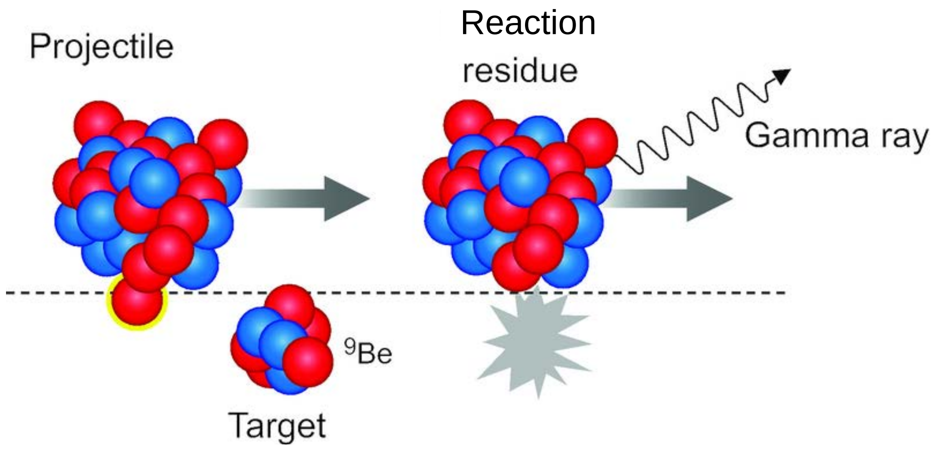
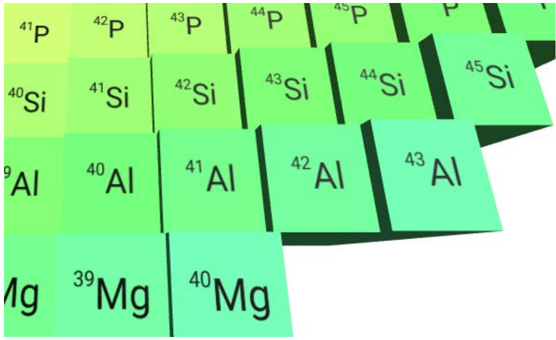


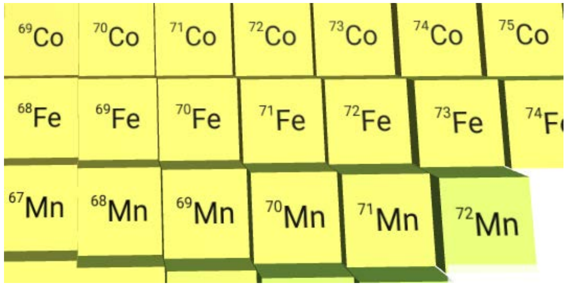
Recent experimental studies of shell evolution in exotic nuclei

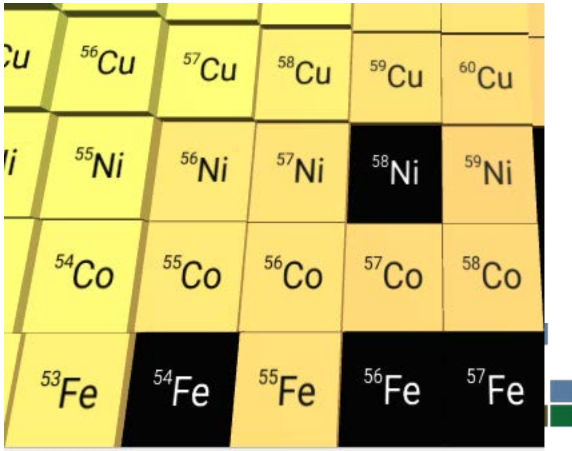
Alexandra Gade
Professor of Physics
Michigan State University

Outline

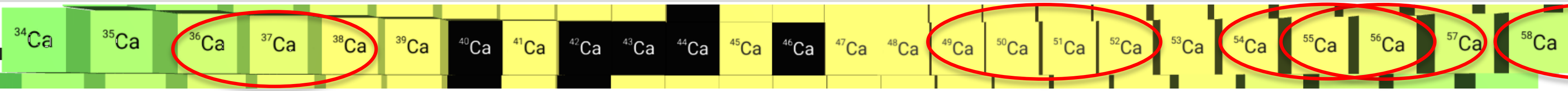
- Introduction
  - Pointing to recent highlights in the field (Ca, Ni and Sn)
- In more detail: Evolution of shell structure
  - Spectroscopy of very neutron-rich nuclei II – ^{42}Si (GRETINA @ S800)
  - Spectroscopy of very neutron-rich nuclei I – ^{70}Fe (GRETINA @ S800)
  - Brief news on the neighborhood of ^{56}Ni (GRETINA@ S800)
- Summary





