$ closed, constant energy expected
  - (doubly)-magic ^{60}Ca disfavored?
- Development of fitted interaction A3DA-t

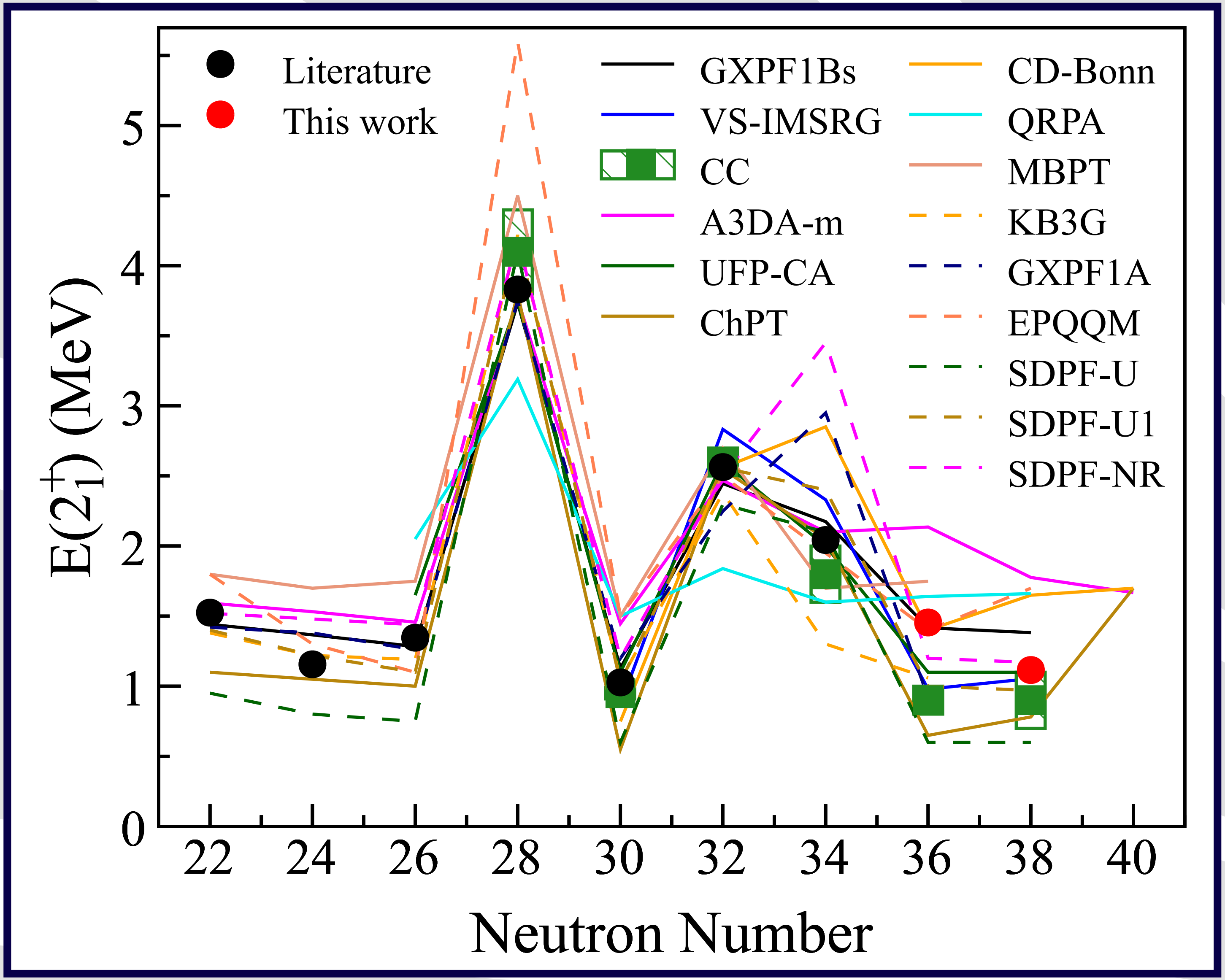
S. Chen, F. Browne et al., PLB 843 138025 (2023).

