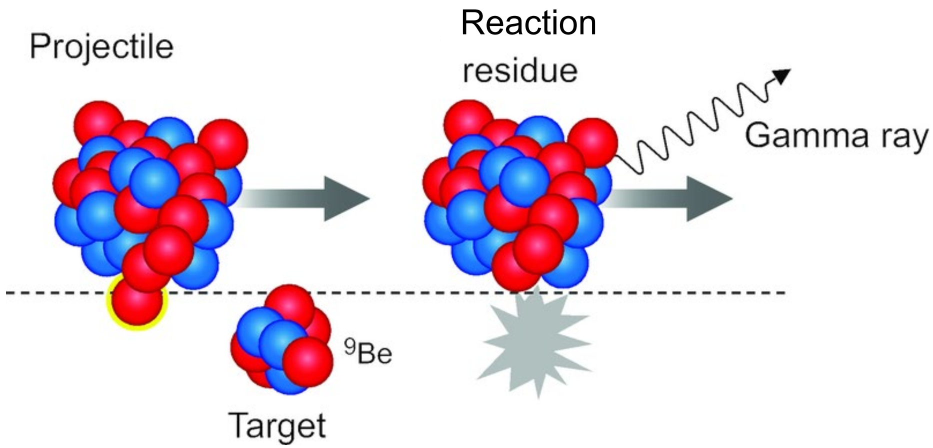


Nuclear spectroscopy with fast beams of rare isotopes

Alexandra Gade
Professor of Physics
Michigan State University

Outline

- Introduction
  - Overview of the second GRETINA campaign at NSCL
- Two nuclear structure examples
  - Spectroscopy of very neutron-rich nuclei I – ^{70}Fe
  - Spectroscopy of very neutron-rich nuclei II – ^{42}Si
- Outlook

Gamma-ray spectroscopy contributes to all science themes at NSCL

Properties of nuclei

- Develop a predictive model of nuclei and their interactions
- Determine the limits of elements and isotopes

γ-ray tagged reactions, excited-state lifetimes

Astrophysical processes

- Origin of the elements in the cosmos
- Explosive environments: novae, supernovae, X-ray bursts …
- Properties of neutron stars

Precise energy of exited states and their properties

Tests of fundamental symmetries

- Effects of symmetry violations are amplified in certain nuclei
- Study of weak interactions