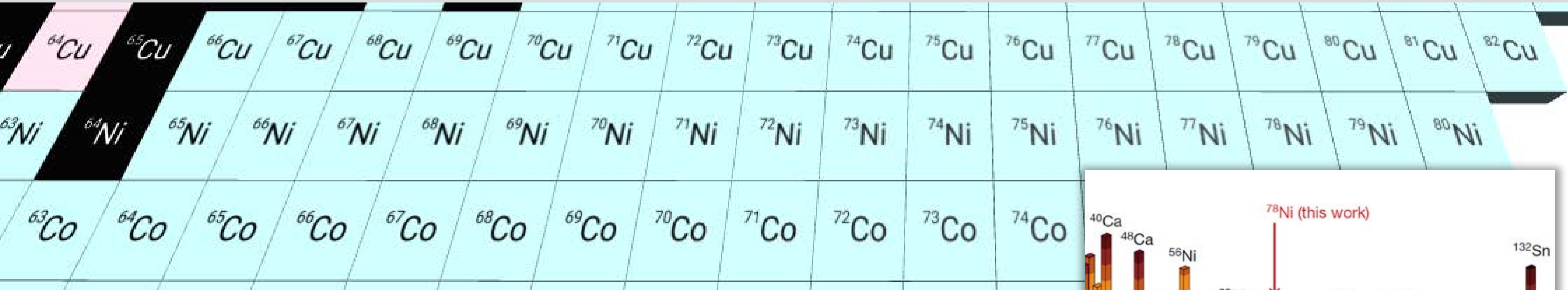


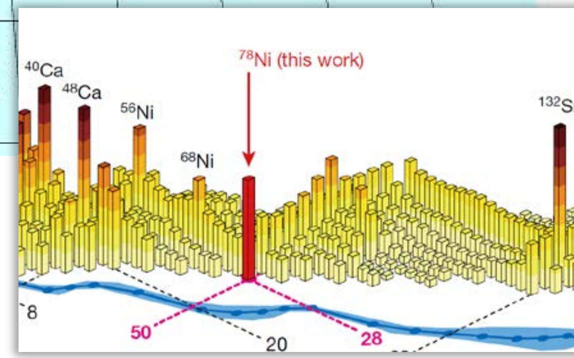
Along *Z=20*

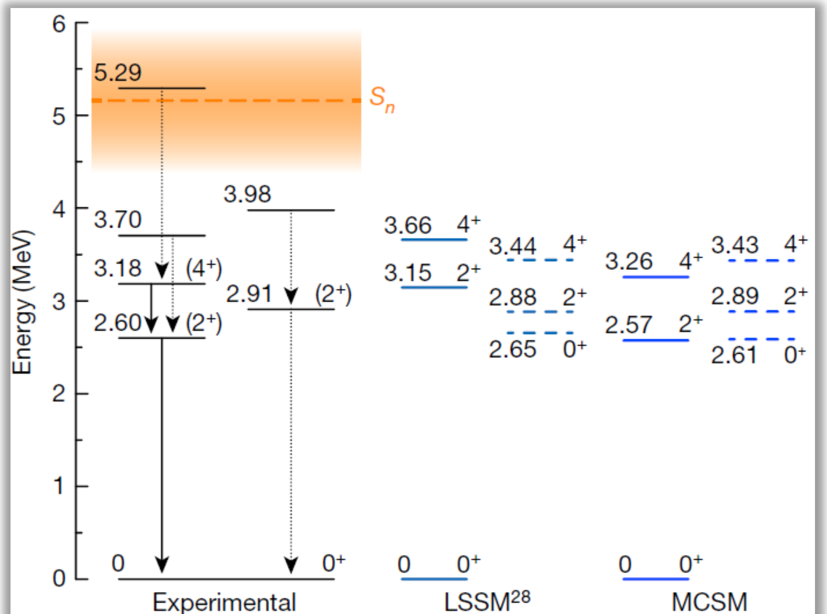


- Why are the charge radii of the neutron-deficient Ca isotopes so small?
  - A. J. Miller *et al.*, Nature Physics 15, 432 (2019)
- Why do the neutron-rich Ca isotopes have so large charge radii?
  - R. F. Garcia Ruiz *et al.*, Nature Physics 12, 594 (2016)
- How heavy are they?
  - S. Michimasa *et al.*, PRL 121, 022506 (2018)
- Excited states at and beyond *N=34*, anybody?
  - D. Steppenbeck *et al.*, Nature 502, 207 (2013), J. Lee (2019)
- How many neutrons can *Z=20* bind?
  - O.B. Tarasov *et al.*, PRL 121, 022501 (2018)

Towards ^{78}Ni

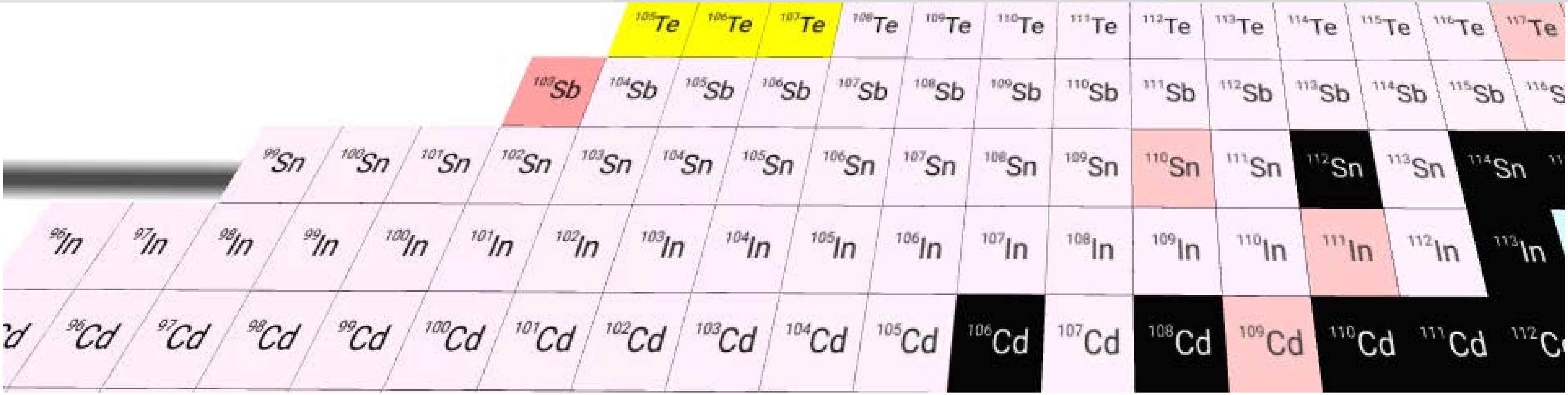


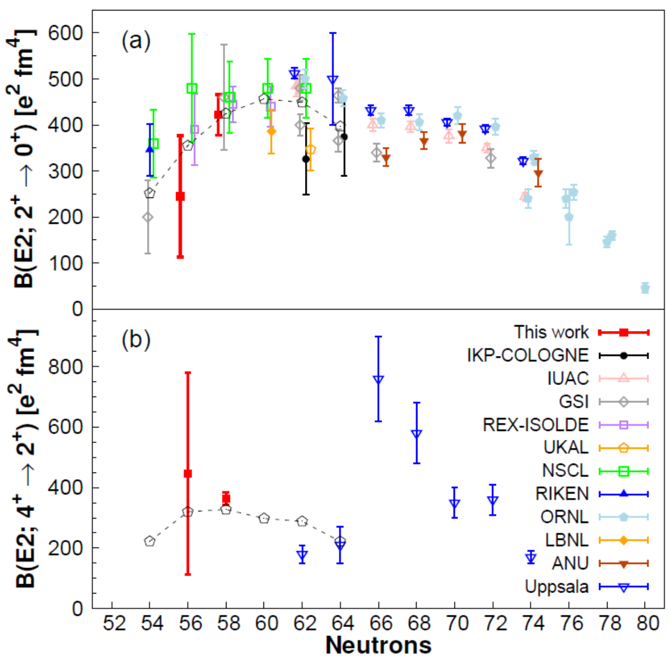




- First spectroscopy of doubly-magic ^{78}Ni
- Spectacular case of shape coexistence proposed with structures that do not decay to each other
- See David Verney's talk on Thursday for the GANIL-based spectroscopy towards ^{78}Ni

Along *Z=50*





- Evolution of collectivity in the tin isotopes towards ^{100}Sn tracked back to an interplay of quadrupole and pairing forces for the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions
- Fantastic experimental work on lifetime measurements following multi-nucleon exchange reactions

M. Siciliano et al., yesterday's talk and arXiv:1905.10313

The menu of examples

- Along magic chains … informs about the changes in the nuclear structure with isospin

- Very challenging benchmarks for theory are posed by studying regions of rapid structural change
  - Such as the neutron-rich *N=28* and *N=40* nuclei
    - » ^{42}Si
    - » ^{70}Fe
- One-slide teaser – a brief look at recent work around *N=Z=28* ^{56}Ni

Spectroscopy of ^{42}Si

Is the structure of ^{42}Si understood?

A. Gade,[1,2] B. A. Brown,[1,2] J. A. Tostevin,[3] D. Bazin,[1,2] P. C. Bender,[1,*] C.M. Campbell,[4] H. L. Crawford,[4] B. Elman,[1,2] K. W. Kemper,[5] B. Longfellow,[1,2] E. Lunderberg,[1,2] D. Rhodes,[1,2] and D. Weisshaar[1]

[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[2]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom*
[4]*Nuclear Science Division, Lawrence Berkeley National Laboratory, California 94720, USA*
[5]*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*

