Marco Rocchini

INFN - Istituto Nazionale di Fisica Nucleare

FIRENZE DIVISION

Axial Shape Asymmetry and Configuration Coexistence in Neutron-Rich ^{74}Zn: Suggestion for a Northern Extension of the N = 40 Island of Inversion

UNIVERSITY of GUELPH

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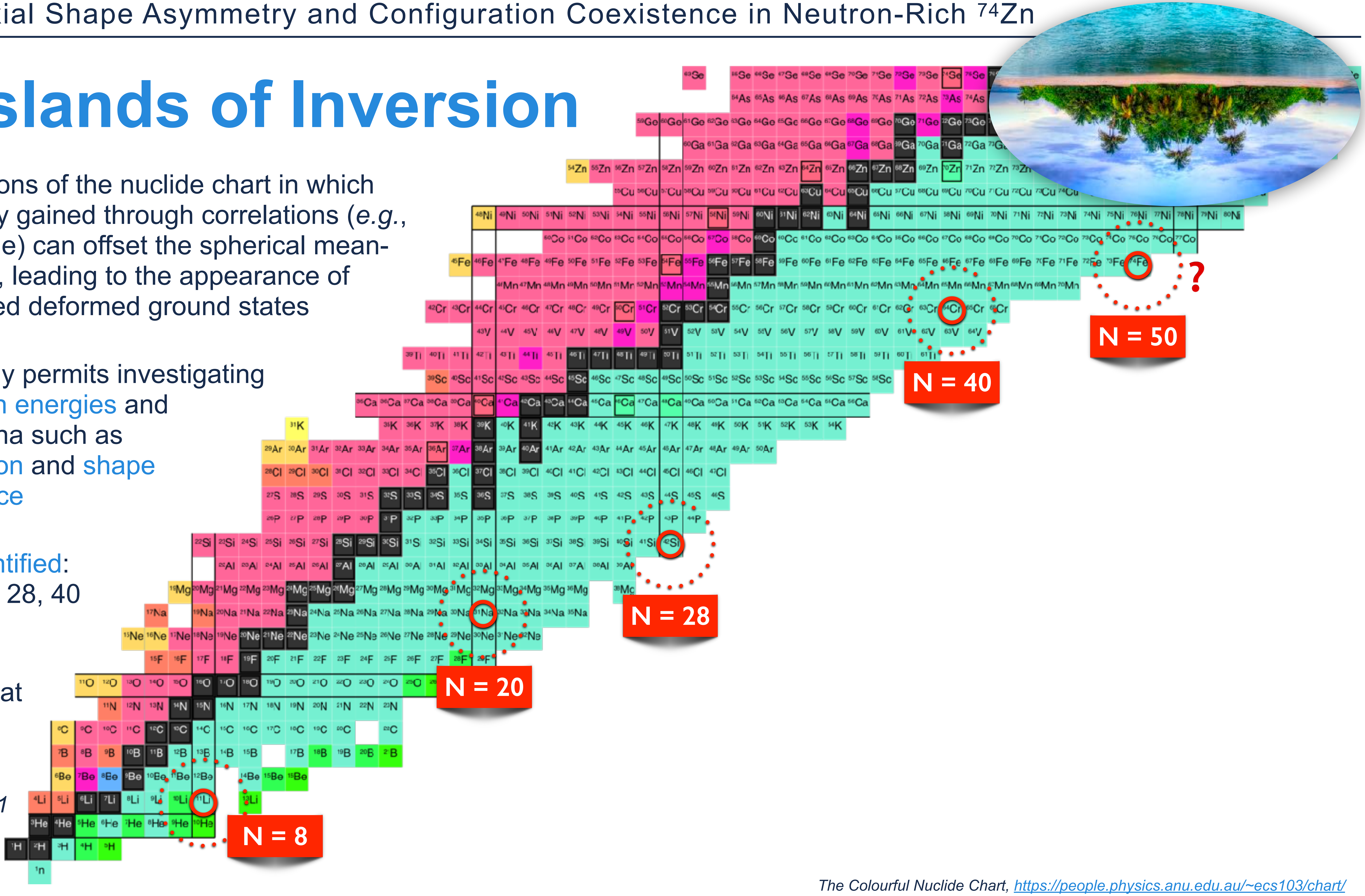
Islands of Inversion

- IoIs, Shape Coexistence and Triaxiality
- GRIFFIN @TRIUMF
- Our Experiment on ^{74}Zn
- γ-γ Angular Correlations
- Experimental Results
- LSSM Calculations
- Shapes and Occupations
- Conclusions

- IoIs: Regions of the nuclide chart in which the energy gained through correlations (*e.g.*, quadrupole) can offset the spherical mean-field gaps, leading to the appearance of unexpected deformed ground states
- Their study permits investigating correlation energies and phenomena such as deformation and shape coexistence
- 4 IoIs identified: N = 8, 20, 28, 40
- 1 new IoI theorised at N = 50 *F. Nowacki et al., PRL 117, 272501 (2016)*



The Colourful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/

Islands of Inversion

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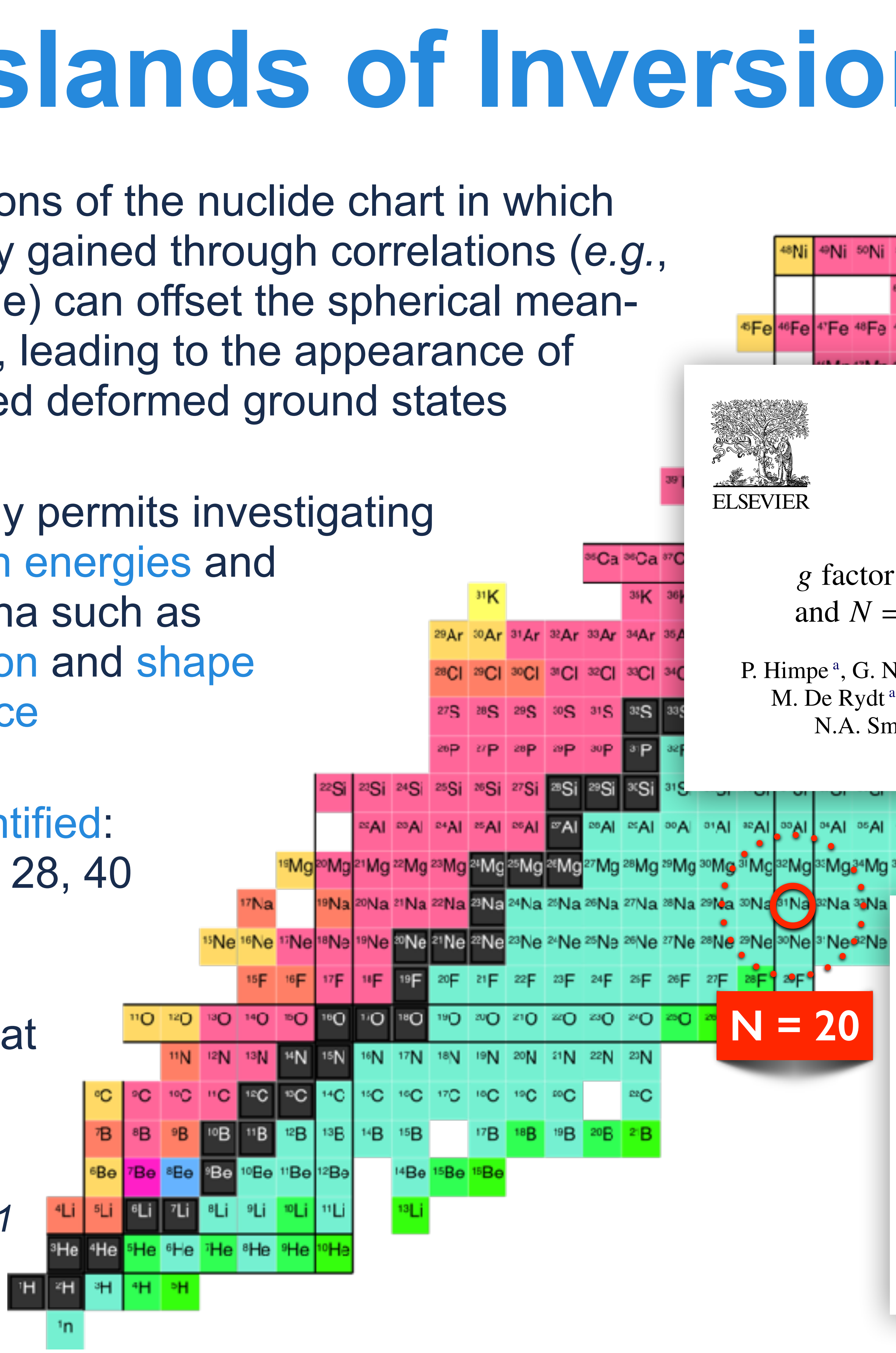

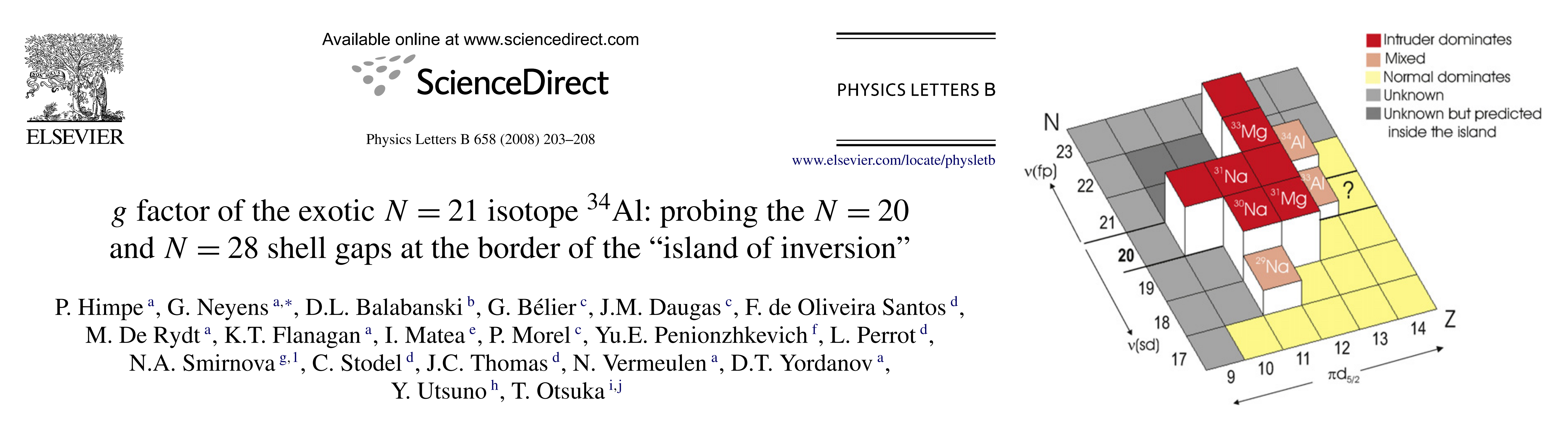
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Physics Letters B 658 (2008) 203–208
PHYSICS LETTERS B
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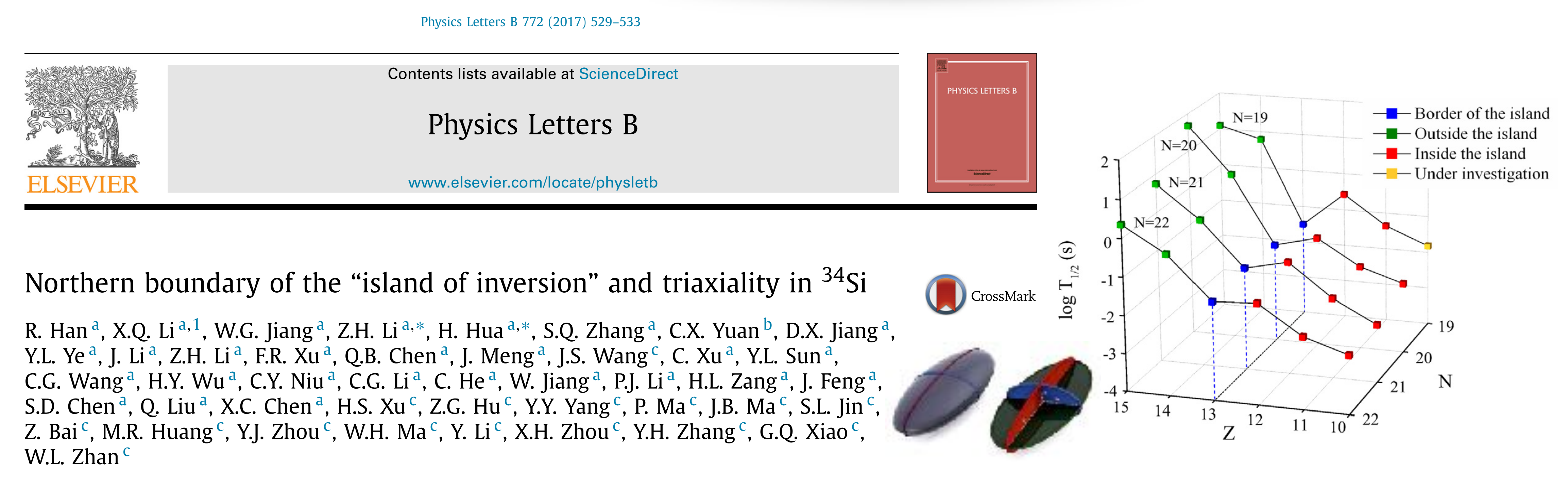
g factor of the exotic $N = 21$ isotope ^{34}Al: probing the $N = 20$ and $N = 28$ shell gaps at the border of the "island of inversion"

P. Himpe[a], G. Neyens[a,*], D.L. Balabanski[b], G. Bélier[c], J.M. Daugas[c], F. de Oliveira Santos[d], M. De Rydt[a], K.T. Flanagan[a], I. Matea[e], P. Morel[c], Yu.E. Penionzhkevich[f], L. Perrot[d], N.A. Smirnova[g,1], C. Stodel[d], J.C. Thomas[d], N. Vermeulen[a], D.T. Yordanov[a], Y. Utsuno[h], T. Otsuka[i,j]

The search for the boundaries of the IoIs


Physics Letters B 772 (2017) 529–533
Contents lists available at ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb
ELSEVIER

