Collectivity Across the Nuclear Chart

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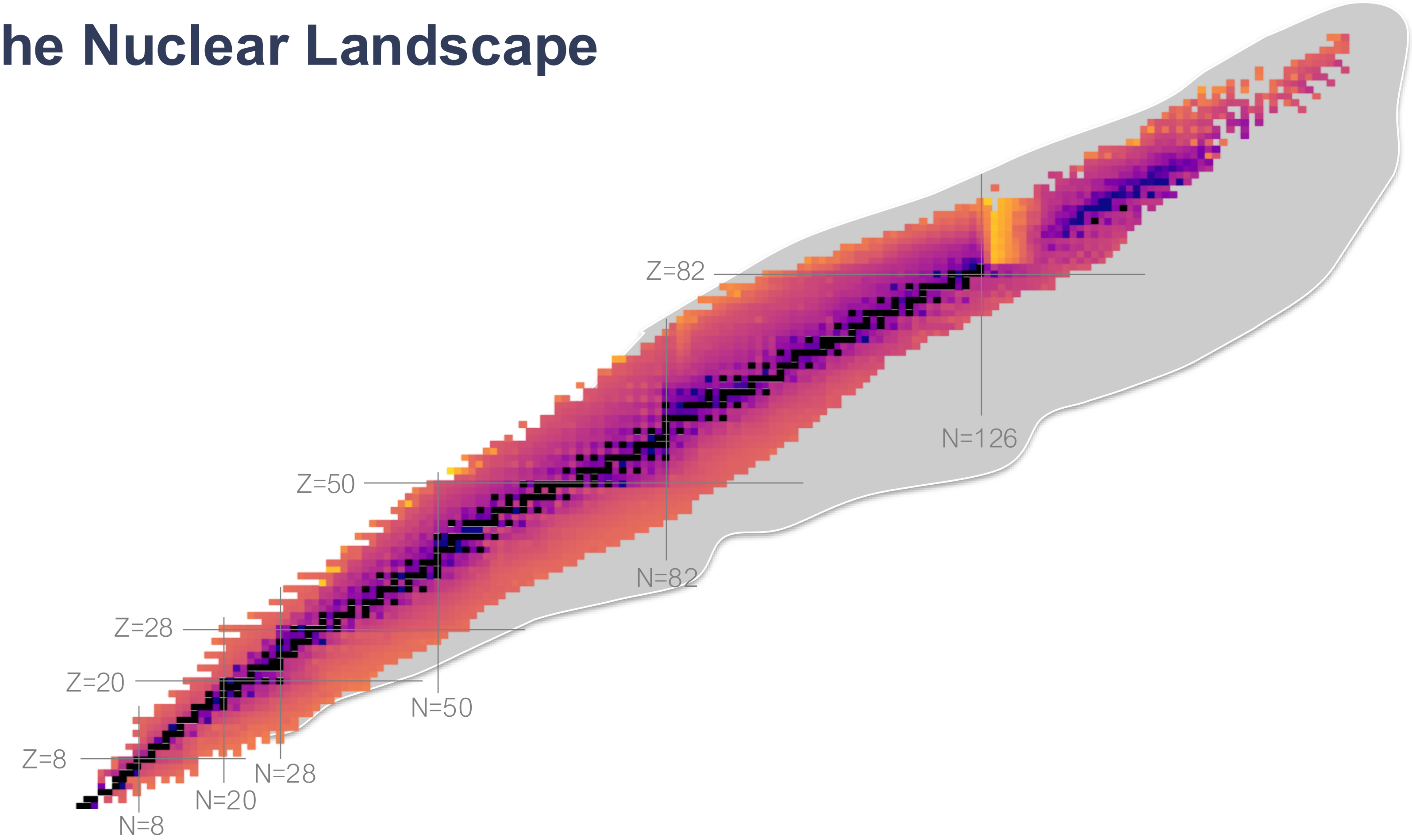
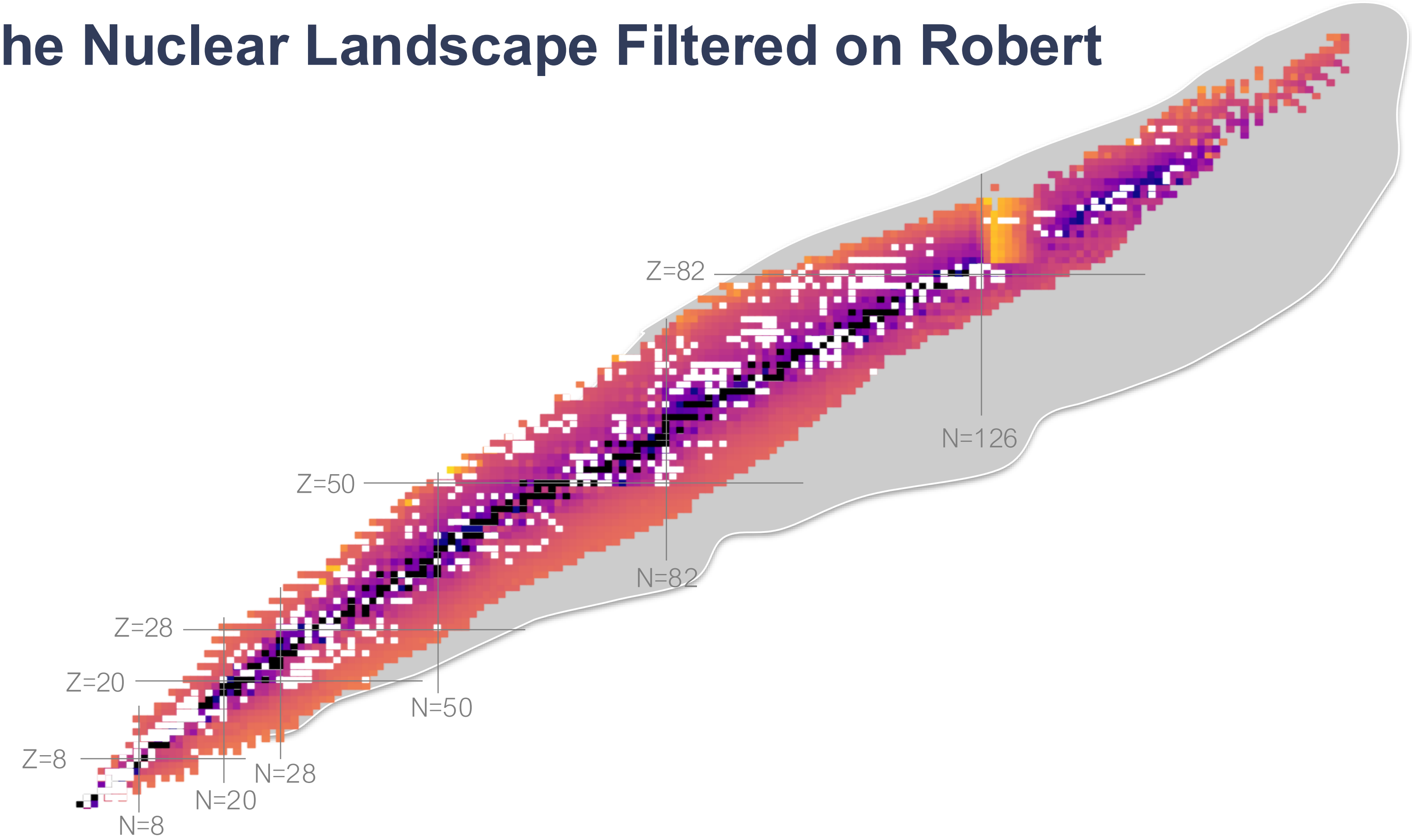
Nuclear Science Division, Lawrence Berkeley National Laboratory

Nuclear Physics Over the Years: From the high spin era to rare isotopes
September 20, 2025