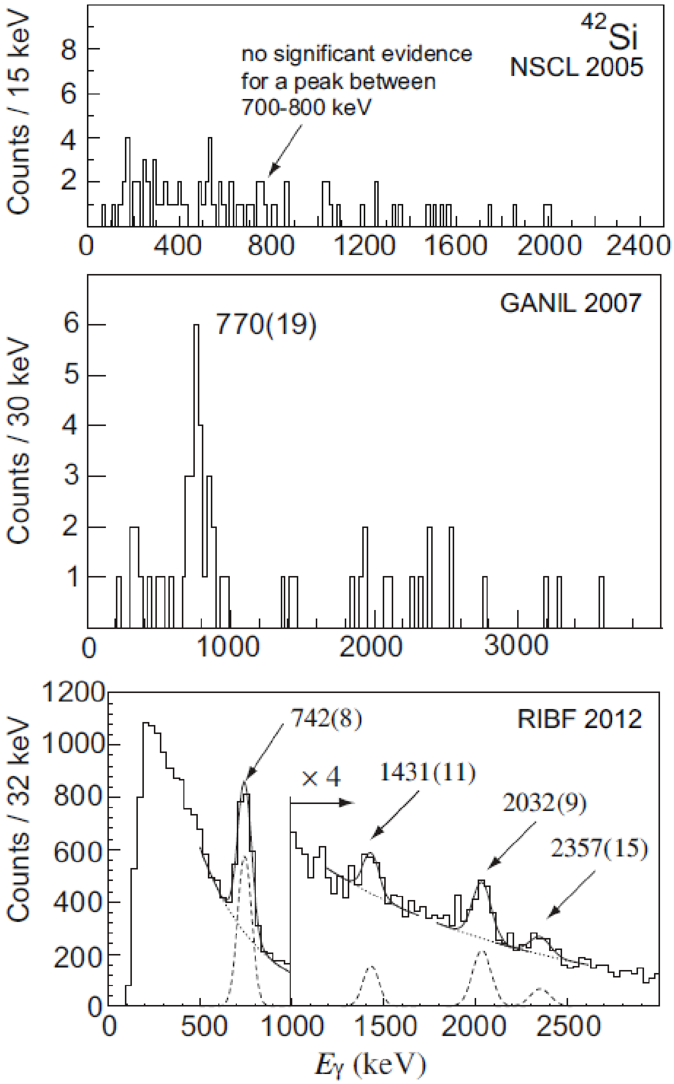
(Dated: April 23, 2019)

A more detailed test of the implementation of nuclear forces that drive shell evolution in the pivotal nucleus ^{42}Si – going beyond earlier comparisons of excited-state energies – is important. The two leading shell-model effective interactions, SDPF-MU and SDPF-U-Si, both of which reproduce the low-lying ^{42}Si(2^+_1) energy, but whose predictions for other observables differ significantly, are interrogated by the population of states in neutron-rich ^{42}Si with a one-proton removal reaction from ^{43}P projectiles at 81 MeV/nucleon. The measured cross sections to the individual ^{42}Si final states are compared to calculations that combine eikonal reaction dynamics with these shell-model nuclear structure overlaps. The differences in the two shell-model descriptions are examined and linked to predicted low-lying excited 0^+ states and shape coexistence. Based on the present data, which are in better agreement with the SDPF-MU calculations, the state observed at 2150(13) keV in ^{42}Si is proposed to be the (0^+_2) level.

Structure of ^{42}Si: A brief history

experiment

- Present-generation RIB facilities
  - Beta-decay half-life of ^{42}Si and particle stability of ^{43}Si → *N=28* broken down
    S. Grevy *et al.*, PLB 594, 252 (2004)
    M. Notani *et al.*, PLB 542, 49 (2002)
  - Pronounced *Z=14* sub-shell gap may prevent ^{42}Si from being deformed
    J. Fridmann *et al.*, Nature 435, 922 (2005)
    J. Fridmann *et al.*, PRC 74, 034313 (2006)
  - Finally: 2^+ at 770(19) keV demonstrates collectivity and breakdown of *N=28*
    B. Bastin *et al.*, PRL 99, 022503 (2007)
- New generation facility
  - First spectroscopy beyond the first 2^+ state $R_{4/2}$ ratio claimed to prove deformation
    S. Takeuchi *et al.*, PRL 109, 182501 (2012)
- At the frontier of experimentation
  - Heaviest Si isotope known: ^{44}Si
  - Lightest *N=28* isotone: ^{40}Mg



A. Gade, Eur. Phys. J. A 51, 118 (2015)

Structure of ^{42}Si: A brief (shell model) status

theory

- Two successful shell-model effective interactions – broadly the same mechanism to produce collective ^{42}Si:
  - Relative to ^{34}Si: reduced *Z=14* sub-shell gap due to neutrons filling $f_{7/2}$
  - Relative to ^{48}Ca: removal of protons from $d_{3/2}$ reduces *N=28* gap
  - Quadrupole correlation across these narrowed gaps mutually enhance each other
- In an SU(3)-like scheme: SDPF-U (SDPF-U-Si)

F. Nowacki, & A. Poves, PRC 79, 014310 (2009)

- Nuclear Jahn-Teller effect: SDPF-MU

Y. Utsuno *et al.*, PRC 86, 051301(R) (2012)

Interesting observation: RIBF ^{42}Si data hard to reconcile with SM x reaction theory

PHYSICAL REVIEW C **87**, 027601 (2013)

Two-proton removal from ^{44}S and the structure of ^{42}Si

J. A. Tostevin,[1,2] B. A. Brown,[1,3] and E. C. Simpson[2]
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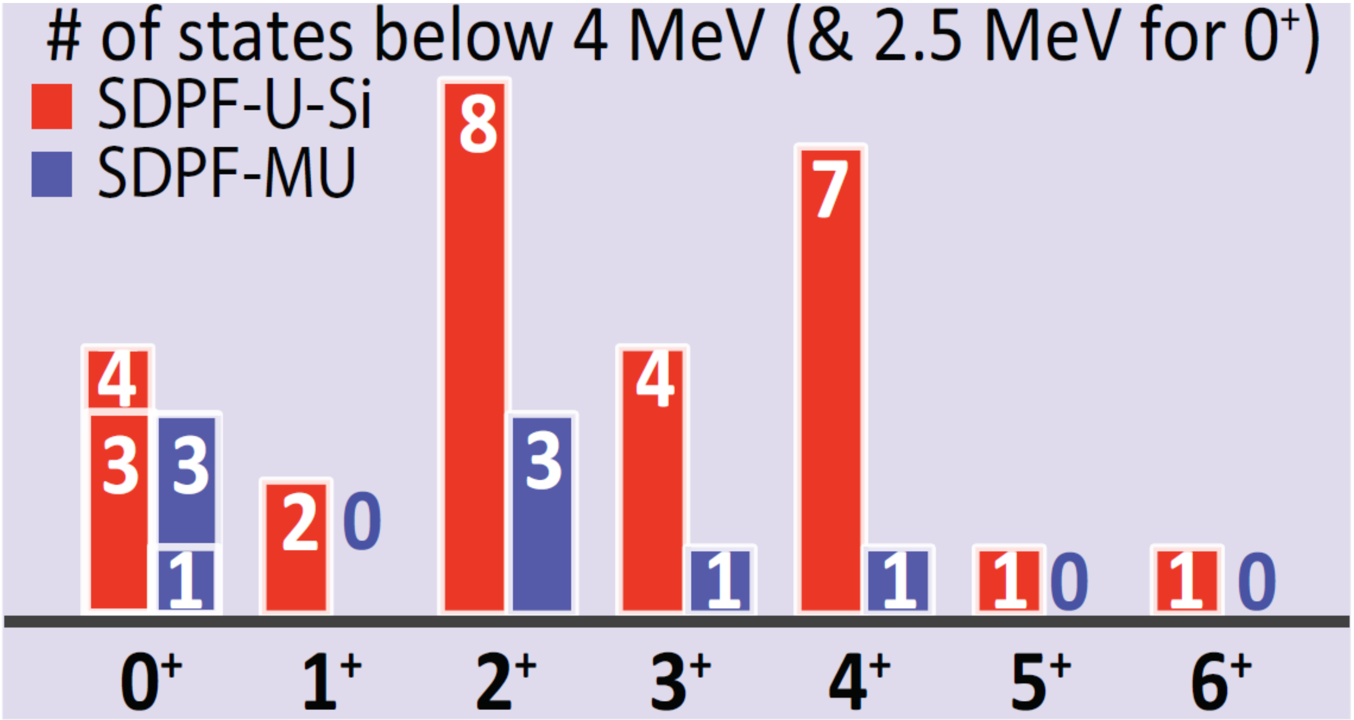
[2]*Department of Physics, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom*
[3]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
(Received 15 November 2012; published 4 February 2013)