Weak interactions from CEX reactions

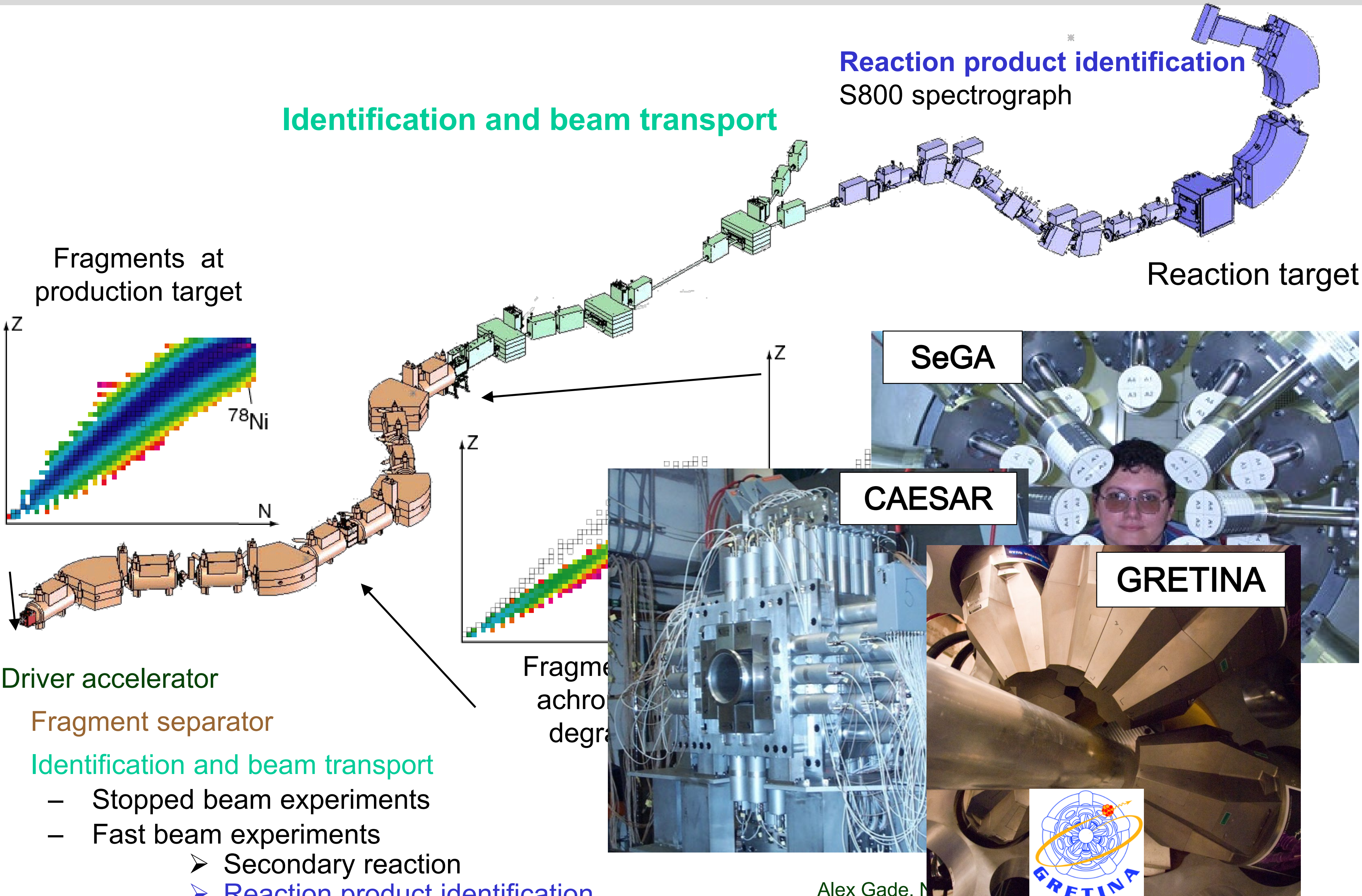
Societal applications and benefits

- Medicine, biology, environment, material sciences, national security

γ-ray tagged surrogate reactions and fission

S. Paschalis et al., NIM A 709, 44 (2013)
D. Weisshaar et al., NIM A 847, 187 (2017)

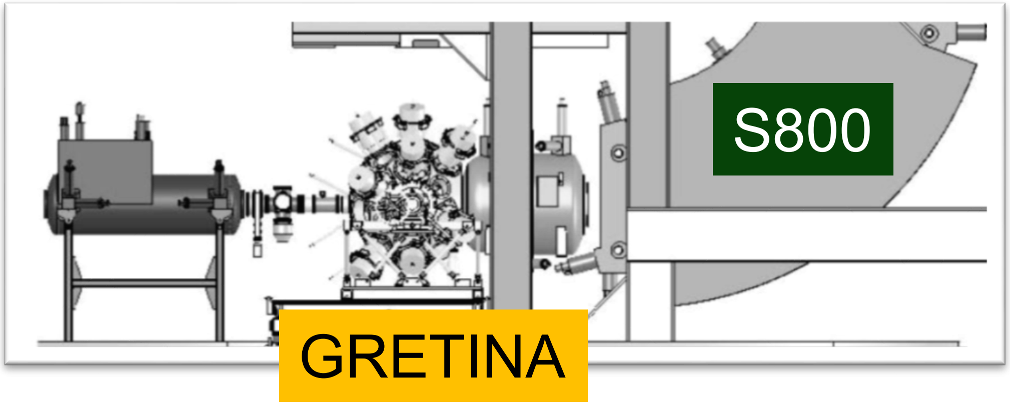
The experimental scheme at NSCL



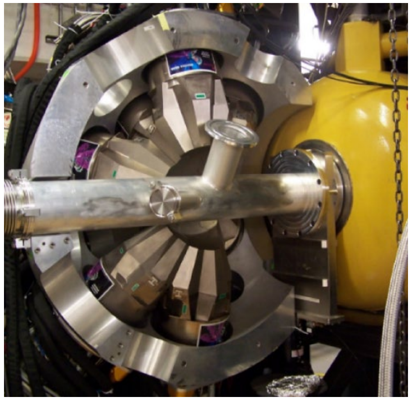
Driver accelerator

- ➢ Fragment separator
- ➢ Identification and beam transport
  - – Stopped beam experiments
  - – Fast beam experiments
    - ➢ Secondary reaction
    - ➢ Reaction product identification

Required for the science: GRETINA in three different configurations at the S800

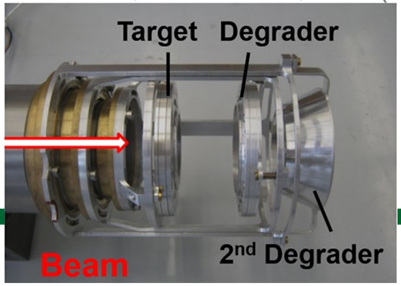


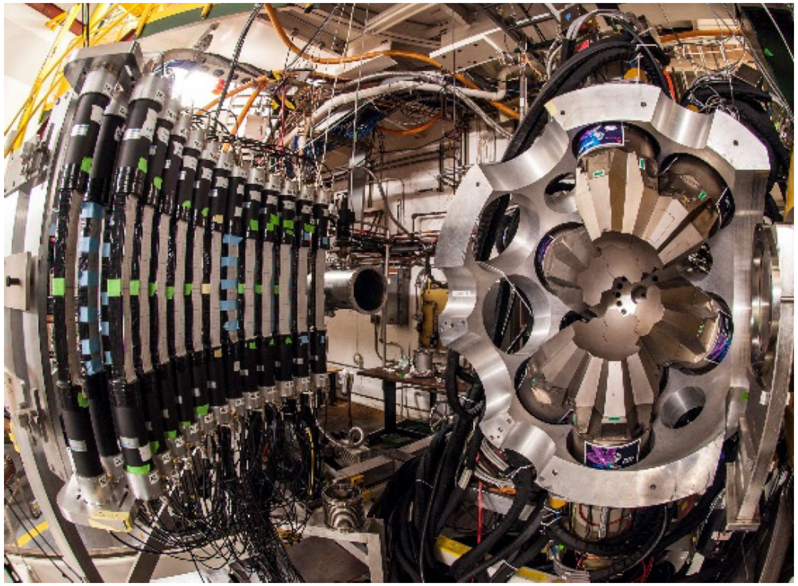
Standard



LH_2 target

H. Iwasaki et al., NIM A 806, 123 (2016)





GRETINA + LENDA

G. Perdikakis et al., NIM A 686, 117 (2012)

Second GRETINA campaign at NSCL

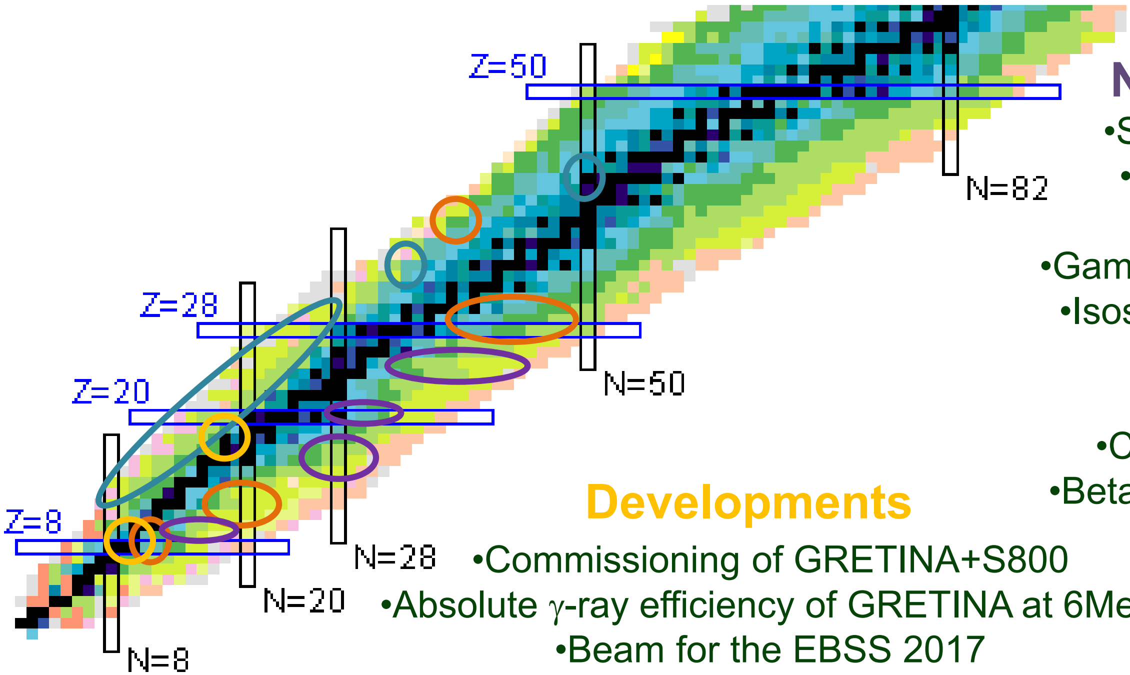
24 experiments (09/2015 – 07/2017)