Northern boundary of the "island of inversion" and triaxiality in ^{34}Si

R. Han[a], X.Q. Li[a,1], W.G. Jiang[a], Z.H. Li[a,*], H. Hua[a,*], S.Q. Zhang[a], C.X. Yuan[b], D.X. Jiang[a], Y.L. Ye[a], J. Li[a], Z.H. Li[a], F.R. Xu[a], Q.B. Chen[a], J. Meng[a], J.S. Wang[c], C. Xu[a], Y.L. Sun[a], C.G. Wang[a], H.Y. Wu[a], C.Y. Niu[a], C.G. Li[a], C. He[a], W. Jiang[a], P.J. Li[a], H.L. Zang[a], J. Feng[a], S.D. Chen[a], Q. Liu[a], X.C. Chen[a], H.S. Xu[c], Z.G. Hu[c], Y.Y. Yang[c], P. Ma[c], J.B. Ma[c], S.L. Jin[c], Z. Bai[c], M.R. Huang[c], Y.J. Zhou[c], W.H. Ma[c], Y. Li[c], X.H. Zhou[c], Y.H. Zhang[c], G.Q. Xiao[c], W.L. Zhan[c]

The Colourful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/

Islands of Inversion

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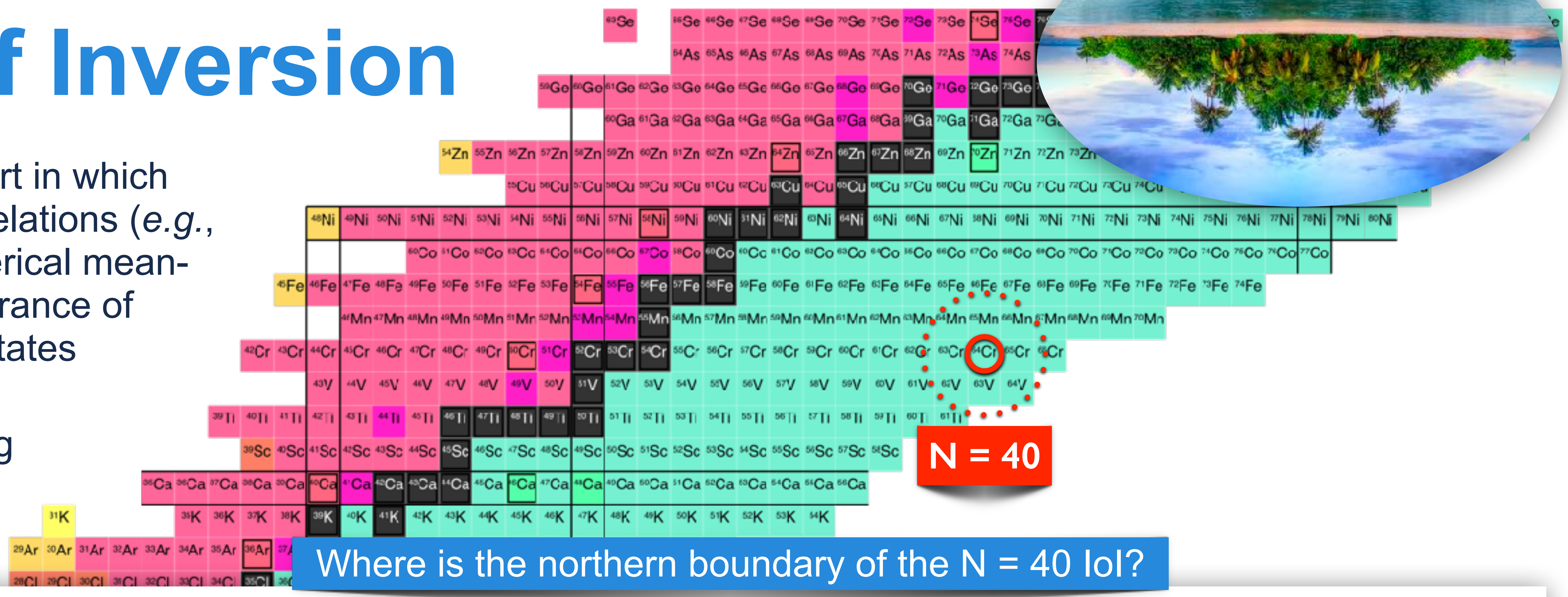
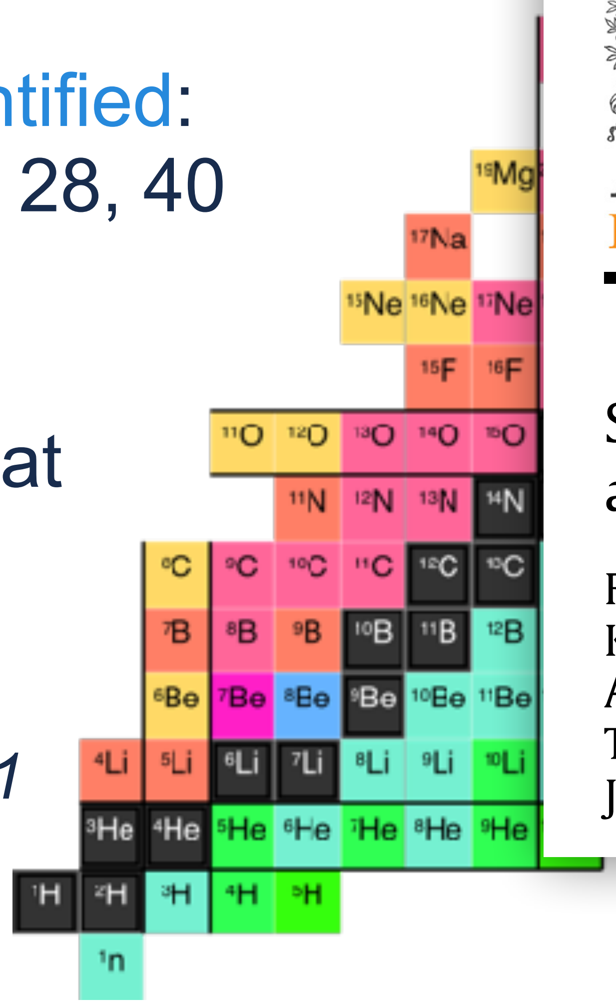
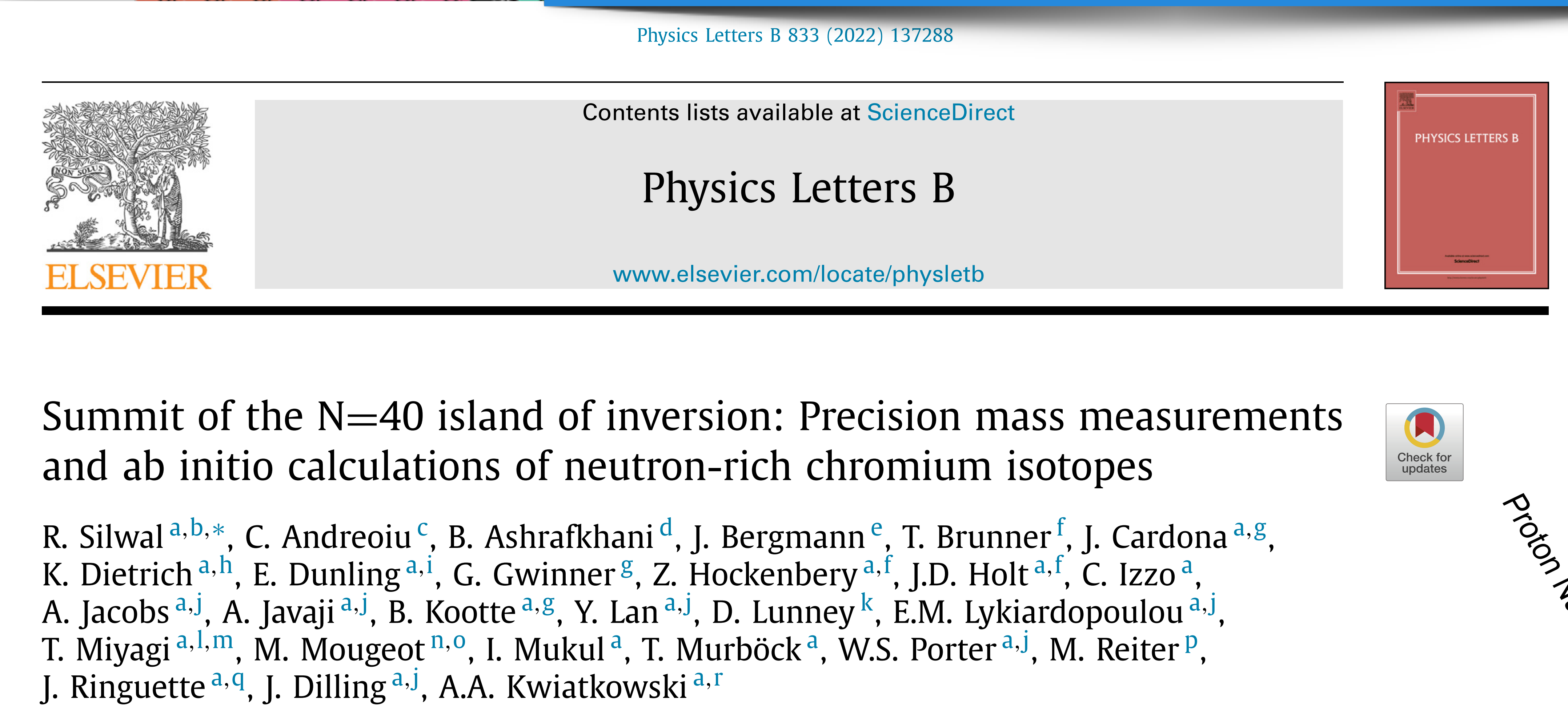




Where is the northern boundary of the N = 40 IoI?



Physics Letters B 833 (2022) 137288

Contents lists available at ScienceDirect

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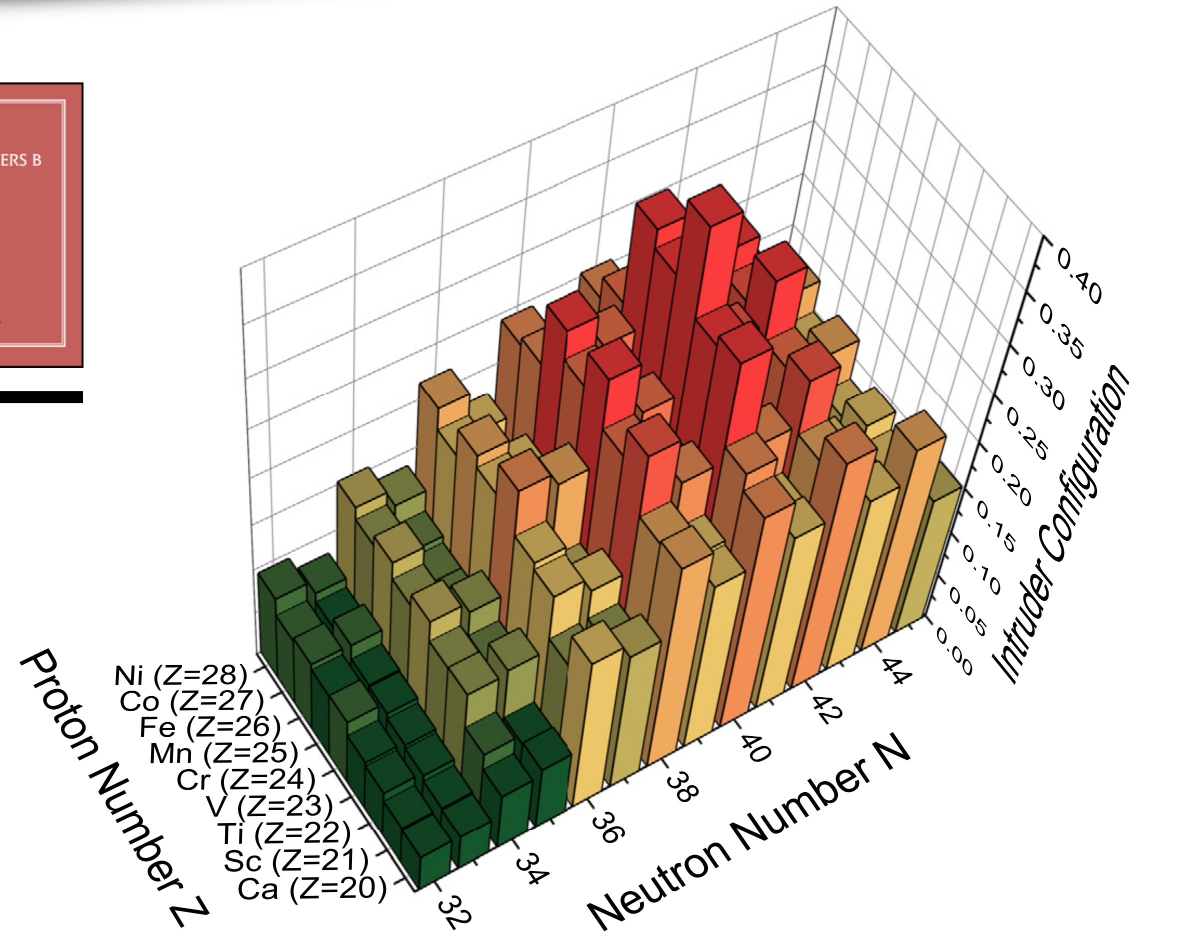
ELSEVIER

Summit of the N=40 island of inversion: Precision mass measurements and ab initio calculations of neutron-rich chromium isotopes

R. Silwal[a,b,*], C. Andreoiu[c], B. Ashrafkhani[d], J. Bergmann[e], T. Brunner[f], J. Cardona[a,g], K. Dietrich[a,h], E. Dunling[a,i], G. Gwinner[g], Z. Hockenbery[a,f], J.D. Holt[a,f], C. Izzo[a], A. Jacobs[a,j], A. Javaji[a,j], B. Kootte[a,g], Y. Lan[a,j], D. Lunney[k], E.M. Lykiardopoulou[a,j], T. Miyagi[a,l,m], M. Mougeot[n,o], I. Mukul[a], T. Murböck[a], W.S. Porter[a,j], M. Reiter[p], J. Ringuette[a,q], J. Dilling[a,j], A.A. Kwiatkowski[a,r]