Huh? … looking at shell model past the first 2^+

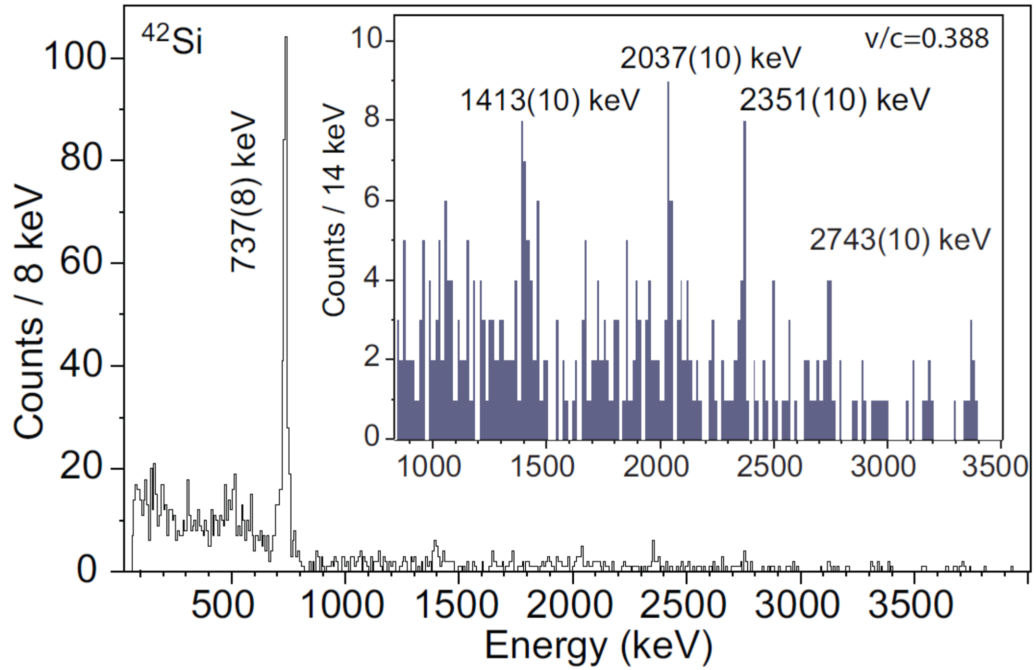
SDPF-U and SDPF-MU could not be more different!



F. Nowacki, & A. Poves, PRC 79, 014310 (2009)
Y. Utsuno *et al.*, PRC 86, 051301(R) (2012)

The experiment – One-proton knockout from ^{43}P

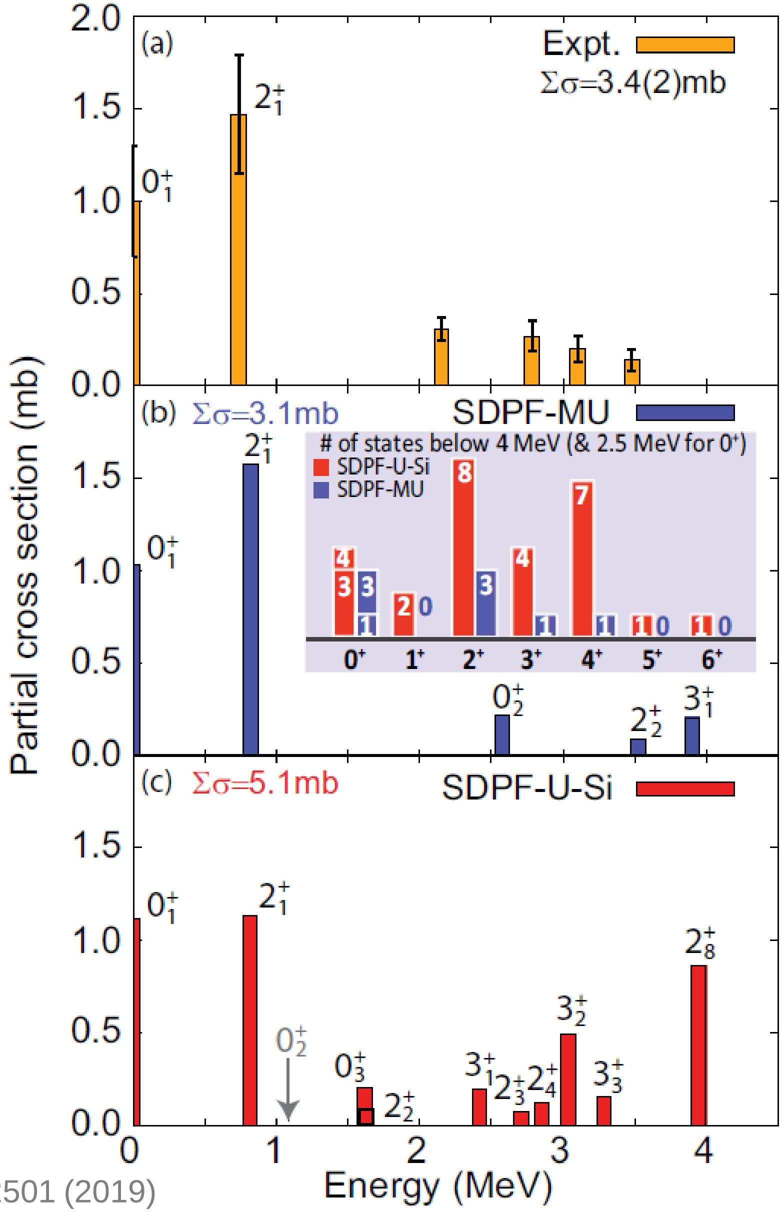
- One-proton knockout is a direct reaction → probes the single-particle degree of freedom
- ^{43}P: ground state is $1/2^+$
  L. A. Riley *et al.*, PRC 78, 011303(R) (2008)
- This means, knockout of *sd*-shell protons cannot populate $J \geq 4$
- All γ-ray transitions except for the 2743 keV line had been reported in the RIBF two-proton removal experiment



- $^{9}Be(^{43}P,^{42}Si+\gamma)X$ at 81 MeV/u
- Gamma rays in GRETINA and projectile-like reaction residues in the S800