Collectivity

- Delineation of the prolate minimum in ^{70}Ni
- Transition rates and halo properties
- Electromagnetic transition rates in ^{21}O
- Lifetimes in neutron-rich odd-A S isotopes
- Collective excitations in the vicinity of Z = 14
- Spectroscopy at and around N=Z ^{80}Zr
- Lifetime measurements in IoI

Nuclear Astrophysics

- Angle integrated measurement of the $^{56}Ni(d,n)^{57}Cu$
- Constraining EC rates in CCS: $^{86}Kr(t,^{3}He+\gamma)$
- Constraining $^{23}Al(p,\gamma)^{24}Si$ reaction rate
- Novel Method to access $^{26m}Al(p,\gamma)$ Resonances
- Constraining (p,γ) resonances in ^{62}Ge



Nuclear Shell Evolution

- Single-particle structure at N=28
- High-l single-particle strengths
- Shell evolution along $1g_{9/2}$
- Gamma-ray spectroscopy beyond N=40
- Isospin symmetry and SFs in $f_{7/2}$ shell
- The Calcium puzzle
- The structure of ^{42}Si
- Core excitations in neutron-rich F
- Beta+ GT strengths from ^{88}Sr and ^{93}Nb

Developments

- Commissioning of GRETINA+S800
- Absolute γ-ray efficiency of GRETINA at 6MeV
- Beam for the EBSS 2017

The menu of examples

- Nuclear structure physics
  - γ-ray spectroscopy at the extremes: ^{70}Fe
- Breakdown of *N=28*
  - Measuring the energy of important capture resonances precisely (and their properties …): ^{42}Si
- 3rd campaign of GRETINA – pictures

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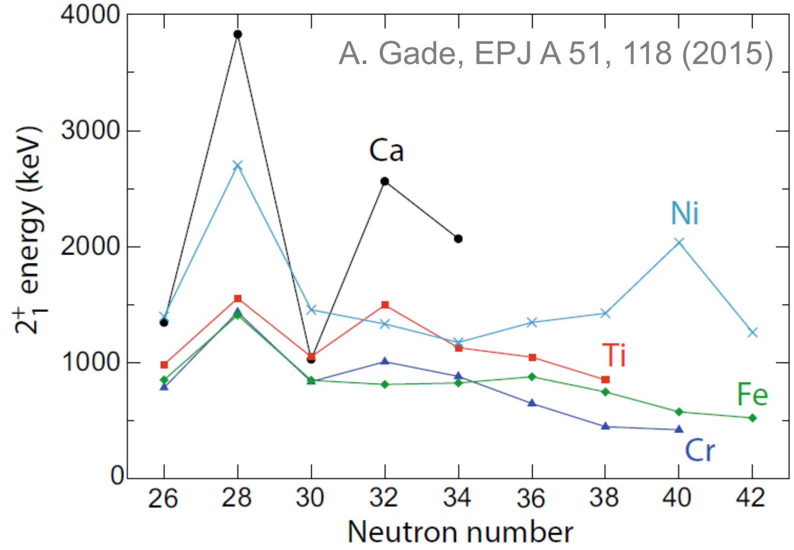
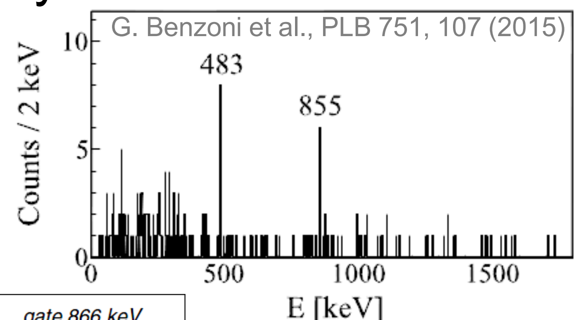
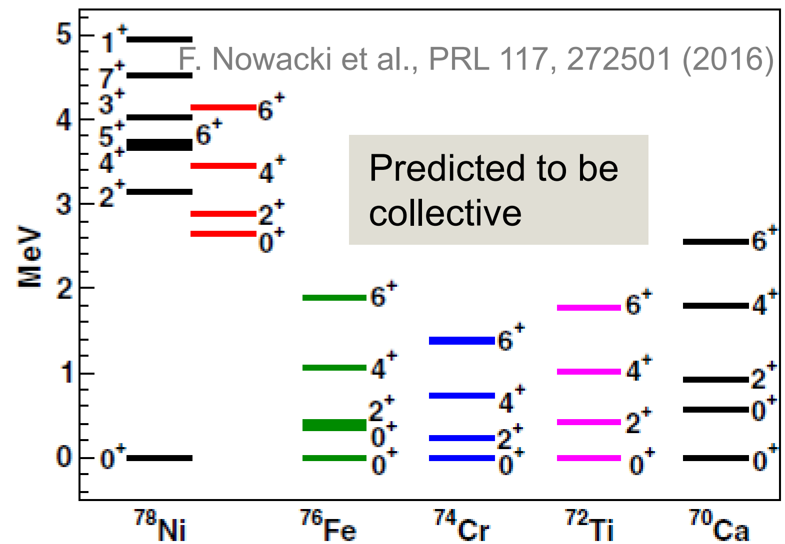
(Received 5 August 2018; revised manuscript received 28 September 2018; published 2 January 2019)