The Colourful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/

Islands of Inversion

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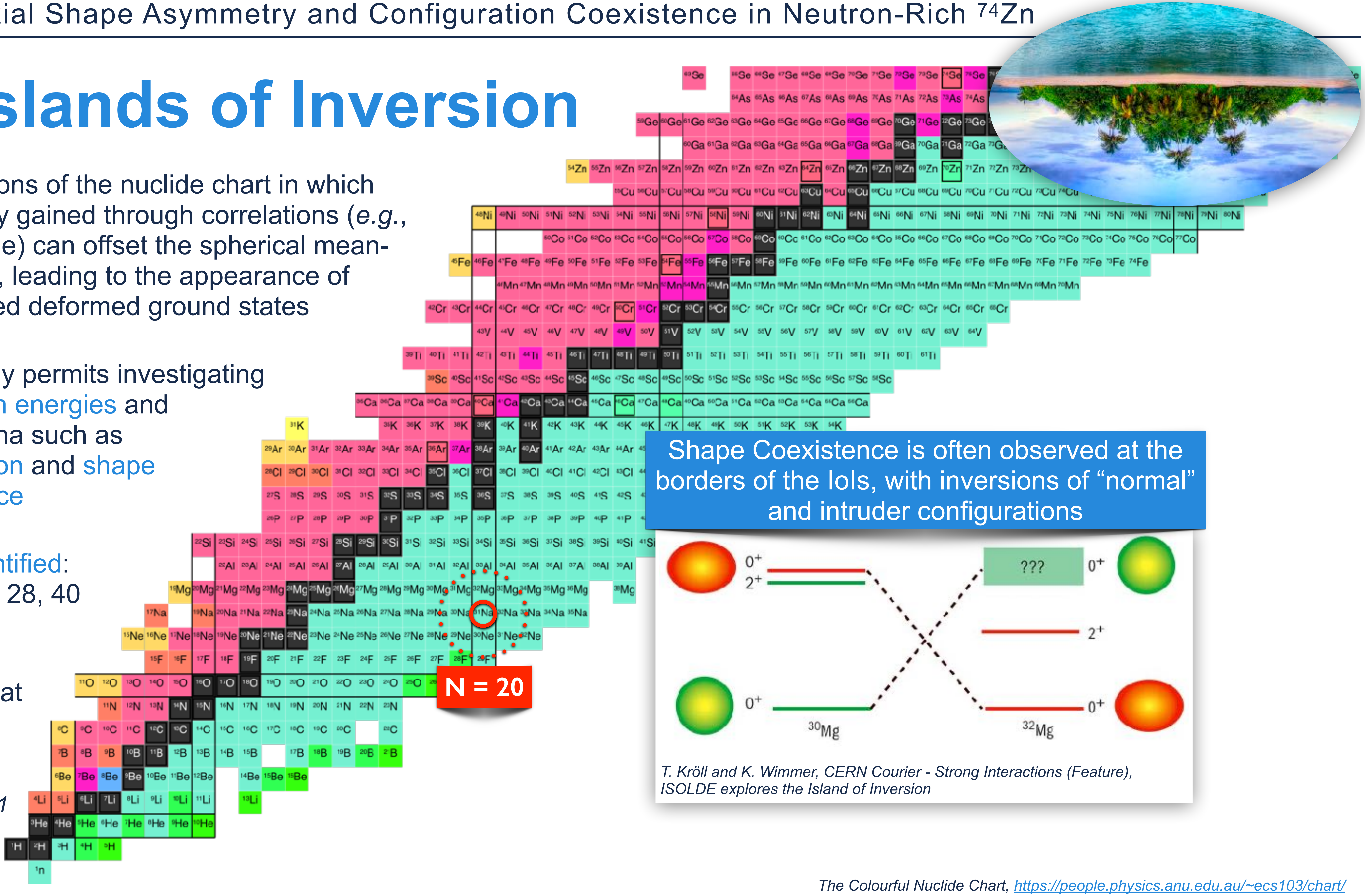
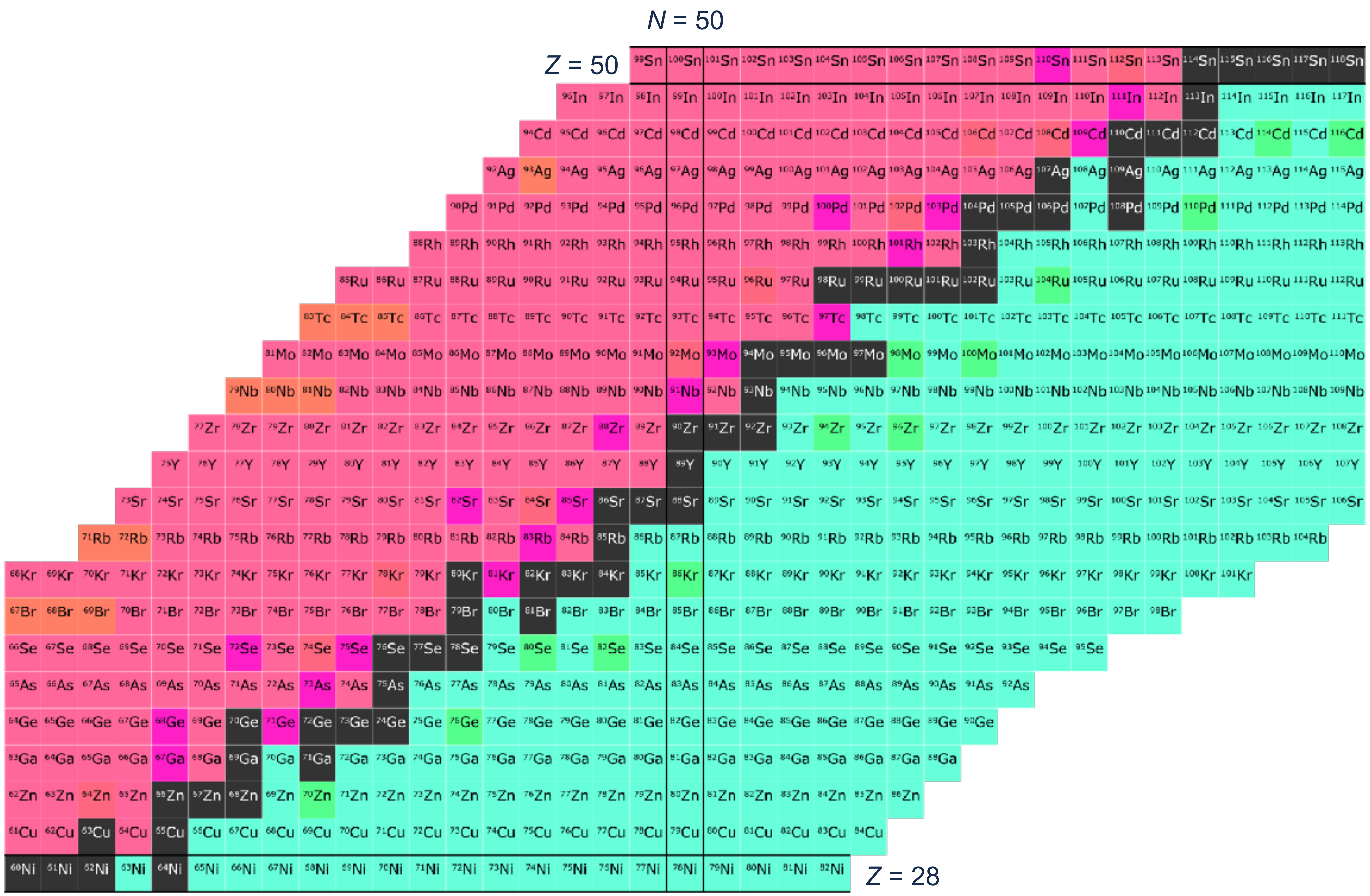


Shape Coexistence is often observed at the borders of the IoIs, with inversions of “normal” and intruder configurations

T. Kröll and K. Wimmer, CERN Courier - Strong Interactions (Feature), ISOLDE explores the Island of Inversion

The Colourful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/

Shape Coexistence between Z = 28 and Z = 50



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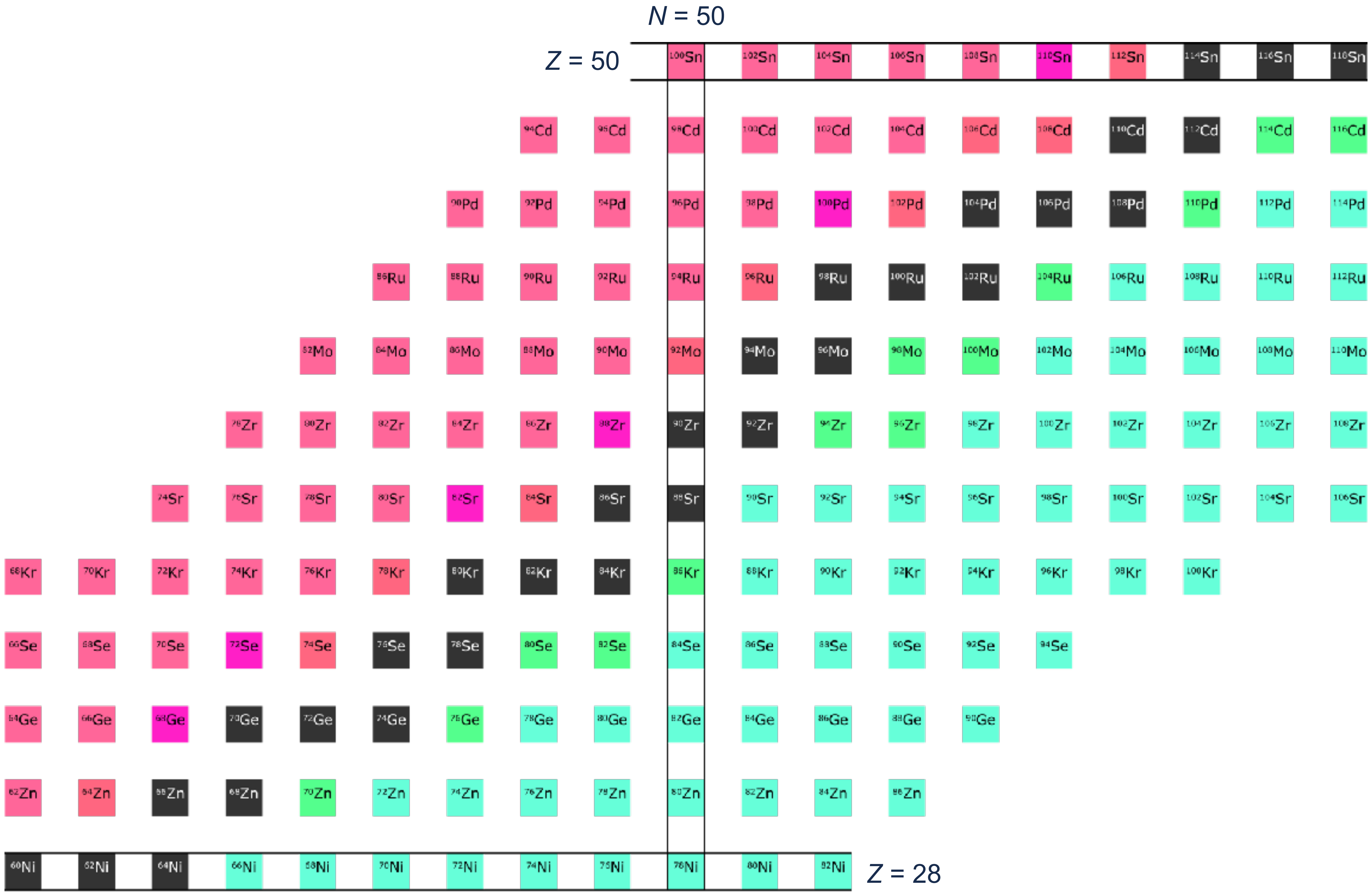

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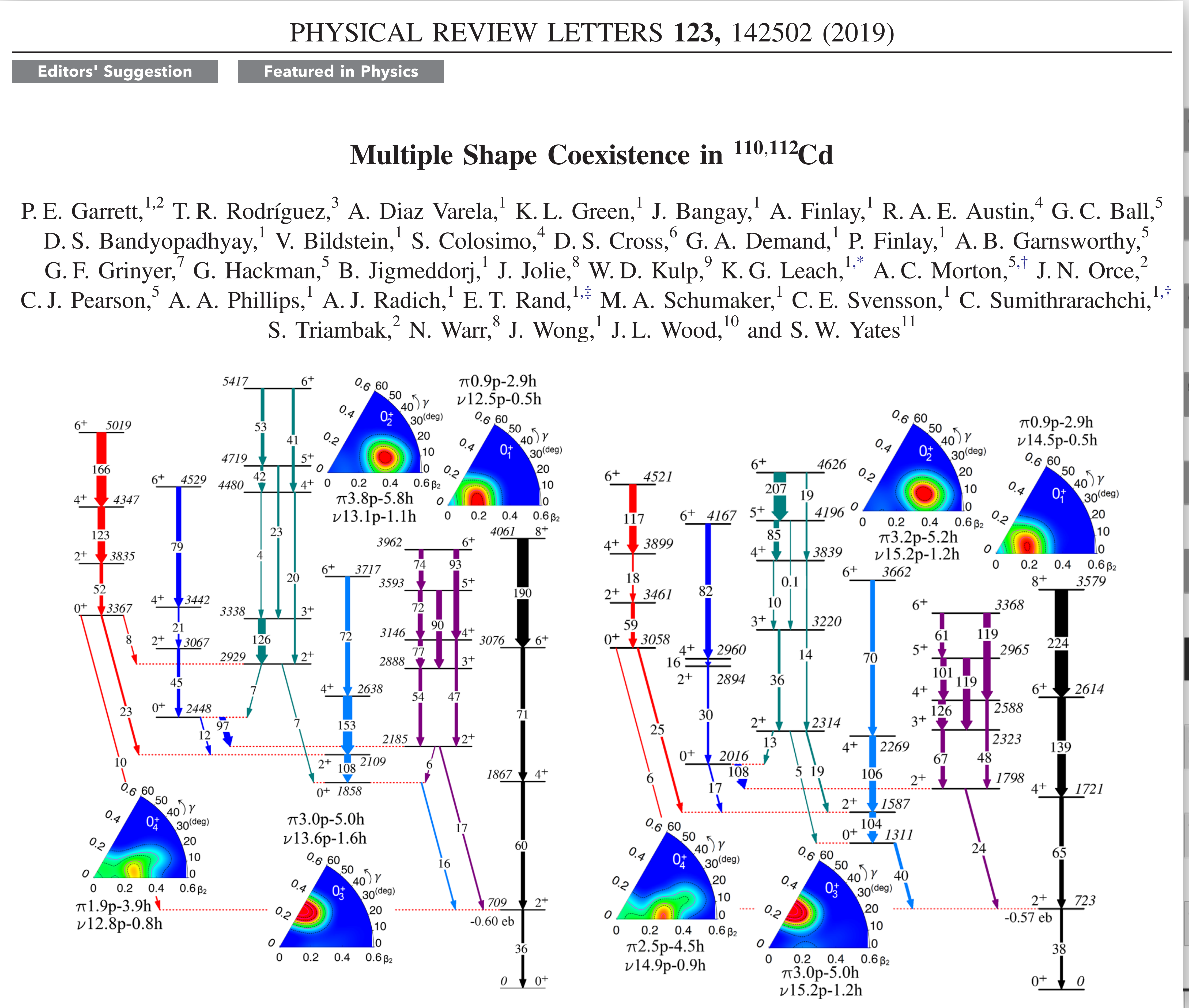
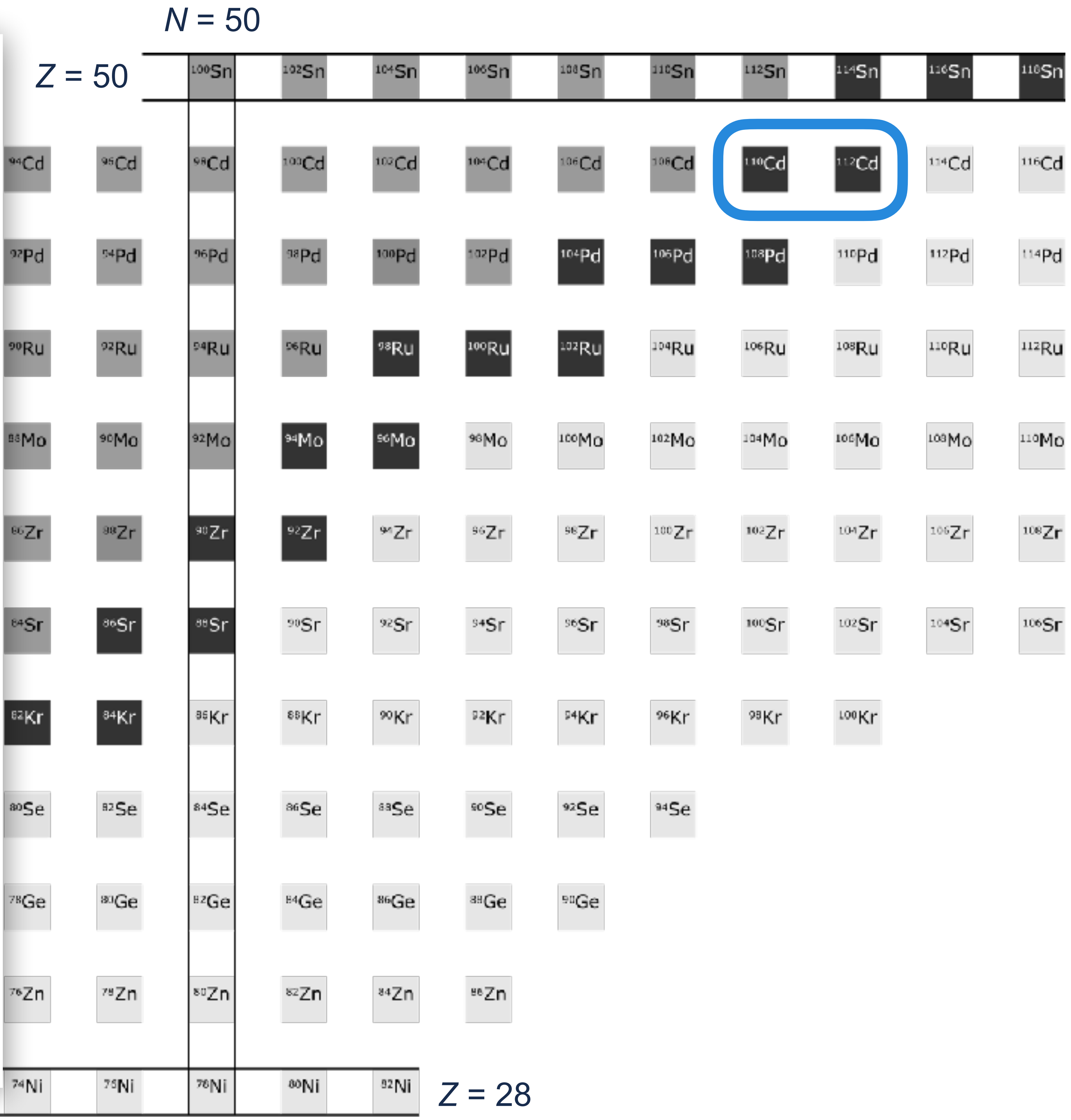