$E(2_1^+)$ in ^{56,58}Ca from ^{57}Sc(p,2p)^{56}Ca and ^{59}Sc(p,2p)^{58}Ca

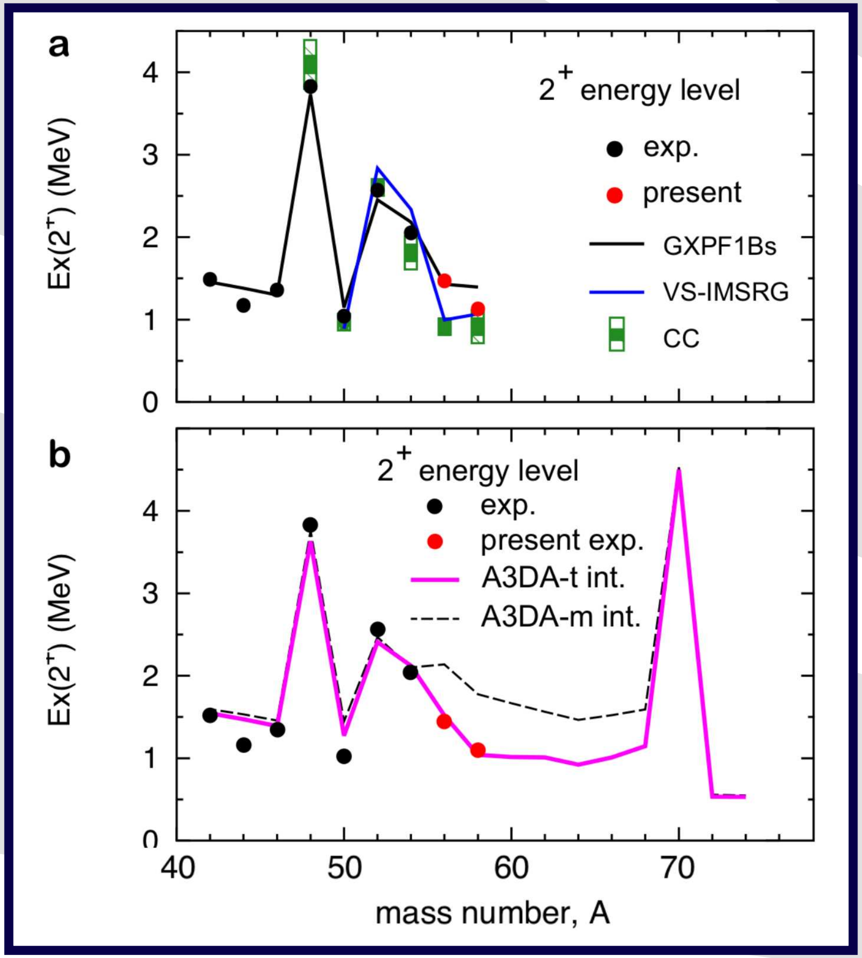
	Experiment				DWIA	VS-IMSRG			GXPF1Bs		
	E_{exp}	σ_{exp}	J^π	nl_j	σ_{sp}	E_x	C^2S_{th}	σ_{th}	E_x	C^2S_{th}	
^{56}Ca	0	0.80(6)	$0^+_{\text{g.s.}}$	$0f_{7/2}$	1.80	0	0.61	1.10	0	0.69	1.24
	1456(12)	0.43(4)	2_1^+	$0f_{7/2}$	1.74	1002	0.29	0.50	1416	0.25	0.44
			4_1^+	$0f_{7/2}$	1.73	1307	0.05	0.09	1776	0.02	0.04
	Inclusive	1.23(5)						1.69			1.72
^{58}Ca	0	0.66(24)	$0^+_{\text{g.s.}}$	$0f_{7/2}$	1.58	0	0.80	1.26	0	0.83	1.31
	1115(34)	0.47(19)	2_1^+	$0f_{7/2}$	1.54	1075	0.16	0.25	1382	0.15	0.23
			4_1^+	$0f_{7/2}$	1.52	1423	0.001	0.002	1772	0.001	0.002
	Inclusive	1.14(15)						1.51			1.54