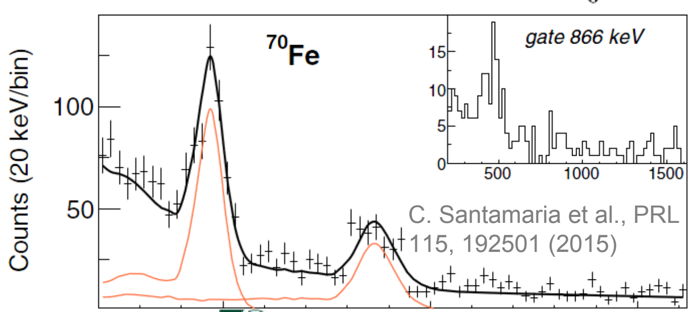
Structure of ^{70}Fe: Single-particle and collective degrees of freedom

- 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)



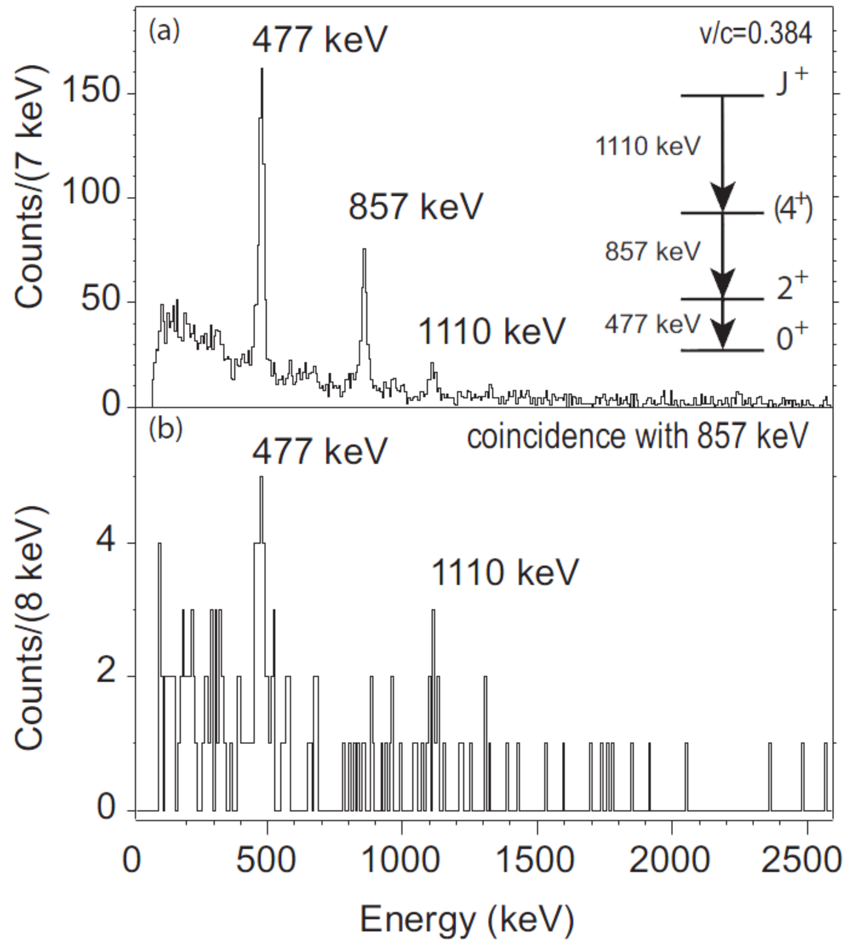






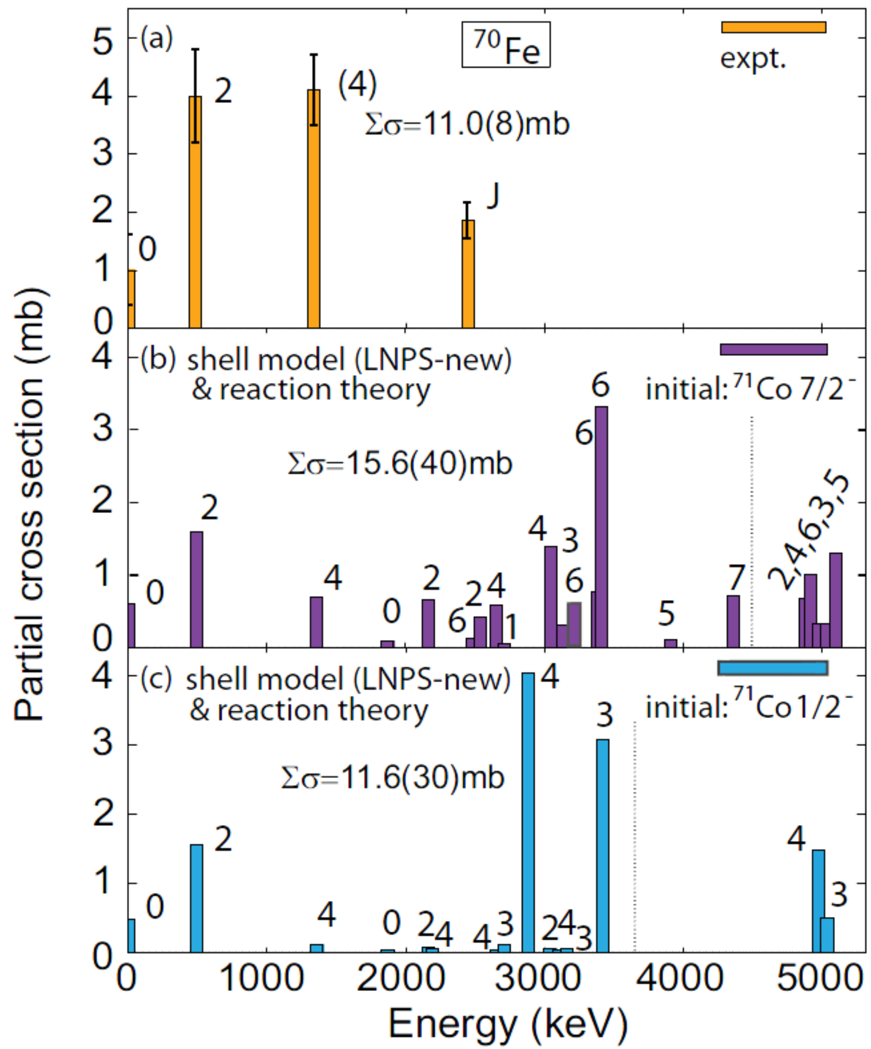
Structure of ^{70}Fe: Single-particle and collective degrees of freedom

