Structural Evolution of Neutron-rich Calcium Isotopes

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The University of Hong Kong

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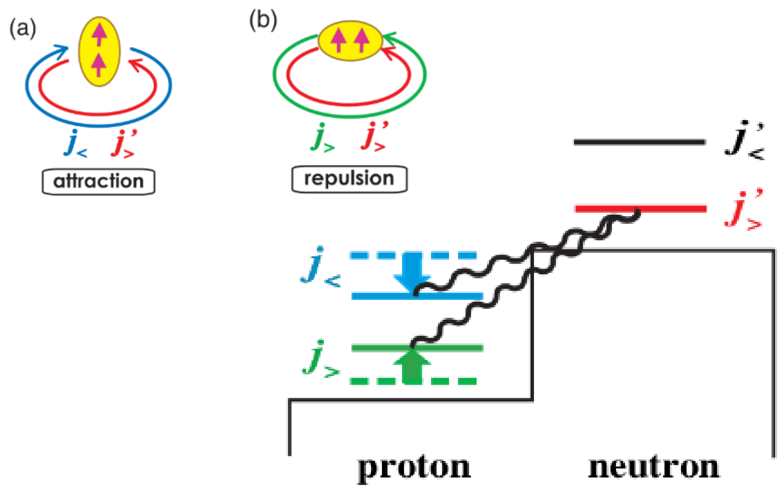
Shell Evolution in Ca Isotopes

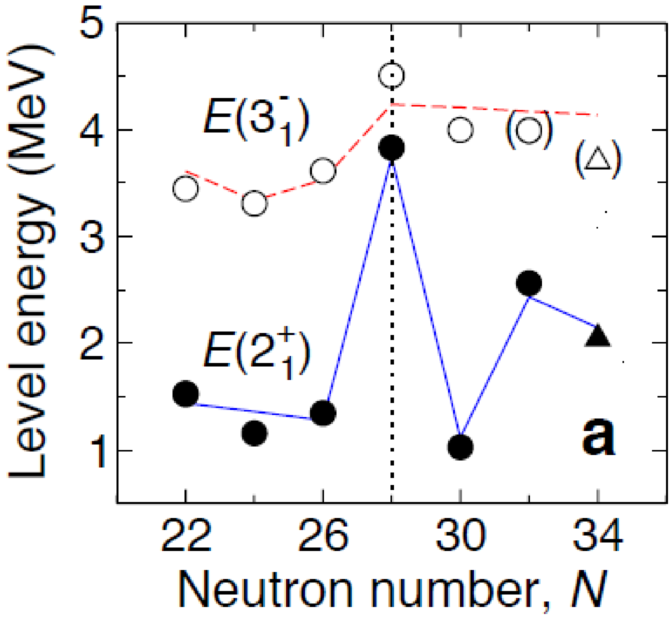
Calcium (Z=20), closed proton shell

- ✓ Structure evolution dominated by valence neutrons
- ✓ Ideal system to test NN- & $3N$-interactions

Absence of strong $\pi f_{7/2} - \nu f_{5/2}$ attraction make N = 32,34 new magic number in calcium



T. Otsuka *et al.*, Phys. Rev. Lett. **95**, 232502 (2005)



Significant Shell Closure

^{52}Ca: N=32

A. Gade et al., Phys. Rev. C 74, 021302 (R) (2006)

^{54}Ca: N=34

D. Steppenback et al., Nature 502,207 (2013)

What is next ?

How strong is $N = 34$ shell closure ?

Neutron knockout reaction from ^{54}Ca: **^{54}Ca(p,pn)^{53}Ca**

Towards ^{60}Ca ?

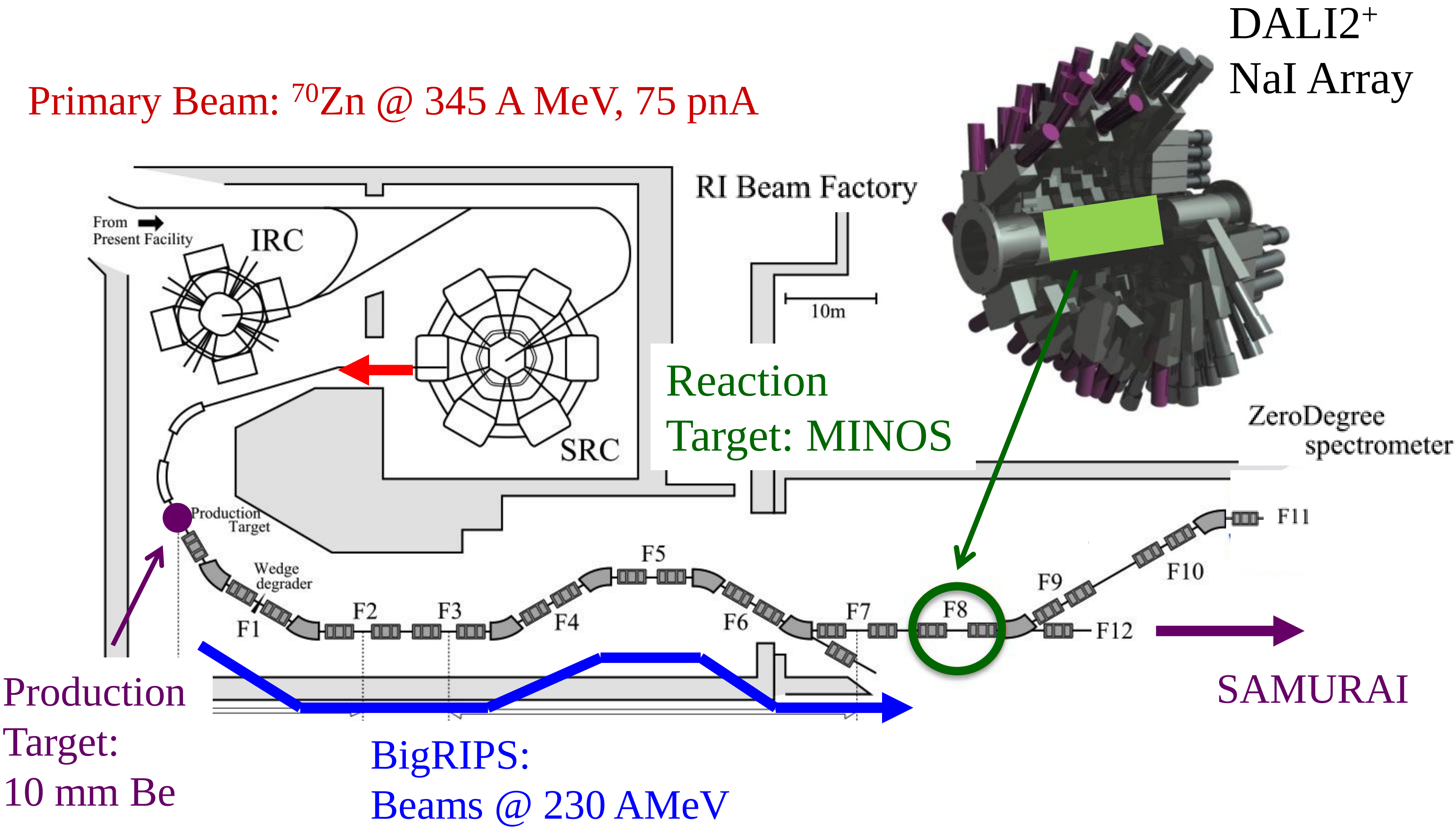
First spectroscopy of ^{56,58}Ca: **^{57,59}Sc(p,2p) ^{56,58}Ca**

Evolution of ν-$f_{7/2}$ orbital along Ca ?

Unbound states of ^{53,55}Ca: **^{54,56}Ca(p,pn) ^{53,55}Sc***

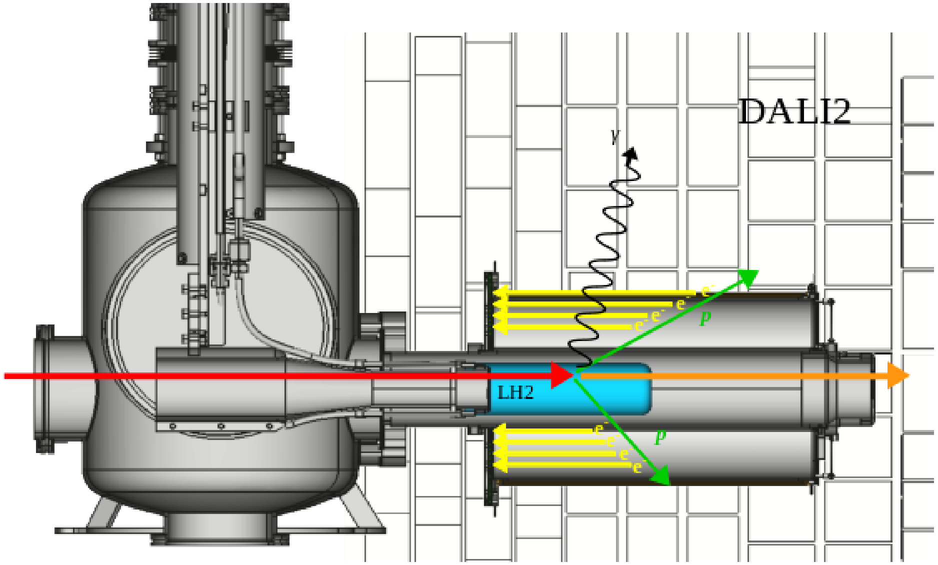
Data from SEASTAR campaign experiment
"Shell Evolution And Search for Two-plus energies At RIBF"

SEASTAR-3 @ RIBF RIKEN



DALI2$^+$ & MINOS

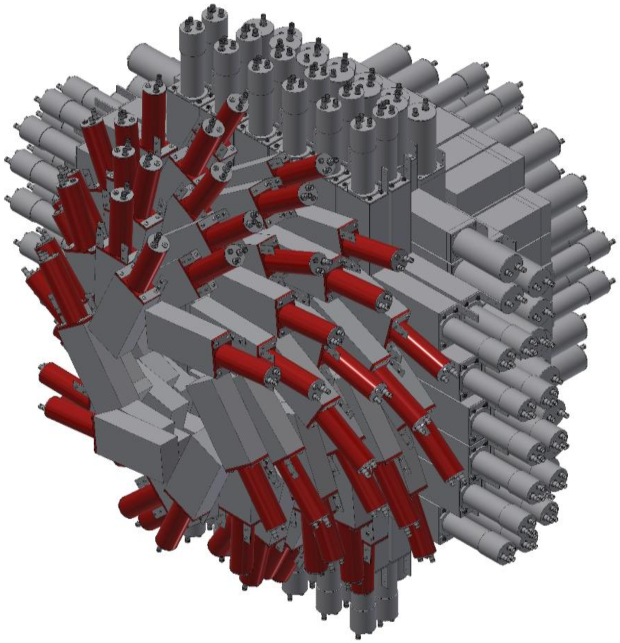
MINOS target system:



A. Obertelli et al., EPJA **50**, 8 (2014)
C. Santamaria et al, NIMA **905**, 13 (2018)

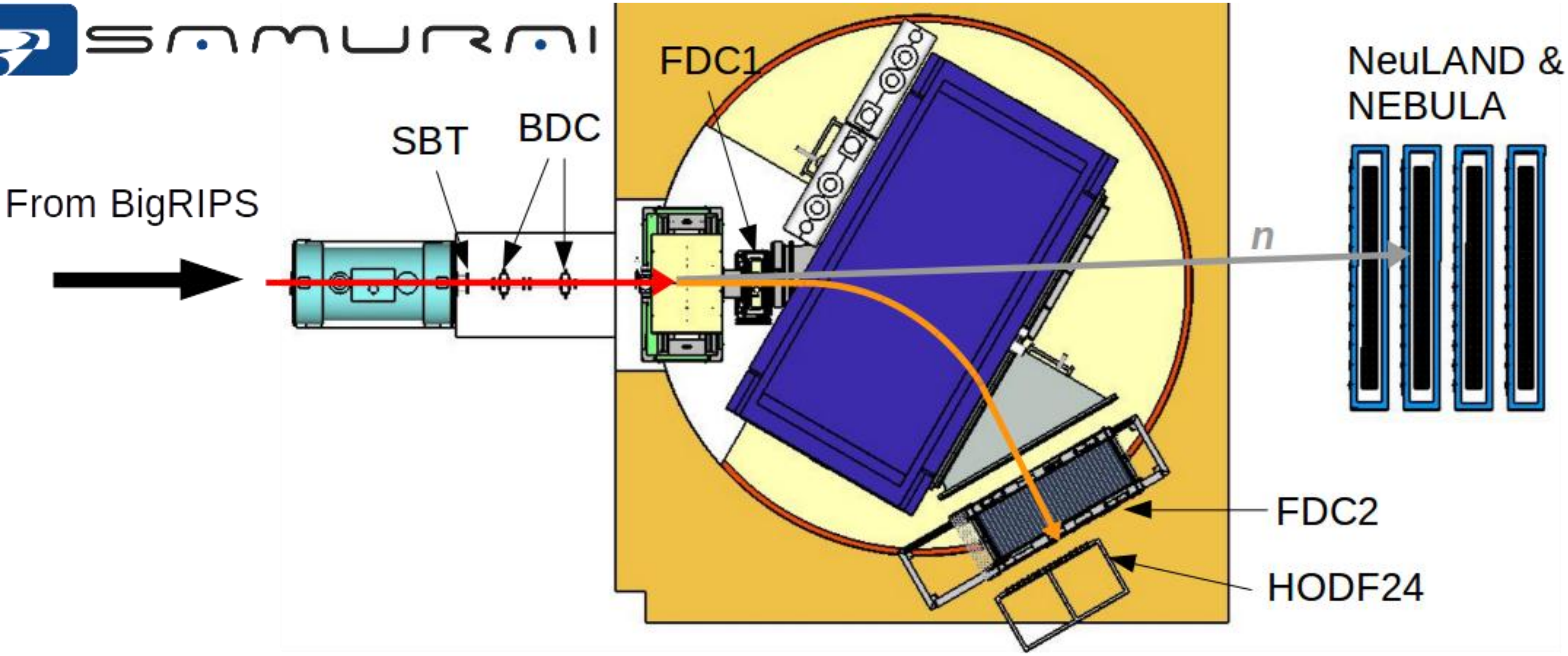
- 150 mm liquid hydrogen
- 300 mm Time Projection Chamber
- 5 mm (FWHM) res. z_vertex
- $\varepsilon_{2p} \sim 91\%$, $\varepsilon_{pn} \sim 70\%$
- center-of-target energy ~220MeV/u