PHYSICAL REVIEW LETTERS **123**, 142502 (2019)

Editors' Suggestion Featured in Physics

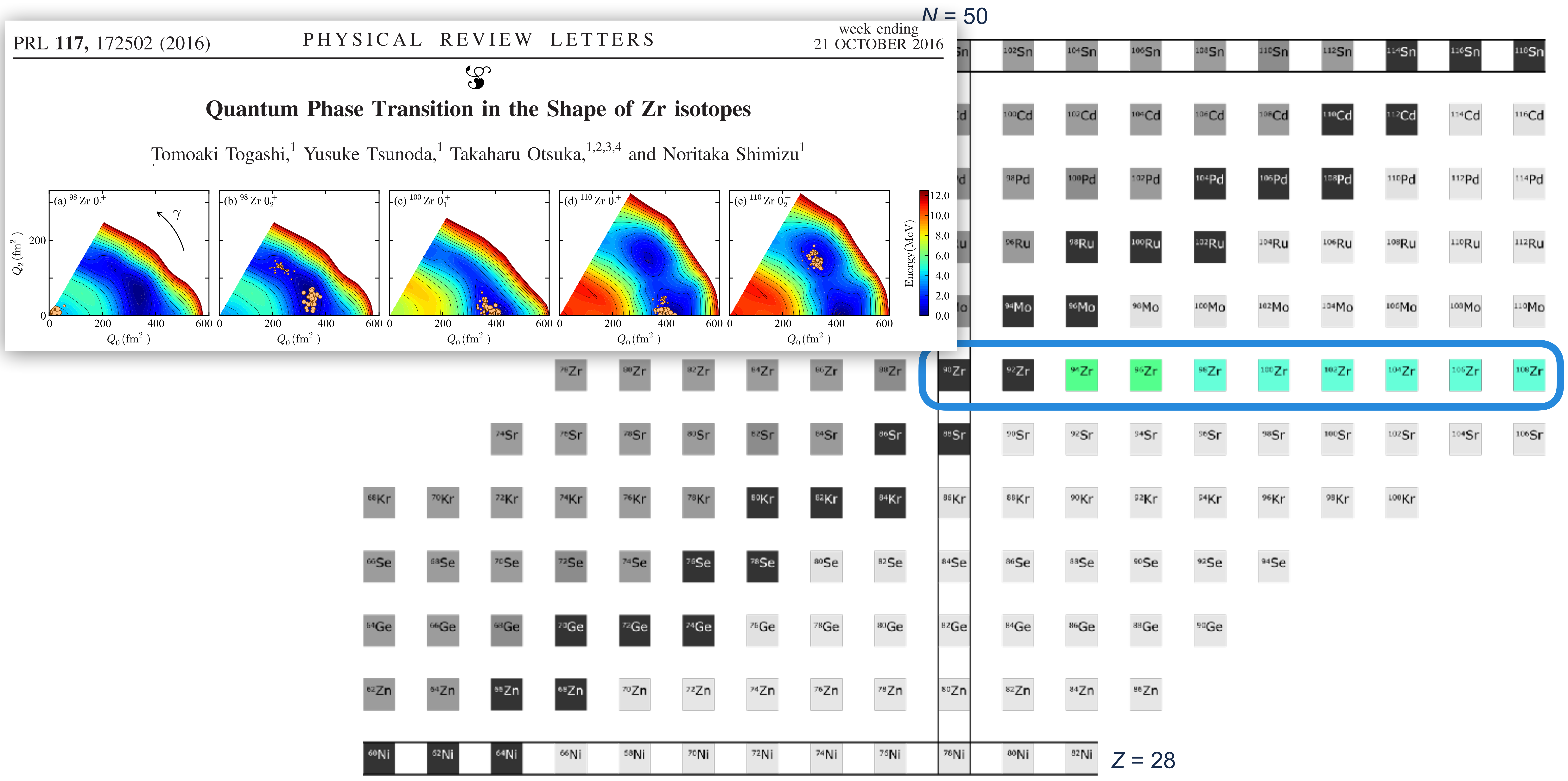
Multiple Shape Coexistence in ^{110,112}Cd

P. E. Garrett,[1,2] T. R. Rodríguez,[3] A. Diaz Varela,[1] K. L. Green,[1] J. Bangay,[1] A. Finlay,[1] R. A. E. Austin,[4] G. C. Ball,[5] D. S. Bandyopadhyay,[1] V. Bildstein,[1] S. Colosimo,[4] D. S. Cross,[6] G. A. Demand,[1] P. Finlay,[1] A. B. Garnsworthy,[5] G. F. Grinyer,[7] G. Hackman,[5] B. Jigmeddorj,[1] J. Jolie,[8] W. D. Kulp,[9] K. G. Leach,[1,*] A. C. Morton,[5,†] J. N. Orce,[2] C. J. Pearson,[5] A. A. Phillips,[1] A. J. Radich,[1] E. T. Rand,[1,‡] M. A. Schumaker,[1] C. E. Svensson,[1] C. Sumithrarachchi,[1,†] S. Triambak,[2] N. Warr,[8] J. Wong,[1] J. L. Wood,[10] and S. W. Yates[11]



The Colourful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/

Shape Coexistence between Z = 28 and Z = 50



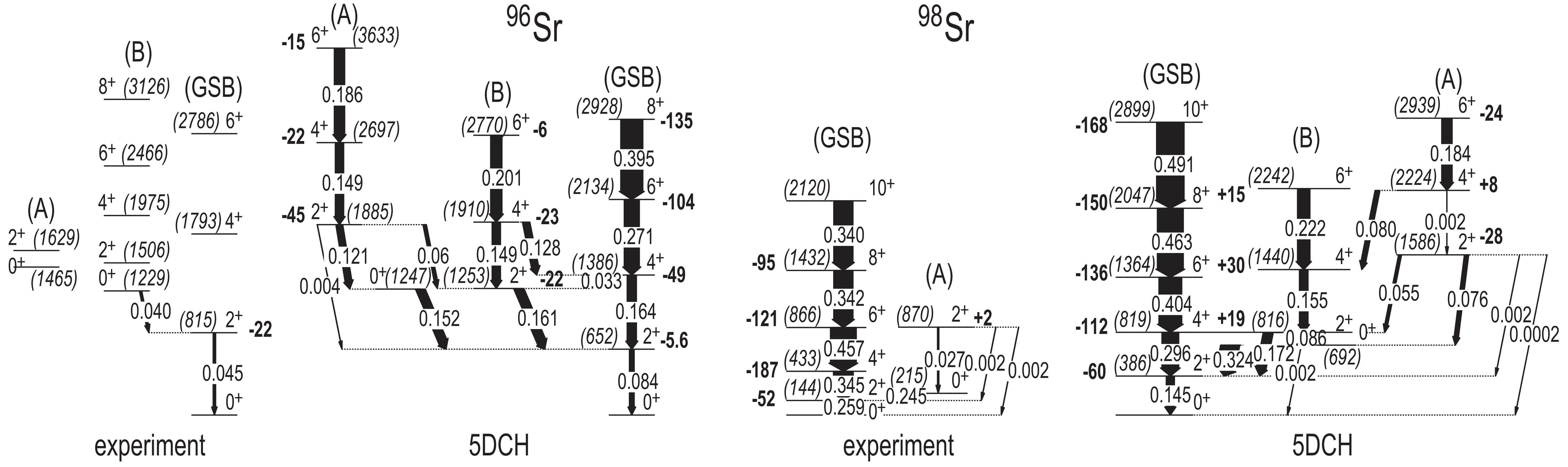
The Colourful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/

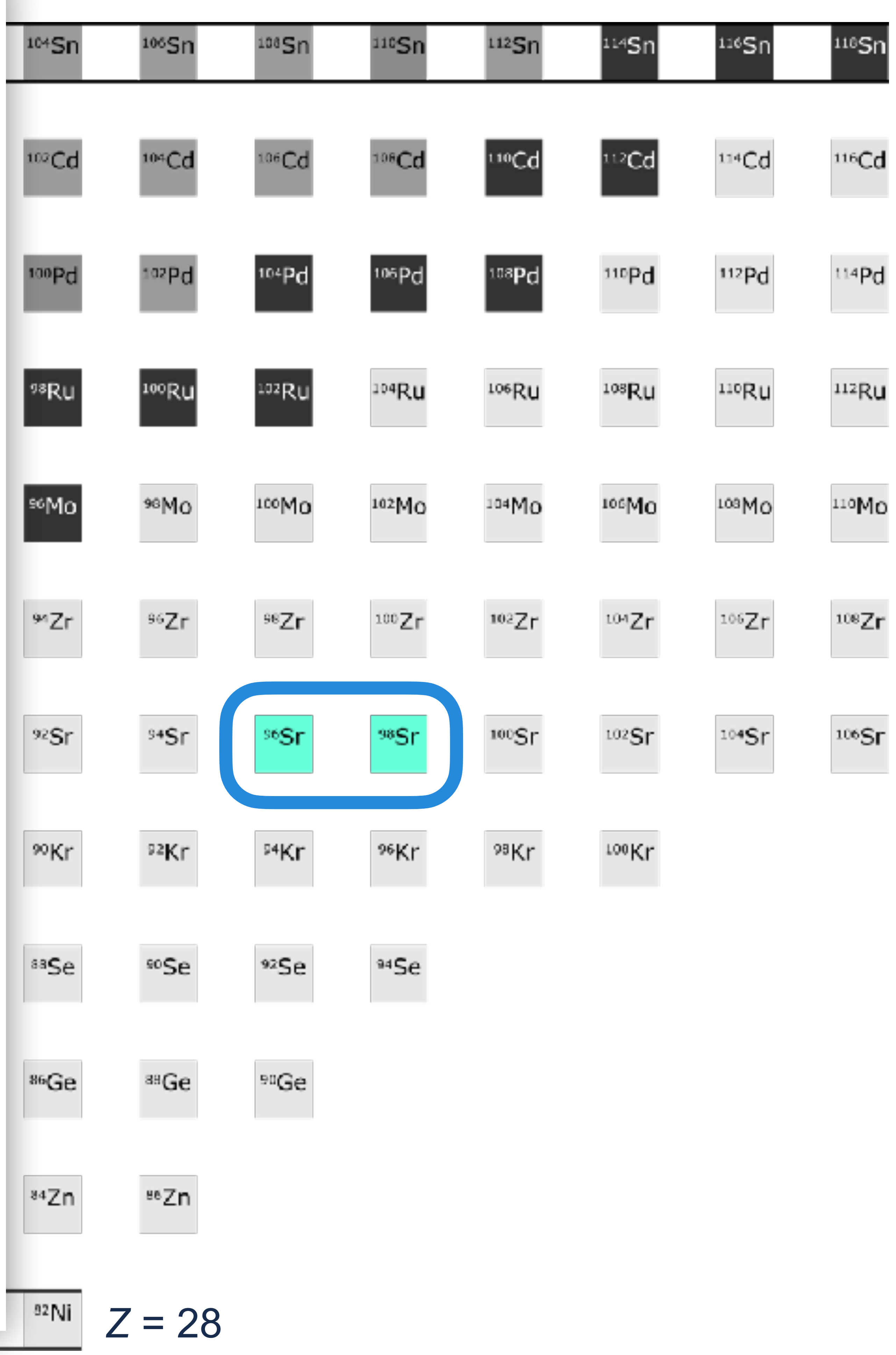
Shape Coexistence between Z = 28 and Z = 50