- 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

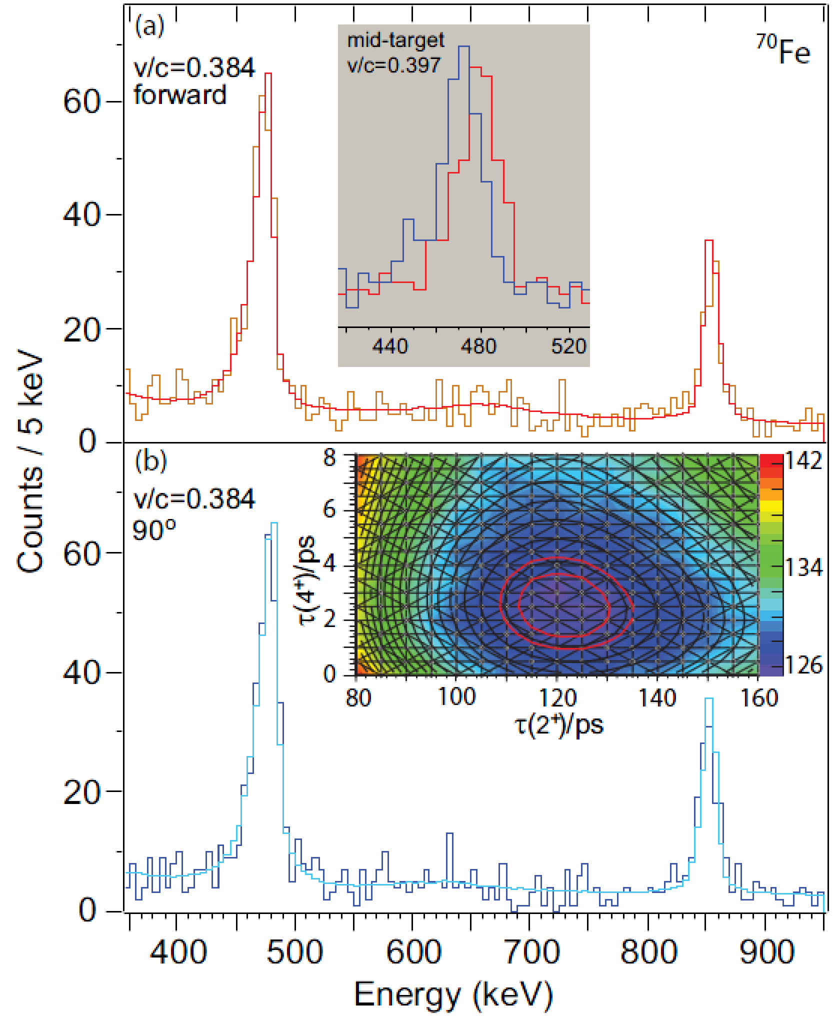
- Comparison to theory
  - Measured partial cross sections for the population of the individual final states are plotted as function of energy
  - Do the same for theory
    - » Reaction theory x spectroscopic factor from shell model
    - » Eikonal reaction theory for one-nucleon knockout
    - » Spectroscopic 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



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

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 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 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)

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]

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[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)

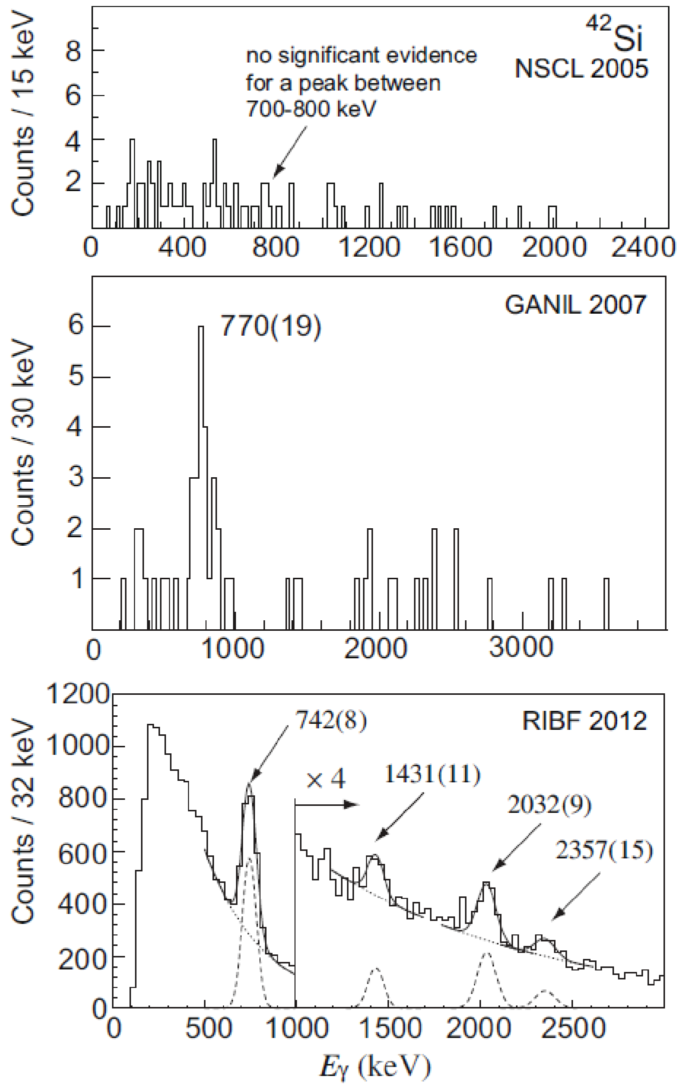
    M. Notani et al., PLB 542, 49 (2002)
  - Pronounced *Z=14* sub-shell gap may prevent ^{42}Si from being deformed

    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) history

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]

