Recent experimental studies of shell evolution in exotic nuclei

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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?**

- **Why do the neutron-rich Ca isotopes have so large charge radii?**

- **How heavy are they?**
  - S. Michimasa *et al.*, PRL 121, 022506 (2018)

- **Excited states at and beyond $N=34$, anybody?**

- **How many neutrons can $Z=20$ bind?**
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

- 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
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 $^{42}\text{Si}$

Is the structure of $^{42}\text{Si}$ understood?

A. Gade, B. A. Brown, J. A. Tostevin, D. Bazin, P. C. Bender, C. M. Campbell, H. L. Crawford, B. Elman, K. W. Kemper, B. Longfellow, E. Lunderberg, D. Rhodes, and D. Weisshaar

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(Dated: April 23, 2019)

A more detailed test of the implementation of nuclear forces that drive shell evolution in the pivotal nucleus $^{42}\text{Si}$ – 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 $^{42}\text{Si}(2^+_1)$ energy, but whose predictions for other observables differ significantly, are interrogated by the population of states in neutron-rich $^{42}\text{Si}$ with a one-proton removal reaction from $^{43}\text{P}$ projectiles at 81 MeV/nucleon. The measured cross sections to the individual $^{42}\text{Si}$ 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 $^{42}\text{Si}$ is proposed to be the $(0_{2^+}^+)$ level.
Structure of $^{42}$Si: A brief history

- **Present-generation RIB facilities**
  - Beta-decay half-life of $^{42}$Si and particle stability of $^{43}$Si $\rightarrow N=28$ 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., 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

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

- 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
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 $^{43}\text{P}$

- One-proton knockout is a direct reaction $\rightarrow$ probes the single-particle degree of freedom

- $^{43}\text{P}$: ground state is $1/2^+$
  
  [Ref. L. A. Riley et al., PRC 78, 011303(R) (2008)]

- This means, knockout of $sd$-shell protons cannot populate $J \geq 4$

- All $\gamma$-ray transitions except for the 2743 keV line had been reported in the RIBF two-proton removal experiment

- $^9\text{Be}(^{43}\text{P},^{42}\text{Si}+\gamma)X$ at 81 MeV/u

- Gamma rays in GRETINA and projectile-like reaction residues in the S800

[Graph showing gamma ray transitions]
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)
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
Recent spectroscopy of $^{40}\text{Mg}$ at RIBF suggests a level scheme that cannot be easily reconciled with shell-model calculations.

Weak-binding effects are proposed to be at play.

Now, if one wants to understand weak-binding effect, start from the shell model that works best for the neighboring isotone $^{42}\text{Si}$: SDPF-MU.
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. Weisschaar,¹ and S. Zhu⁵

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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 $\beta$ decay
- $(p,2p)$

A. Gade, EPJ A 51, 118 (2015)

F. Nowacki et al., PRL 117, 272501 (2016)

Experiment

- $^9\text{Be}(^{71}\text{Co}, ^{70}\text{Fe}+\gamma)X$ at 87 MeV/u; typical $^{71}\text{Co}$ rate: 65/second
- $^{70}\text{Fe}$ unambiguously identified in the S800, coincident $\gamma$ 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 $\gamma$ rays observed, one is new, two agree with previous results
- All three are in coincidence $\rightarrow$ level scheme established

A catch – Shell model predicts a $^{71}\text{Co}$ $7/2^-$ ground state and a $1/2^-$ isomer
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 × 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

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

Structure of $^{70}$Fe: Single-particle and collective degrees of freedom – crime and punishment
Structure of $^{70}$Fe: Collective degrees of freedom – for free!

- Sensitivity to excited-state lifetimes!
  - Spectra taken under 58° and 90° do not line up at the same energies → the different $\gamma$-ray transitions are emitted at different velocities, aka the states have different lifetimes and $\gamma$-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
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!

John Martin, Paradise Lost 1841

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


A. Gade et al., PRC 99, 011301(R) (2019)
$N=Z=28 \ ^{56}\text{Ni}$

Recent nucleon-adding and removing transfer/knockout reactions

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

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

**$^{56}\text{Ni}(d,n)^{57}\text{Cu}$**

<table>
<thead>
<tr>
<th>$E_{\text{ex}}$ (MeV)</th>
<th>$J^\pi$</th>
<th>$I$</th>
<th>$\sigma_{\text{exp}}$ (mb)</th>
<th>$\sigma_{\text{th}}$ (mb)</th>
<th>$C^2S_{(d,n)}$</th>
<th>$C^2S_{\text{SM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.028</td>
<td>5/2(^-)</td>
<td>3</td>
<td>2.00(40)</td>
<td>2.62</td>
<td>0.76(28)</td>
<td>0.75</td>
</tr>
<tr>
<td>1.109</td>
<td>1/2(^-)</td>
<td>1</td>
<td>0.28(6)</td>
<td>0.45</td>
<td>0.62(22)</td>
<td>0.71</td>
</tr>
<tr>
<td>2.398</td>
<td>5/2(^-)</td>
<td>3</td>
<td>&lt;0.2</td>
<td>2.61</td>
<td>&lt;8\times10(^{-2})</td>
<td>1.8\times10(^{-3})</td>
</tr>
<tr>
<td>2.525</td>
<td>7/2(^-)</td>
<td>3</td>
<td>&lt;0.2</td>
<td>14.5</td>
<td>—</td>
<td>3.9\times10(^{-2})</td>
</tr>
</tbody>
</table>

**$^{56}\text{Ni}(d,p)^{57}\text{Ni}$**

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<th>$E_{\text{ex}}$ (MeV)</th>
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<th>$\sigma_{\text{exp}}$ (mb)</th>
<th>$\sigma_{\text{th}}$ (mb)</th>
<th>$C^2S_{(d,p)}$</th>
<th>$C^2S_{\text{SM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.768</td>
<td>5/2(^-)</td>
<td>3</td>
<td>2.10(60)</td>
<td>2.77</td>
<td>0.77(31)</td>
<td>0.74</td>
</tr>
<tr>
<td>1.122</td>
<td>1/2(^-)</td>
<td>1</td>
<td>0.50(15)</td>
<td>0.68</td>
<td>0.73(31)</td>
<td>0.69</td>
</tr>
<tr>
<td>2.443</td>
<td>5/2(^-)</td>
<td>3</td>
<td>&lt;0.4</td>
<td>2.61</td>
<td>&lt;0.1</td>
<td>3\times10(^{-4})</td>
</tr>
<tr>
<td>2.579</td>
<td>7/2(^-)</td>
<td>3</td>
<td>1.24(36)</td>
<td>14.9</td>
<td>8(3)\times10(^{-2})</td>
<td>4.1\times10(^{-2})</td>
</tr>
</tbody>
</table>

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**$^{56}\text{Ni}(d,p)^{57}\text{Ni}$**

- **(a)**
- **(b)**

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Alex Gade, Colloque GANIL 2019
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

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... and the funding agencies

$^{70}\text{Fe}$:

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 (BNL). 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.

$^{42}\text{Si}$:

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 (BNL). 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 (BNL). 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.