The Nuclear Landscape



The Nuclear Landscape Filtered on Robert



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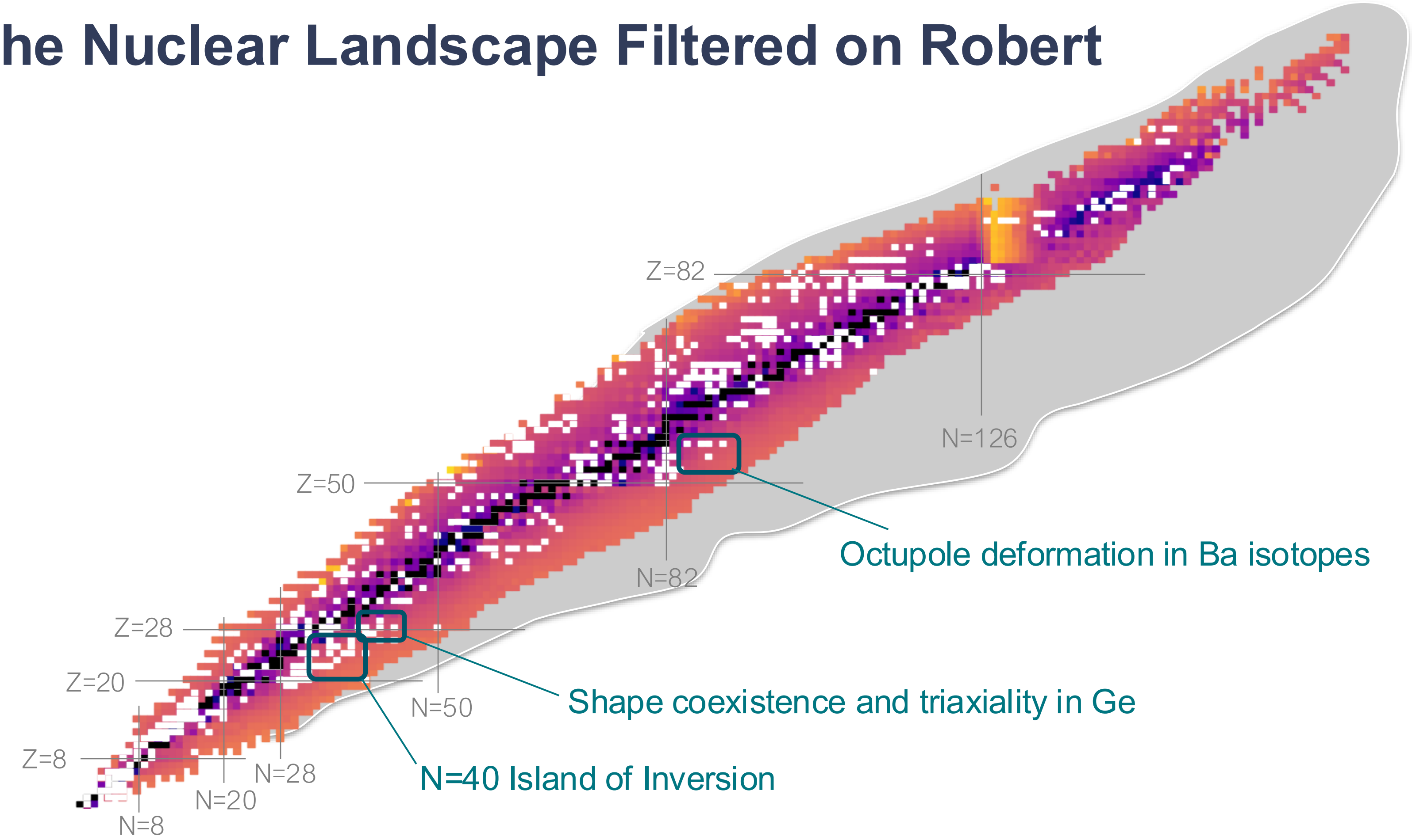

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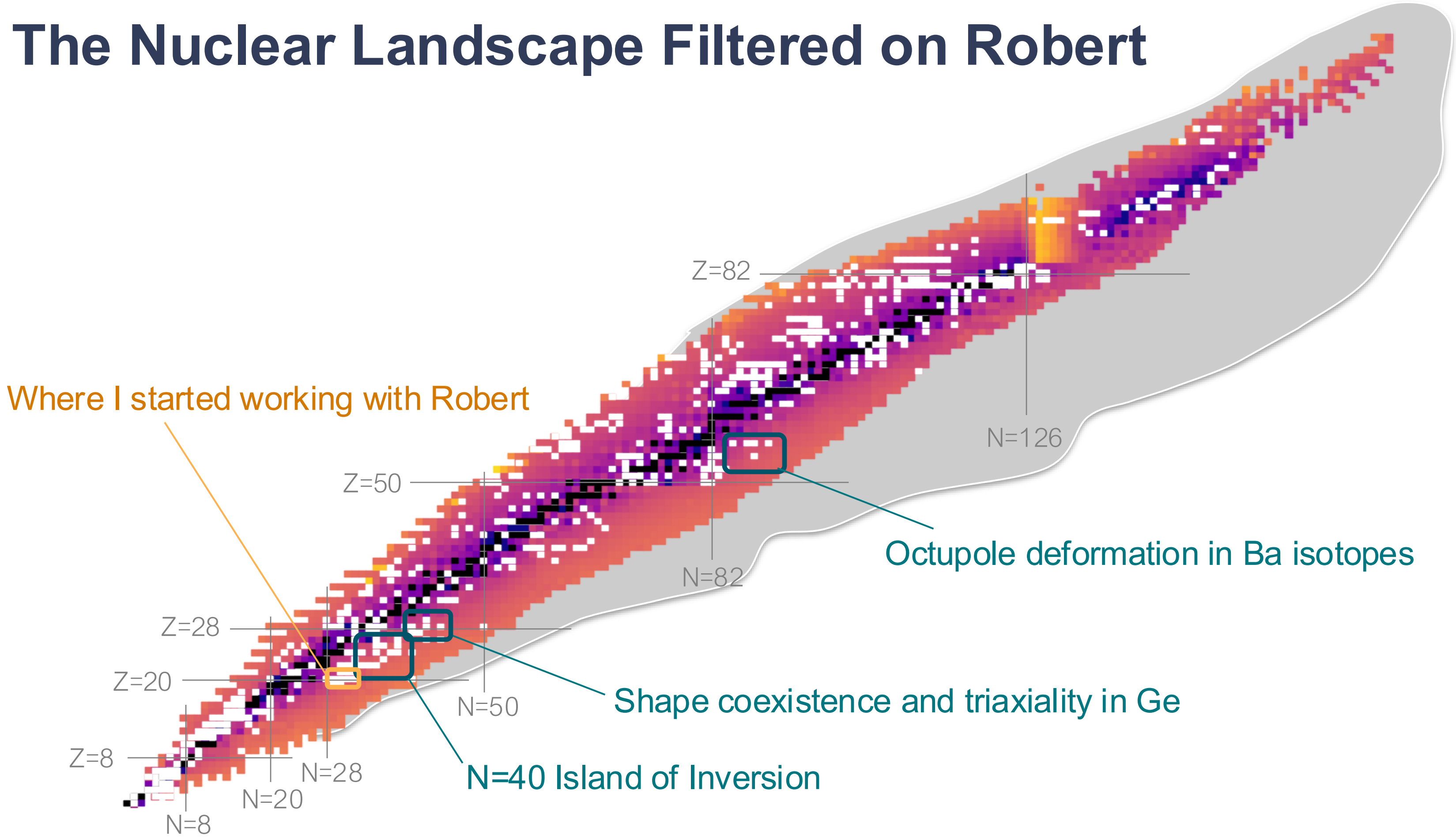

Decay Properties of Neutron-Rich Sc and Ca Isotopes

PHYSICAL REVIEW C **82**, 014311 (2010)

β decay and isomeric properties of neutron-rich Ca and Sc isotopes

H. L. Crawford,[1,2] R. V. F. Janssens,[3] P. F. Mantica,[1,2] J. S. Berryman,[1,2] R. Broda,[4] M. P. Carpenter,[3] N. Cieplicka,[4] B. Fornal,[4] G. F. Grinyer,[2] N. Hoteling,[3,5] B. P. Kay,[3] T. Lauritsen,[3] K. Minamisono,[2] I. Stefanescu,[3,5] J. B. Stoker,[1,2] W. B. Walters,[5] and S. Zhu[3]

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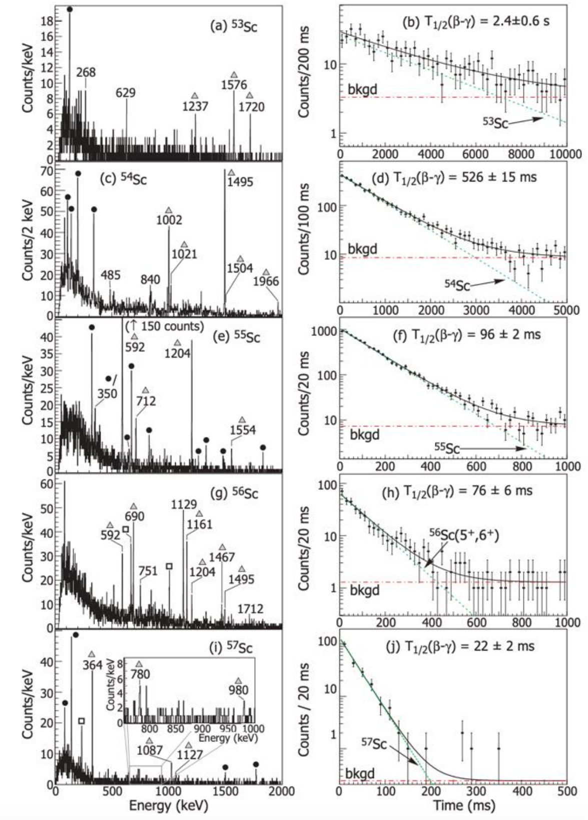
(Received 14 November 2009; revised manuscript received 10 May 2010; published 21 July 2010)

The isomeric and β-decay properties of neutron-rich $^{53-57}$Sc and ^{53,54}Ca nuclei near neutron number $N = 32$ are reported, and the low-energy level schemes of ^{53,54,56}Sc and $^{53-57}$Ti are presented. The low-energy level structures of the $_{21}$Sc isotopes are discussed in terms of the coupling of the valence $1f_{7/2}$ proton to states in the corresponding $_{20}$Ca cores. Implications with respect to the robustness of the $N = 32$ subshell closure are discussed, as well as the repercussions for a possible $N = 34$ subshell closure.