[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
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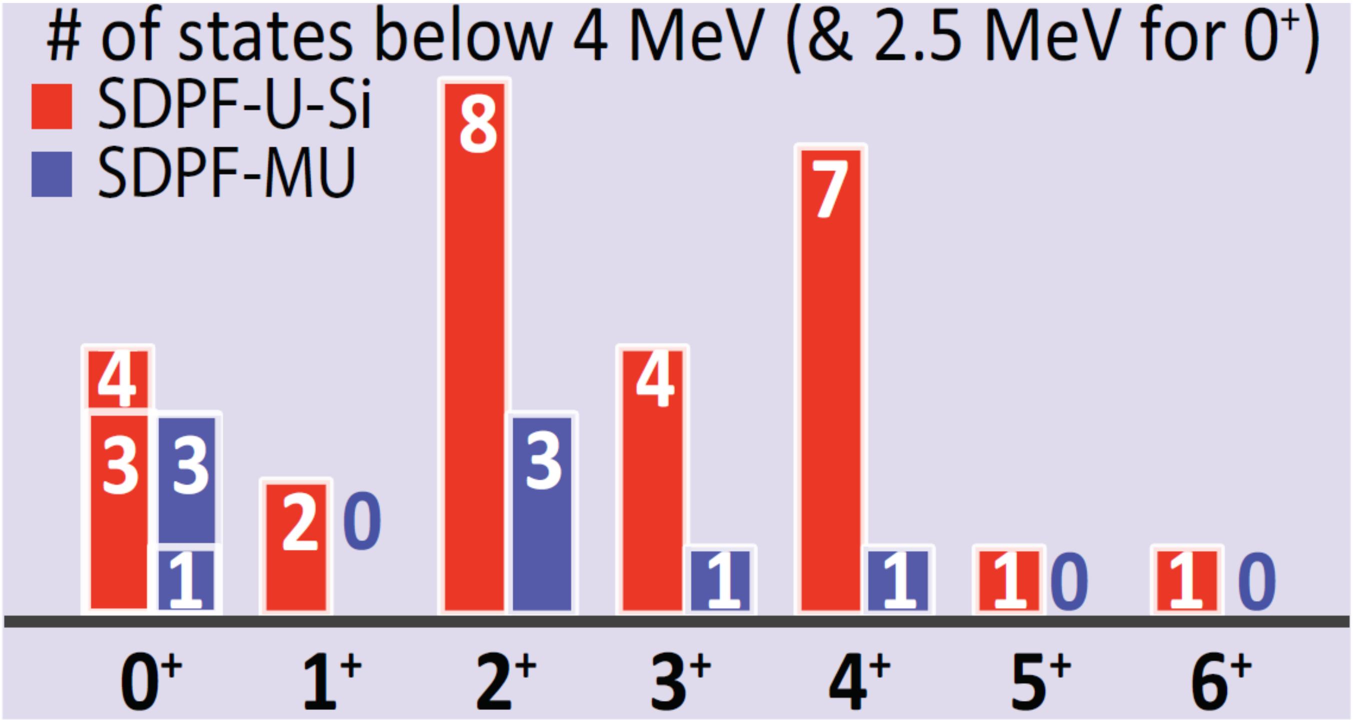
(Received 15 November 2012; published 4 February 2013)