DALI2$^+$ array:



- 226 NaI(Tl) crystals
- 7% (FWHM) res. at 1MeV
- 34% eff. at 1MeV

SAMURAI Spectrometer



Charge particles:

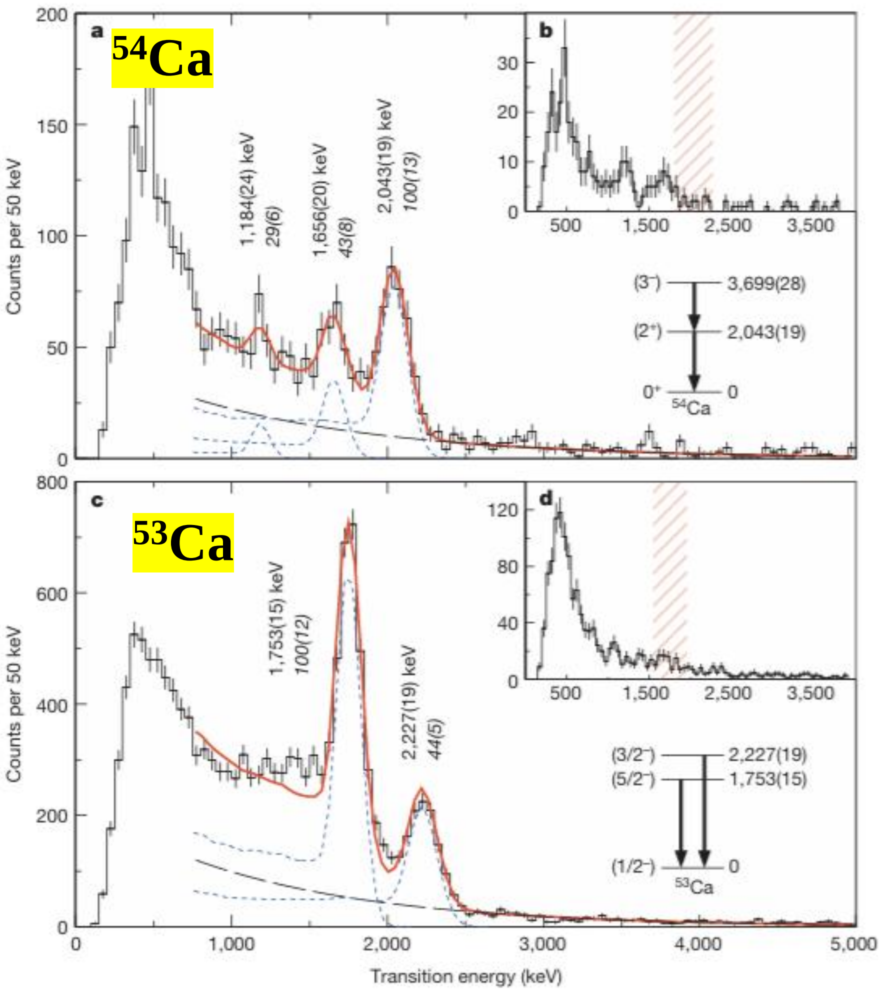
- $B\rho$: FDC1, FDC2 tracking
- Time-of-Flight: SBT-Hodoscope
- ΔE: Hodoscope

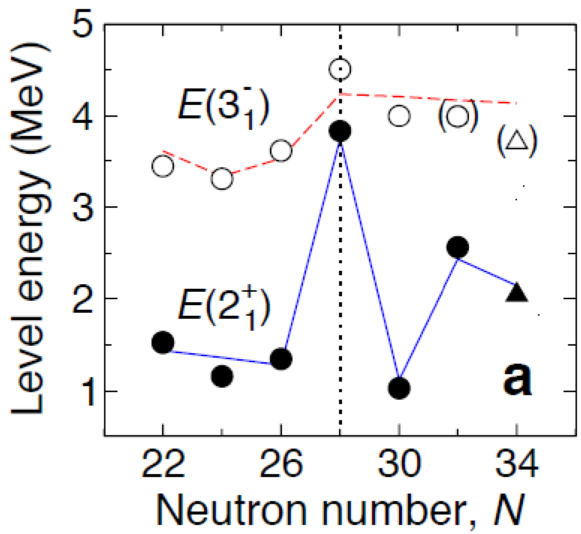
Neutrons:

- NeuLAND + NEBULA
- Acceptance:
  - X: $\pm 10^\circ$
  - Y: $\pm 5^\circ$

I. How strong is N = 34 shell closure ?

D. Steppenback et al., Nature 502,207 (2013)



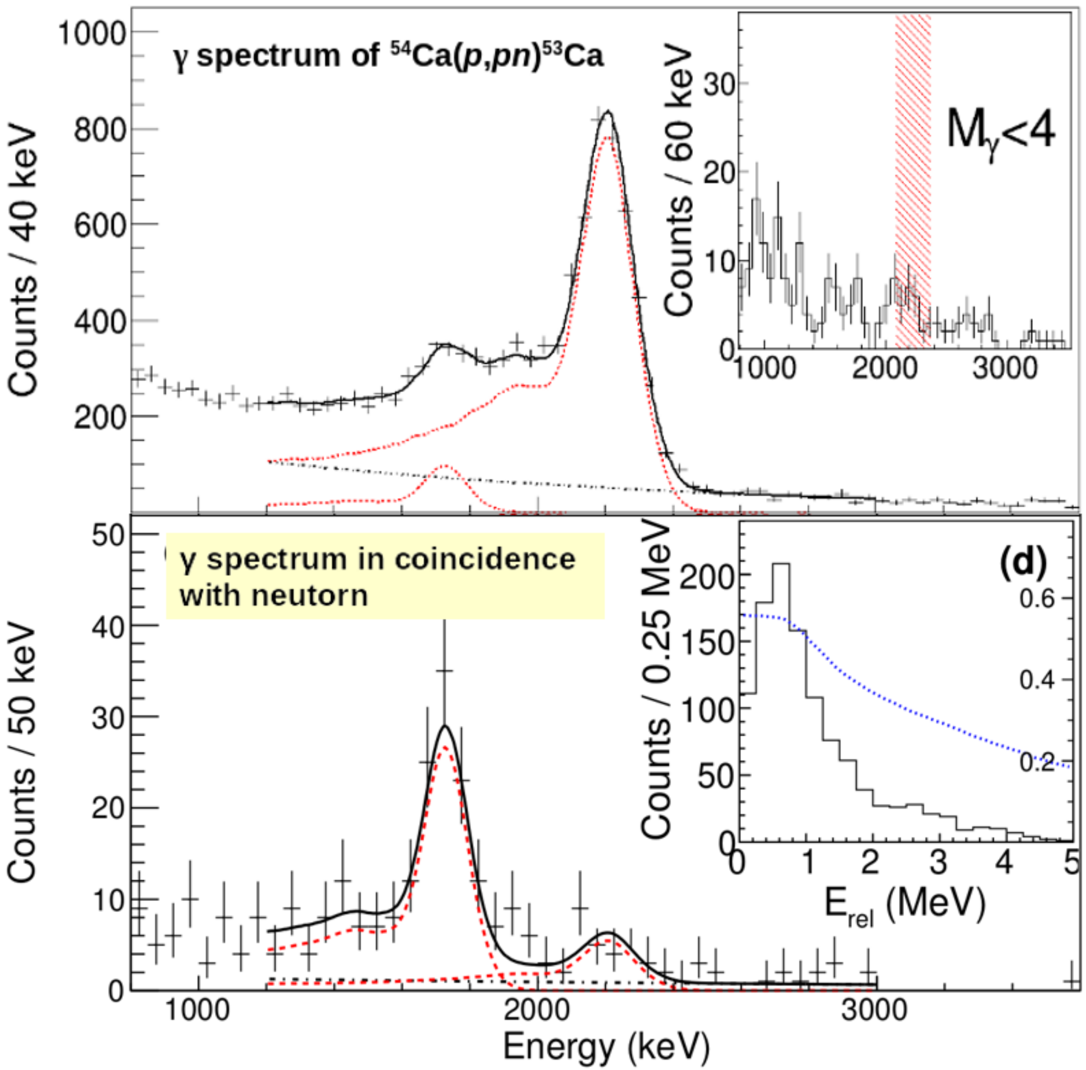


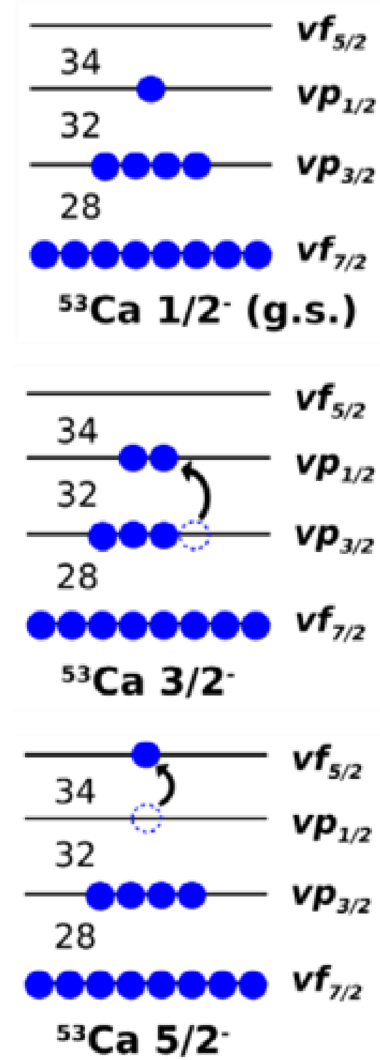
^{53}Ca populated via ^{55}Sc→ ^{53}Ca
(Not direct reaction)

- No structure information from cross sections
- No spin-parity assignment

I. How strong is N = 34 shell closure ?

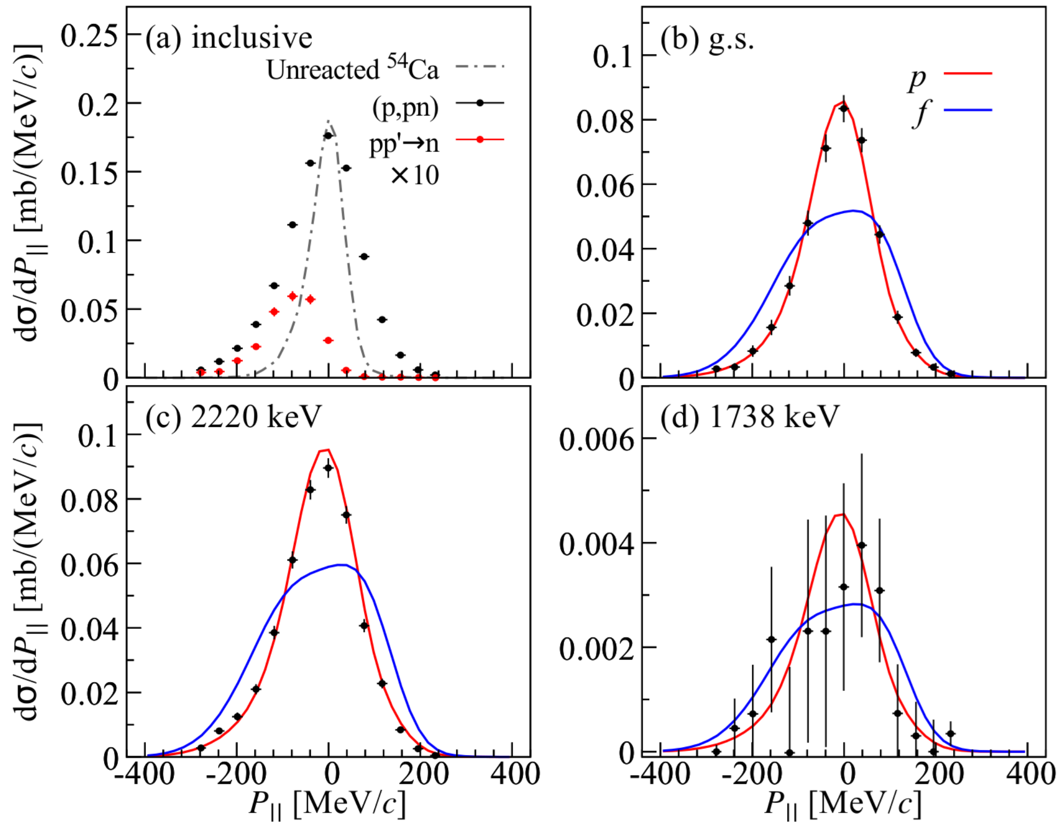
Direct probe of the g.s. wave-function of ^{54}Ca