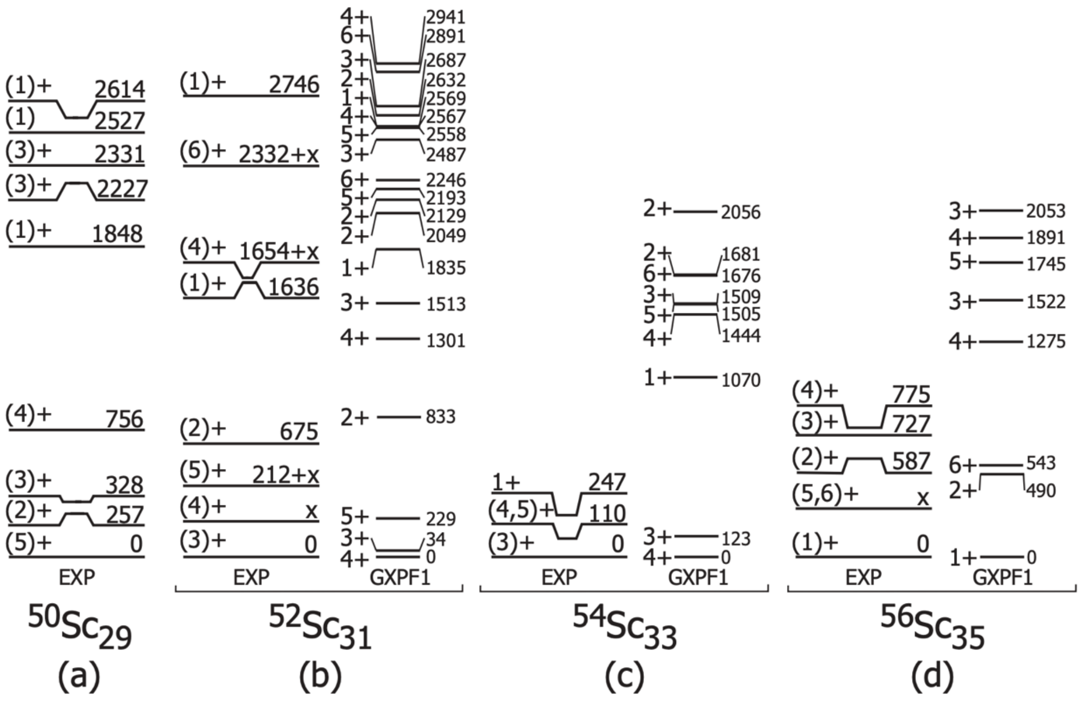
DOI: 10.1103/PhysRevC.82.014311 PACS number(s): 23.40.−s, 23.20.Lv, 27.40.+z, 29.38.Db

Decay Properties of Neutron-Rich Sc and Ca Isotopes



- A measurement of the decay of neutron-rich Sc and Ca isotopes was discretionary time at NSCL to attempt to measure the decay of ^{54}K into ^{54}Ca
- Unfortunately, this objective wasn’t met, but there was more than enough for a PhD thesis !
- Systematic study of the decays into Sc and Ti allowed level schemes to be explored and discussion of the potential (at that time) N=32,34 ‘magic’ numbers

Decay Properties of Neutron-Rich Sc and Ca Isotopes



- Consider structure in terms of coupling of $f_{7/2}$ proton to pf(g)-shell neutrons
- 1+ states can only arise from coupling with $f_{5/2}$ neutron – points to relatively close spacing with $p_{1/2}$ and weak N=34 gap in Sc – compressed spectrum in ^{54,56}Sc compared to GXPF1 which included > 1MeV gap

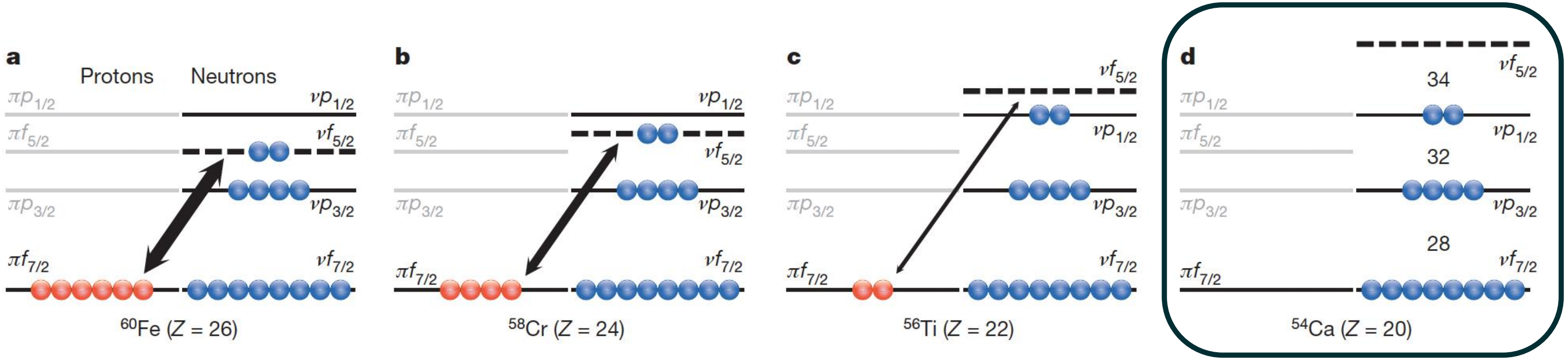
The N=34 Shell Closure?

LETTER

doi:10.1038/nature12522

Evidence for a new nuclear ‘magic number’ from the level structure of ^{54}Ca

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]



The N=34 Shell Closure?

LETTER

doi:10.1038/nature12522

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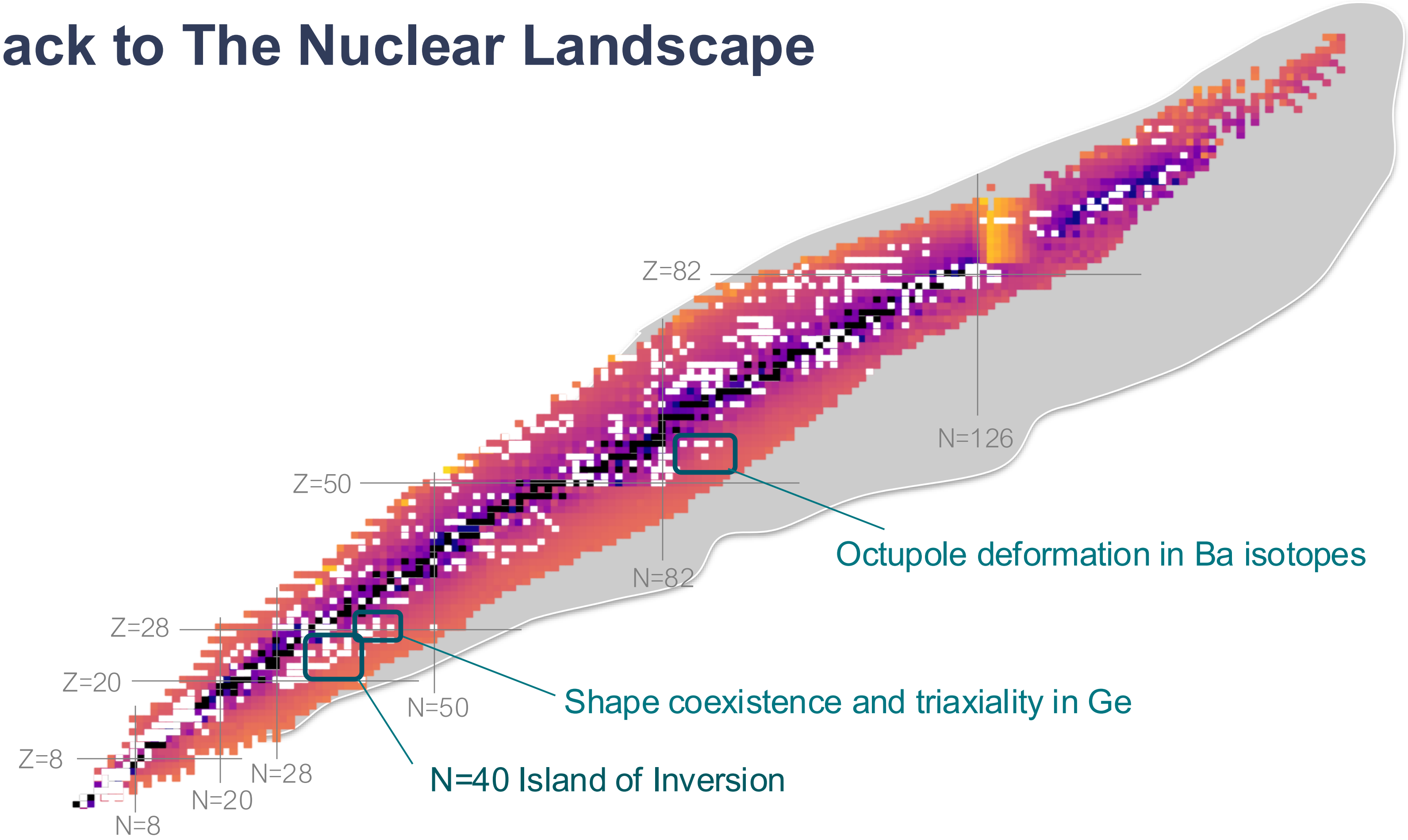
PHYSICAL REVIEW C **96**, 064310 (2017)