Confronting partial cross sections with theory

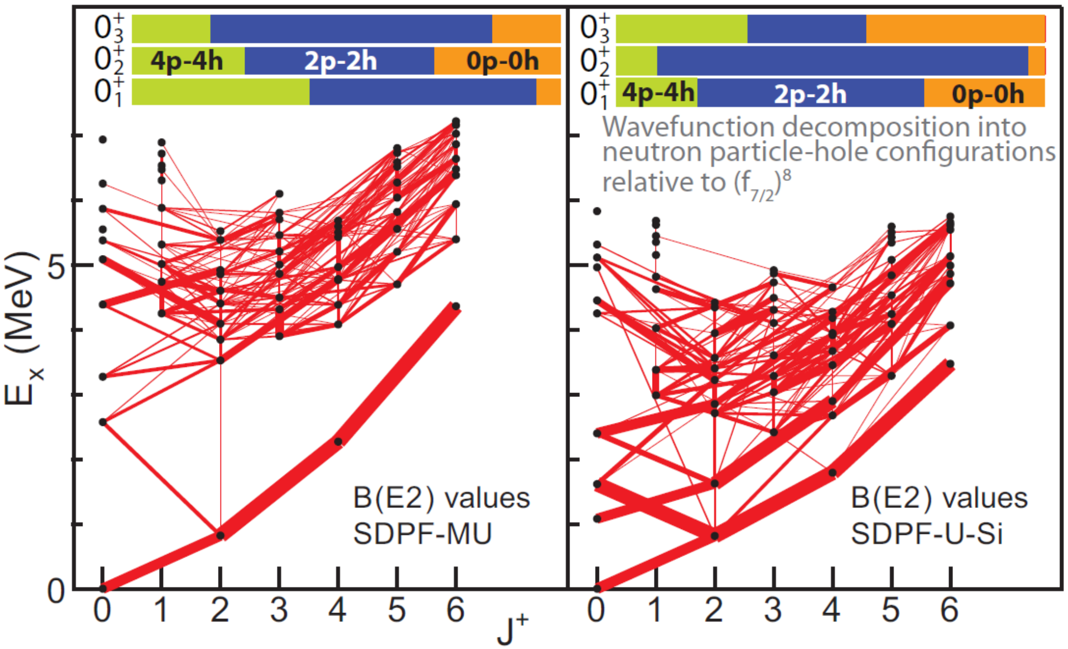
- SDPF-MU describes the data rather well
  - Suggests that the 2.1 MeV level assigned 4^+ by Takeuchi *et al.* based on systematics is more likely a 0^+ state (also most consistent with the two-proton knockout theory study of the RIBF data by Tostevin *et al.*)
- The exceptionally high level density predicted by SDPF-U-Si cannot be supported by the data



A. Gade, B.A. Brown, J. A. Tostevin *et al.*, PRL122, 222501 (2019)

Alex Brown's closer look at the shell model level densities

- B(E2) network shows the stark difference in the shell model predictions
  - SDPF-U has a very compressed spectrum relative to MU and predicts interesting low-lying shape/configuration coexistence
  - The neutron wave function decomposition shows the differences between the predicted 0^+ states. SDPF-MU predicts rather mixed configurations



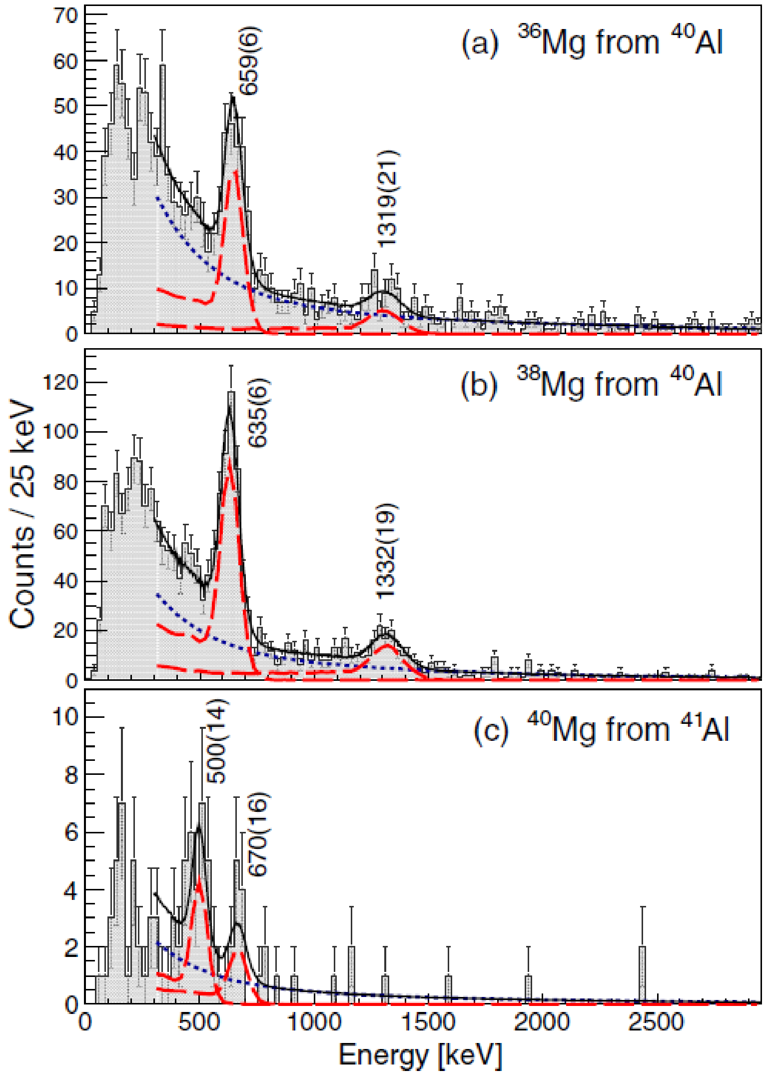
^{42}Si broader context

- Recent spectroscopy of ^{40}Mg at RIBF suggests a level scheme that cannot be easily reconciled with shell-model calculations
- Weak-binding effects are proposed to be at play

H. L. Crawford *et al.*, PRL 122, 052501 (2019)

- Now, if one wants to understand weak-binding effect, start from the shell model that works best for the neighboring isotone ^{42}Si: SDPF-MU

H. L. Crawford et al., PRL 122, 052501 (2019)



Spectroscopy of ^{70}Fe

PHYSICAL REVIEW C **99**, 011301(R) (2019)

Rapid Communications

Structure of ^{70}Fe: Single-particle and collective degrees of freedom

A. Gade,[1,2] R. V. F. Janssens,[3] J. A. Tostevin,[4] D. Bazin,[1,2] J. Belarge,[1,*] P. C. Bender,[1,†] S. Bottoni,[5,‡] M. P. Carpenter,[5] B. Elman,[1,2] S. J. Freeman,[6] T. Lauritsen,[5] S. M. Lenzi,[7] B. Longfellow,[1,2] E. Lunderberg,[1,2] A. Poves,[8] L. A. Riley,[9] D. K. Sharp,[6] D. Weisshaar,[1] and S. Zhu[5]

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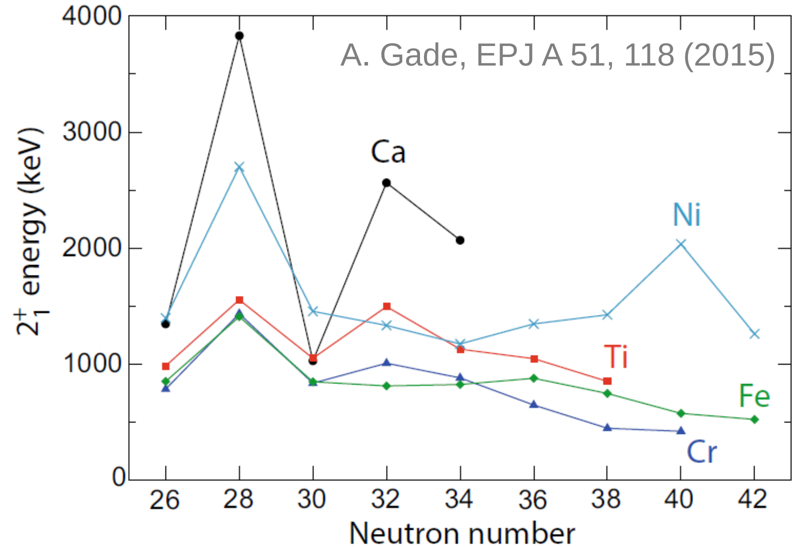
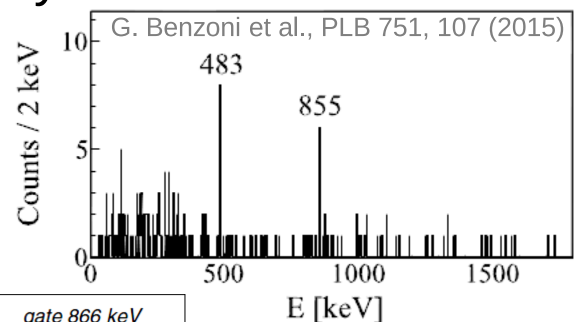
(Received 5 August 2018; revised manuscript received 28 September 2018; published 2 January 2019)