PRL **116,** 022701 (2016) PHYSICAL REVIEW LETTERS week ending 15 JANUARY 2016

Spectroscopic Quadrupole Moments in ^{96,98}Sr: Evidence for Shape Coexistence in Neutron-Rich Strontium Isotopes at $N = 60$

E. Clément,[1,2,*] M. Zielińska,[3,4] A. Görgen,[5] W. Korten,[3] S. Péru,[6] J. Libert,[6] H. Goutte,[3] S. Hilaire,[6] B. Bastin,[1] C. Bauer,[7] A. Blazhev,[8] N. Bree,[9] B. Bruyneel,[8] P. A. Butler,[10] J. Butterworth,[11] P. Delahaye,[1,2] A. Dijon,[1] D. T. Doherty,[3] A. Ekström,[12] C. Fitzpatrick,[13] C. Fransen,[8] G. Georgiev,[14] R. Gernhäuser,[15] H. Hess,[8] J. Iwanicki,[4] D. G. Jenkins,[11] A. C. Larsen,[5] J. Ljungvall,[14] R. Lutter,[15] P. Marley,[11] K. Moschner,[8] P. J. Napiorkowski,[4] J. Pakarinen,[2] A. Petts,[10] P. Reiter,[8] T. Renstrøm,[5] M. Seidlitz,[8] B. Siebeck,[8] S. Siem,[5] C. Sotty,[14] J. Srebrny,[4] I. Stefanescu,[9] G. M. Tveten,[5,2] J. Van de Walle,[2] M. Vermeulen,[11] D. Voulot,[2] N. Warr,[8] F. Wenander,[2] A. Wiens,[8] H. De Witte,[9] and K. Wrzosek-Lipska[4]





The Colourful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/

Shape Coexistence between Z = 28 and Z = 50

IoIs, Shape Coexistence and Triaxiality

GRIFFIN @TRIUMF

Our Experiment on ^{74}Zn

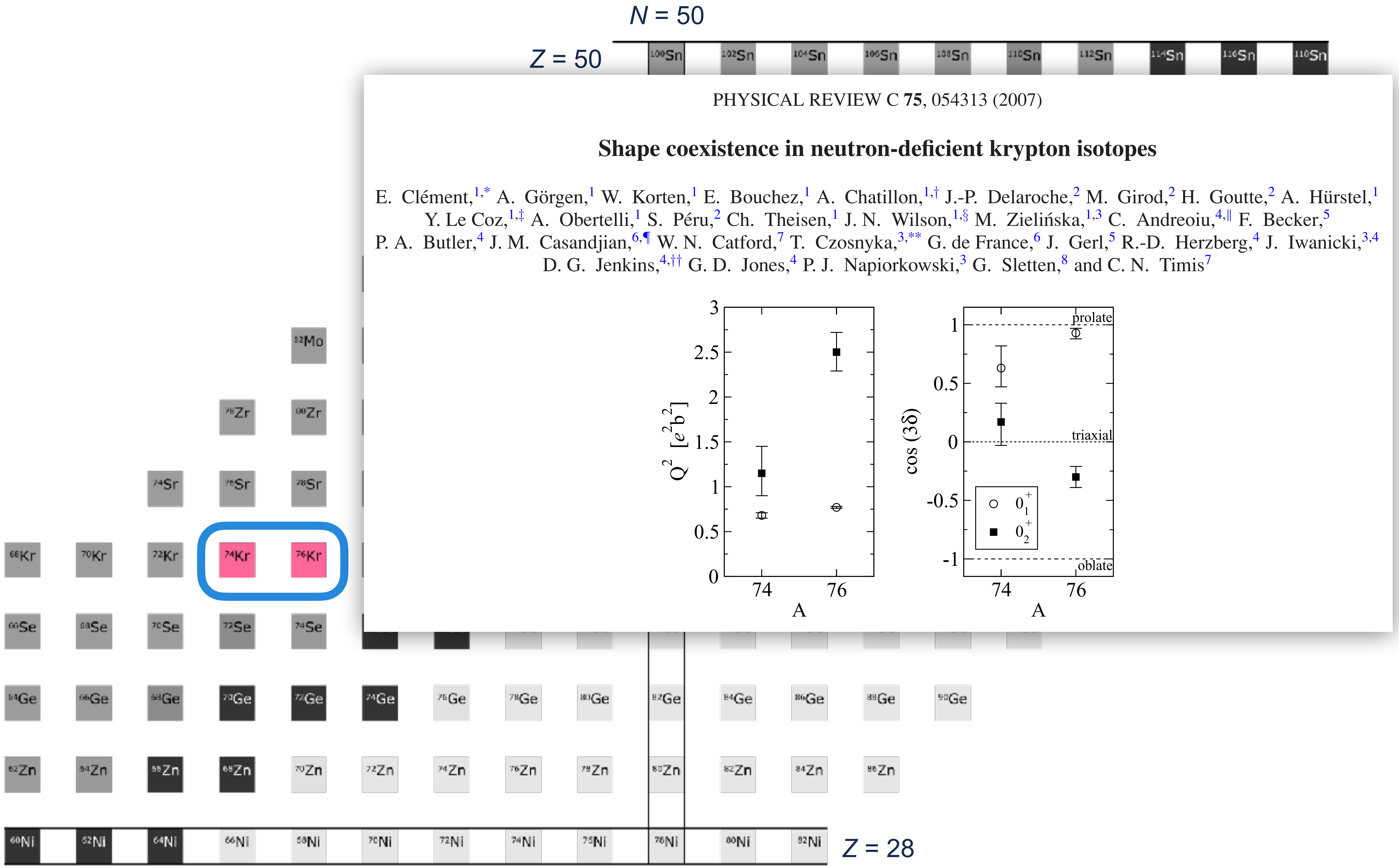
γ-γ Angular Correlations

Experimental Results

LSSM Calculations

Shapes and Occupations

Conclusions



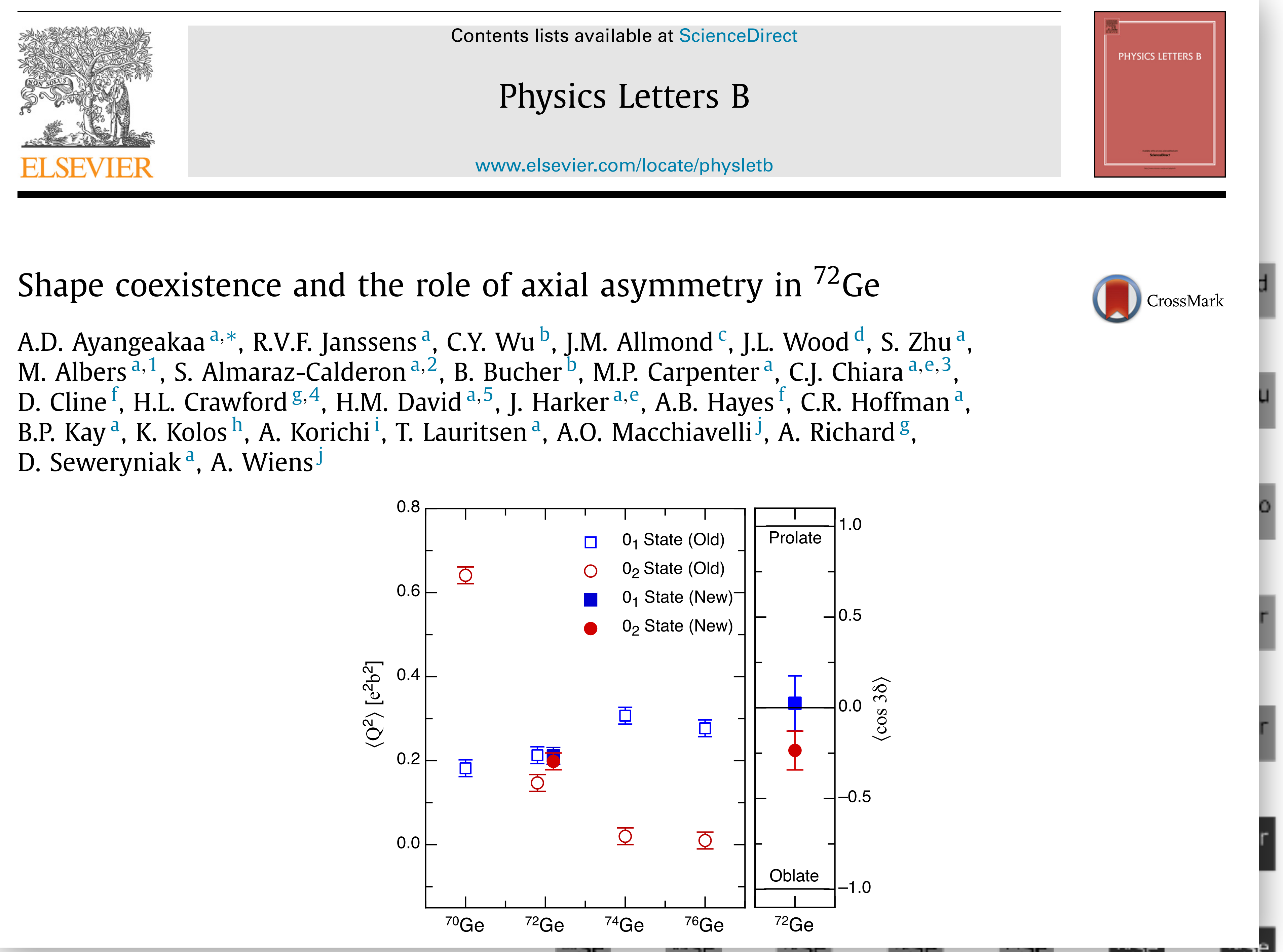
PHYSICAL REVIEW C **75**, 054313 (2007)

Shape coexistence in neutron-deficient krypton isotopes

E. Clément,[1,*] A. Görgen,[1] W. Korten,[1] E. Bouchez,[1] A. Chatillon,[1,†] J.-P. Delaroche,[2] M. Girod,[2] H. Goutte,[2] A. Hürstel,[1] Y. Le Coz,[1,‡] A. Obertelli,[1] S. Péru,[2] Ch. Theisen,[1] J. N. Wilson,[1,§] M. Zielińska,[1,3] C. Andreoiu,[4,‖] F. Becker,[5] P. A. Butler,[4] J. M. Casandjian,[6,¶] W. N. Catford,[7] T. Czosnyka,[3,**] G. de France,[6] J. Gerl,[5] R.-D. Herzberg,[4] J. Iwanicki,[3,4] D. G. Jenkins,[4,††] G. D. Jones,[4] P. J. Napiorkowski,[3] G. Sletten,[8] and C. N. Timis[7]

The Colourful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/

Shape Coexistence between Z = 28 and Z = 50



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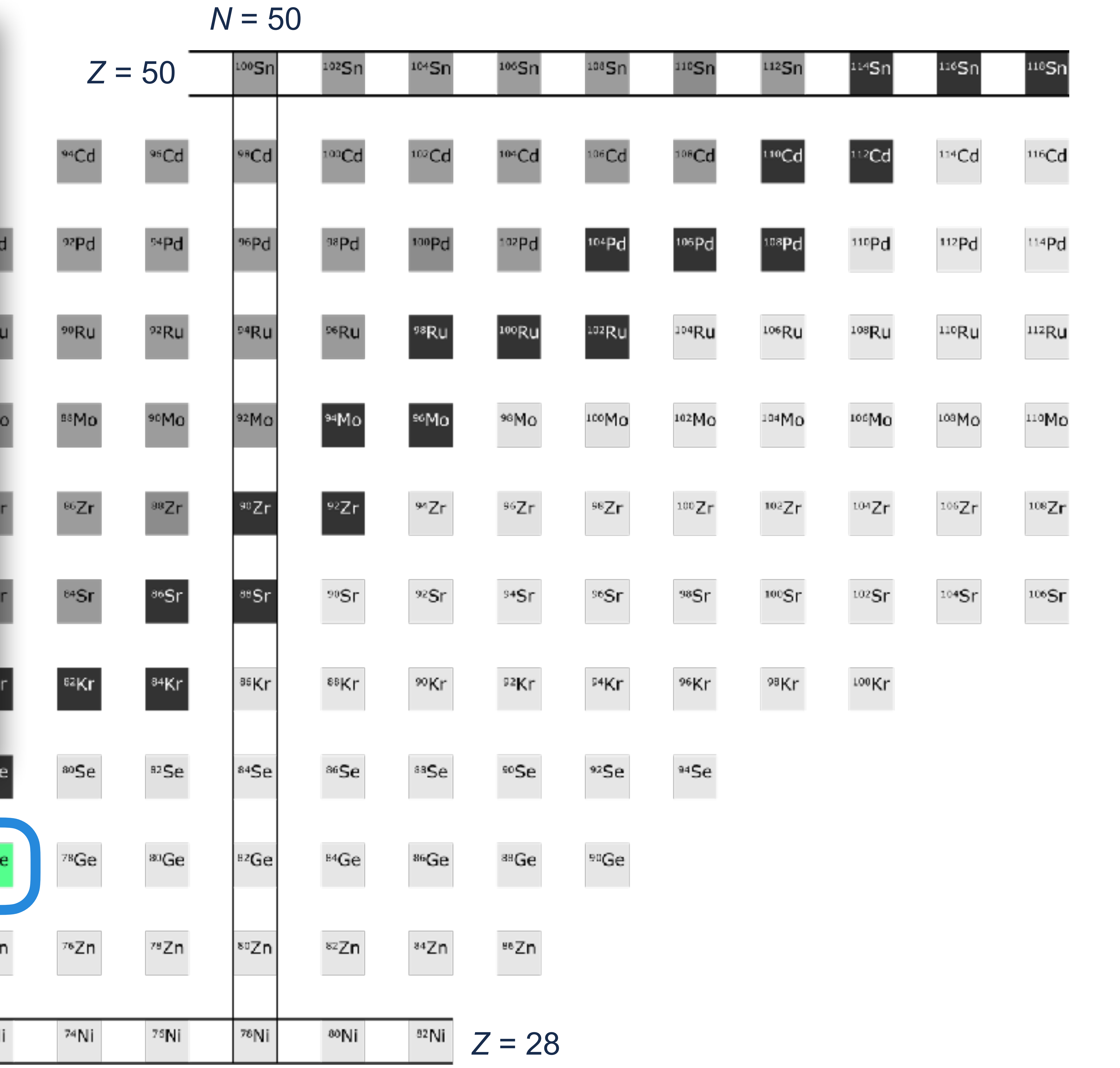
Shape coexistence and the role of axial asymmetry in ^{72}Ge