Structure of ^{55}Sc and development of the $N = 34$ subshell closure

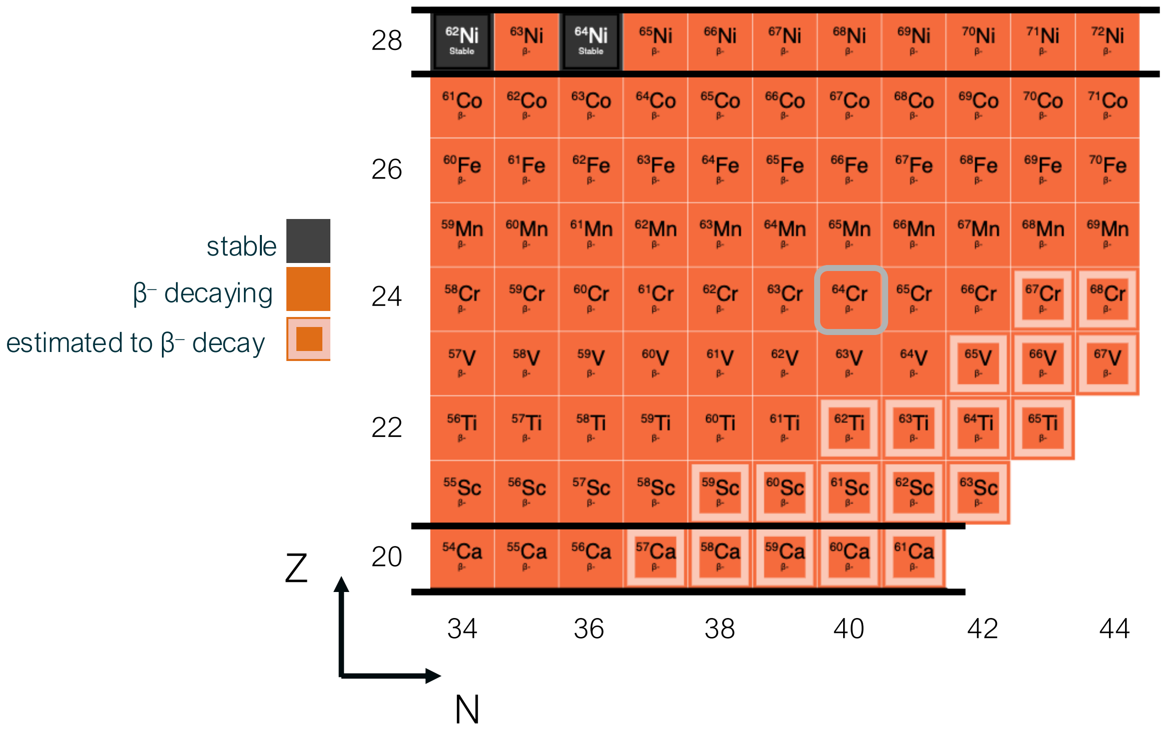
D. Steppenbeck,[1,*] S. Takeuchi,[2] N. Aoi,[3] P. Doornenbal,[1] M. Matsushita,[4] H. Wang,[1] H. Baba,[1] S. Go,[4,†] J. D. Holt,[5] J. Lee,[1,‡] K. Matsui,[6] S. Michimasa,[4] T. Motobayashi,[1] D. Nishimura,[7] T. Otsuka,[4,6,†] H. Sakurai,[1,6] Y. Shiga,[8] P.-A. Söderström,[1,§] S. R. Stroberg,[5] T. Sumikama,[9,†] R. Taniuchi,[1,6] J. A. Tostevin,[10] Y. Utsuno,[11] J. J. Valiente-Dobón,[12] and K. Yoneda[1]

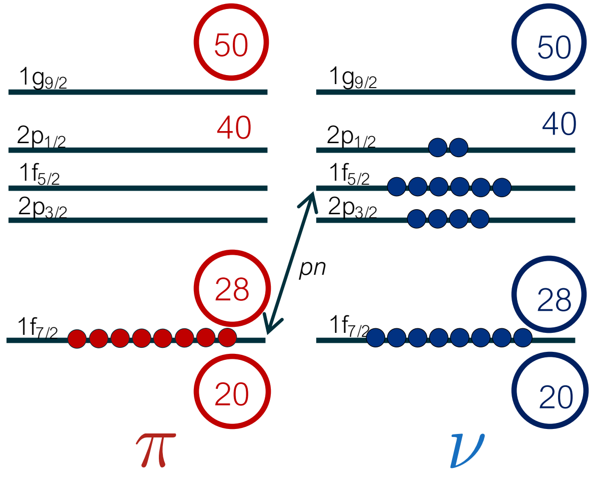
The results indicates a rapid weakening of the N=34 subshell closure in *pf*-shell nuclei at $Z > 20$, even when only a single proton occupies the $\pi f_{7/2}$ orbital.

Back to The Nuclear Landscape



The N=40 Island of Inversion





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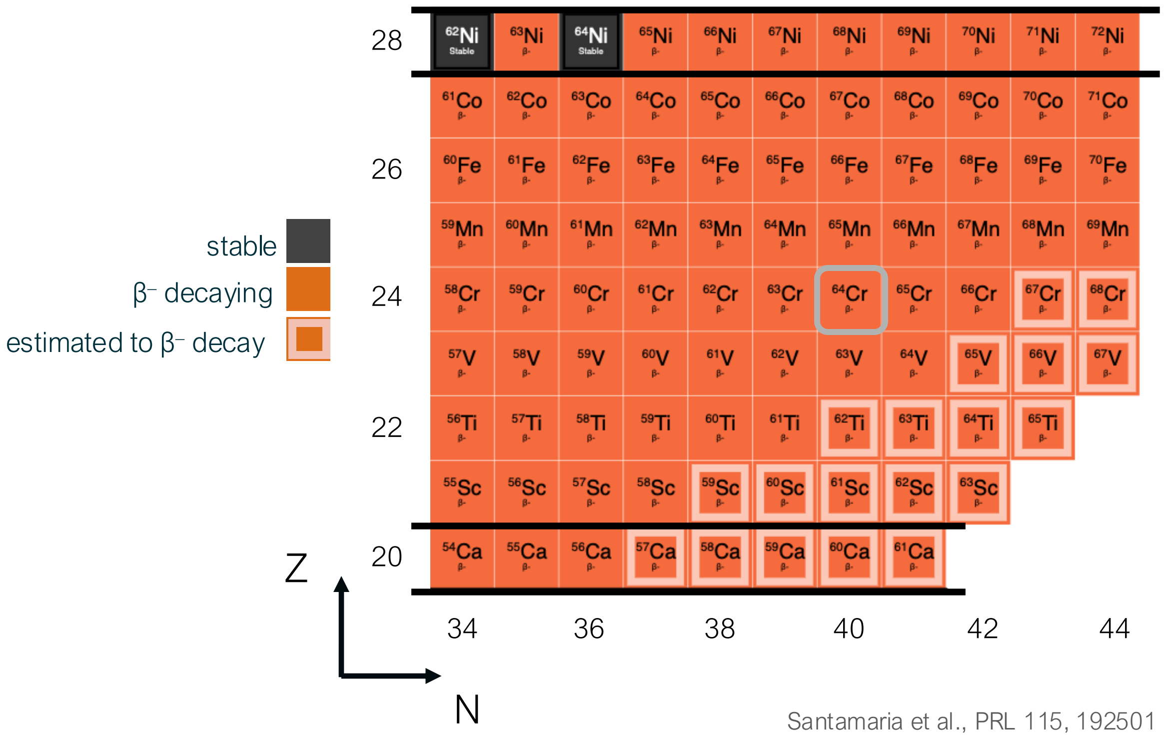

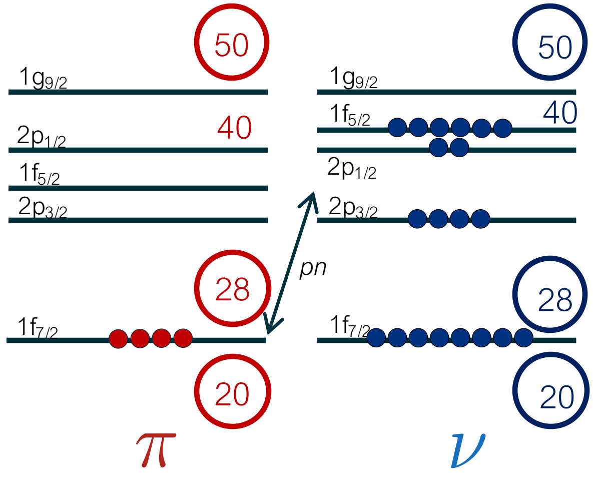

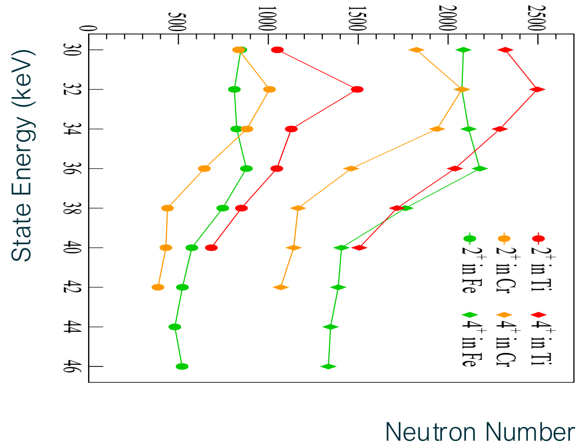

Santamaria et al., PRL 115, 192501 (2015).
Cortés et al., PLB 800, 135071 (2020)
Crawford *et al.*, PRL 110, 242701 (2013)