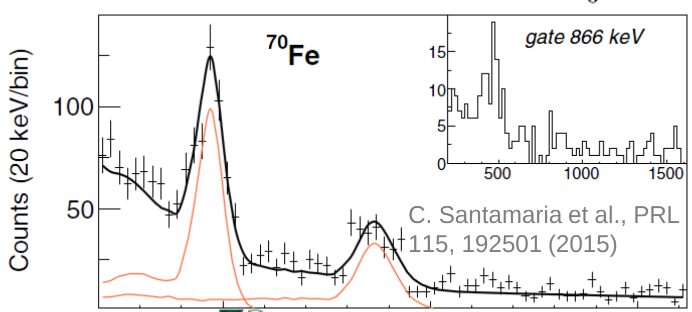
Structure of ^{70}Fe: Single-particle and collective degrees of freedom

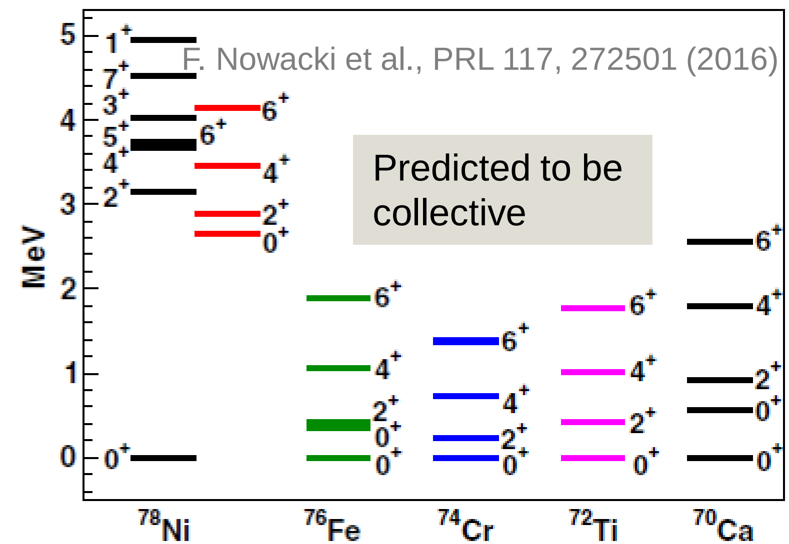
- Motivation
  - ^{70}Fe is located in between two Island of Inversion, located around *N=40*, and predicted at *N=50*
  - The shell evolution is driven by single-particle shifts and QQ interactions
  - Interplay of single-particle and collective degrees of freedom poses sensitive benchmark for theory



- Known before?
  - RIKEN β decay
  - (p,2p)

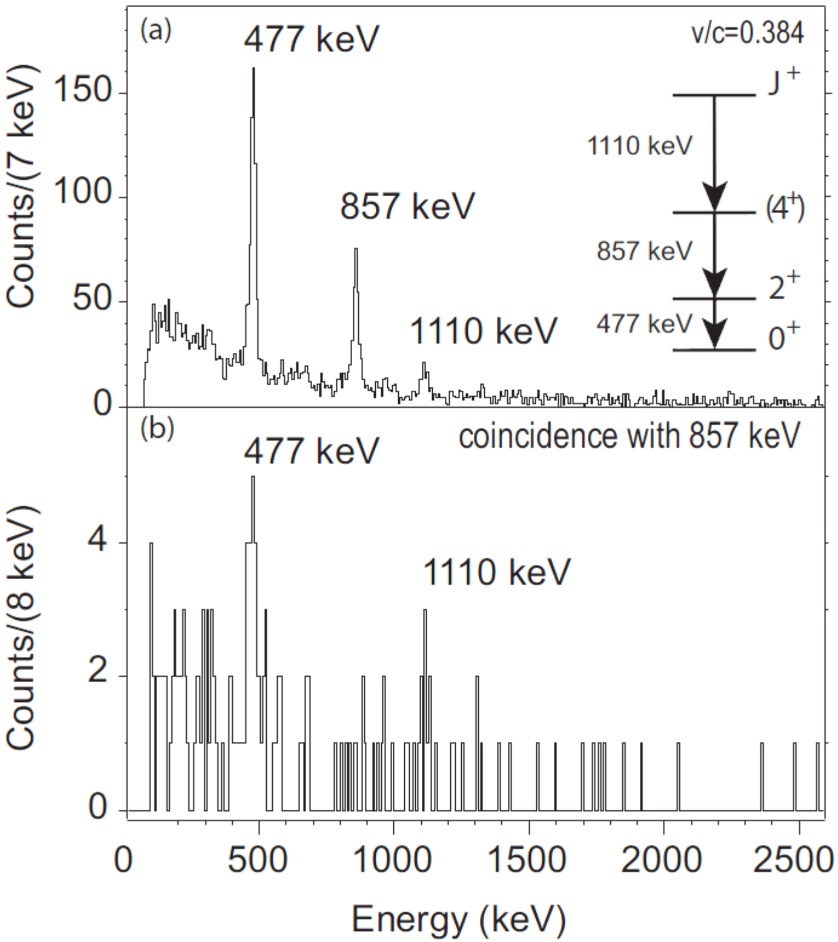






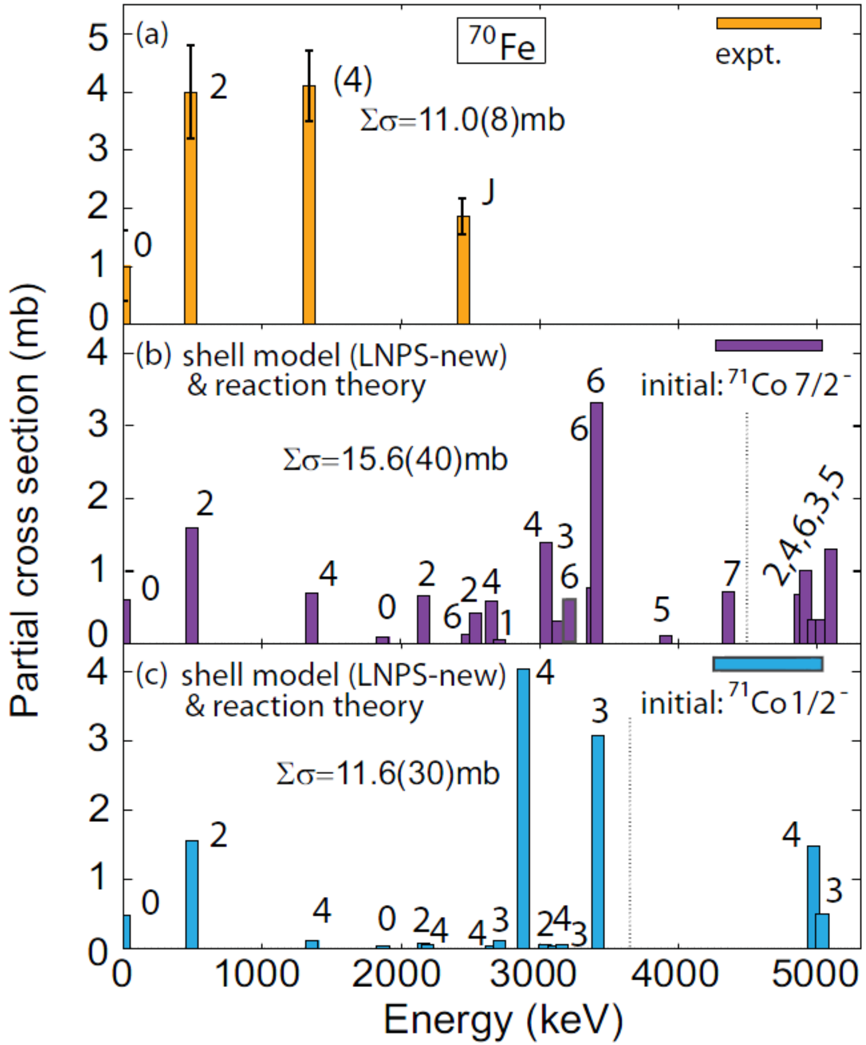
Structure of ^{70}Fe: Single-particle and collective degrees of freedom