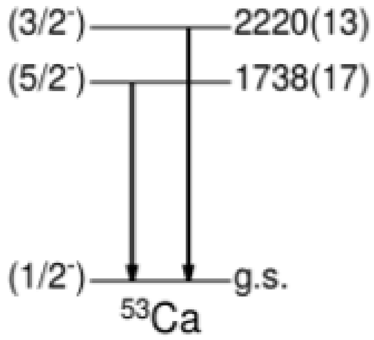




Neutron knockout from ^{54}Ca

Momentum distributions of ^{54}Ca(*p*,*pn*)^{53}Ca channel



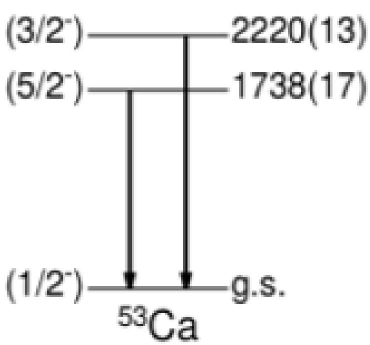


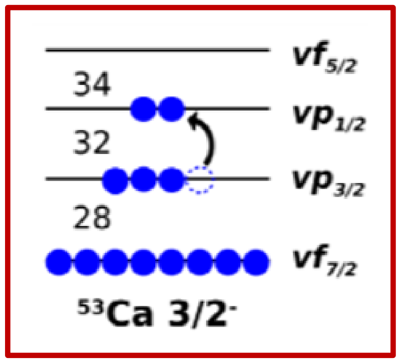
$P_{//}$ from Distorted wave impulse approximation (DWIA) calculations (K. Ogata)

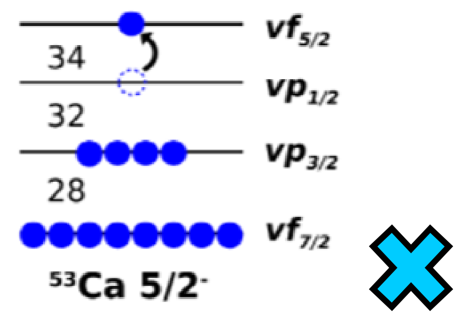
Cross sections of ^{54}Ca(p,pn)^{53}Ca

Data K. Ogata T. Otsuka V. Somà

				DWIA	GXPF1Bs			NNLO$_{sat}$			$NN+3N$ (lnl)		
	J^π	$-1n$	σ_{-1n}	σ_{sp}	E$_x$ (keV)	C^2S	σ^{th}_{-1n}	E$_x$ (keV)	C^2S	σ^{th}_{-1n}	E$_x$ (keV)	C^2S	σ^{th}_{-1n}
g.s.	$1/2^-$	$p_{1/2}$	15.9(17)	7.27	0	1.82	13.2	0	1.56	11.3	0	1.58	11.6
2220(13)	$3/2^-$	$p_{3/2}$	19.1(12)	6.24	2061	3.55	22.2	2635	3.12	18.5	2611	3.17	17.0
1738(17)	$5/2^-$	$f_{5/2}$	1.0(3)	4.19	1934	0.19	0.8	1950	0.01	0.1	2590	0.02	0.1
Inclusive			36.0(12)				36.2			29.9			28.7





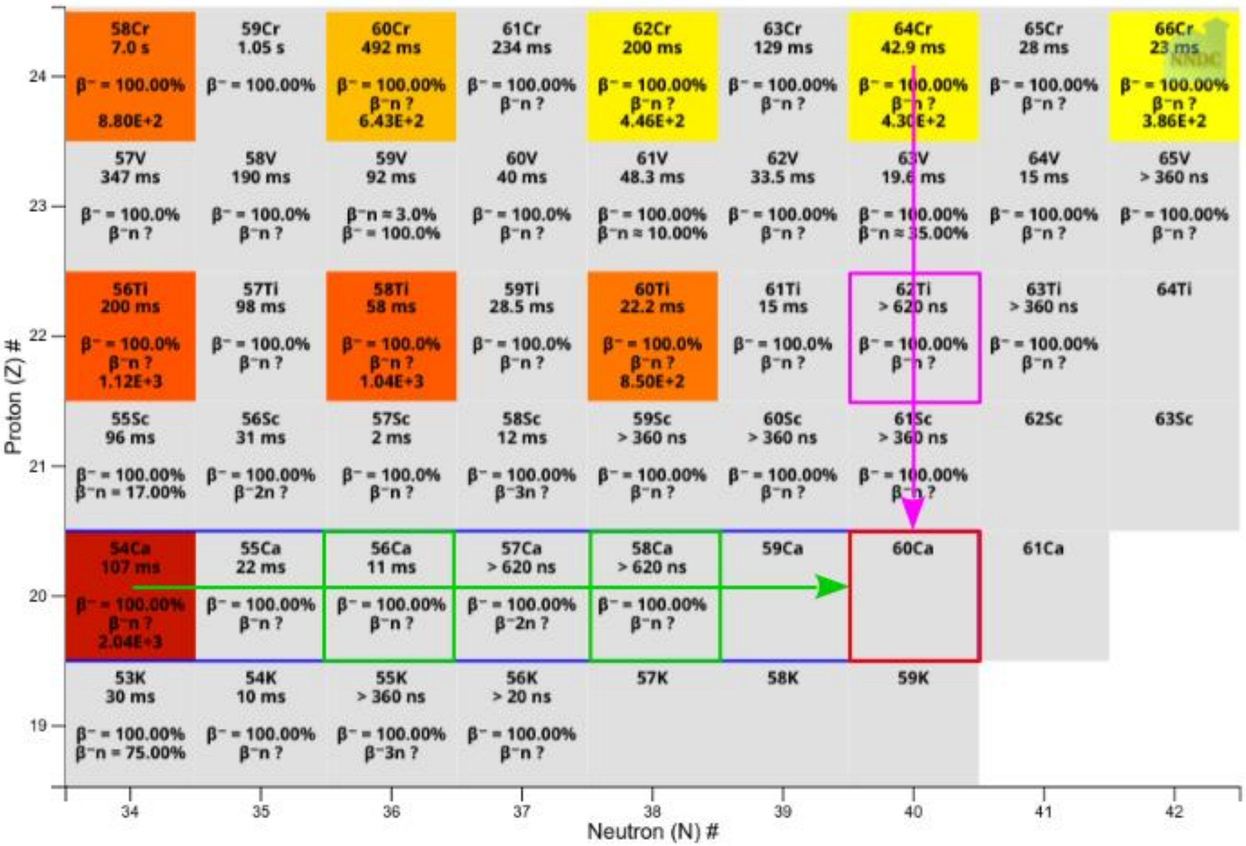


Little f wave component in ^{54}Ca g.s. ⇒ strong N = 34 shell closure in ^{54}Ca

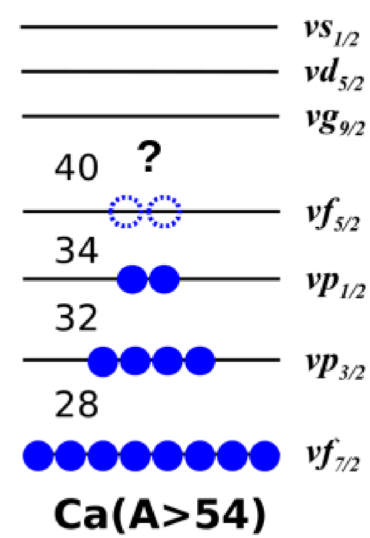
Consistent with shell-model and ab initio calculations

S. Chen, J. Lee *et al.*, Phys. Rev. Lett. **123**,142501 (2019)

II. Approaching ^{60}Ca ?



Effective neutron single-particle energies



***N* = 40 shell gap preserved in ^{60}Ca?**

- Following *N* = 40 isotonic chain: **First spectroscopy of ^{62}Ti**
  - Small decrease of quadrupole collectivity in ^{62}Ti
  - Favors ^{60}Ca **NOT** being doubly magic

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

- Following Z = 20 isotopic chain: **First spectroscopy of ^{56,58}Ca**

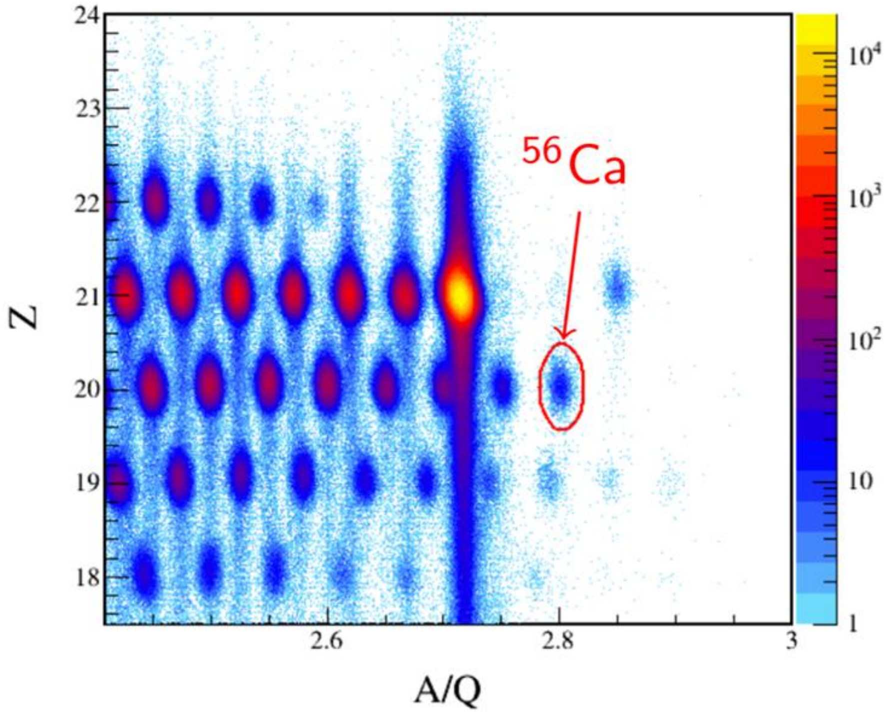
First spectroscopy of ^{56,58}Ca

RI beam intensity

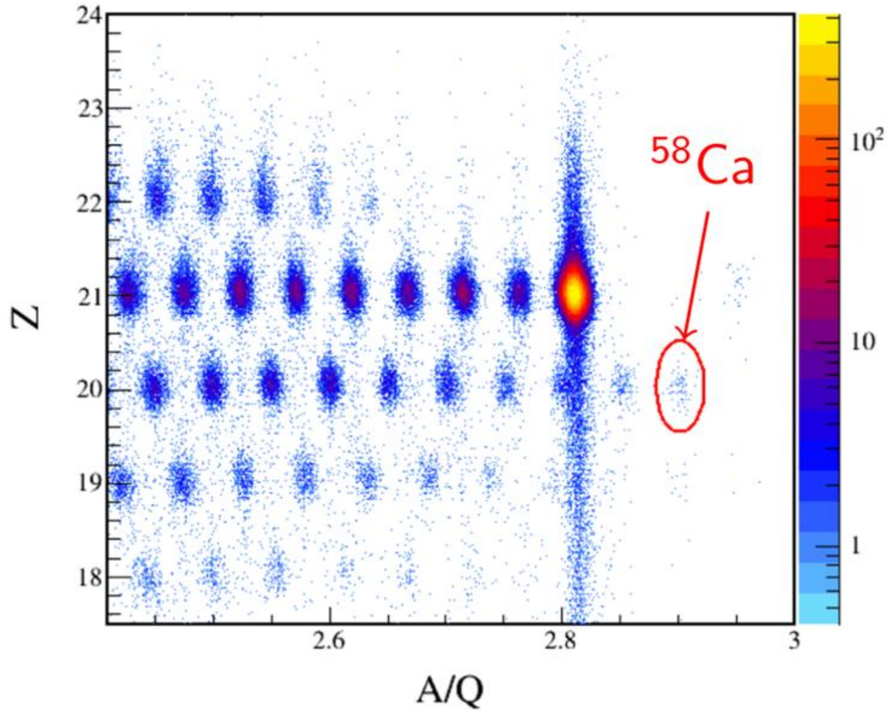
- ^{57}Sc intensity 13.6 particles/sec
- ^{57}Sc Energy@F7 252 MeV/u