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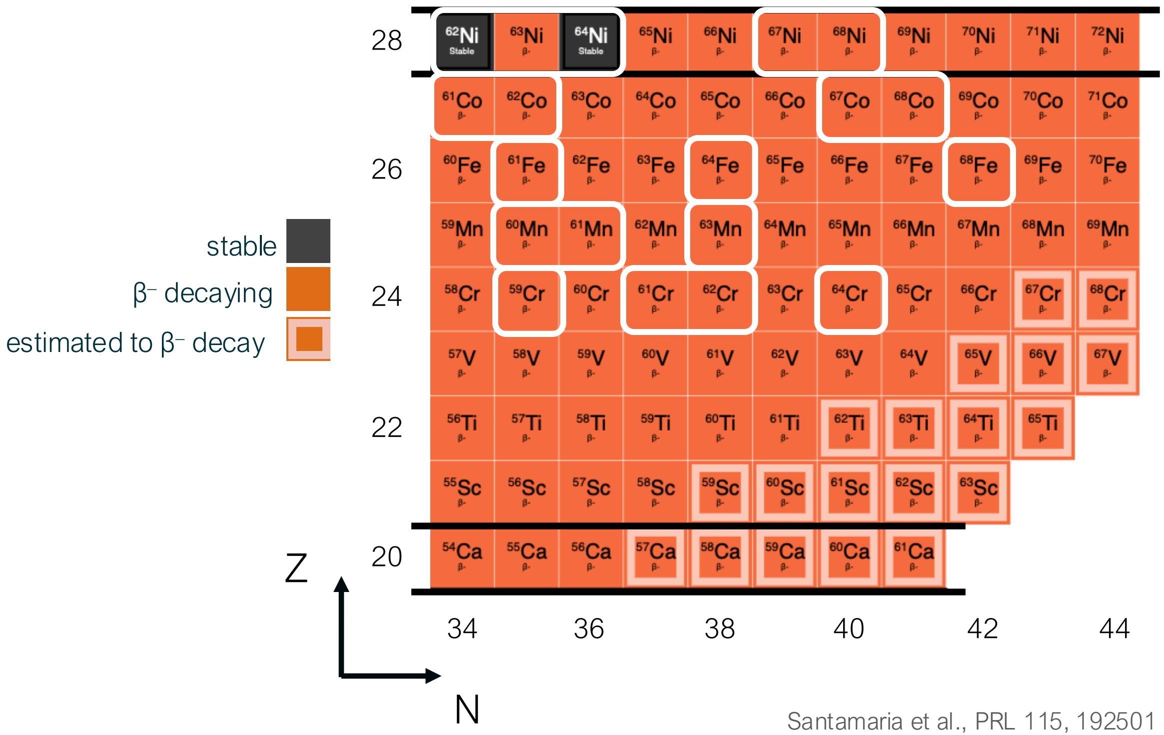

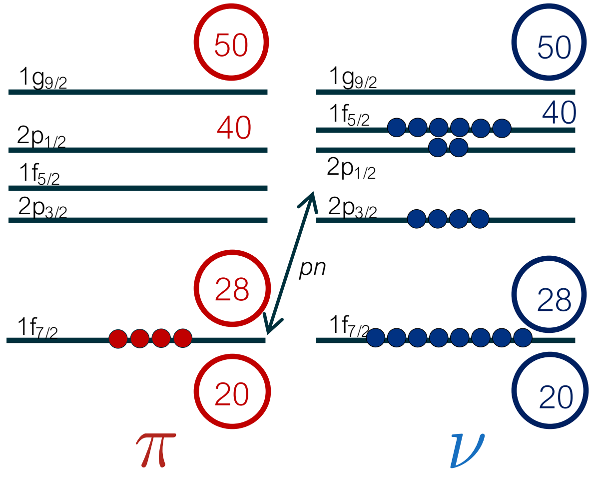

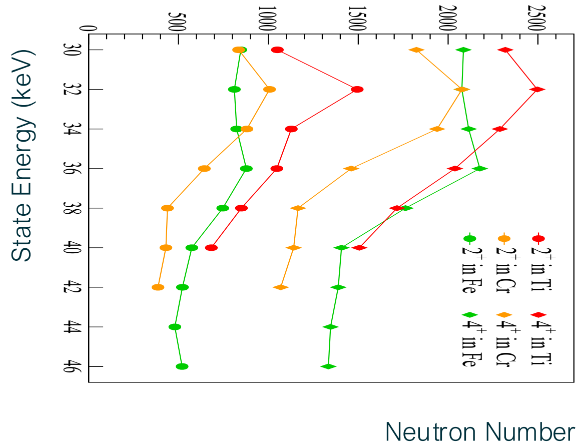

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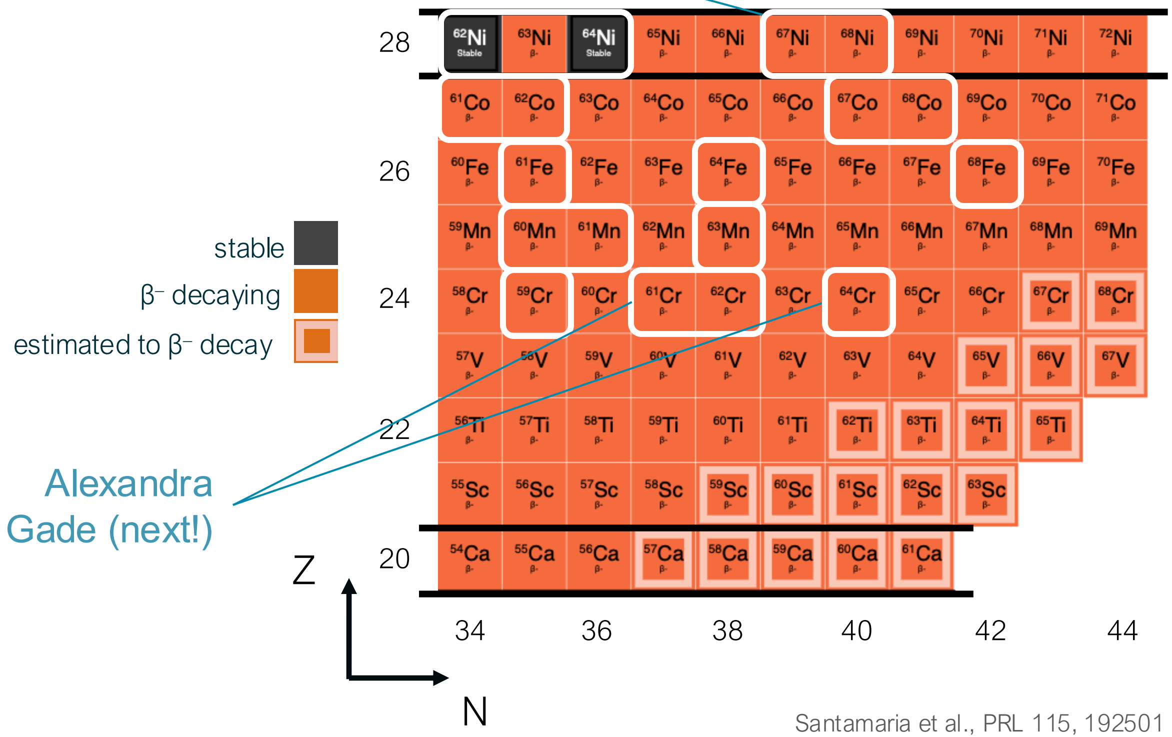

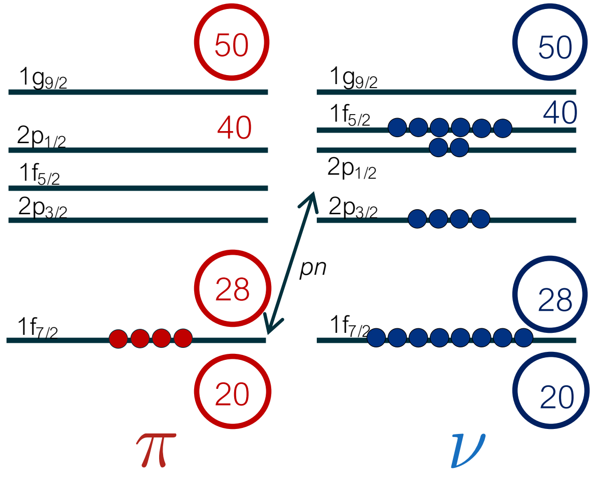

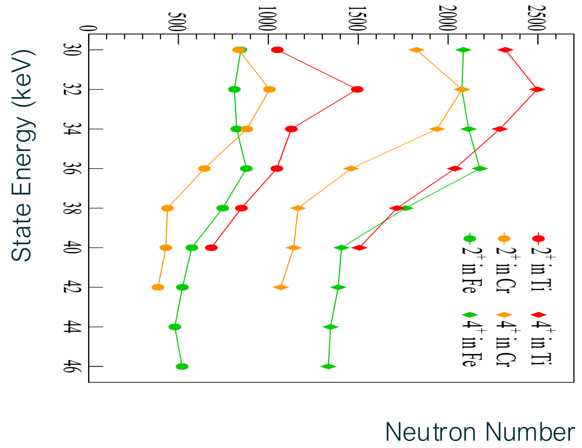

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Cortés et al., PLB 800, 135071 (2020)
Crawford *et al.*, PRL 110, 242701 (2013)

The N=40 Island of Inversion with GRETINA

Direct Lifetime Measurements of the Excited States in ^{72}Ni - K. Kolos et al. (2016)

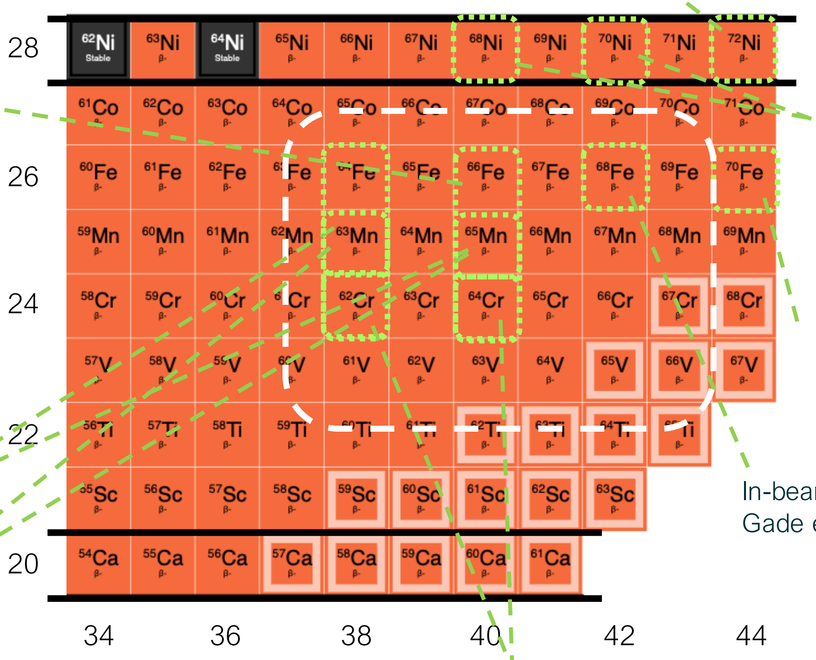
Triaxiality in ^{66}Fe - E. Rice et al. (2025)