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

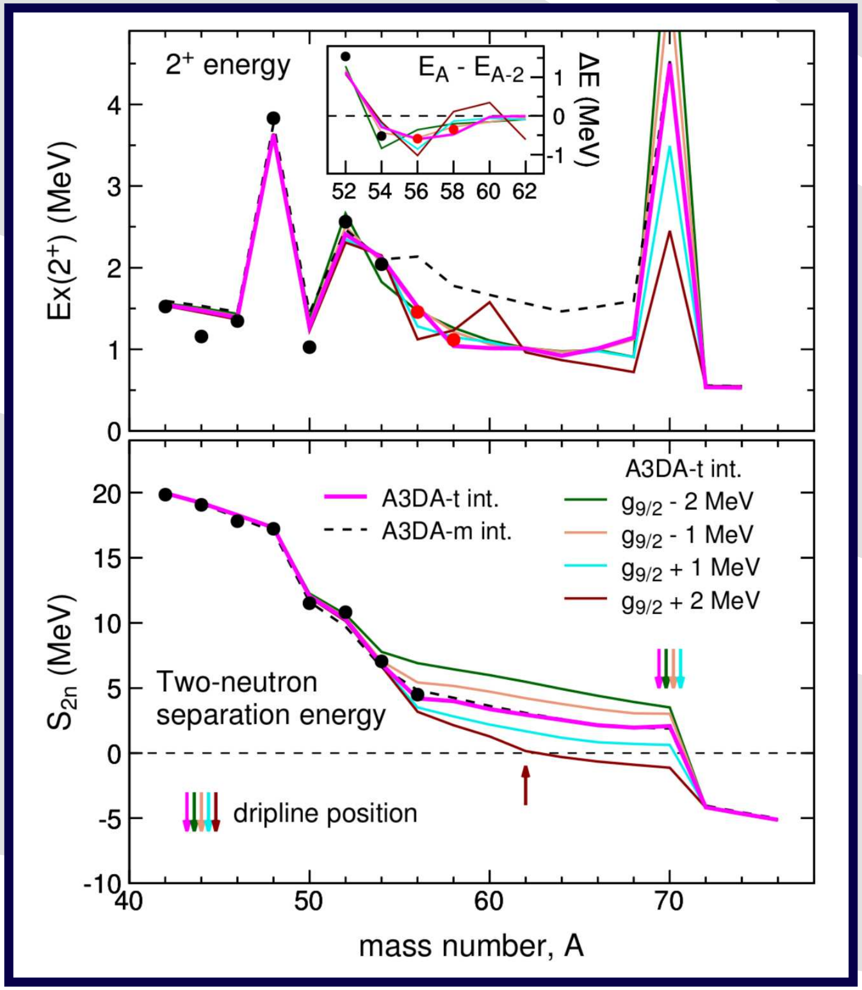


First Spectroscopy of ^{56,58}Ca



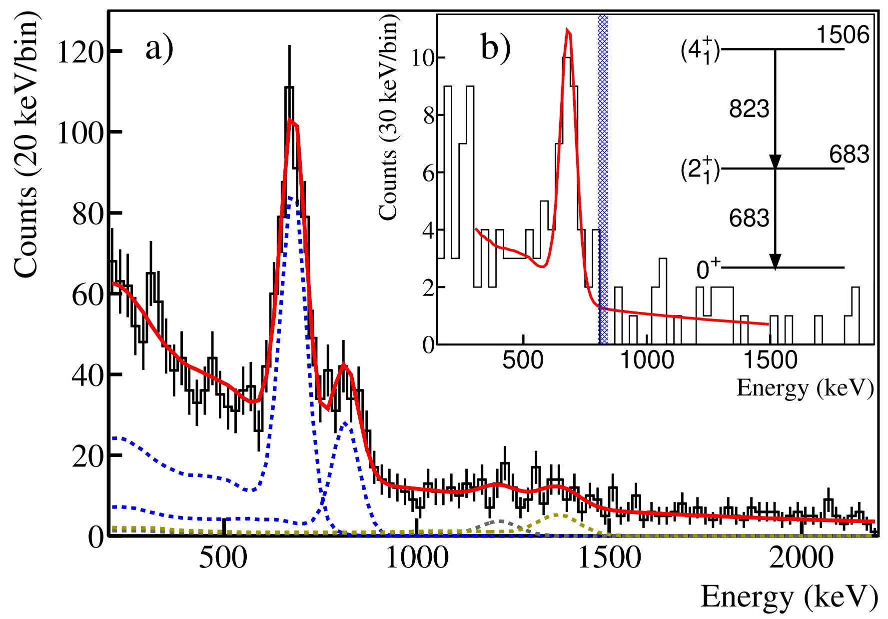
- GXPF1Bs:
  Shell-model
  neutron pf shell
- VS-IMSRG:
  Valence-space in-medium similarity renormalization group
  1.8/2.0 (EM) interaction
  neutron pf shell
- CC: Coupled-cluster theory
  Two-particle removed/attached equation-of-motion (2PR/2PA-EOM)
- A3DA-t: Revision of A3DA-m interaction fitted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