- ^{59}Sc intensity 0.3 particles/sec
- ^{59}Sc Energy@F7 242 MeV/u

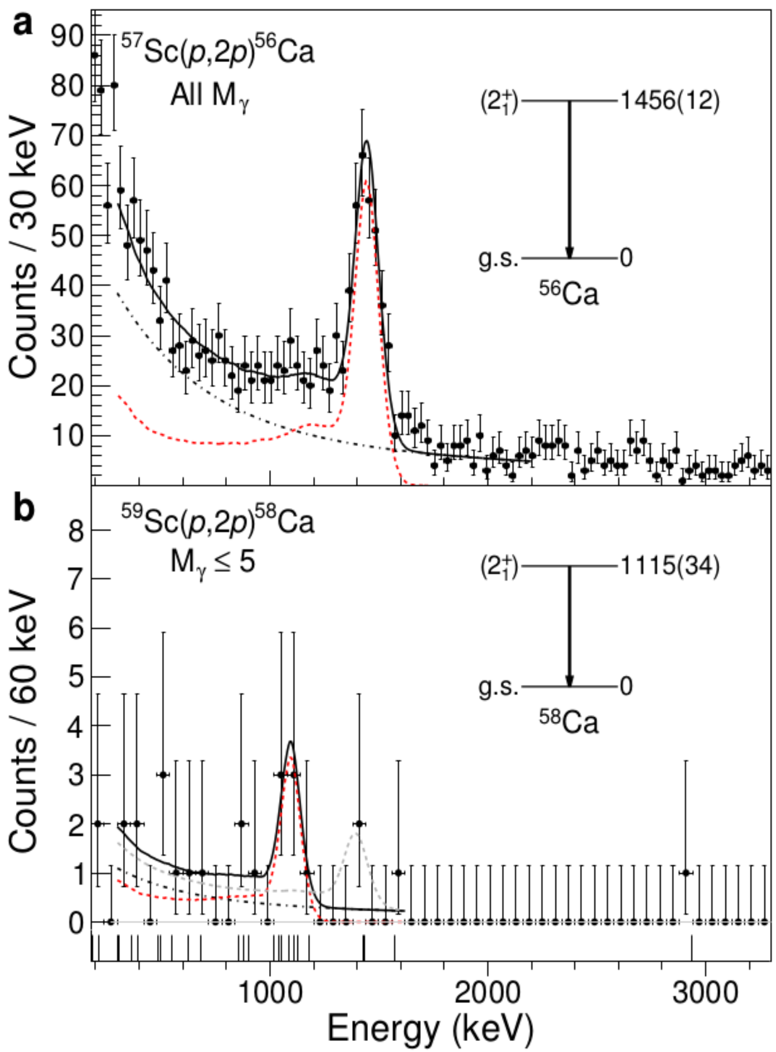
Fragments of ^{57}Sc beam

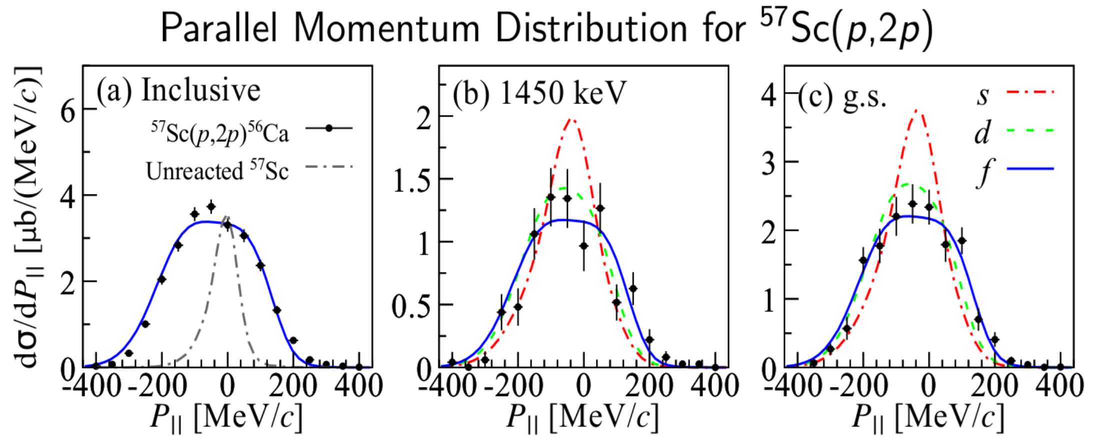


Fragments of ^{59}Sc beam



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

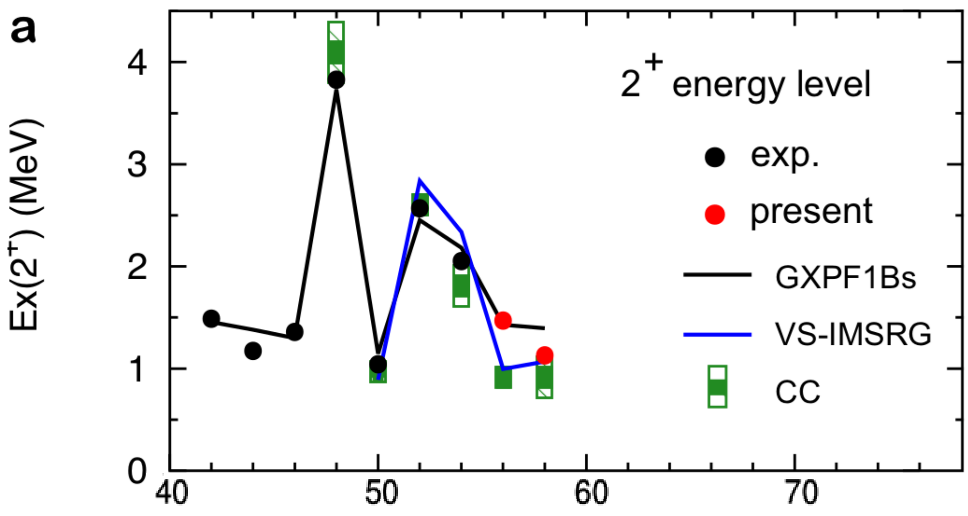




	Experiment				DWIA	VS-IMSRG			GXPF1Bs			A3DA-t		
	E_{exp}	σ_{exp}	J^π	nl_j	σ_{sp}	E_x	C^2S_{th}	σ_{th}	E_x	C^2S_{th}	σ_{th}	E_x	C^2S_{th}	σ_{th}
^{56}Ca	0	0.80(6)	$0^+_{g.s.}$	$0f_{7/2}$	1.80	0	0.61	1.10	0	0.69	1.24	0	0.62	1.11
	1456(12)	0.43(4)	2^+_1	$0f_{7/2}$	1.74	1002	0.29	0.50	1416	0.25	0.44	1519	0.27	0.47
			4^+_1	$0f_{7/2}$	1.73	1307	0.05	0.09	1776	0.02	0.04	2339	0.01	0.02
	Inclusive	1.23(5)						1.69			1.72			1.60
^{58}Ca	0	0.66(24)	$0^+_{g.s.}$	$0f_{7/2}$	1.58	0	0.80	1.26	0	0.83	1.31	0	0.46	0.73
	1115(34)	0.47(19)	2^+_1	$0f_{7/2}$	1.54	1075	0.16	0.25	1382	0.15	0.23	1040	0.42	0.65
			4^+_1	$0f_{7/2}$	1.52	1423	0.001	0.002	1772	0.001	0.002	2084	0.05	0.08
	Inclusive	1.14(15)						1.51			1.54			1.46

- Maximum likelihood fit to unbinned data gives 2.8σ
- Comparable inclusive and exclusive cross section between $^{57}Sc(p,2p)^{56}Ca$ and $^{59}Sc(p,2p)^{58}Ca$
- σ_{exp} reasonably reproduced by $\sigma_{th} = C^2S_{th} \cdot \sigma_{sp}$

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



GXPF1Bs (T. Otsuka), neutron *pf* shell

VS-IMSRG (J.D. Holt)
1.8/2.0 (EM) interaction
neutron *pf* shell

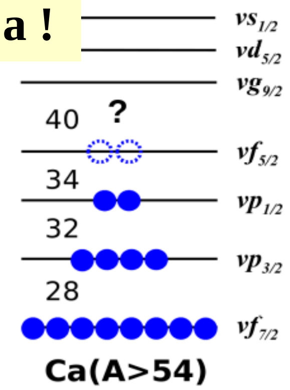
CC coupled-cluster theory (G. Hagen)
(2PR/2PA-EOM), 1.8/2.0 (EM) interaction

$E_x(2^+)$ drops from ^{56}Ca to ^{58}Ca !

Particle-hole symmetry breaks

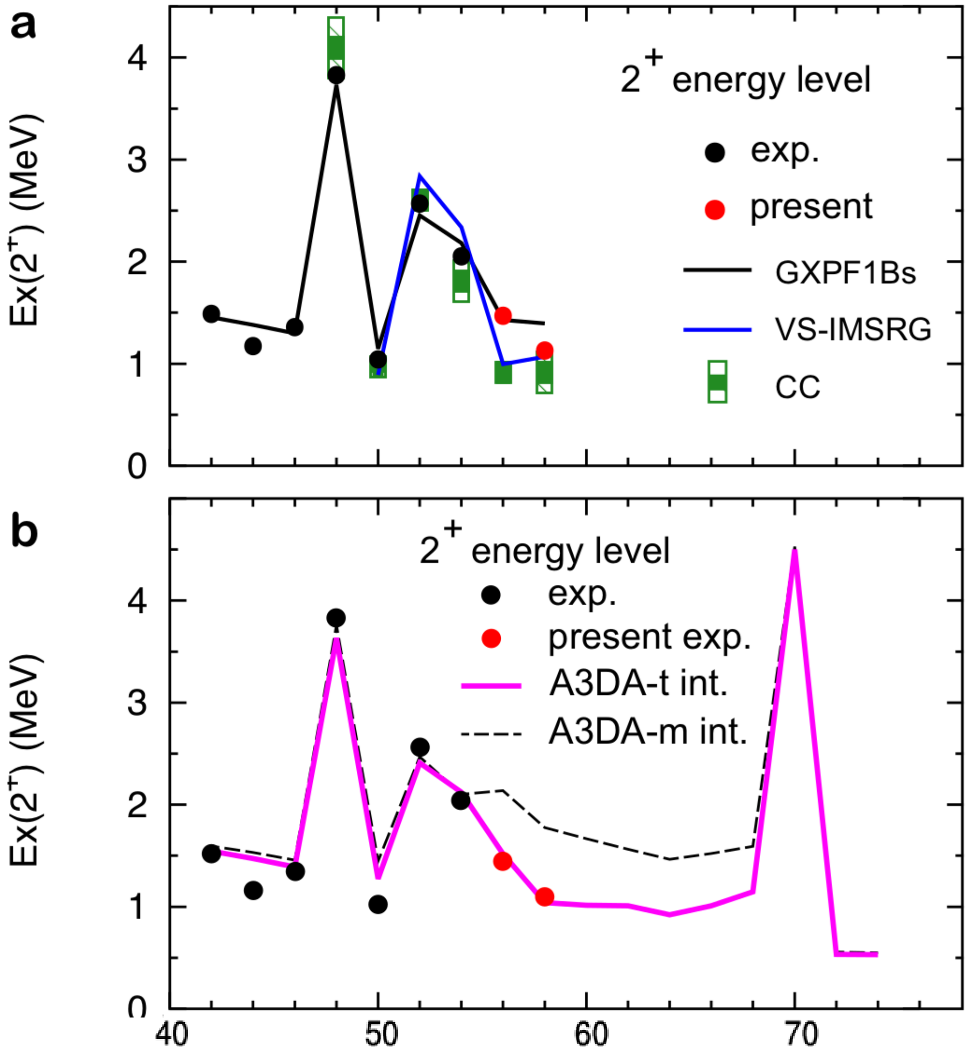
→ **non-isolated $f_{5/2}$ orbital**

→ **No *N*=40 shell closure**



S. Chen, F. Browne, P. Doornenbal, J. Lee *et al.*,
Phys. Lett. B **843**, 138025 (2023)

First spectroscopy of ^{56,58}Ca



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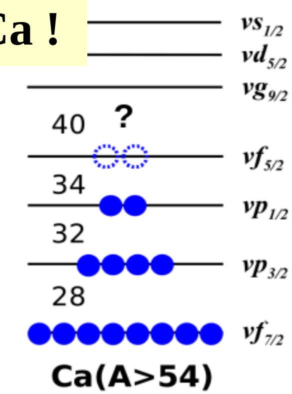