Identification of deformed intruder states in semi-magic ^{70}Ni – C. Chiara et al. (2015)
Neutron knockout from ^{68,70}Ni – F. Recchia et al. (2016)
Probing the role of proton cross-shell excitations in ^{70}Ni – B. Elman et al. (2019)

stable

β⁻ decaying

estimated to β⁻ decay



Structure of ^{70}Fe – A. Gade et al. (2019)
Coulomb Excitation of ^{70}Fe – E. Rice et al. (2025)

Proton knockout along N=38 and N=40 - C. Porzio et al. (2025)

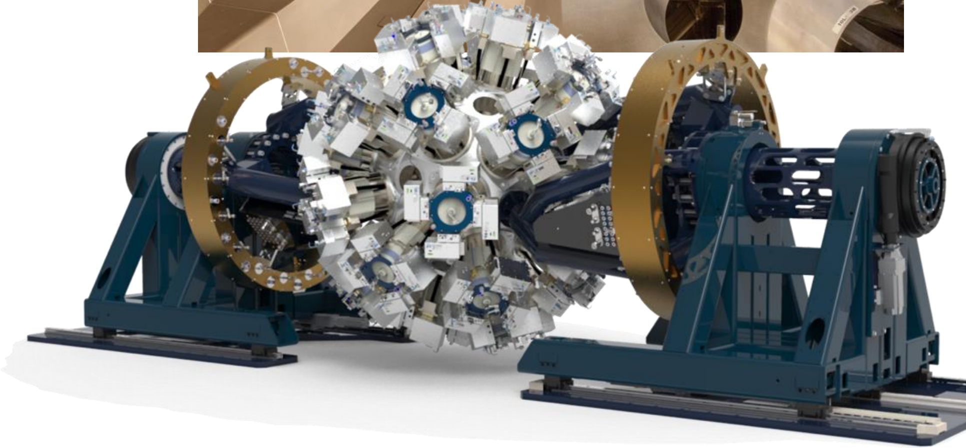
In-beam γ-ray spectroscopy of ^{68}Fe - A. Gade et al. (2021)

Coulomb Excitation of Mn Near N=40 – HLC et al. (202X)

In-beam γ-ray spectroscopy of ^{62,64}Cr - A. Gade et al. (2021)
In-beam spectroscopy reveals competing nuclear shapes in ^{62}Cr – A. Gade et al. (2024)

GRETINA and GRETA

- The physics impact of GRETINA over the past > 10 years has been substantial
- GRETINA was constructed 2003-2011, with a subsequent “enhancement” phase
- GRETA, the full 4π realization of a tracking array received CD-4A in August and will start source commissioning at FRIB in the next few months
- Robert has been a **vocal supporter and advocate for GRETA** since the beginning

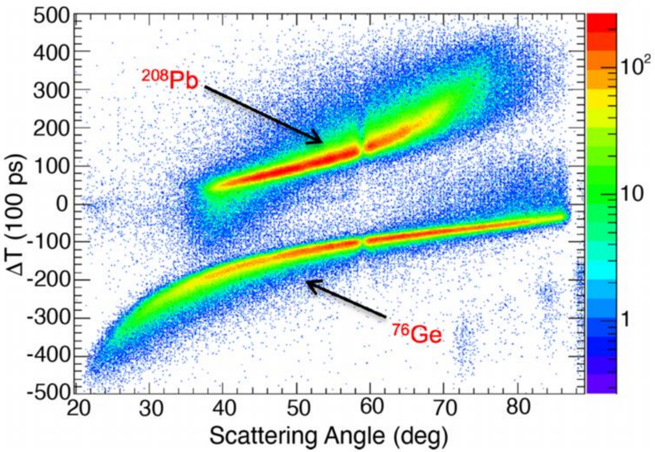


Triaxiality in Ge

- Above the N=40 IoI, ^{76}Ge has been a focus across nuclear physics as a candidate for $0\nu\beta\beta$ decay, which highlighted the need to understand the structure in this (and neighbouring nuclei) to reliably calculate the necessary nuclear matrix elements
- The Ge isotopes in this region were known to have complex wavefunctions and variation in their excitation spectra; theory predictions also suggested the importance of triaxiality
- GRETINA + CHICO2 at ATLAS offered a path forward to characterize, in detail these systems using Coulomb excitation

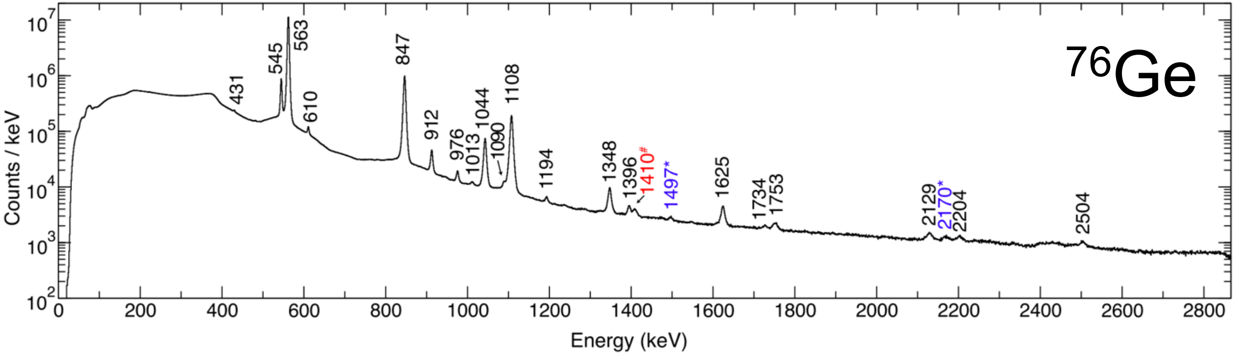
A. D. Ayangeakaa, R. V. F. Janssens *et al*., Phys. Rev. C 107, 044314 (2023).

Triaxiality in Ge



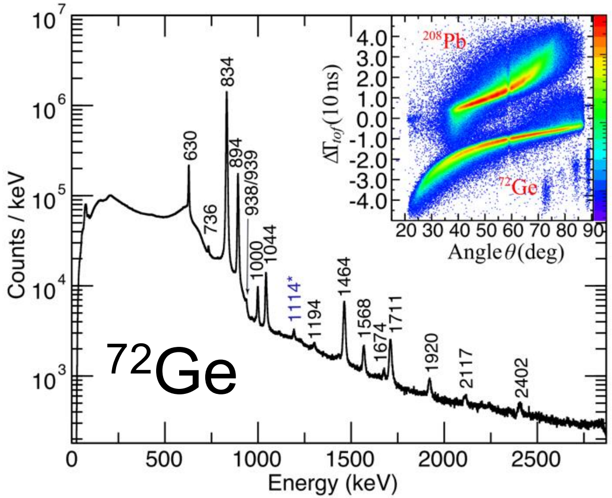
- Coulomb excitation of ^{76}Ge, detailed GOSIA analysis and comparison to theory/model predictions confirmed a rigid triaxial deformation
- This contrasts with the soft triaxial potential in ^{76}Se which will impact NME important to $0\nu\beta\beta$

A. D. Ayangeakaa, R. V. F. Janssens *et al*., Phys. Rev. Lett. **123**, 102501 (2019).
J. Henderson *et al*., Phys. Rev. C **99**, 054313 (2019).
A. D. Ayangeakaa, R. V. F. Janssens *et al*., Phys. Rev. C **107**, 044314 (2023).

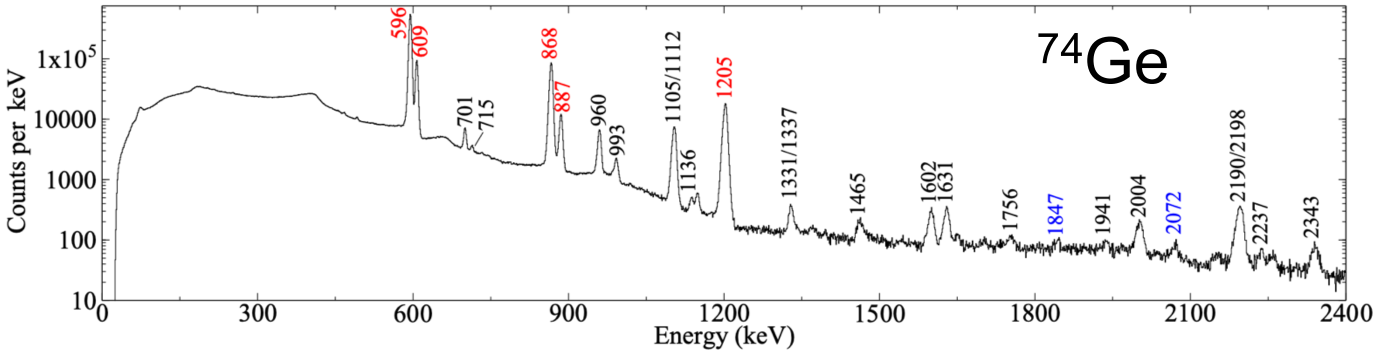


Triaxiality in Ge

- Experiments in neighouring ^{72,74}Ge further confirmed the importance of triaxiality, suggesting triaxial shape coexistence between the two lowest 0^{+} states in both systems



A. D. Ayangeakaa, R. V. F. Janssens *et al*., Phys. Lett. B **754**, 254 (2016).
N. Sensharma *et al*., Phys. Rev. C **112**, 024311 (2025).