First Spectroscopy of ^{56,58}Ca



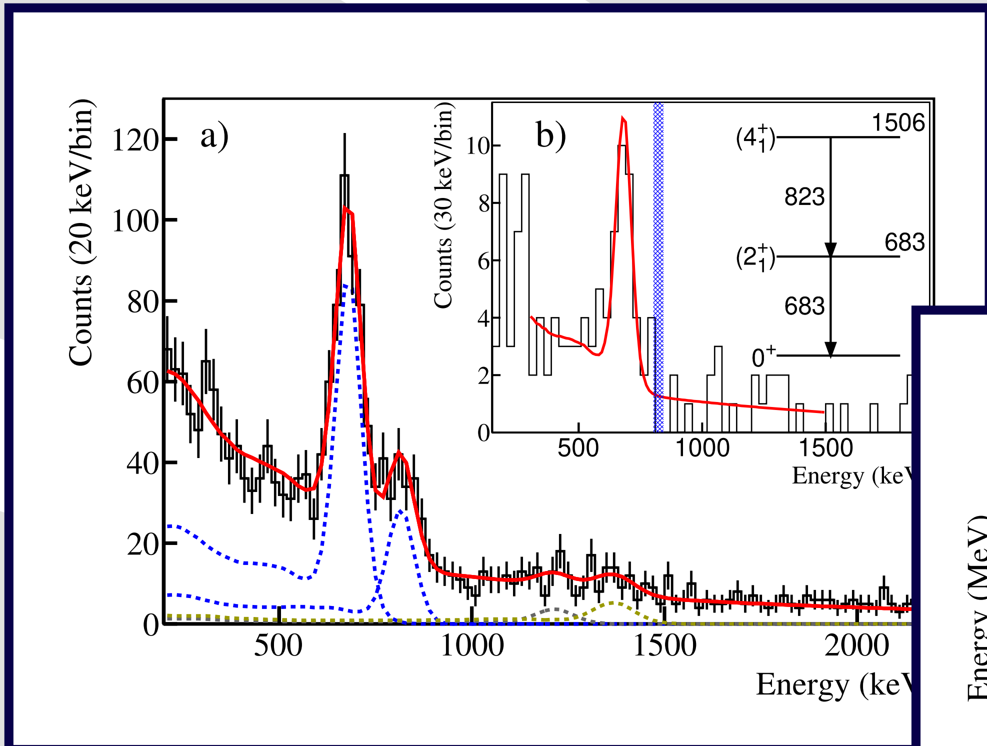
- Predictions with A3DA-T
- Sensitivity of the neutron $0g_{9/2}$ SPE $\rightarrow$ variation of up to ± 2 MeV
  - ✦ Positive shifts of $0g_{9/2}$ SPE $\rightarrow$ low $E(2_1^+)$ and S_{2n} of ^{56}Ca
  - ✦ Negative shifts of $0g_{9/2}$ SPE $\rightarrow$ quenching of $N = 34$ shell gap