Huh … Looking at shell model past the first 2^+

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

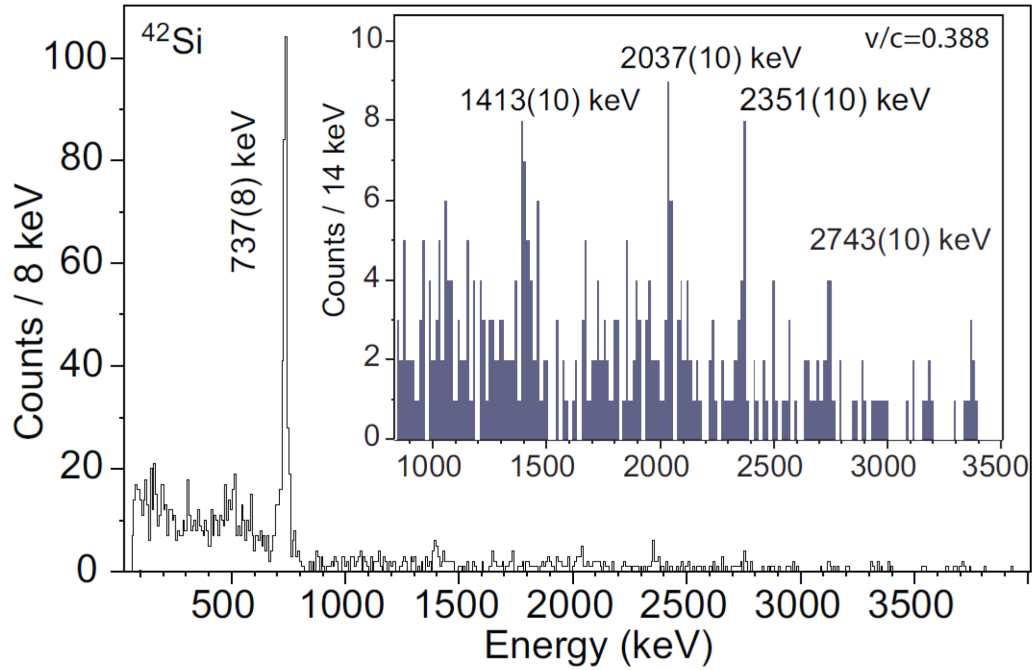


F. Nowacki, & A. Poves, PRC 79, 014310 (2009)
Y. Utsuno et al., PRC 86, 051301(R) (2012)

A. Gade, B.A. Brown, J. A. Tostevin et al., PRL, in press

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

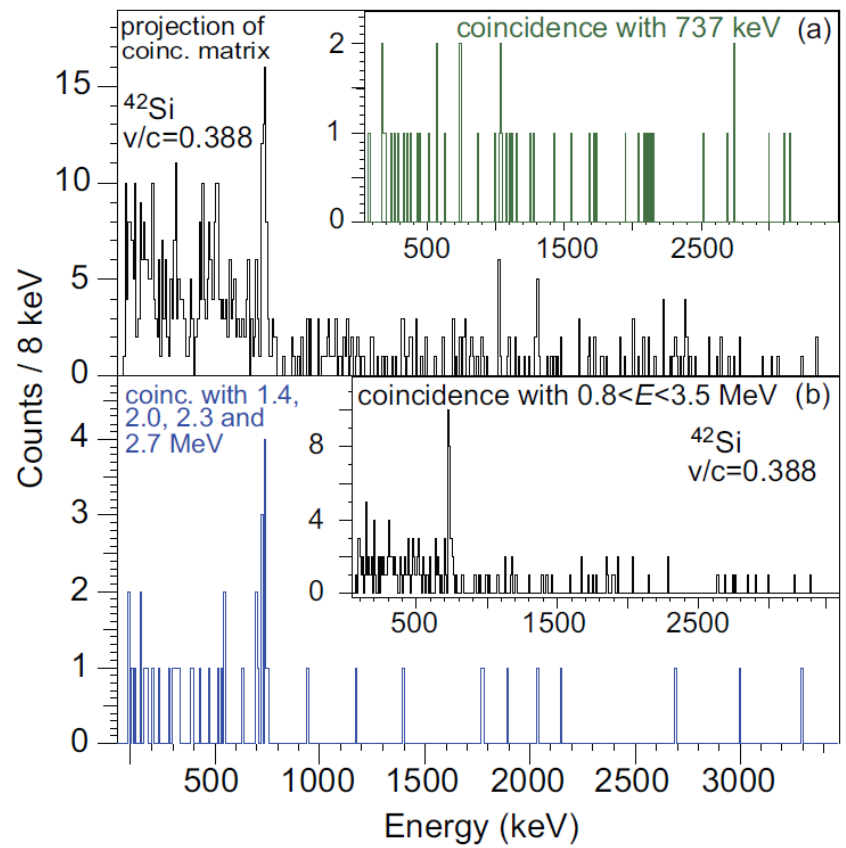
- Again, one-proton knockout is a direct reaction → probes the single-particle degree of freedom
- ^{43}P: ground state is $1/2^+$
  L. A. Riley et al., PRC 78, 011303(R) (2008)
- This means, knockout of *sd*-shell protons cannot populate $J \geq 4$
- All γ-ray transitions except for the 2743 keV line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



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

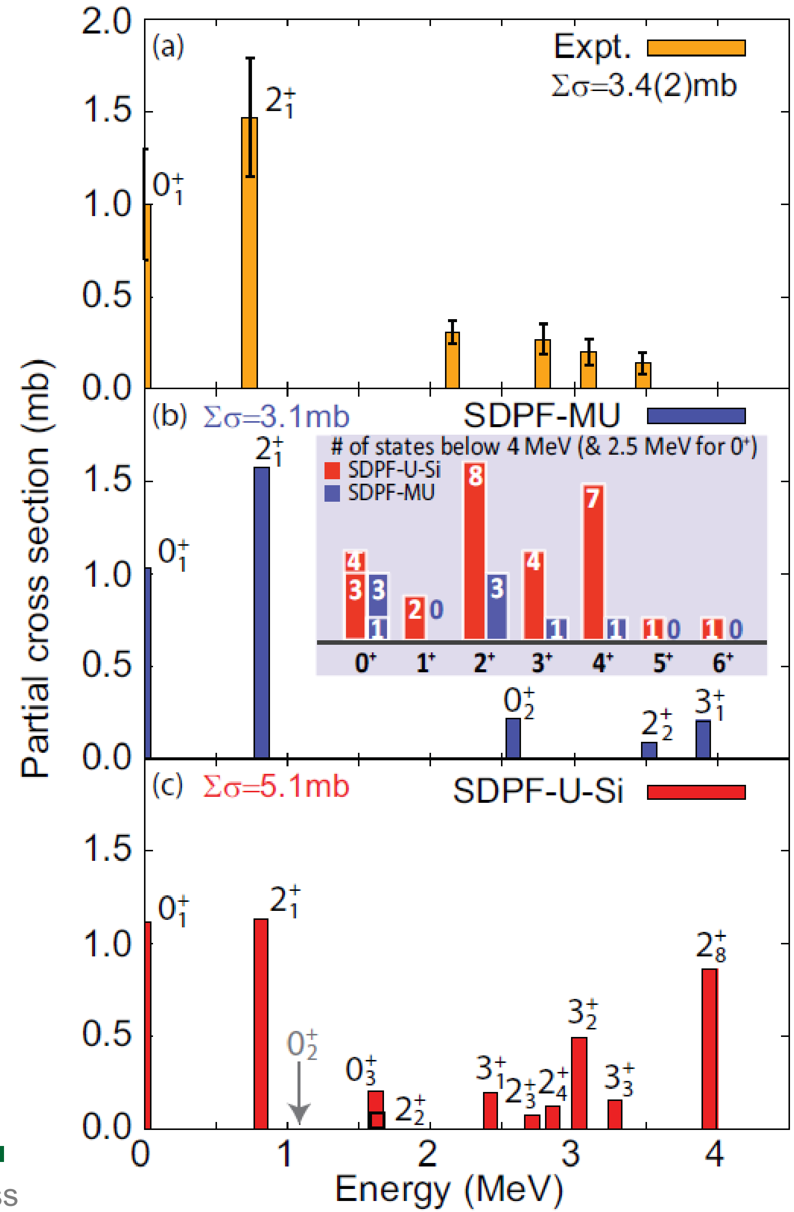
Can we say something about coincidences?

- Very clean spectrum, first 2^+ dominates, everything else is very weak
  - Projection of $\gamma\gamma$ matrix shows lots of counts beyond first 2^+
  - Too little statistics for individual coincidences
  - But: Consistency argument from OR gates of all high-lying peaks and a wide gate that takes the Compton continua into account as well