A.D. Ayangeakaa [a,*], R.V.F. Janssens [a], C.Y. Wu [b], J.M. Allmond [c], J.L. Wood [d], S. Zhu [a], M. Albers [a,1], S. Almaraz-Calderon [a,2], B. Bucher [b], M.P. Carpenter [a], C.J. Chiara [a,e,3], D. Cline [f], H.L. Crawford [g,4], H.M. David [a,5], J. Harker [a,e], A.B. Hayes [f], C.R. Hoffman [a], B.P. Kay [a], K. Kolos [h], A. Korichi [i], T. Lauritsen [a], A.O. Macchiavelli [j], A. Richard [g], D. Seweryniak [a], A. Wiens [j]



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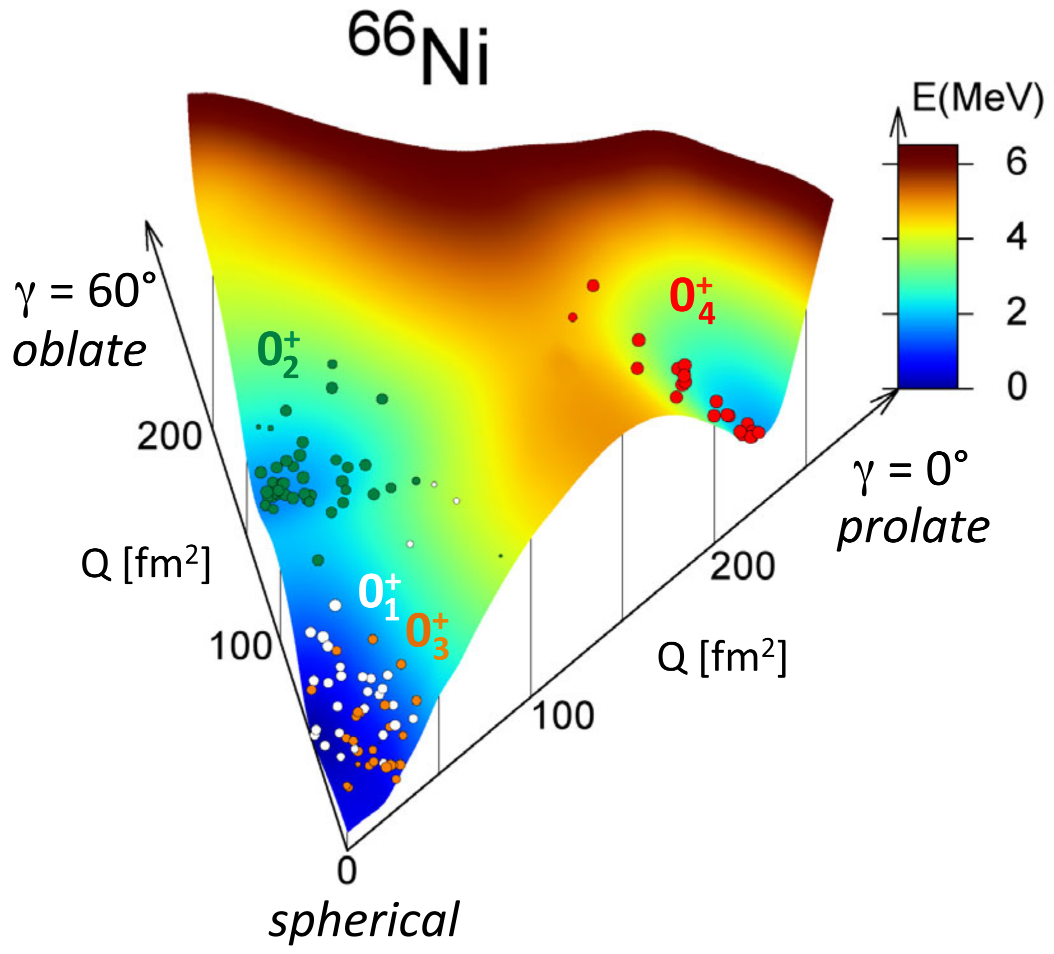
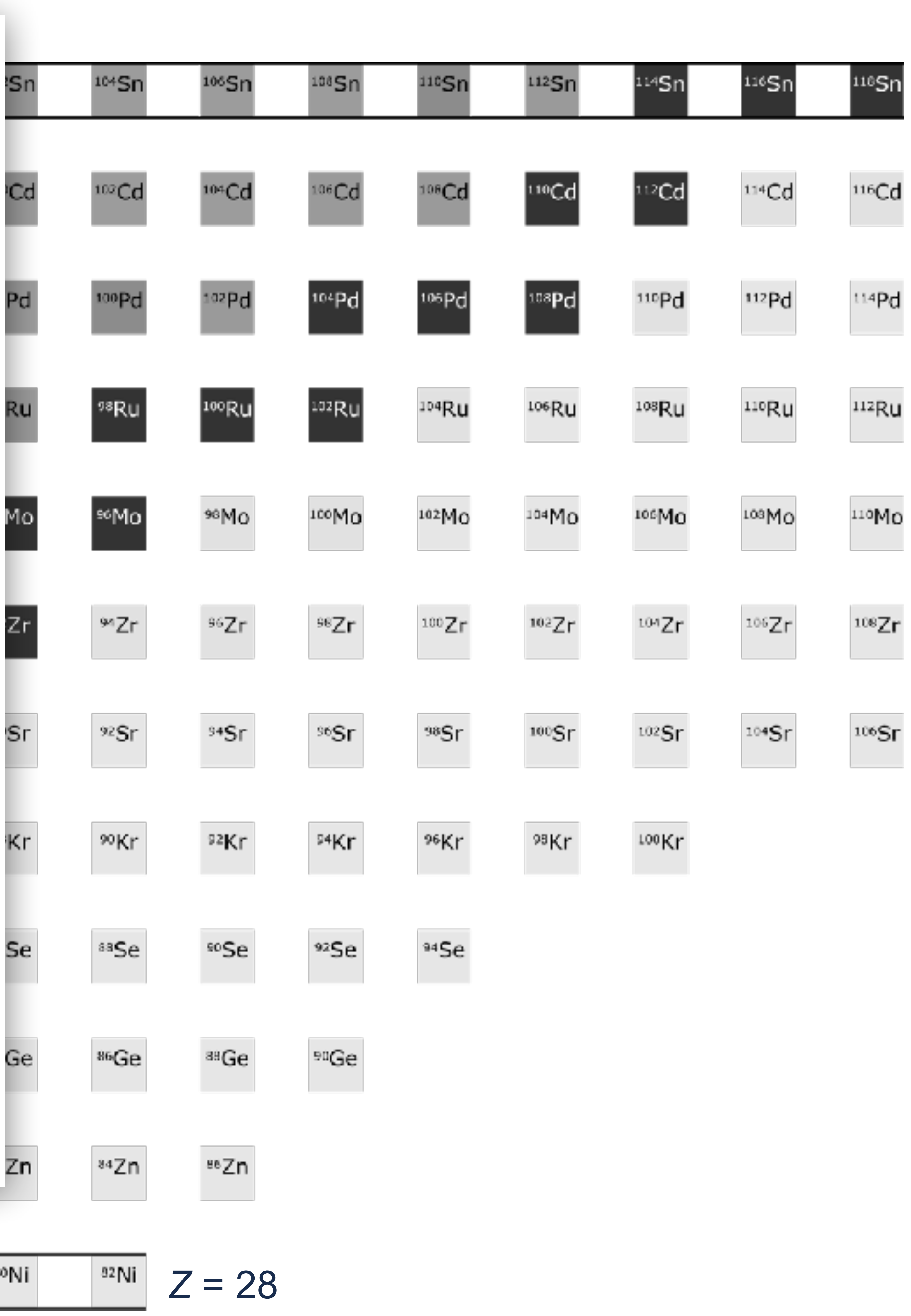
Shape Coexistence between Z = 28 and Z = 50

PRL **118,** 162502 (2017) PHYSICAL REVIEW LETTERS week ending 21 APRIL 2017

Multifaceted Quadruplet of Low-Lying Spin-Zero States in ^{66}Ni: Emergence of Shape Isomerism in Light Nuclei

S. Leoni,[1,2,*] B. Fornal,[3] N. Mărginean,[4] M. Sferrazza,[5] Y. Tsunoda,[6] T. Otsuka,[6,7,8,9] G. Bocchi,[1,2] F. C. L. Crespi,[1,2] A. Bracco,[1,2] S. Aydin,[10] M. Boromiza,[4,11] D. Bucurescu,[4] N. Cieplicka-Oryǹczak,[2,3] C. Costache,[4] S. Călinescu,[4] N. Florea,[4] D. G. Ghiţă,[4] T. Glodariu,[4] A. Ionescu,[4,11] Ł.W. Iskra,[3] M. Krzysiek,[3] R. Mărginean,[4] C. Mihai,[4] R. E. Mihai,[4] A. Mitu,[4] A. Negreţ,[4] C. R. Niţă,[4] A. Olăcel,[4] A. Oprea,[4] S. Pascu,[4] P. Petkov,[4] C. Petrone,[4] G. Porzio,[1,2] A. Şerban,[4,11] C. Sotty,[4] L. Stan,[4] I. Ştiru,[4] L. Stroe,[4] R. Şuvăilă,[4] S. Toma,[4] A. Turturică,[4] S. Ujeniuc,[4] and C. A. Ur[12]





The Colourful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/

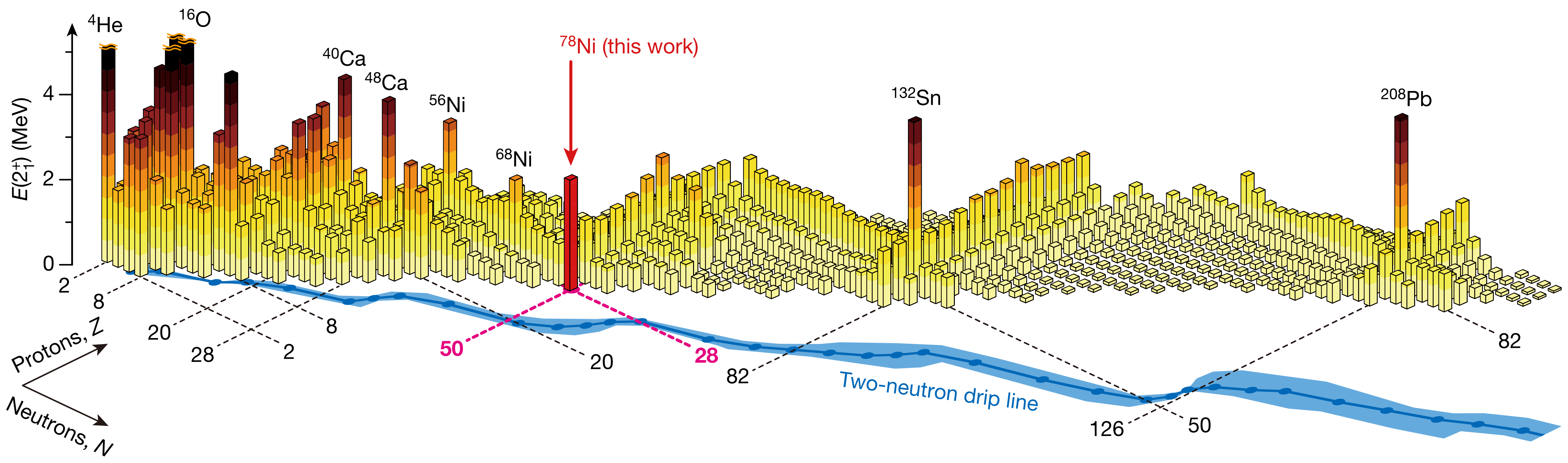
Shape Coexistence between Z = 28 and Z = 50

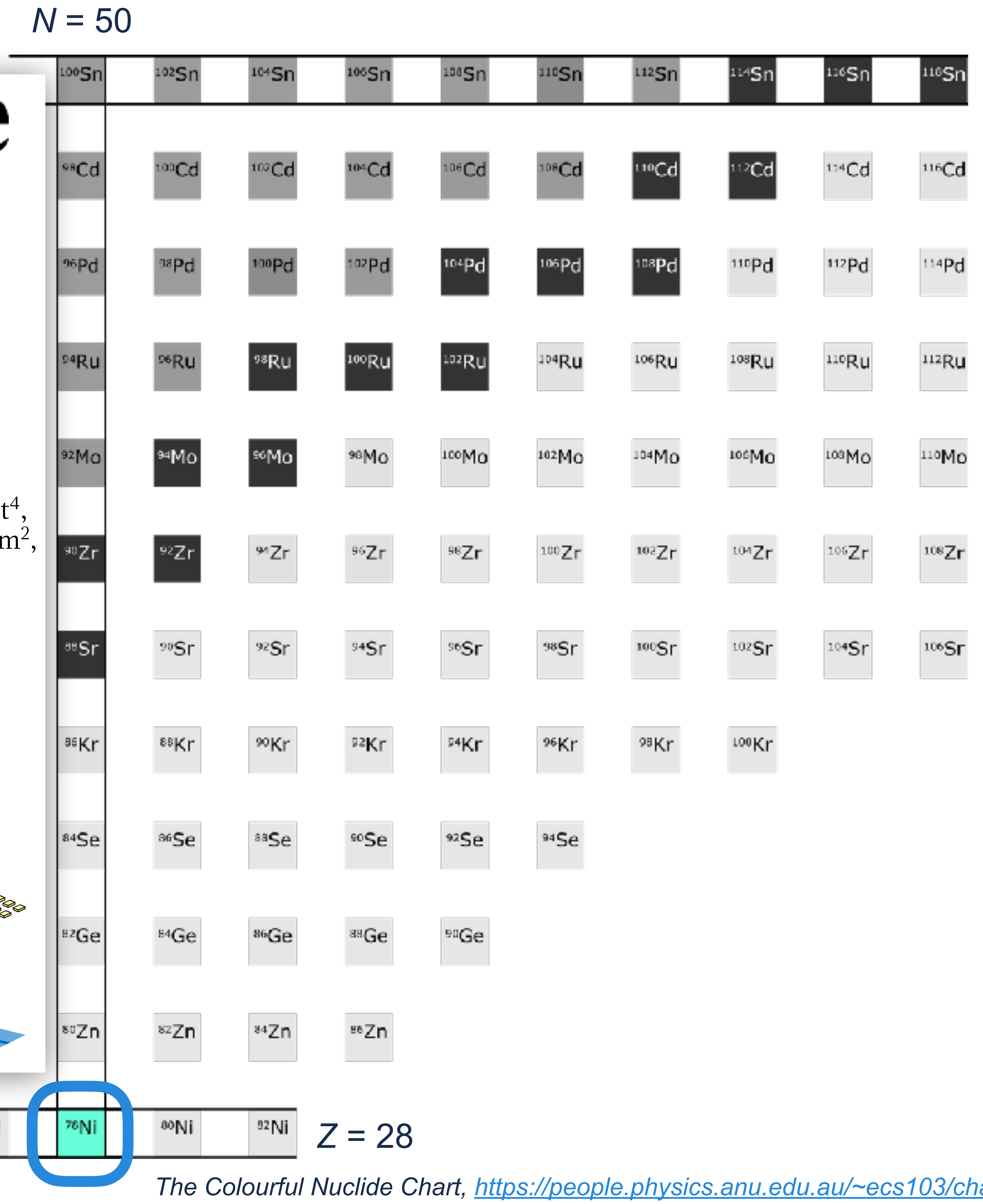
Shape Coexistence is predicted in ^{78}Ni but still no firm proof