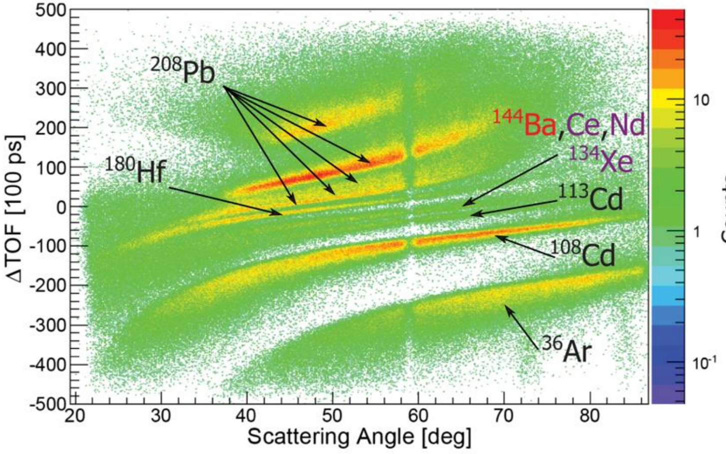


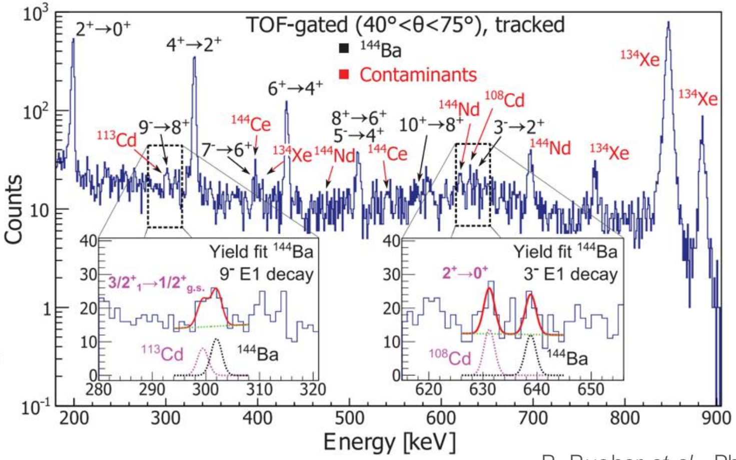
Octupoles in Ba

- The neutron-rich Ba isotopes are one region of the chart where octupole correlations were expected, with 56 protons and 88 neutrons in ^{144}Ba, two ‘octupole magic numbers’ where single-particle states separated by $\Delta l = \Delta j = 3$ orbitals are near the Fermi surface
- Before 2016, only indirect evidence for octupole correlations in the Ba isotopes had been observed (e.g. enhanced E1 transitions between g.s. and negative-parity band)
- Enter CARIBU + GRETINA + CHICO2…

Octupoles in Ba

- Coulomb excitation of ^{144}Ba, and the yield of the gamma rays depopulating the 3^- and related states enabled extraction of a E3 matrix element
- The value of $B(E3{:}3^- \rightarrow 0^+) = 48^{+25}_{-34}$ W.u. was much higher than model predictions, motivating further measurements in neighbouring isotopes (e.g. ^{143}Ba), and additional measurements in ^{144}Ba

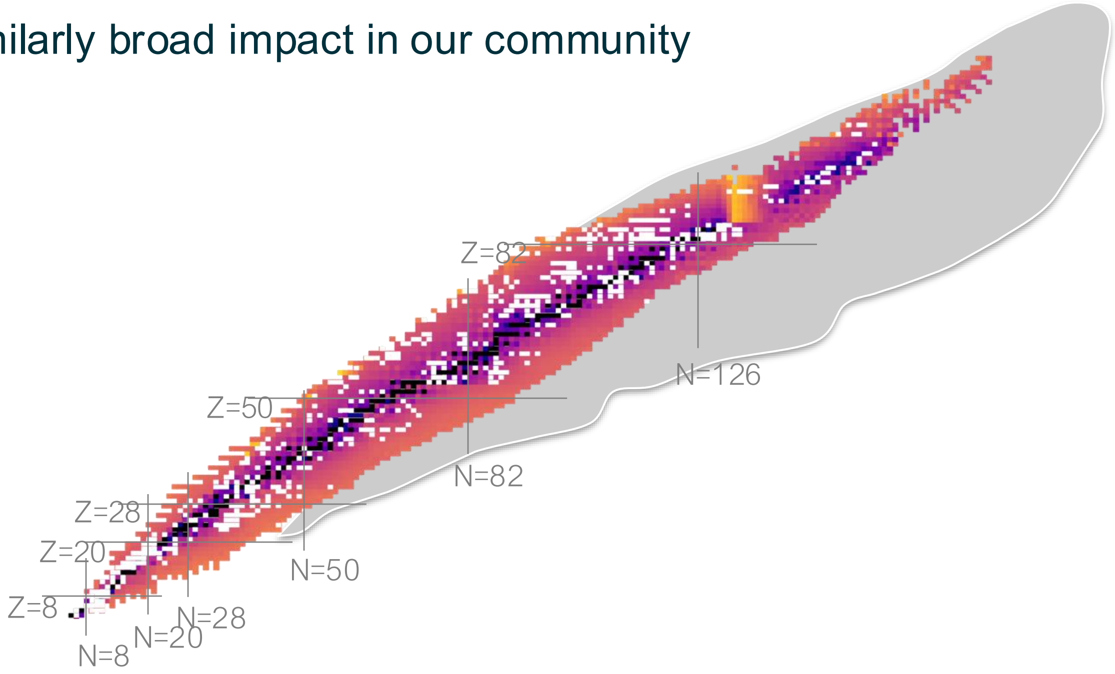




B. Bucher *et al*., Phys. Rev. Lett. **116**, 112503 (2016).
C. Morse *et al*., Phys. Rev. C **102**, 054328 (2020).

Summary

- The range of collectivity and deformation across the nuclear chart is broad, with variation in both the origin and nature of the emergent structures
- Robert has had a similarly broad impact in our community



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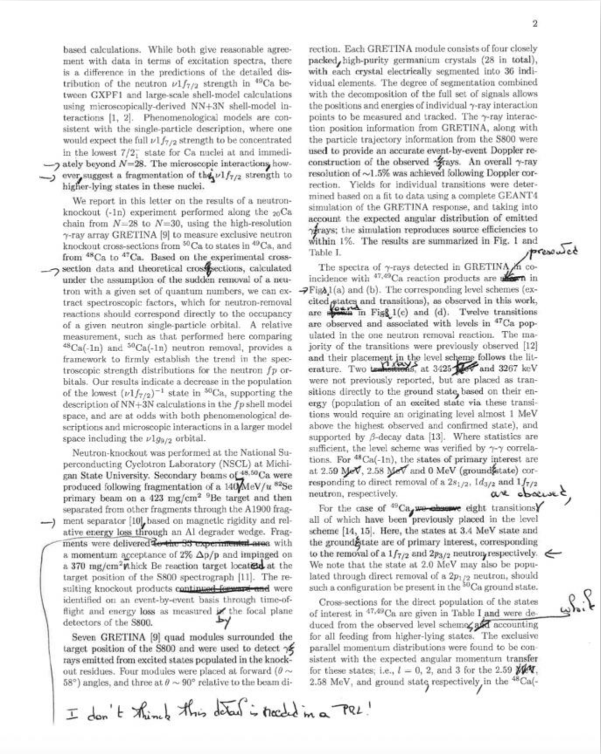

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based calculations. While both give reasonable agreement with data in terms of excitation spectra, there is a difference in the predictions of the detailed distribution of the neutron $\nu 1f_{7/2}$ strength in ^{49}Ca between GXPF1 and large-scale shell-model calculations using microscopically-derived NN+3N shell-model interactions [1, 2]. Phenomenological models are consistent with the single-particle description, where one would expect the full $\nu 1f_{7/2}$ strength to be concentrated in the lowest $7/2^-_1$ state for Ca nuclei at and immediately beyond N=28. The microscopic interactions however suggest a fragmentation of the $\nu 1f_{7/2}$ strength to higher-lying states in these nuclei.

We report in this letter on the results of a neutron-knockout (-1n) experiment performed along the $_{20}$Ca chain from N=28 to N=30, using the high-resolution γ-ray array GRETINA [9] to measure exclusive neutron knockout cross-sections from ^{50}Ca to states in ^{49}Ca, and from ^{48}Ca to ^{47}Ca. Based on the experimental cross-section data and theoretical cross sections, calculated under the assumption of the sudden removal of a neutron with a given set of quantum numbers, we can extract spectroscopic factors, which for neutron-removal reactions should correspond directly to the occupancy of a given neutron single-particle orbital. A relative measurement, such as that performed here comparing ^{48}Ca(-1n) and ^{50}Ca(-1n) neutron removal, provides a framework to firmly establish the trend in the spectroscopic strength distributions for the neutron fp orbitals. Our results indicate a decrease in the population of the lowest $(\nu 1f_{7/2})^{-1}$ state in ^{50}Ca, supporting the description of NN+3N calculations in the fp shell model space, and are at odds with both phenomenological descriptions and microscopic interactions in a larger model space including the $\nu 1g_{9/2}$ orbital.