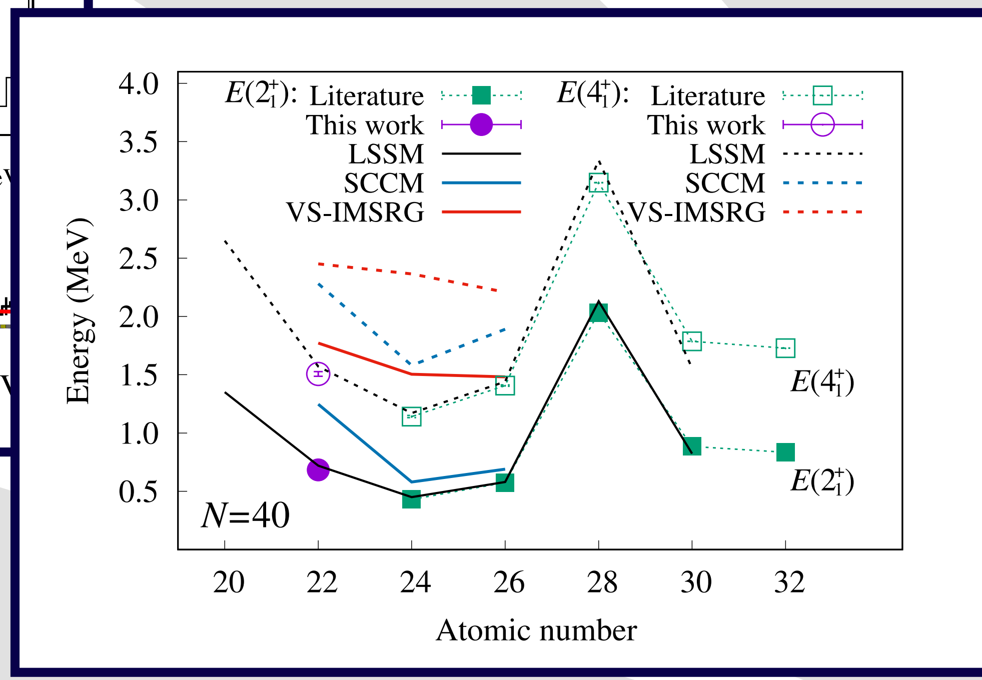
N = 40 Structure towards ^{60}Ca: ^{63}V(p,2p)^{62}Ti