- Experiment
  - ^{9}Be(^{71}Co,^{70}Fe+γ)X at 87 MeV/u; typical ^{71}Co rate: 65/second
  - ^{70}Fe unambiguously identified in the S800, coincident γ rays event-by-event Doppler reconstructed from GRETINA's interaction points
- Results
  - Inclusive cross section for the reaction to happen: 11.0(8) mb
  - Three γ rays observed, one is new, two agree with previous results
  - All three are in coincidence → level scheme established
- A catch – Shell model predicts a ^{71}Co $7/2^-$ ground state and a $1/2^-$ isomer



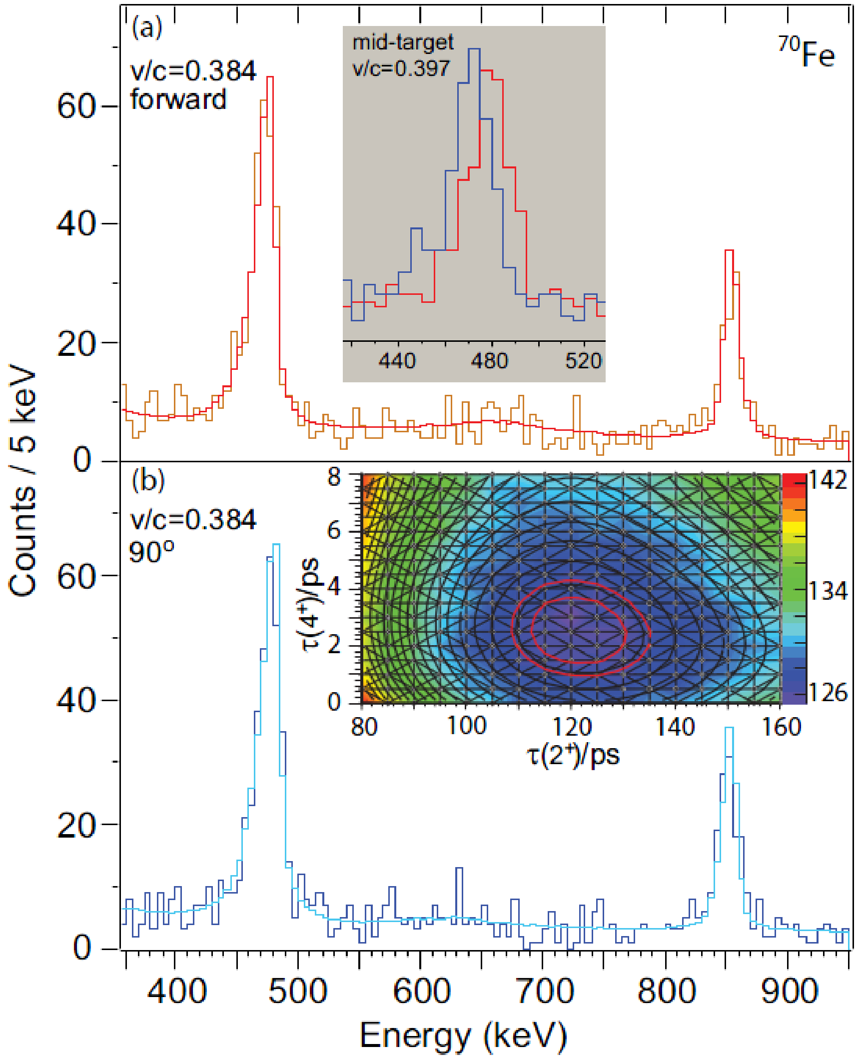
Structure of ^{70}Fe: Single-particle and collective degrees of freedom – crime and punishment

- Comparison to theory
  - Measured partial cross sections for the population of the individual final states are plotted as function of energy
  - Do the same for theory
    - » Reaction theory x spectroscopic factor from shell model
    - » Eikonal reaction theory for one-nucleon knockout
    - » Spectroscopic factors from LNPS-new effective shell model interaction
    - » Do that assuming knockout from 7/2- and 1/2- since we don't know …
  - You get what you asked for: A big mess and theory does not look like experiment … at all



Structure of ^{70}Fe: Collective degrees of freedom – for free!

- Sensitivity to excited-state lifetimes!
  - Spectra taken under 58º and 90º do not line up at the same energies → the different γ-ray transitions are emitted at different velocities, aka the states have different lifetimes and γ-ray emission occurs at different depths in the target
  - GEANT simulations reproduce the observed shifts if $\tau(2^+)$=120(20) ps and $\tau(4^+)$=2-4 ps
    - » Shell model: $\tau(2^+)$=81 ps and $\tau(4^+)$=3 ps
    - » Broad agreement – shell model describes the collectivity well



A. Gade *et al.*, PRC 99, 011301(R) (2019)

Structure of ^{70}Fe: What is going on?

^{70}Fe – will be a formidable benchmark for future calculations

- Fact is …
  - LNPS-new describes very well the excitation energies and electromagnetic transition strengths in the region and in ^{70}Fe
- What about the spectroscopic factors
  - Shell model predicts more than 100 states below S_n=5.32 MeV – adding more relevant configurations outside of the model space would increase that number and the level of fragmentation
- Possible explanation: Spectroscopic strength is more fragmented than present model spaces allow. This would spread the cross section over many states with a little strength each → in the experiment, the weak feeders funnel through the low-lying states and remain unobserved

Pandemonium-like Effect!

The essential decay of pandemonium: A demonstration of errors in complex beta-decay schemes

J. C. Hardy, L. C. Carraz, B. Jonson, and P. G. Hansen, Phys. Lett. 71, 307 (1977)

A. Gade *et al.*, PRC 99, 011301(R) (2019)

$N=Z=28$ ^{56}Ni

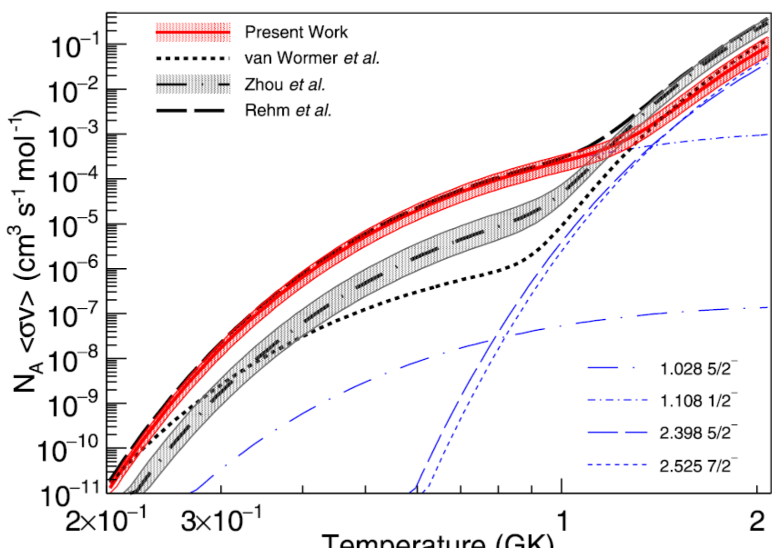
Recent nucleon-adding and removing transfer/knockout reactions