Particle-hole symmetry breaks

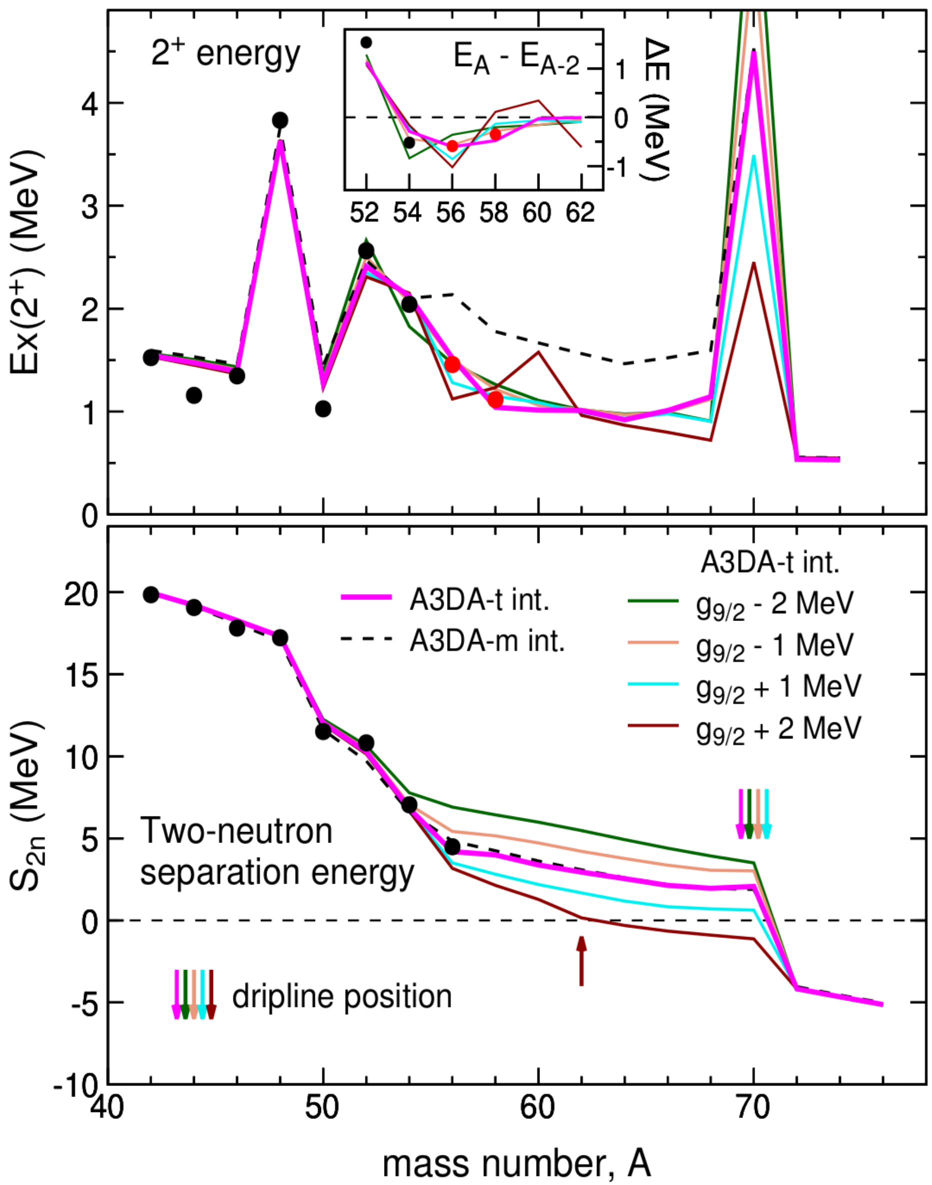
→ **non-isolated $f_{5/2}$ orbital**

→ **No *N*=40 shell closure**

A3DA-t:
revision of A3DA-m interaction, fitting to existing $E(2^+_1)$ and S_{2n} data (Y. Tsunoda and T. Otsuka), neutron pf-$g_{9/2}$-$d_{5/2}$ orbitals

***N*=50 shell closure**

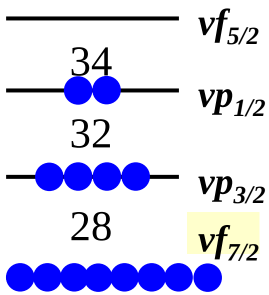
First spectroscopy of ^{56,58}Ca



- Sensitivity of the neutron $0g_{9/2}$ single-particle-energy (SPE) characterized by varying up to ±2 MeV
  - Positive shifts $0g_{9/2}$ SPE lead to too low $E(2^+_1)$ and S_{2n} of ^{56}Ca
  - Negative shifts $0g_{9/2}$ SPE lead to high neutron $0g_{9/2}$ occupation in ^{54}Ca, quenching of $N = 34$ shell gap
- Indicate the vanish of $N = 40$ shell in ^{60}Ca, and drives the dripline of Ca isotopes to at least ^{70}Ca

S. Chen, F. Browne, P. Doornenbal, J. Lee *et al.*, Phys. Lett. B **843**, 138025 (2023)

III. Evolution of ν-$f_{7/2}$ orbital along Z = 20



Ca (Z=20)

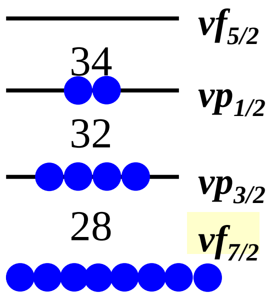
IMP & Shell Model (GXPF1X)

→ full ν-$f_{7/2}$ strength concentrated in $7/2^-$ state at and immediately beyond N=28

Single-particle nature of $7/2^-$ state

III. Evolution of ν-$f_{7/2}$ orbital along Z = 20

H.L. Crawford *et al.*, Phys. Rev. C **95**, 064317 (2017)



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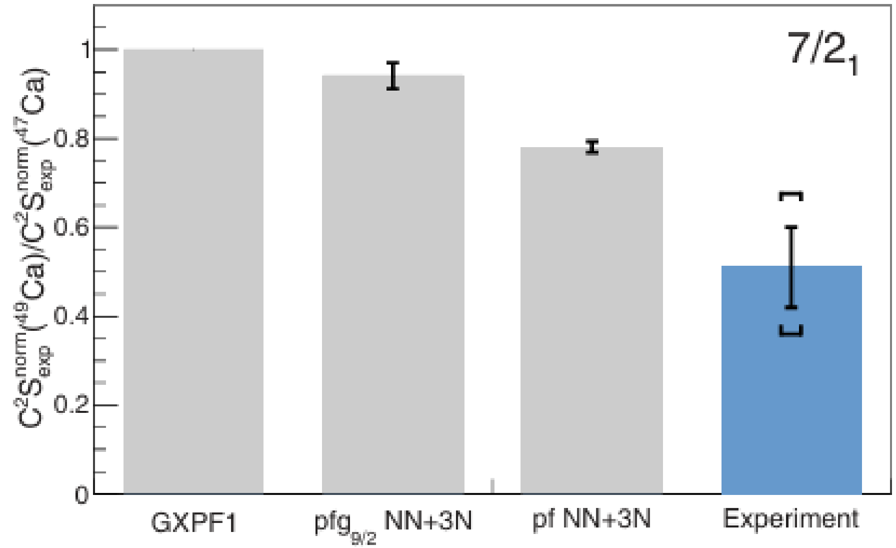

n-knockout: ^{48}Ca → ^{47}Ca, ^{50}Ca → ^{49}Ca

C^{2}S for $\nu 0f_{7/2}$: 6.4 (^{47}Ca), 3.4 (^{49}Ca)

Reduction of ν-$f_{7/2}$ strength in ^{49}Ca than ^{47}Ca

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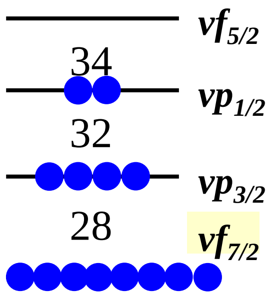

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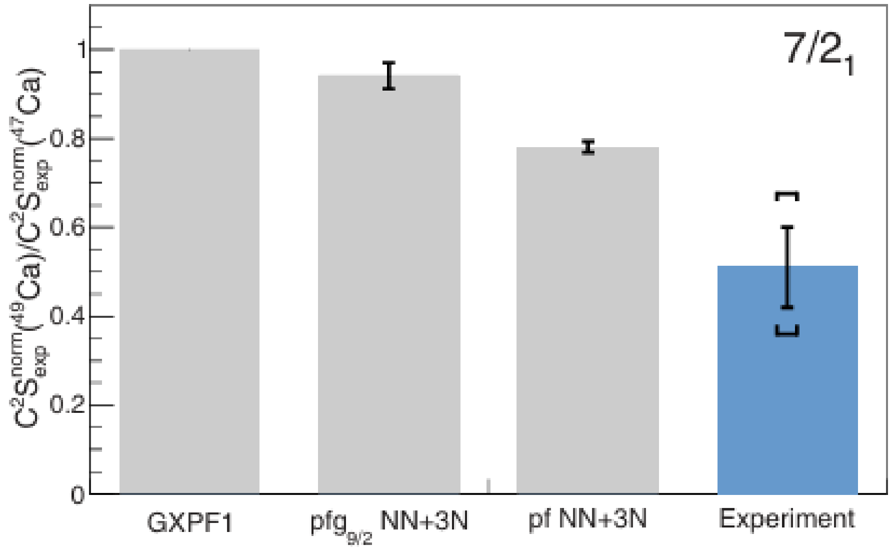

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Reduction of ν-$f_{7/2}$ strength in ^{49}Ca than ^{47}Ca

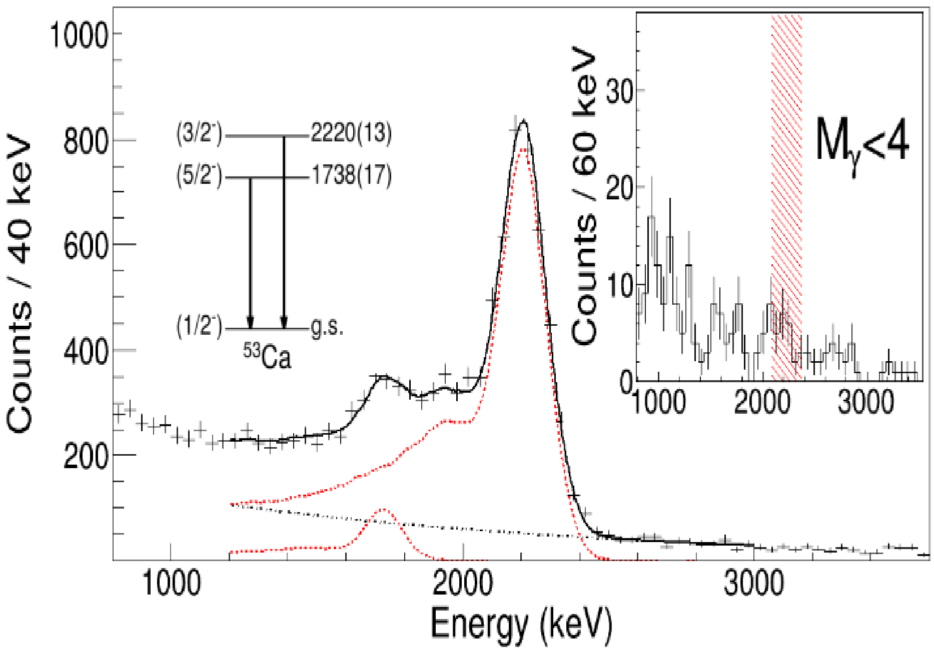
- **^{52}Ca(*p*,*pn*)^{51}Ca** →C^2S for $\nu 0f_{7/2}$ hole state: 6.6 (10) – consistent with ^{47}Ca

  M. Enciu, H.N. Liu *et al.*, Phys. Rev. Lett. **129**, 262501 (2022)

What is $\nu 0f_{7/2}$ strength in more n-rich Ca isotope ?