Confronting partial cross sections with theory

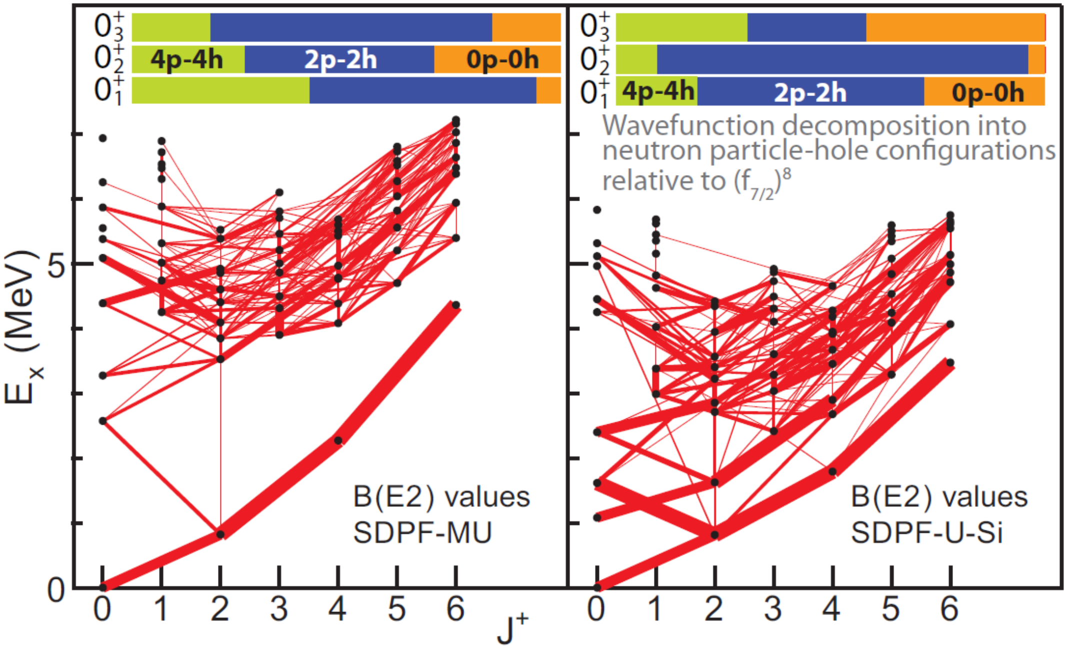
- SDPF-MU describes the data rather well
  - Suggests that the 2.1 MeV level assigned 4^+ by Takeuchi *et al.* based on systematics is more likely a 0^+ state (also most consistent with the two-proton knockout theory study of the RIBF data by Tostevin *et al.*)
- The exceptionally high level density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



A. Gade, B.A. Brown, J. A. Tostevin et al., PRL, in press

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



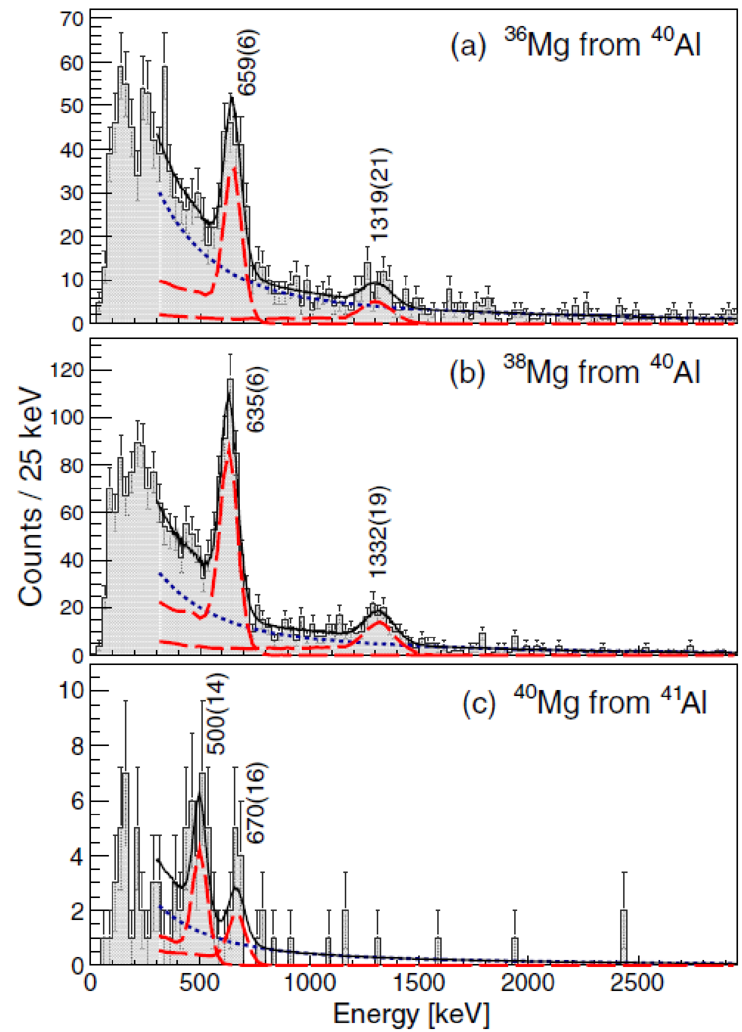
^{42}Si broader context

- 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

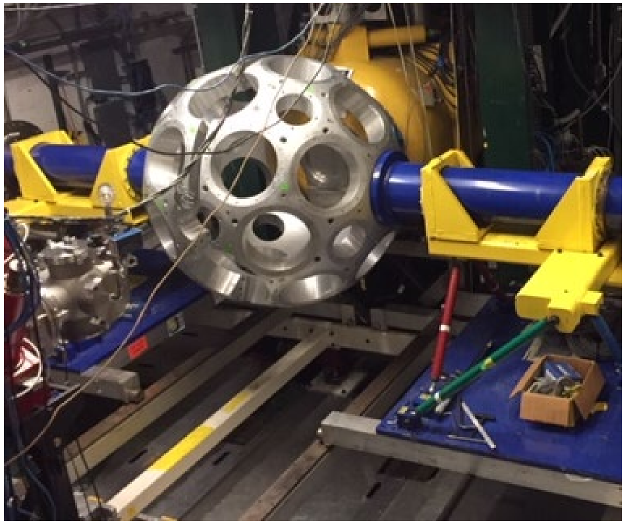
H. L. Crawford et al., PRL 122, 052501 (2019)

- 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)



Getting ready for the 3rd GRETINA campaign at NSCL to start in June, 2019



Pictures as of last week

Summary

- GRETINA's campaigns at the S800 spectrograph have enabled a broad science program
  - Two examples for very neutron-rich systems:
    - » ^{70}Fe: Pandemonium? We did not order that mess …
    - » ^{42}Si: Discriminating between predictions that could hardly be more different … or looking beyond the first 2^+ and cross section information was key
- GRETINA has returned to NSCL for a campaign to start in June – the last campaign at NSCL before FRIB

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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Is the structure of ^{42}Si understood?

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(Dated: April 23, 2019)

… and the funding agencies

^{70}Fe:

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^{42}Si:

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