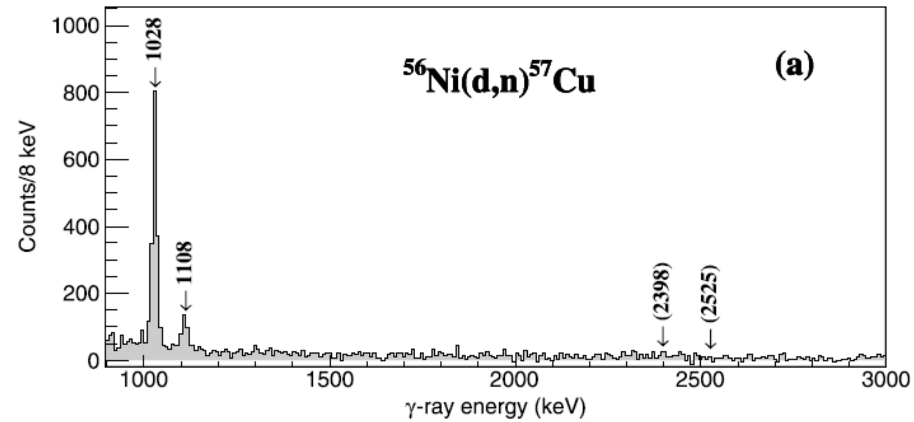
- Nucleon-adding transfer reactions onto ^{56}Ni
- Extracted spectroscopic factors agree with GXPF1A

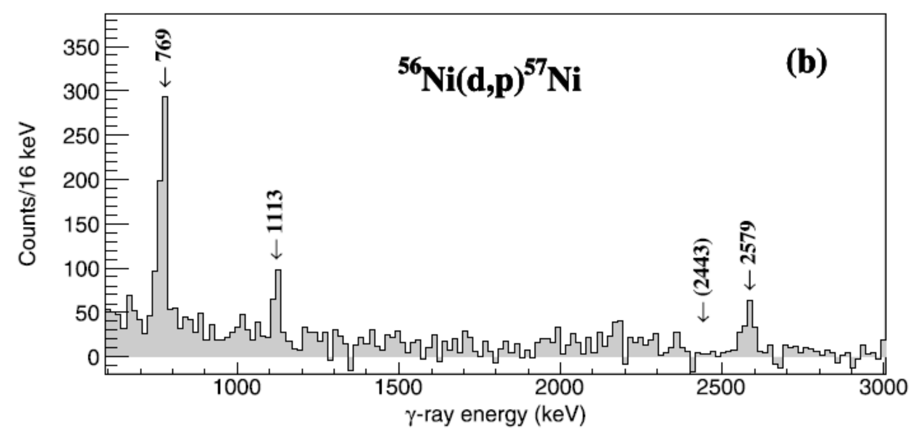
D. Kahl *et al.*, PLB 797, 134803 (2019)

^{56}Ni$(d,n)^{57}$Cu						
E_{ex}	J^{π}	ℓ	σ_{exp} (mb)	σ_{th} (mb)	$C^2S_{(d,n)}$	C^2S_{SM}
1.028	5/2$^-$	3	2.00(40)	2.62	0.76(28)	0.75
1.109	1/2$^-$	1	0.28(6)	0.45	0.62(22)	0.71
2.398	5/2$^-$	3	<0.2	2.61	$< 8 \times 10^{-2}$	1.8×10^{-3}
2.525	7/2$^-$	3	<0.2	14.5	–	3.9×10^{-2}

^{56}Ni$(d,p)^{57}$Ni						
E_{ex}	J^{π}	ℓ	σ_{exp} (mb)	σ_{th} (mb)	$C^2S_{(d,p)}$	C^2S_{SM}
0.768	5/2$^-$	3	2.10(60)	2.77	0.77(31)	0.74
1.122	1/2$^-$	1	0.50(15)	0.68	0.73(31)	0.69
2.443	5/2$^-$	3	<0.4	2.61	< 0.1	3×10^{-4}
2.579	7/2$^-$	3	1.24(36)	14.9	$8(3) \times 10^{-2}$	4.1×10^{-2}







Summary

- The study of shell evolution has seen highlights along magic chains and in regions of rapid structural change
  - Two examples for very neutron-rich systems:
    - » ^{42}Si: Discriminating between predictions that could hardly be more different … or looking beyond the first 2^+ and excitation energies was key
    - » ^{70}Fe: Pandemonium? We did not order that mess …
  - And brief news on ^{56}Ni
- In-beam gamma-ray spectroscopy is a great tool to track the evolution of nuclear structure

Thank you

… and my many collaborators:

Structure of ^{70}Fe: Single-particle and collective degrees of freedom

A. Gade,[1,2] R. V. F. Janssens,[3] J. A. Tostevin,[4] D. Bazin,[1,2] J. Belarge,[1,*] P. C. Bender,[1,†] S. Bottoni,[5,‡] M. P. Carpenter,[5] B. Elman,[1,2] S. J. Freeman,[6] T. Lauritsen,[5] S. M. Lenzi,[7] B. Longfellow,[1,2] E. Lunderberg,[1,2] A. Poves,[8] L. A. Riley,[9] D. K. Sharp,[6] D. Weisshaar,[1] and S. Zhu[5]

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(Dated: April 23, 2019)

... and the funding agencies

^{70}Fe:

This work was supported by the U.S. National Science Foundation (NSF) under Cooperative Agreement No. PHY-1565546 (NSCL) and Grant No. PHY-1617250 (Ursinus), by the U.S. Department of Energy (DOE) National Nuclear Security Administration under Awards No. DE-NA0003180 and No. DE-NA0000979, and by the DOE-SC Office of Nuclear Physics under Grants No. DE-FG02-08ER41556 (NSCL), No. DE-FG02-97ER41041 (UNC), No. DE-FG02-97ER41033 (TUNL), and No. DE-AC02-06CH11357 (ANL). GRETINA was funded by the DOE, Office of Science. Operation of the array at NSCL was supported by the DOE under Grants No. DE-SC0014537 (NSCL) and No. DE-AC02-05CH11231 (LBNL). J.A.T., S.J.F., and D.K.S. acknowledge support from the Science and Technology Facilities Council (U.K.) Grants No. ST/L005743/1 and No. ST/L005794/1, respectively. We also thank T. J. Carroll for the use of the Ursinus College Parallel Computing Cluster, supported by NSF Grant No. PHY-1607335. A.P. was supported, in part, by MINECO (Spain) Grant No. FPA2014-57196 and the Severo Ochoa Programme No. SEV-2016-0597.

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This work was supported by the US National Science Foundation (NSF) under Cooperative Agreement No. PHY-1565546 and Grant No. PHY-1811855, by the US Department of Energy (DOE) National Nuclear Security Administration through the Nuclear Science and Security Consortium under award number DE-NA0003180, and by the DOE-SC Office of Nuclear Physics under Grant No. DE-FG02-08ER41556 (NSCL) and DE-AC02-05CH11231 (LBNL). GRETINA was funded by the DOE, Office of Science. Operation of the array at NSCL was supported by the DOE under Grant No. DE-SC0014537 (NSCL) and DE-AC02-05CH11231 (LBNL). J.A.T. acknowledges support from the Science and Technology Facilities Council (U.K.) Grant No. ST/L005743/1. Discussions with A. Poves are acknowledged.