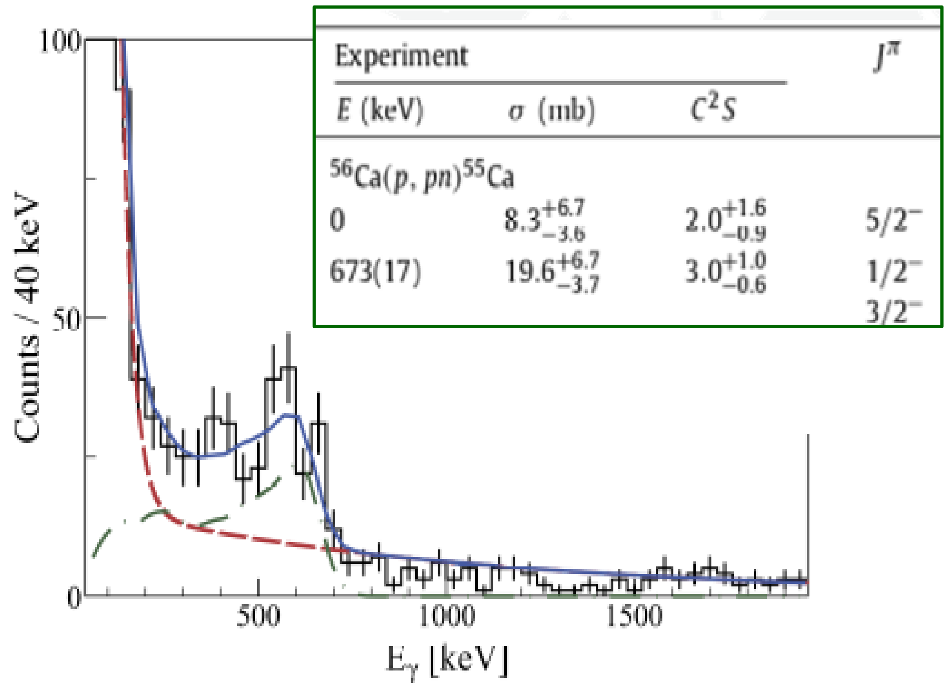
Evolution of ν-$f_{7/2}$ orbital along Z = 20

γ spectrum of ^{54}Ca(*p,pn*)^{53}Ca



S. Chen, J. Lee *et al.*, Phys. Rev. Lett. **123**,142501 (2019)

γ spectrum of ^{56}Ca(*p,pn*)^{55}Ca



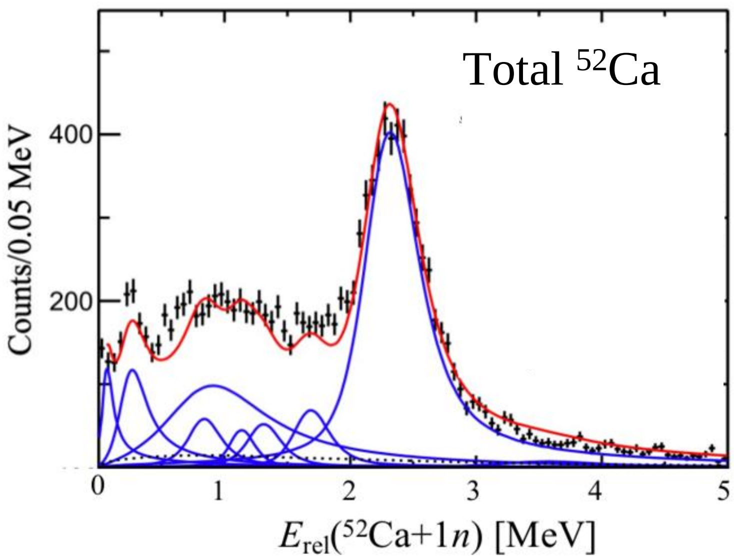
T. Koiwai, *et al.*, Phys. Lett. B **827**, 136953 (2022)

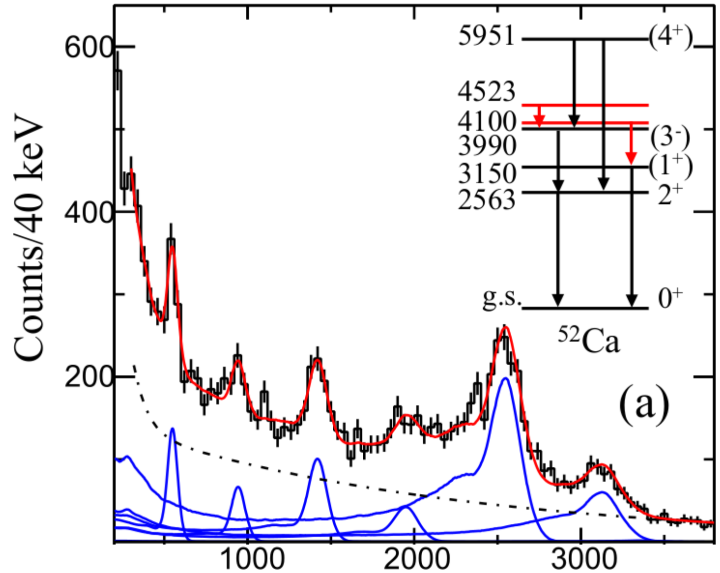
No $\nu 0f_{7/2}$ strength observed below neutron separation energy S_n in ^{53,55}Ca → unbound states

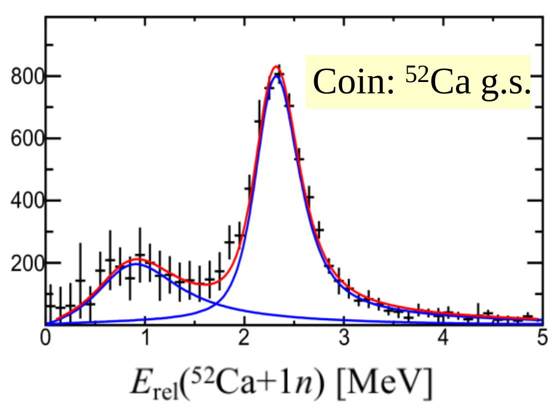
First invariant-mass measurement in ^{53}Ca

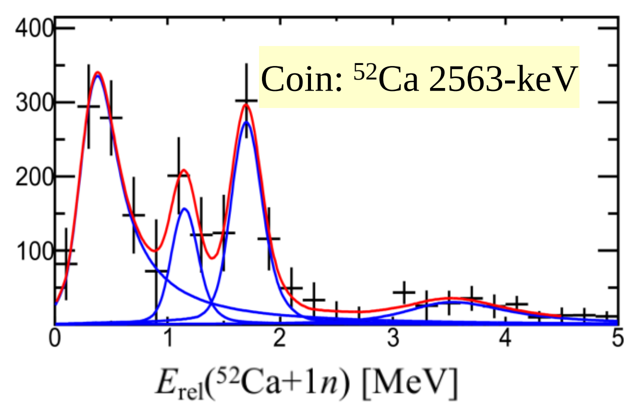
$^{54}\mathrm{Ca}(p,pn)^{53}\mathrm{Ca}^{*} \rightarrow {}^{52}\mathrm{Ca}+1n$

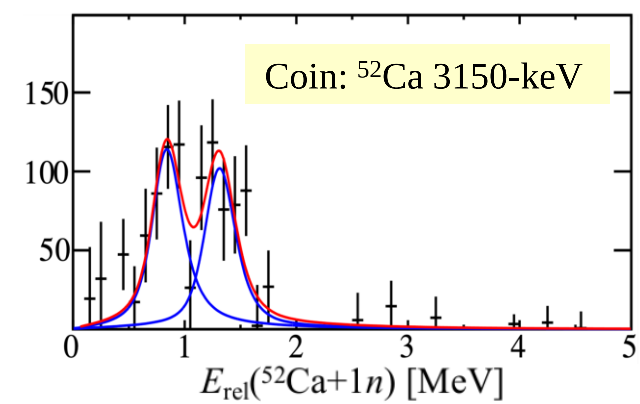
$$E_{ex} = E_{rel} + S_n + (E_\gamma)$$



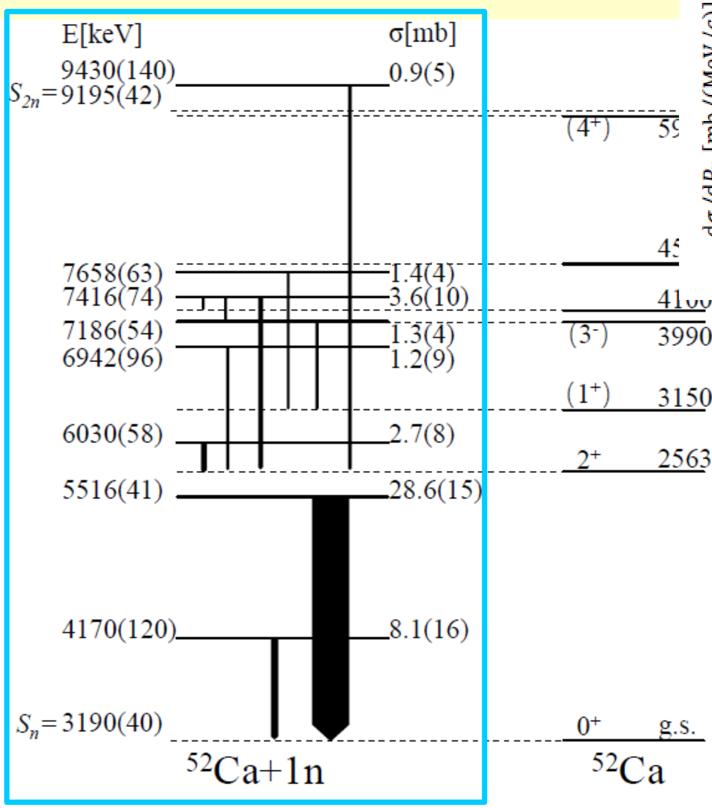




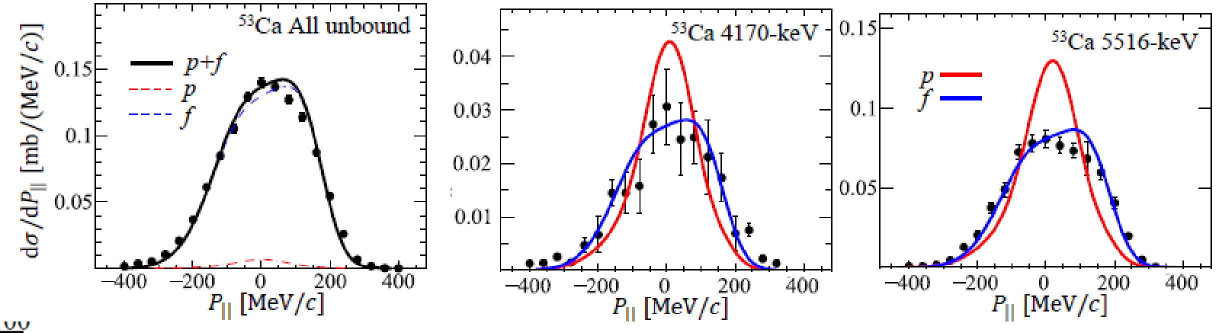


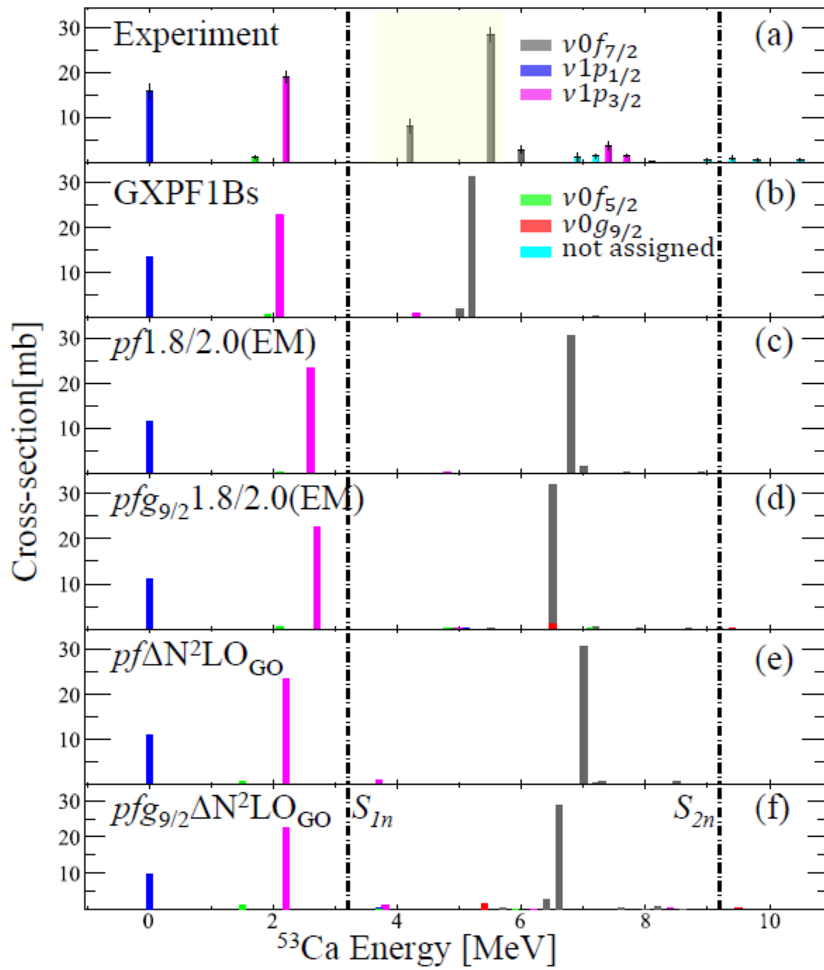


$^{54}Ca(p,pn)^{53}Ca^{*} \rightarrow ^{52}Ca+1n$



PMD and $\sigma_{s.p.}$ from DWIA (K. Yoshida, K. Ogata)





Shell model +
GXPF1Bs
(Y. Utsuno)

VS-IMSRG +
chiral NN+3N
(B. S. Hu, J. Holt)

5516-keV state: $\nu 0f_{7/2}$, C^2S=6.5(3)