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

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



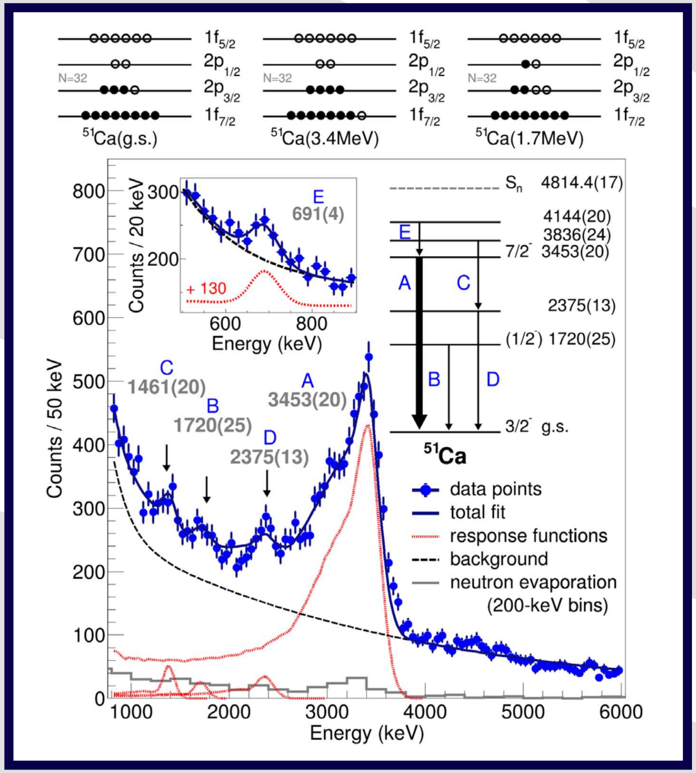


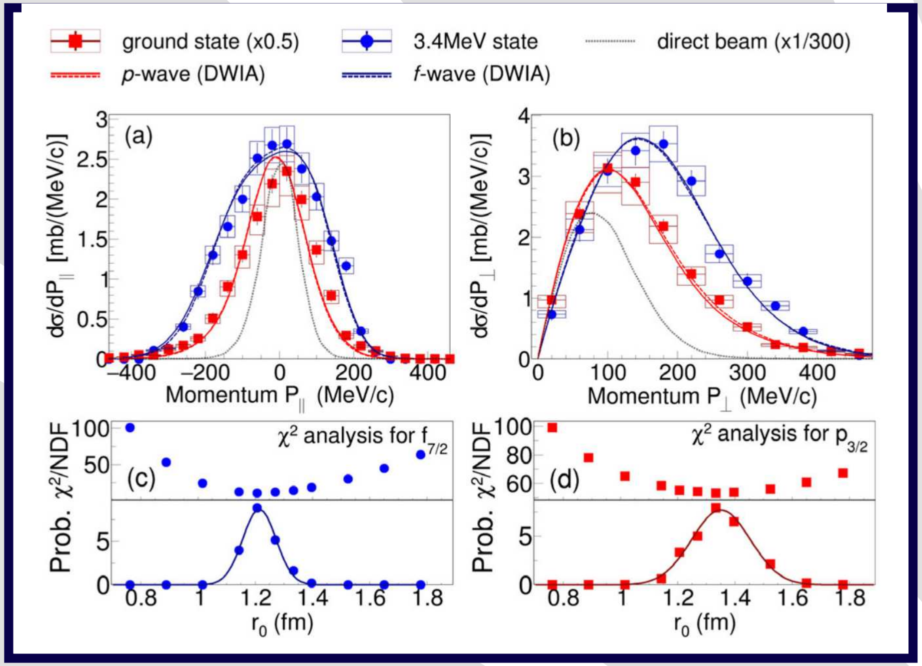
LNPS: S. Lenzi, F. Nowacki, A. Proves, K. Sieja
VS-IM-SRG: J.D. Holt, J. Menéndez, A. Schwenk, J. Simonis, S.R. Stroberg
SCCM: T. Rodriguez

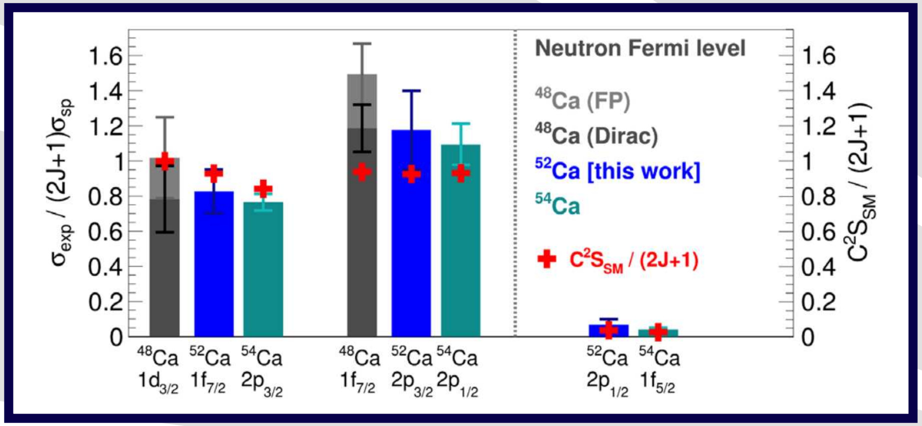
M.L. Cortés, W. Rodriguez et al., Phys. Lett. B 800, 135071 (2020).

Structure of Odd Ca Isotopes $^{51,53,55}Ca$

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).

Summary

Summary

- Ca isotopes ideal benchmark for nuclear structure and reaction theories
- Obtained comprehensive data set in n-rich nuclei around $Z = 20$
  - Spectroscopy of $^{51\text{–}58}$Ca
  - Many other isotopes
- $N = 32, 34$ magic numbers
  - $N = 32, 34$ shell closures as strong as $N = 28$
  - Large rms radius for $1p_{3/2}$ orbital
- Approaching ^{60}Ca
  - Effective interaction LNPS reproduces $E(2_1^+)$, $E(4_1^+)$ along $N = 40$
  - $E(2_1^+)$ in Ca isotopes challenge theory
- Single particle strengths
  - Pure $0f_{7/2}$ strength in ^{52,54}Ca
  - Marginal occupation of $1p_{1/2}$ in ^{52}Ca and of $0f_{5/2}$ in ^{54}Ca

Thank You!

Backup slides