Neutron-knockout was performed at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. Secondary beams of ^{48,50}Ca were produced following fragmentation of a 140 MeV/u ^{82}Se primary beam on a 423 mg/cm^2 ^{9}Be target and then separated from other fragments through the A1900 fragment separator [10] based on magnetic rigidity and relative energy loss through an Al degrader wedge. Fragments were delivered to the S3 experimental area with a momentum acceptance of 2% $\Delta p/p$ and impinged on a 370 mg/cm^2 thick Be reaction target located at the target position of the S800 spectrograph [11]. The resulting knockout products continued forward and were identified on an event-by-event basis through time-of-flight and energy loss as measured in the focal plane detectors of the S800.

Seven GRETINA [9] quad modules surrounded the target position of the S800 and were used to detect γ rays emitted from excited states populated in the knockout residues. Four modules were placed at forward ($\theta \sim 58°$) angles, and three at $\theta \sim 90°$ relative to the beam direction. Each GRETINA module consists of four closely packed high-purity germanium crystals (28 in total), with each crystal electrically segmented into 36 individual elements. The degree of segmentation combined with the decomposition of the full set of signals allows the positions and energies of individual γ-ray interaction points to be measured and tracked. The γ-ray interaction position information from GRETINA, along with the particle trajectory information from the S800 were used to provide an accurate event-by-event Doppler reconstruction of the observed γ rays. An overall γ-ray resolution of ~1.5% was achieved following Doppler correction. Yields for individual transitions were determined based on a fit to data using a complete GEANT4 simulation of the GRETINA response, and taking into account the expected angular distribution of emitted γ rays; the simulation reproduces source efficiencies to within 1%. The results are summarized in Fig. 1 and Table I.

The spectra of γ-rays detected in GRETINA in coincidence with ^{47,49}Ca reaction products are shown in Fig. 1(a) and (b). The corresponding level schemes (excited states and transitions), as observed in this work, are shown in Fig. 1(c) and (d). Twelve transitions are observed and associated with levels in ^{47}Ca populated in the one neutron removal reaction. The majority of the transitions were previously observed [12] and their placement in the level scheme follows the literature. Two transitions, at 3425 keV and 3267 keV were not previously reported, but are placed as transitions directly to the ground state based on their energy (population of an excited state via these transitions would require an originating level almost 1 MeV above the highest observed and confirmed state), and supported by β-decay data [13]. Where statistics are sufficient, the level scheme was verified by γ-γ correlations. For ^{48}Ca(-1n), the states of primary interest are at 2.59 MeV, 2.58 MeV and 0 MeV (ground state) corresponding to direct removal of a $2s_{1/2}$, $1d_{3/2}$ and $1f_{7/2}$ neutron, respectively.

For the case of ^{49}Ca, we observe eight transitions all of which have been previously placed in the level scheme [14, 15]. Here, the states at 3.4 MeV state and the ground state are of primary interest, corresponding to the removal of a $1f_{7/2}$ and $2p_{3/2}$ neutron respectively. We note that the state at 2.0 MeV may also be populated through direct removal of a $2p_{1/2}$ neutron, should such a configuration be present in the ^{50}Ca ground state.

Cross-sections for the direct population of the states of interest in ^{47,49}Ca are given in Table I and were deduced from the observed level scheme and accounting for all feeding from higher-lying states. The exclusive parallel momentum distributions were found to be consistent with the expected angular momentum transfer for these states; i.e., l = 0, 2, and 3 for the 2.59 MeV, 2.58 MeV, and ground state respectively in the ^{48}Ca(-

My cleanest page of feedback from Robert – only 2 hyphen issues (personal best)!!

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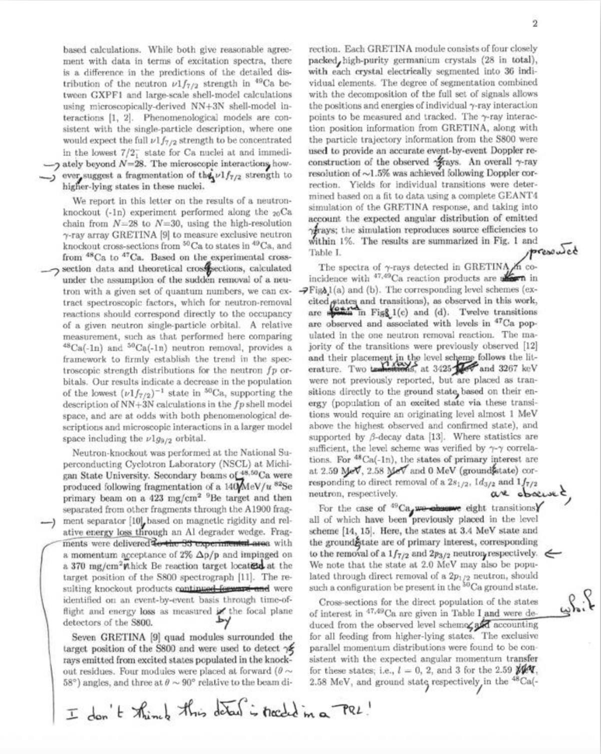
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We report in this letter on the results of a neutron-knockout (-1n) experiment performed along the $_{20}$Ca chain from N=28 to N=30, using the high-resolution γ-ray array GRETINA [9] to measure exclusive neutron knockout cross-sections from ^{50}Ca to states in ^{49}Ca, and from ^{48}Ca to ^{47}Ca. Based on the experimental cross-section data and theoretical cross sections, calculated under the assumption of the sudden removal of a neutron with a given set of quantum numbers, we can extract spectroscopic factors, which for neutron-removal reactions should correspond directly to the occupancy of a given neutron single-particle orbital. A relative measurement, such as that performed here comparing ^{48}Ca(-1n) and ^{50}Ca(-1n) neutron removal, provides a framework to firmly establish the trend in the spectroscopic strength distributions for the neutron fp orbitals. Our results indicate a decrease in the population of the lowest $(\nu 1f_{7/2})^{-1}$ state in ^{50}Ca, supporting the description of NN+3N calculations in the fp shell model space, and are at odds with both phenomenological descriptions and microscopic interactions in a larger model space including the $\nu 1g_{9/2}$ orbital.

Neutron-knockout was performed at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. Secondary beams of ^{48,50}Ca were produced following fragmentation of a 140 MeV/u ^{82}Se primary beam on a 423 mg/cm^2 ^{9}Be target and then separated from other fragments through the A1900 fragment separator [10] based on magnetic rigidity and relative energy loss through an Al degrader wedge. Fragments were delivered to the S3 experimental area with a momentum acceptance of 2% $\Delta p/p$ and impinged on a 370 mg/cm^2 thick Be reaction target located at the target position of the S800 spectrograph [11]. The resulting knockout products continued forward and were identified on an event-by-event basis through time-of-flight and energy loss as measured in the focal plane detectors of the S800.

Seven GRETINA [9] quad modules surrounded the target position of the S800 and were used to detect γ rays emitted from excited states populated in the knockout residues. Four modules were placed at forward ($\theta \sim 58°$) angles, and three at $\theta \sim 90°$ relative to the beam direction. Each GRETINA module consists of four closely packed high-purity germanium crystals (28 in total), with each crystal electrically segmented into 36 individual elements. The degree of segmentation combined with the decomposition of the full set of signals allows the positions and energies of individual γ-ray interaction points to be measured and tracked. The γ-ray interaction position information from GRETINA, along with the particle trajectory information from the S800 were used to provide an accurate event-by-event Doppler reconstruction of the observed γrays. An overall γ-ray resolution of ~1.5% was achieved following Doppler correction. Yields for individual transitions were determined based on a fit to data using a complete GEANT4 simulation of the GRETINA response, and taking into account the expected angular distribution of emitted γrays; the simulation reproduces source efficiencies to within 1%. The results are summarized in Fig. 1 and Table I.

The spectra of γ-rays detected in GRETINA in coincidence with ^{47,49}Ca reaction products are shown in Fig. 1(a) and (b). The corresponding level schemes (excited states and transitions), as observed in this work, are shown in Fig. 1(c) and (d). Twelve transitions are observed and associated with levels in ^{47}Ca populated in the one neutron removal reaction. The majority of the transitions were previously observed [12] and their placement in the level scheme follows the literature. Two transitions, at 3425 keV and 3267 keV were not previously reported, but are placed as transitions directly to the ground state based on their energy (population of an excited state via these transitions would require an originating level almost 1 MeV above the highest observed and confirmed state), and supported by β-decay data [13]. Where statistics are sufficient, the level scheme was verified by γ-γ correlations. For ^{48}Ca(-1n), the states of primary interest are at 2.59 MeV, 2.58 MeV and 0 MeV (ground state) corresponding to direct removal of a $2s_{1/2}$, $1d_{3/2}$ and $1f_{7/2}$ neutron, respectively.

For the case of ^{49}Ca, we observe eight transitions all of which have been previously placed in the level scheme [14, 15]. Here, the states at 3.4 MeV state and the ground state are of primary interest, corresponding to the removal of a $1f_{7/2}$ and $2p_{3/2}$ neutron respectively. We note that the state at 2.0 MeV may also be populated through direct removal of a $2p_{1/2}$ neutron, should such a configuration be present in the ^{50}Ca ground state.

Cross-sections for the direct population of the states of interest in ^{47,49}Ca are given in Table I and were deduced from the observed level scheme and accounting for all feeding from higher-lying states. The exclusive parallel momentum distributions were found to be consistent with the expected angular momentum transfer for these states; i.e., l = 0, 2, and 3 for the 2.59 MeV, 2.58 MeV, and ground state respectively in the ^{48}Ca(-

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Thank you