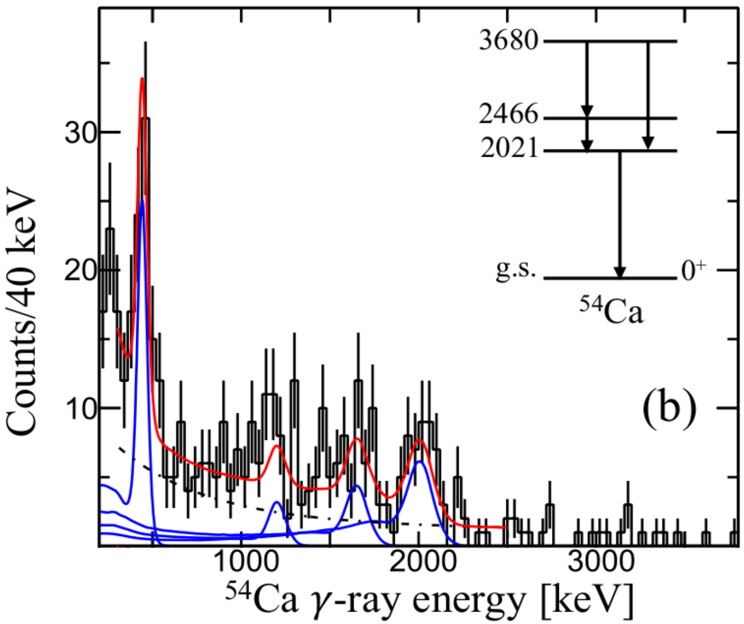
→ nearly pure neutron-hole state

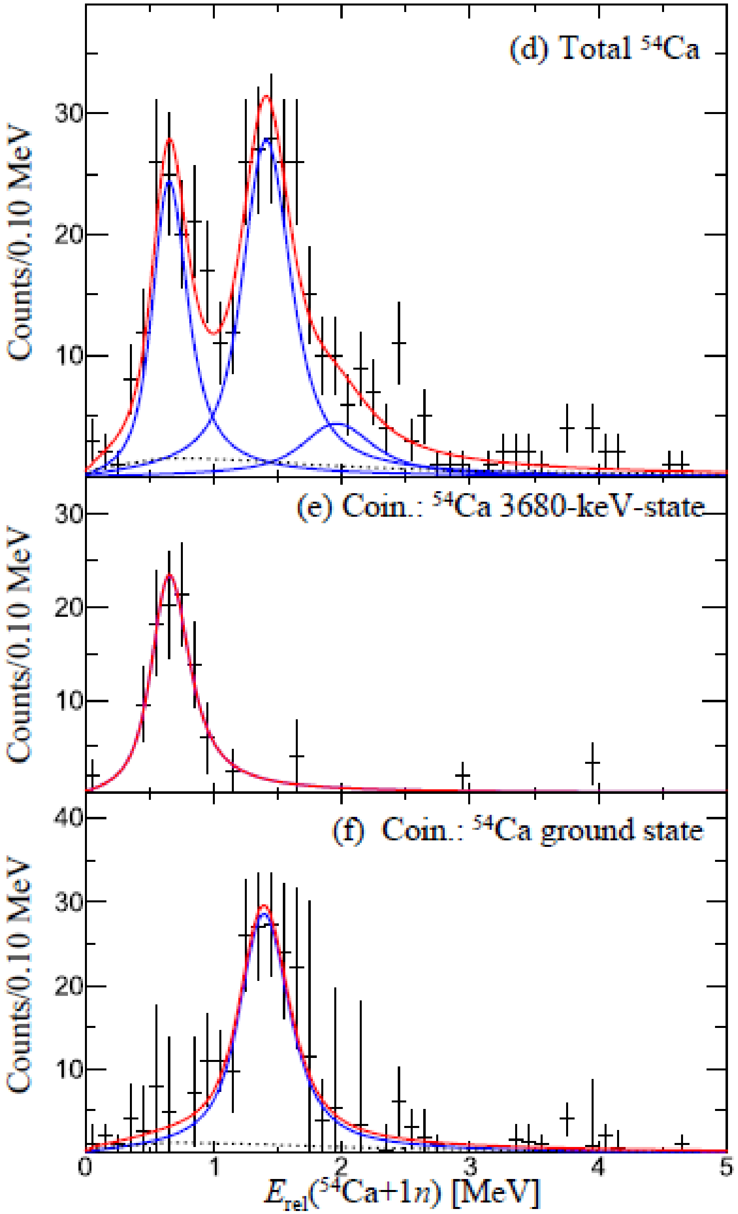
(IPM: C^2S=2J+1)

First invariant-mass measurement in ^{55}Ca

$^{56}Ca(p,pn)^{55}Ca^{*} \rightarrow ^{54}Ca+1n$

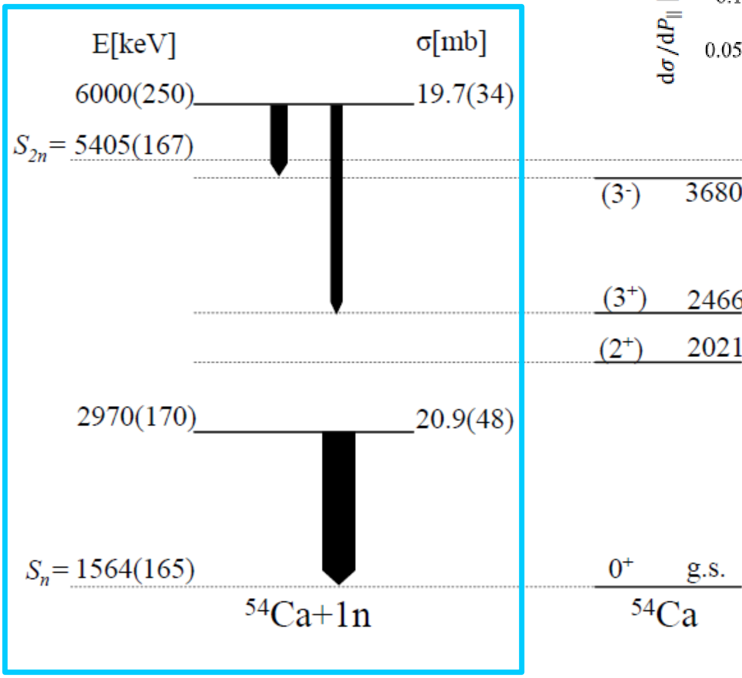
$$E_{ex} = E_{rel} + S_n + (E_{\gamma})$$

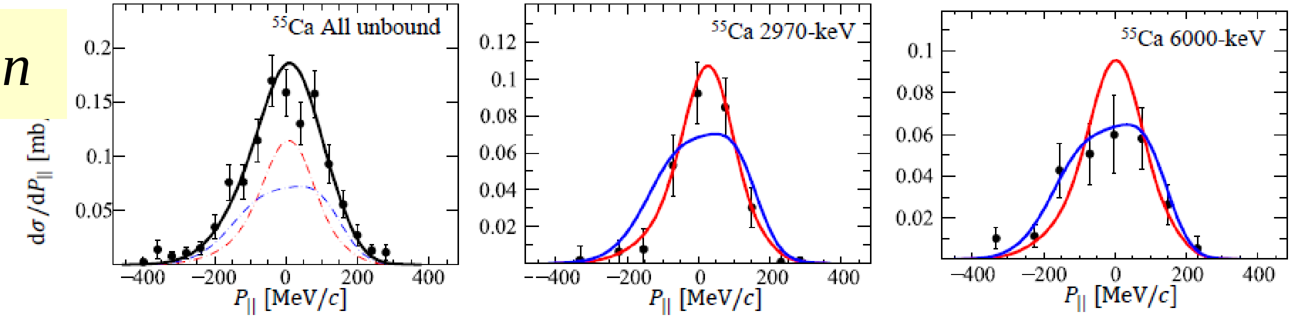


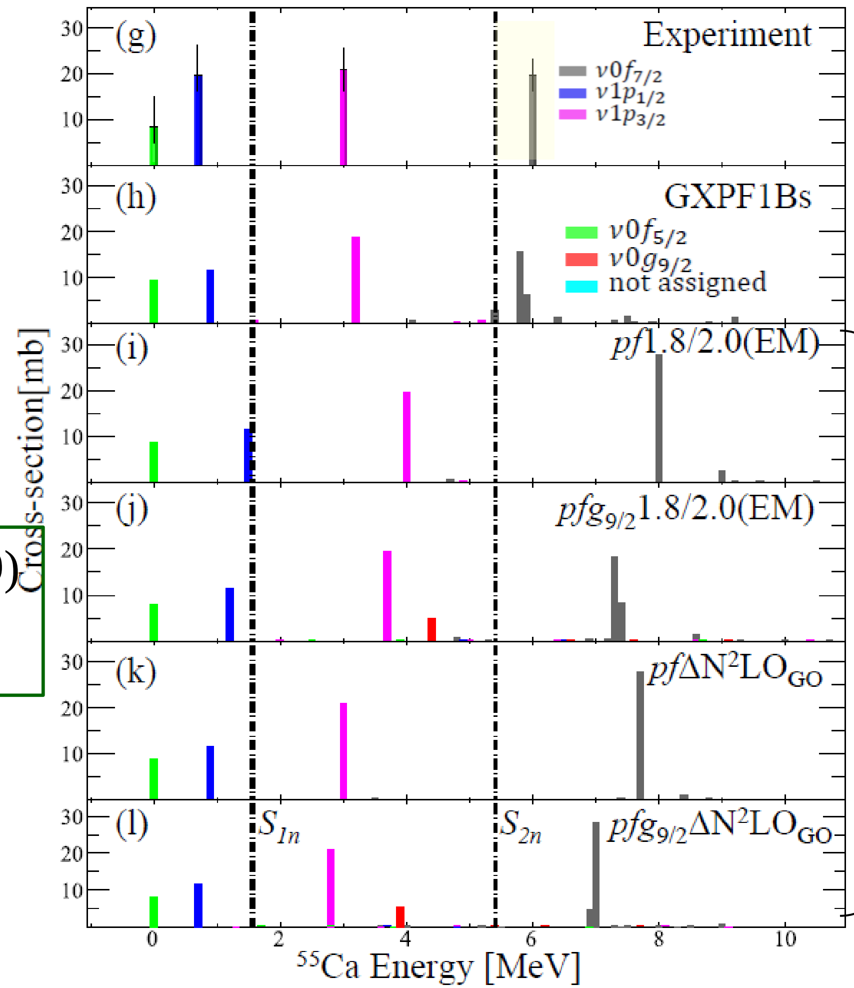


PMD and $\sigma_{s.p.}$ from DWIA (K. Yoshida, K. Ogata)

$^{56}Ca(p,pn)^{55}Ca^{*} \rightarrow {}^{54}Ca+1n$







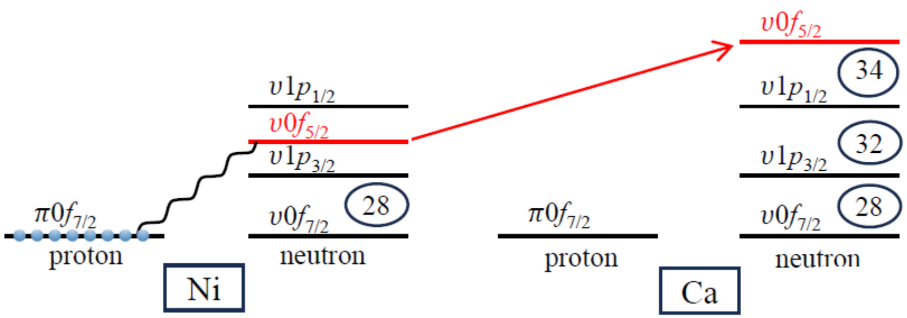
Shell model + GXPF1Bs (Y. Utsuno)

VS-IMSRG + chiral NN+3N (B. S. Hu, J. Holt)

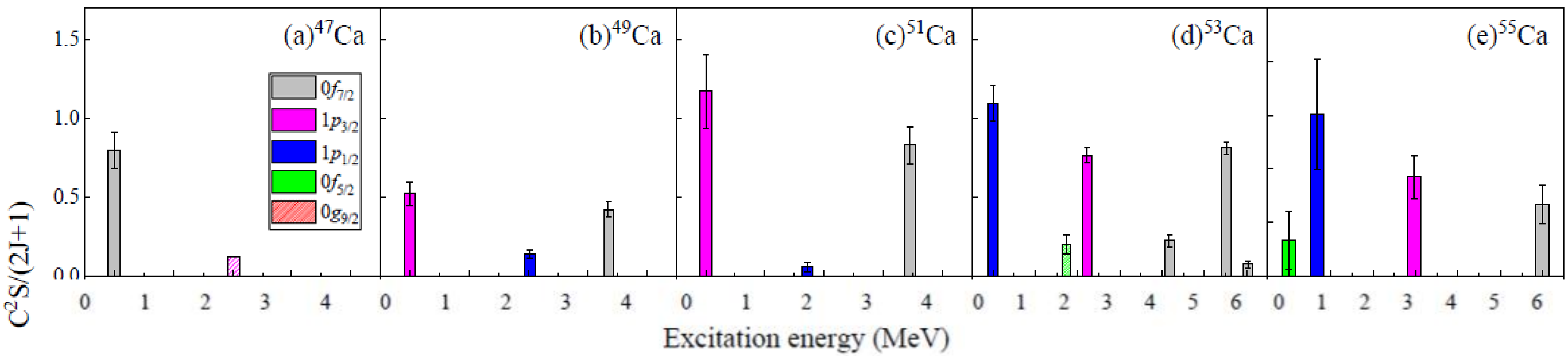
6000-keV state: $\nu 0f_{7/2}$, C^2S=4.8-5.9(9)

→ Mainly neutron-hole state

Shell evolution in Ca to Ni for *pf* orbitals



π-$f_{7/2}$ not occupied → vanishing $j_>$-$j_<$ proton-neutron coupling shifts ν-$f_{5/2}$ above