nature

^{78}Ni revealed as a doubly magic stronghold against nuclear deformation

R. Taniuchi[1,2], C. Santamaria[2,3], P. Doornenbal[2*], A. Obertelli[2,3,4], K. Yoneda[2], G. Authelet[3], H. Baba[2], D. Calvet[3], F. Château[3], A. Corsi[3], A. Delbart[3], J.-M. Gheller[3], A. Gillibert[3], J. D. Holt[5], T. Isobe[2], V. Lapoux[3], M. Matsushita[6], J. Menéndez[6], S. Momiyama[1,2], T. Motobayashi[2], M. Niikura[1], F. Nowacki[7], K. Ogata[8,9], H. Otsu[2], T. Otsuka[1,2,6], C. Péron[3], S. Péru[10], A. Peyaud[3], E. C. Pollacco[3], A. Poves[11], J.-Y. Roussé[3], H. Sakurai[1,2], A. Schwenk[4,12,13], Y. Shiga[2,14], J. Simonis[4,12,15], S. R. Stroberg[5,16], S. Takeuchi[2], Y. Tsunoda[6], T. Uesaka[2], H. Wang[2], F. Browne[17], L. X. Chung[18], Z. Dombradi[19], S. Franchoo[20], F. Giacoppo[21], A. Gottardo[20], K. Hadyńska-Klęk[21], Z. Korkulu[19], S. Koyama[1,2], Y. Kubota[2,6], J. Lee[22], M. Lettmann[4], C. Louchart[4], R. Lozeva[7,23], K. Matsui[1,2], T. Miyazaki[1,2], S. Nishimura[2], L. Olivier[20], S. Ota[6], Z. Patel[24], E. Şahin[21], C. Shand[24], P.-A. Söderström[2], I. Stefan[20], D. Steppenbeck[6], T. Sumikama[25], D. Suzuki[20], Z. Vajta[19], V. Werner[4], J. Wu[2,26] & Z. Y. Xu[22]

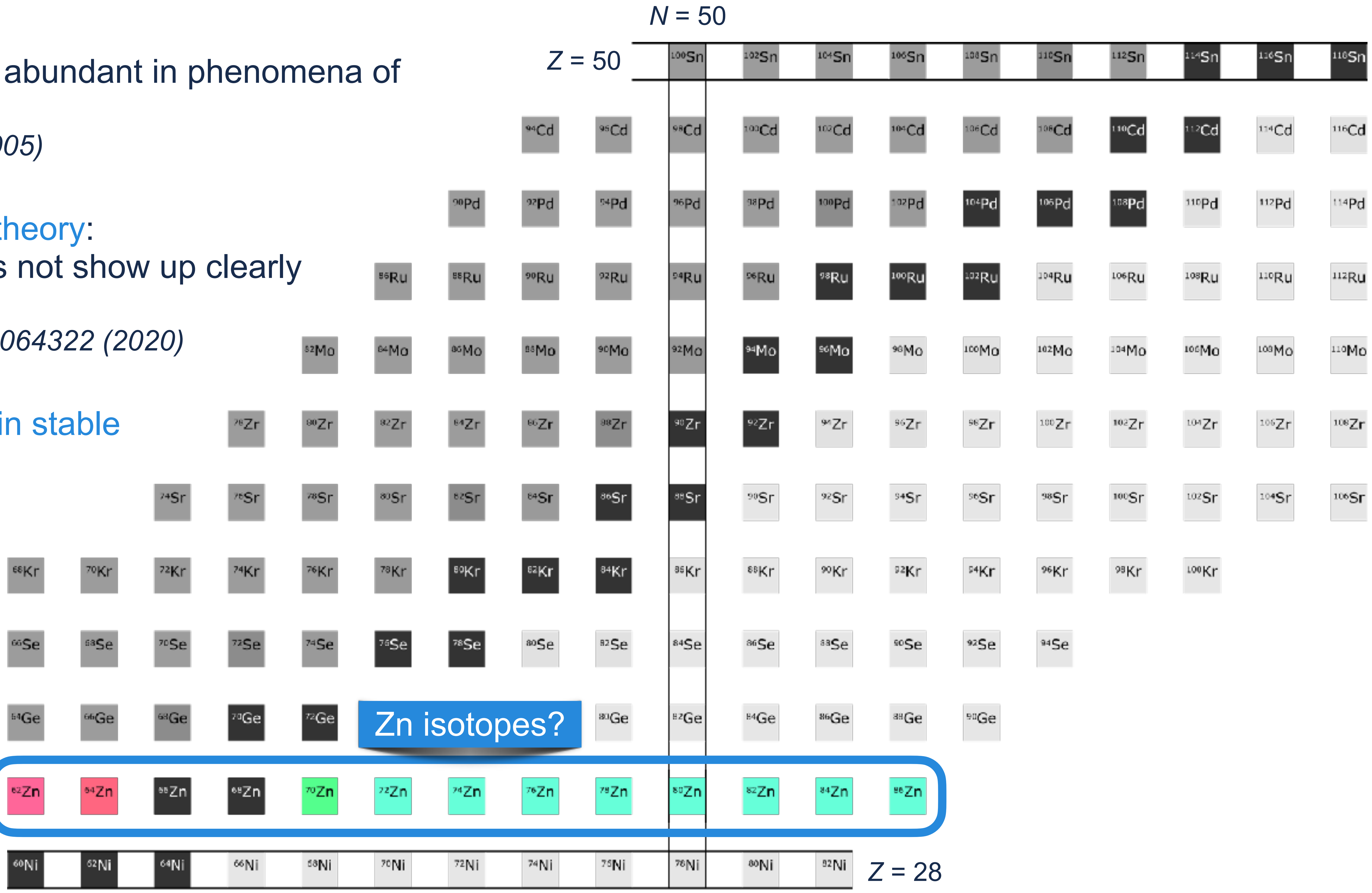




The Colourful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/

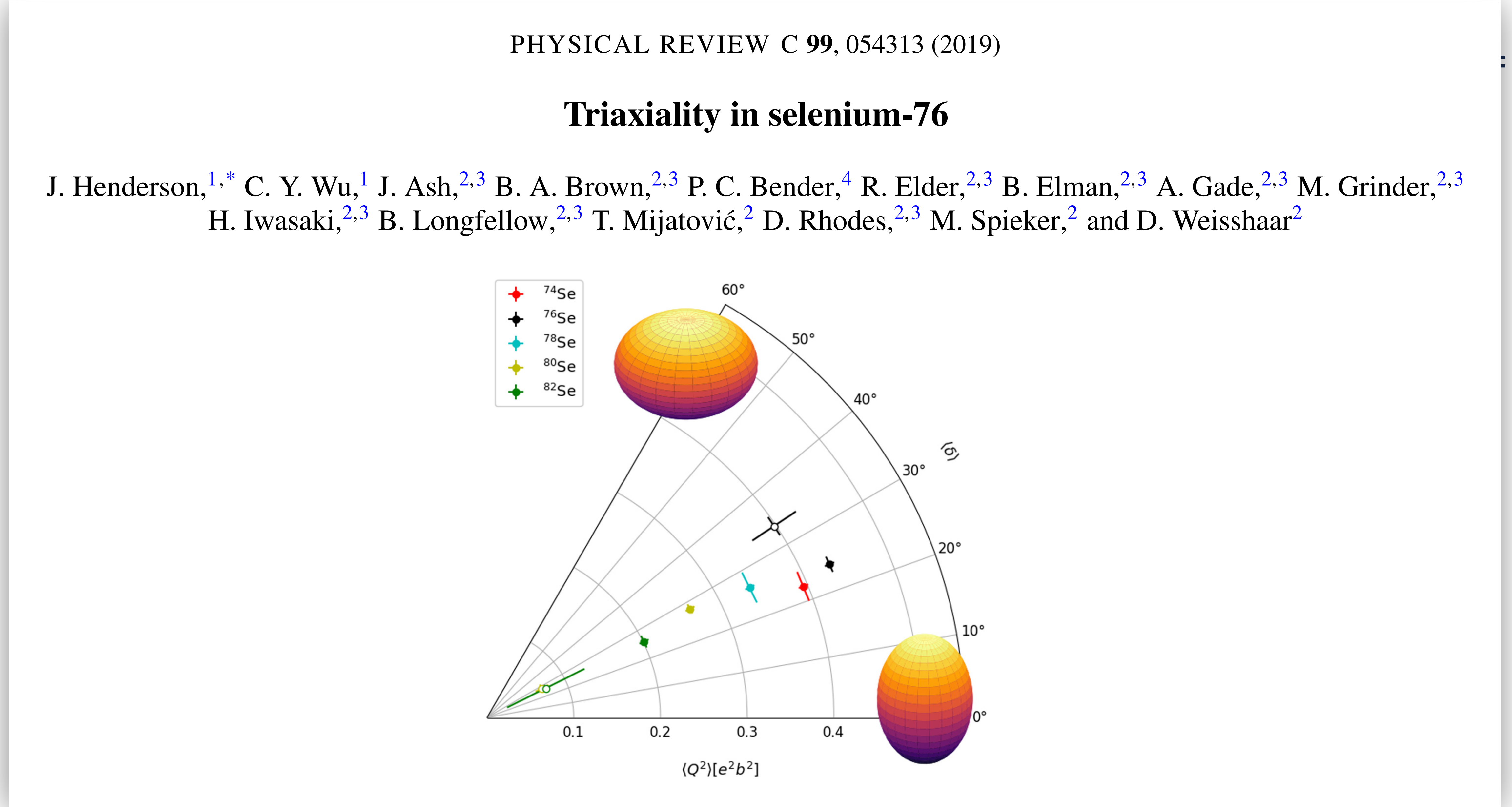
Shape Coexistence between Z = 28 and Z = 50

- Relativistic mean-field:
  Cit. “The Zn isotopic chain is abundant in phenomena of shape coexistence”
  W.Z. Jiang et al., EPJA 25, 29 (2005)
- Covariant density functional theory:
  Cit. “Shape coexistence does not show up clearly in Zn isotopes”
  N.J. Abu Awwad et al., PRC 101, 064322 (2020)
- Little experimental evidence in stable isotopes:
  A. Passoja et al., NPA 438, 413 (1985)
  M. Rocchini et al., PRC 103, 014311 (2021)
  M. Koizumi et al., NPA 730, 46 (2004)
- No firm proof in the radioactive, neutron-rich isotopes



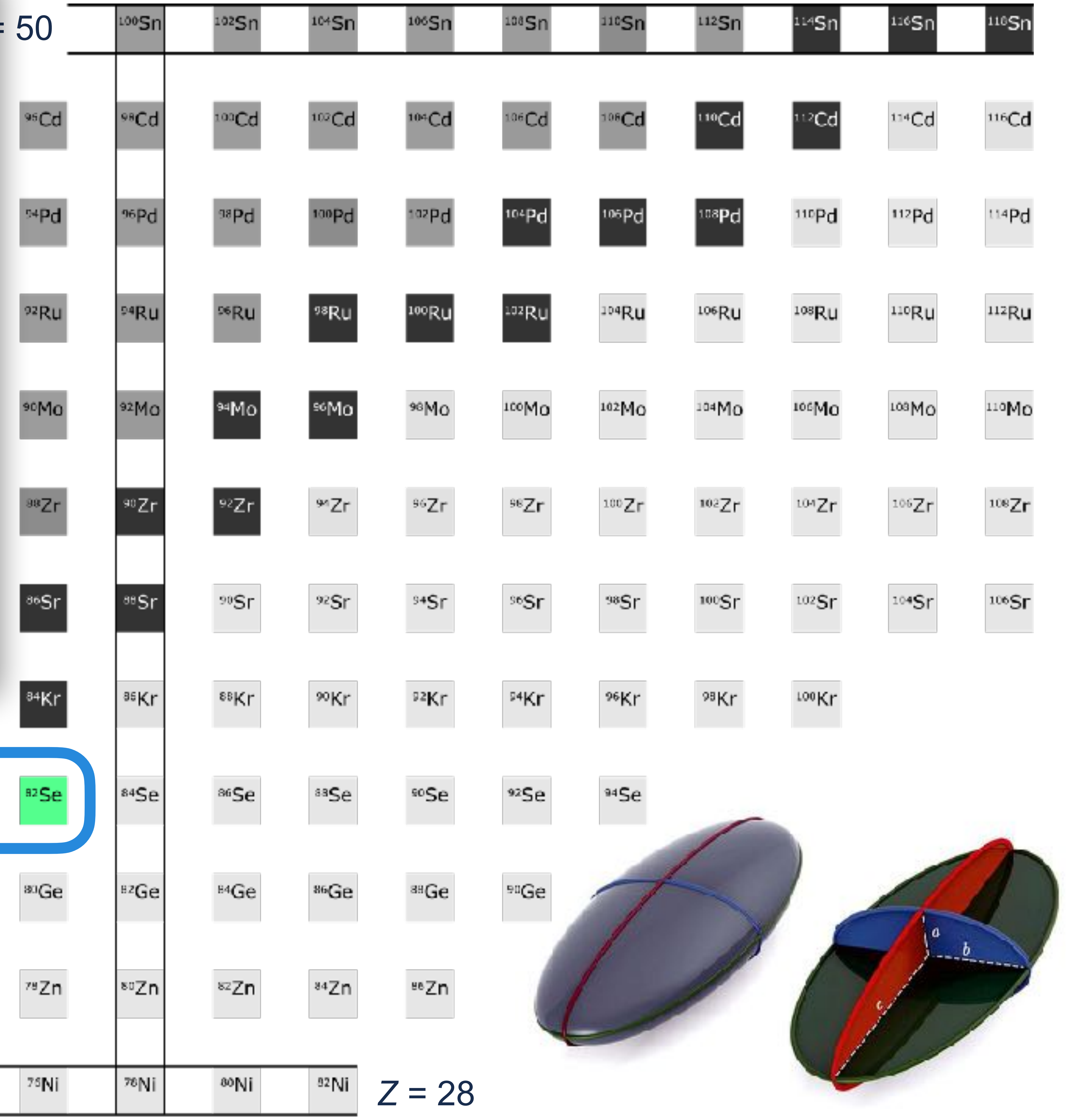
The Colourful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/

Triaxiality in the Se, Ge and Zn Isotopes


PHYSICAL REVIEW C **99**, 054313 (2019)