Shell gap $f_{7/2}$ -$p_{3/2}$ orbitals = ~3 MeV

→ robustness of N=28 shell closure with deeply bound ν-$f_{7/2}$ orbit

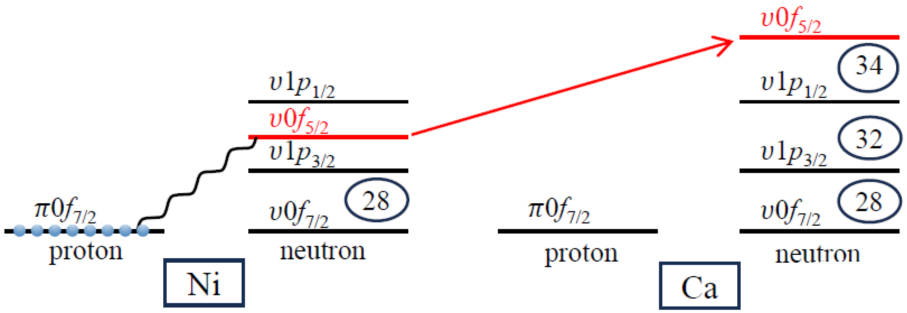
Persistence of 0$f_{7/2}$ single-particle strength up to ^{54}Ca

→ absence of 0$f_{5/2}$, 0$g_{9/2}$ component – evidence for N= 32, 34 magicity

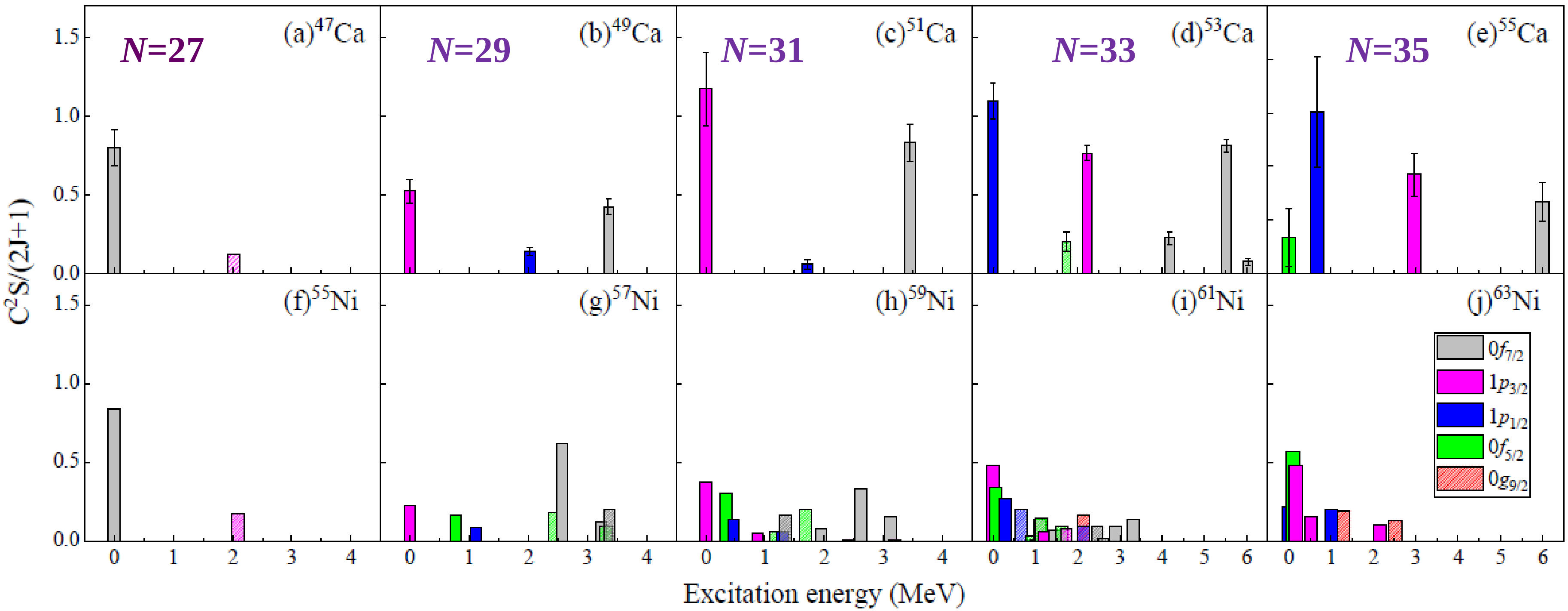
Contraction with ^{49}Ca result– considerable reduction of 0$f_{7/2}$ strength

P. Li, J. Lee *et al.*, Phys. Lett. B 855, 138828 (2024).

Shell evolution in Ca to Ni for *pf* orbitals



π-$f_{7/2}$ not occupied → vanishing $j_>$-$j_<$ proton-neutron coupling shifts ν-$f_{5/2}$ above



- The presence or absence of the $\pi f_{7/2}$ orbital has significant consequences on the strength distribution of single-particle orbitals(especially for N_{residue}>31) .

P. Li, J. Lee *et al.*, Phys. Lett. B 855, 138828 (2024).

Conclusions

How strong is *N* = 34 shell closure ?

- Neutron knockout reaction from ^{54}Ca confirms strong N = 34 shell closure

Towards ^{60}Ca ?

- First spectroscopy of ^{56,58}Ca indicates the vanish of N = 40 shell in ^{60}Ca, and drives the dripline of Ca isotopes to at least ^{70}Ca

Evolution of ν-$f_{7/2}$ orbital along Ca ?

- Probing unbound states in ^{53,55}Ca by neutron removal from deeply bound orbitals shows persistence of $0f_{7/2}$ single-particle strength up to ^{54}Ca
- Robustness of N=28 shell closure
- Another evidence for N= 32, 34 magicity

Ca results -- SEASTAR collaboration

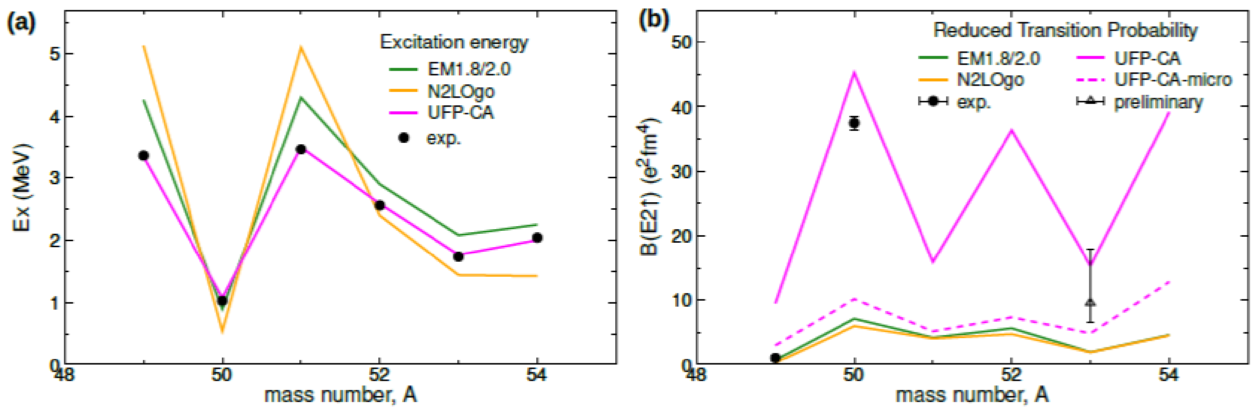
N. Alamanos, T. Aumann, G. de Angelis, N. Aoi, H. Baba, C. Barbieri, C. Bertulani, C. Bernards, A. Blazhev, S. Boissinot, F. Browne, A. Bruce, B. Cakirli, B. Cederwall, S. Chen, N. Cooper, A. Corsi, M. L. Cortés, L.X. Chung, F. Delaunay, B. Ding, Z. Dombradi, P. Doornenbal, T. Duguet, Z. Elekes, M. Enciu, F. Flavigny, S. Franchoo, R. Gerst, J. Gibelin, A. Gillibert, S. Go, M. Gorska, A. Gottardo, S. Grevy, J.D. Holt, E. Ideguchi, T. Isobe, M. Juhasz, A. Jungclaus, N. Kobayashi, T. Kobayashi, T. Koiwai, Y. Kondo, W. Korten, T. Kroell, Y. Kubota, I. Kuti, V. Lapoux, S. LeBlond, S. Lenzi, M. Lettmann, J. Lee, S. Lenzi, P. Li, B.D. Lin, H. Liu, X. Liu, Z. Liu, G. Lorusso, C. Louchart, R. Lozeva, F.M. Marques, I. Matea, K. Matsui, Y. Matsuda, M. Matsushita, J. Menendez, D. Mengoni, S. Michimasa, T. Miyazaki, S. Momiyama, P. Morfouace, K. Moschner, T. Motobayashi, T. Nakamura, D. Napoli, F. Naqvi, M. Niikura, M. Nishimura, S. Nishimura, C. Nita, F. Nowacki, A. Obertelli, L. Olivier, N. Orr, S. Ota, H. Otsu, T. Otsuka, N. Paul, N. Pietralla, Zs. Podolyak, E.C. Pollacco, G. Potel, G. Randisi, F. Recchia, T.R. Rodriguez, E. Sahin, H. Sakurai, C. Santamaria, M. Sasano, H. Sato, A. Schwenk, C. Shand, Y. Shiga, Y. Shimizu, S. Shimoura, J. Simonis, P.A. Soederstroem, D. Sohler, Y. Sun, V. Soma, I. Stefan, D. Steppenbeck, T. Sumikama, Y. Sun, D. Suzuki, H. Suzuki, S. Takeuchi, J. Tanaka, M. Tanaka, R. Taniuchi, Y. Togano, Y. Tsunoda, K.N. Tuan, T. Uesaka, Y. Utsuno, J. Valiente Dobon, Zs. Vajta, D. Verney, H. Wang, V. Werner, K. Wimmer, Zh. Xu, R. Yokoyama, K. Yoneda, K. Yoshida, R. Zidarova

Upcoming Experiment

Coulomb excitation of $^{50-54}$Ca: E2 strength beyond N=28

Spokesperson: Sidong Chen (University of York)

June 2025, RIKEN

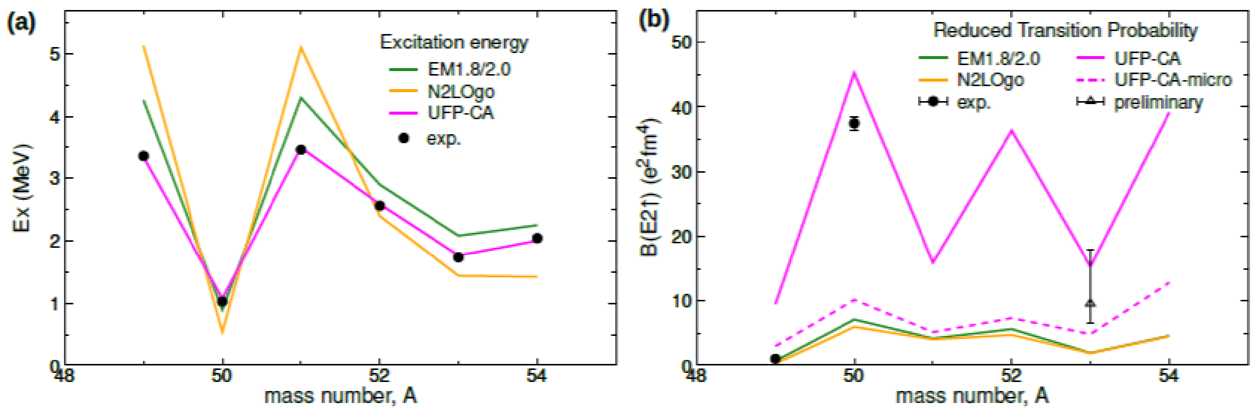


Upcoming Experiment

Coulomb excitation of $^{50-54}$Ca: E2 strength beyond *N*=28

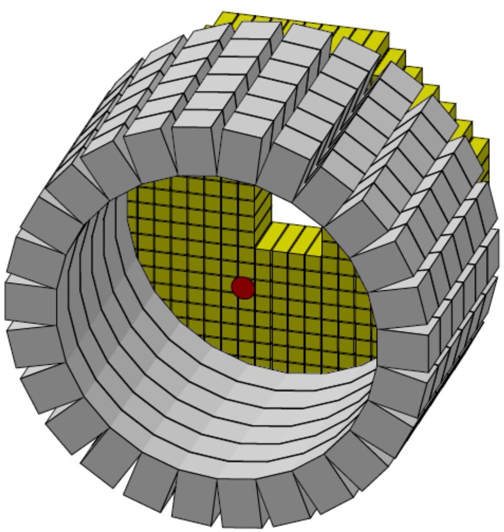
Spokesperson: Sidong Chen (University of York)

June 2025,
RIKEN



New High Resolution Scintillation Array

HYPATIA : **HY**brid **P**hoton detector **A**rray
To **I**nvestigate **A**tomic nuclei



Talk by Pieter Doornenbal
Towards next-generation in-beam gamma-ray spectroscopy at the RIBF with HYPATIA
May 27 (Tue), 12:10 PM
Room 1: 2F Grand Ballroom #201-202

Thank you for your attention

The University of Hong Kong