Triaxiality in selenium-76

J. Henderson,[1,*] C. Y. Wu,[1] J. Ash,[2,3] B. A. Brown,[2,3] P. C. Bender,[4] R. Elder,[2,3] B. Elman,[2,3] A. Gade,[2,3] M. Grinder,[2,3] H. Iwasaki,[2,3] B. Longfellow,[2,3] T. Mijatović,[2] D. Rhodes,[2,3] M. Spieker,[2] and D. Weisshaar[2]



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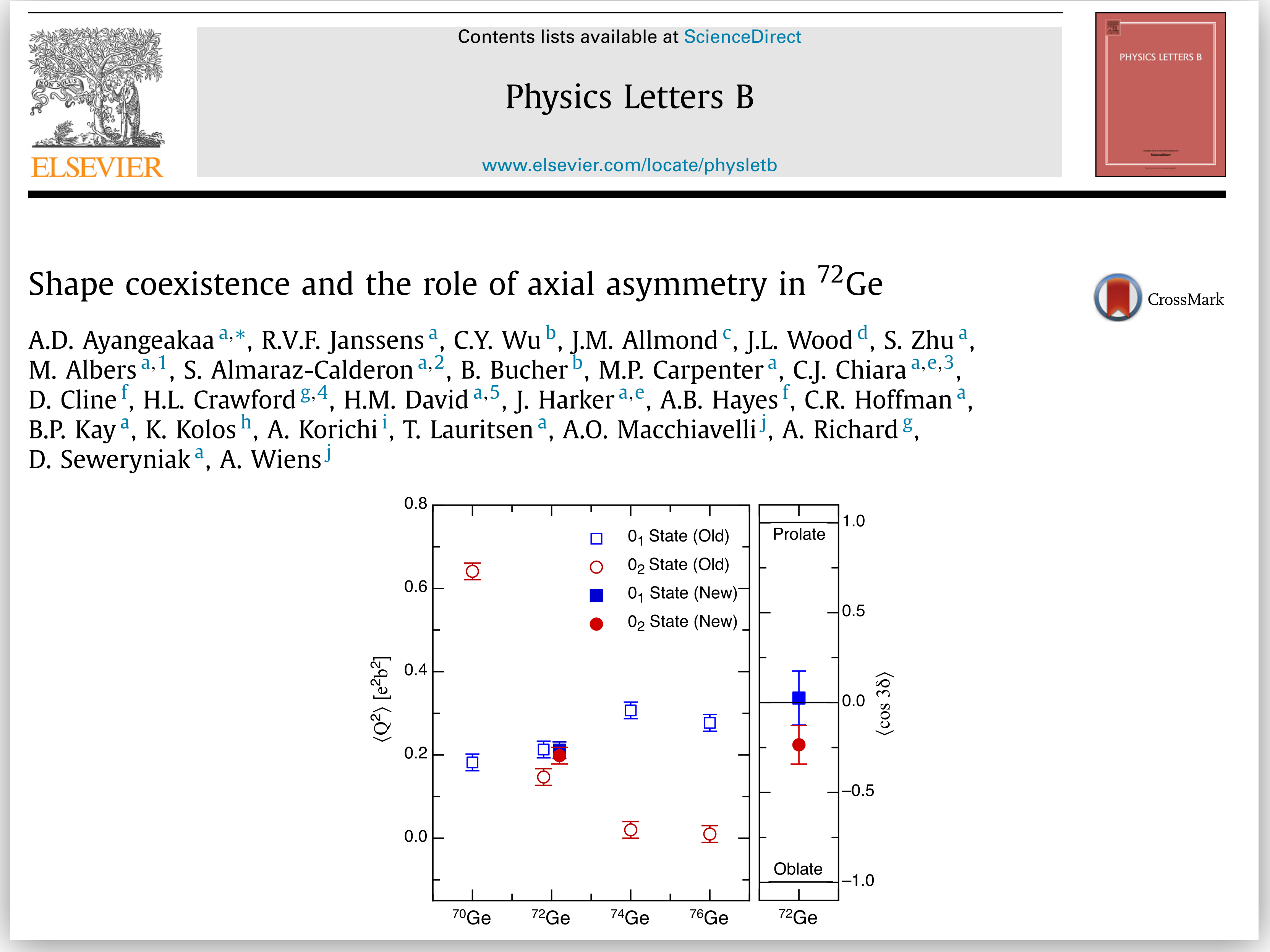
Triaxiality in the Se, Ge and Zn Isotopes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Shape coexistence and the role of axial asymmetry in ^{72}Ge

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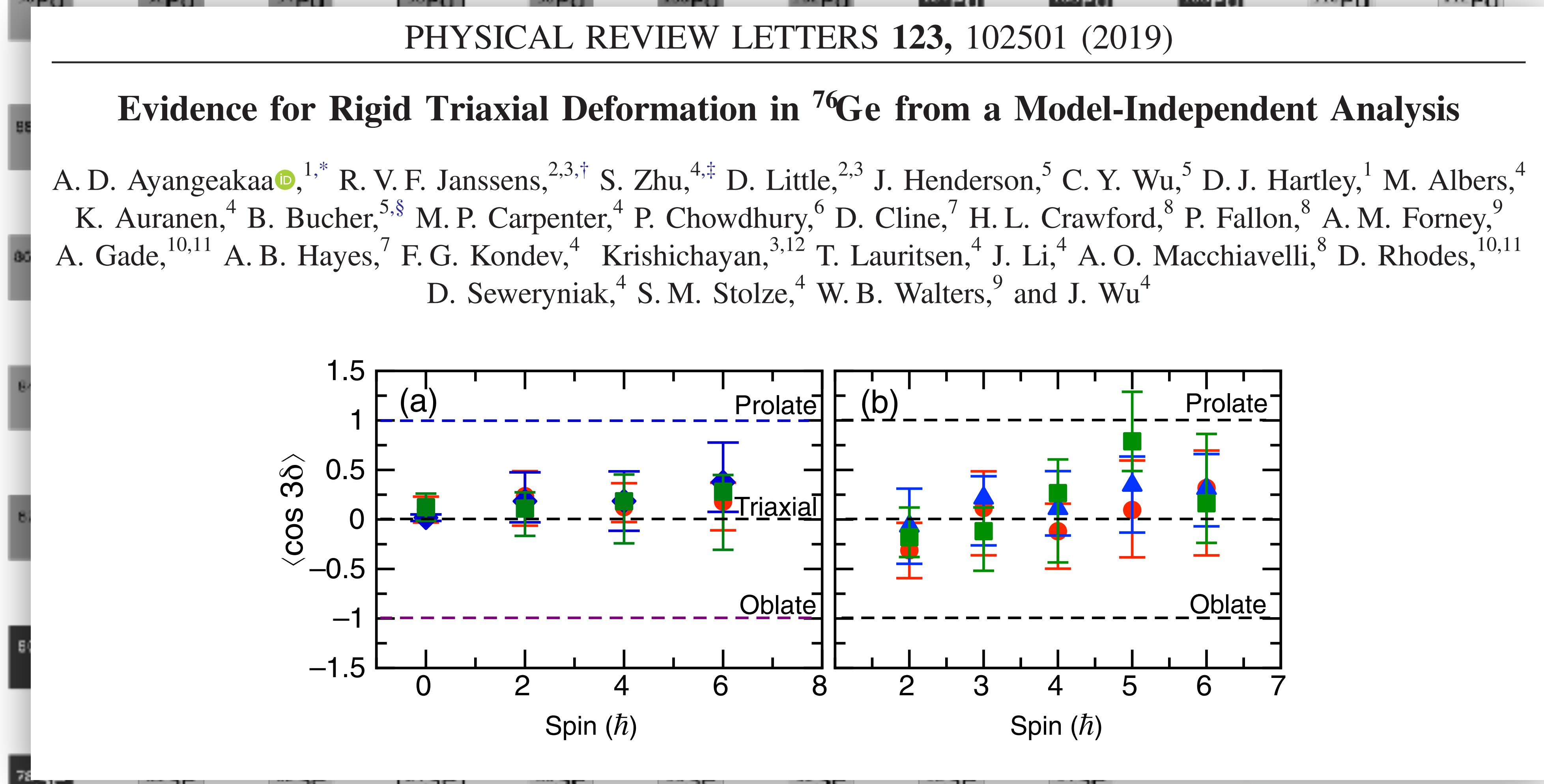
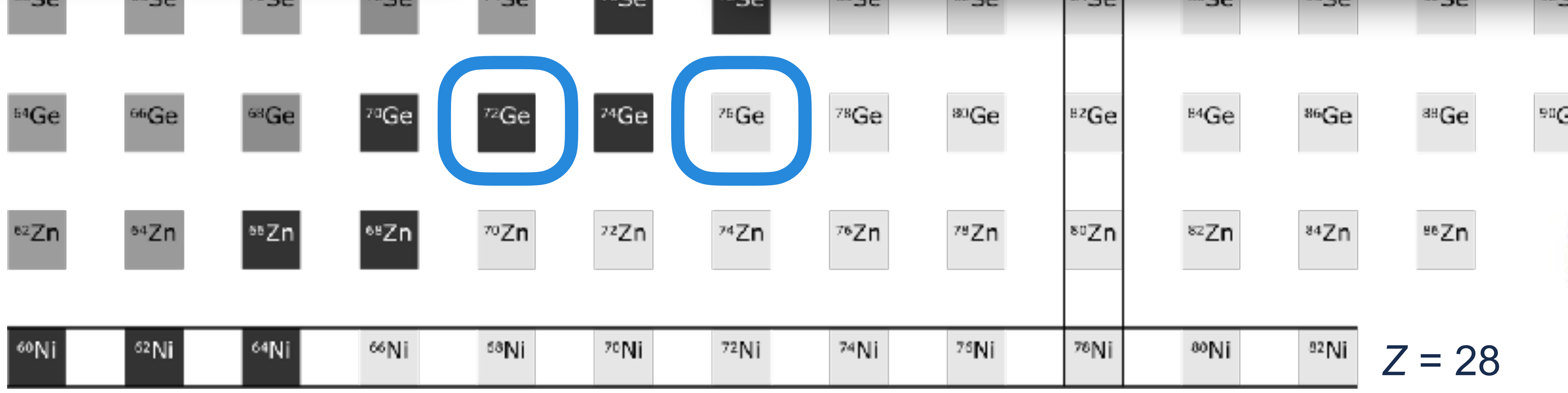

PHYSICAL REVIEW LETTERS 123, 102501 (2019)

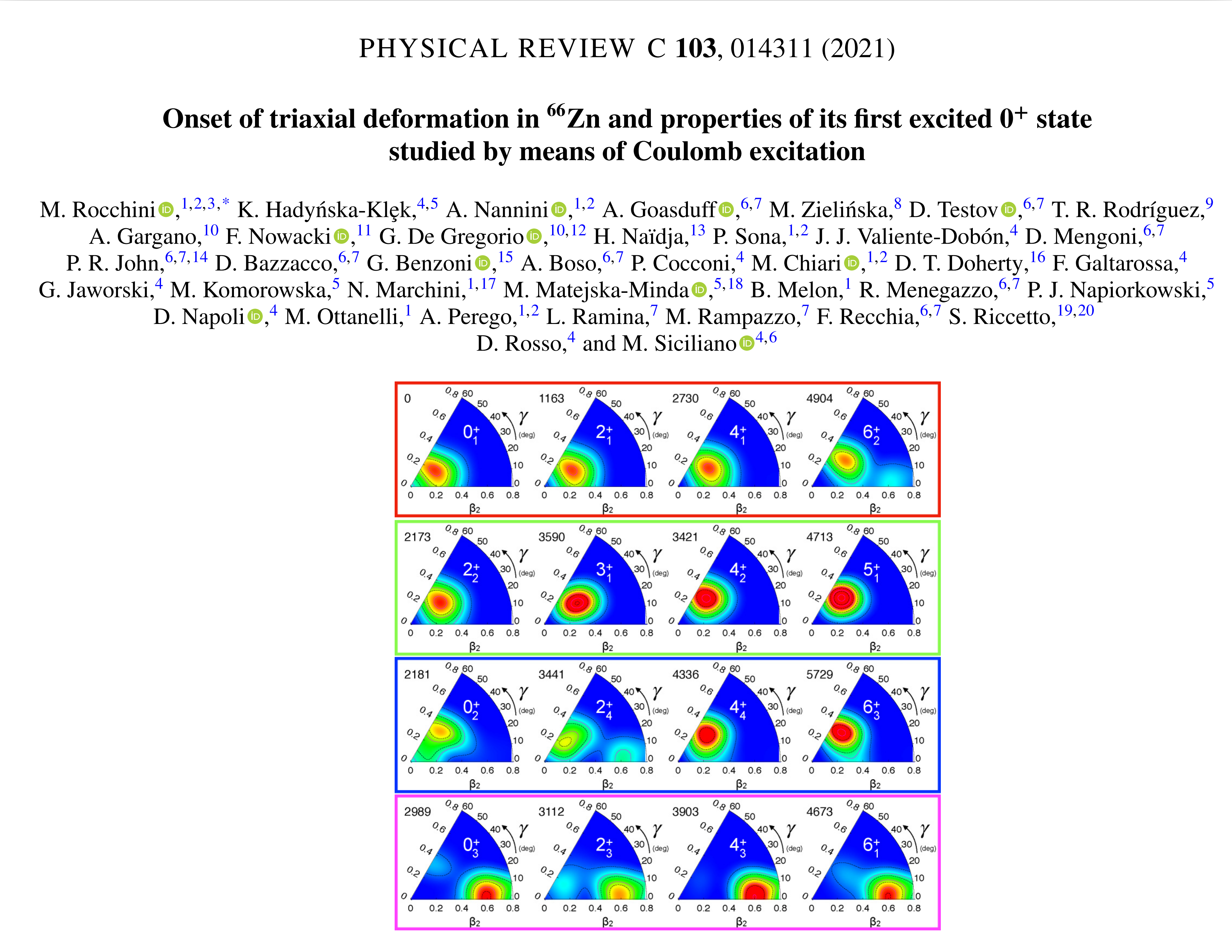
Evidence for Rigid Triaxial Deformation in ^{76}Ge from a Model-Independent Analysis

A. D. Ayangeakaa,[1,*] R. V. F. Janssens,[2,3,†] S. Zhu,[4,‡] D. Little,[2,3] J. Henderson,[5] C. Y. Wu,[5] D. J. Hartley,[1] M. Albers,[4] K. Auranen,[4] B. Bucher,[5,§] M. P. Carpenter,[4] P. Chowdhury,[6] D. Cline,[7] H. L. Crawford,[8] P. Fallon,[8] A. M. Forney,[9] A. Gade,[10,11] A. B. Hayes,[7] F. G. Kondev,[4] Krishichayan,[3,12] T. Lauritsen,[4] J. Li,[4] A. O. Macchiavelli,[8] D. Rhodes,[10,11] D. Seweryniak,[4] S. M. Stolze,[4] W. B. Walters,[9] and J. Wu[4]



The Colourful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/

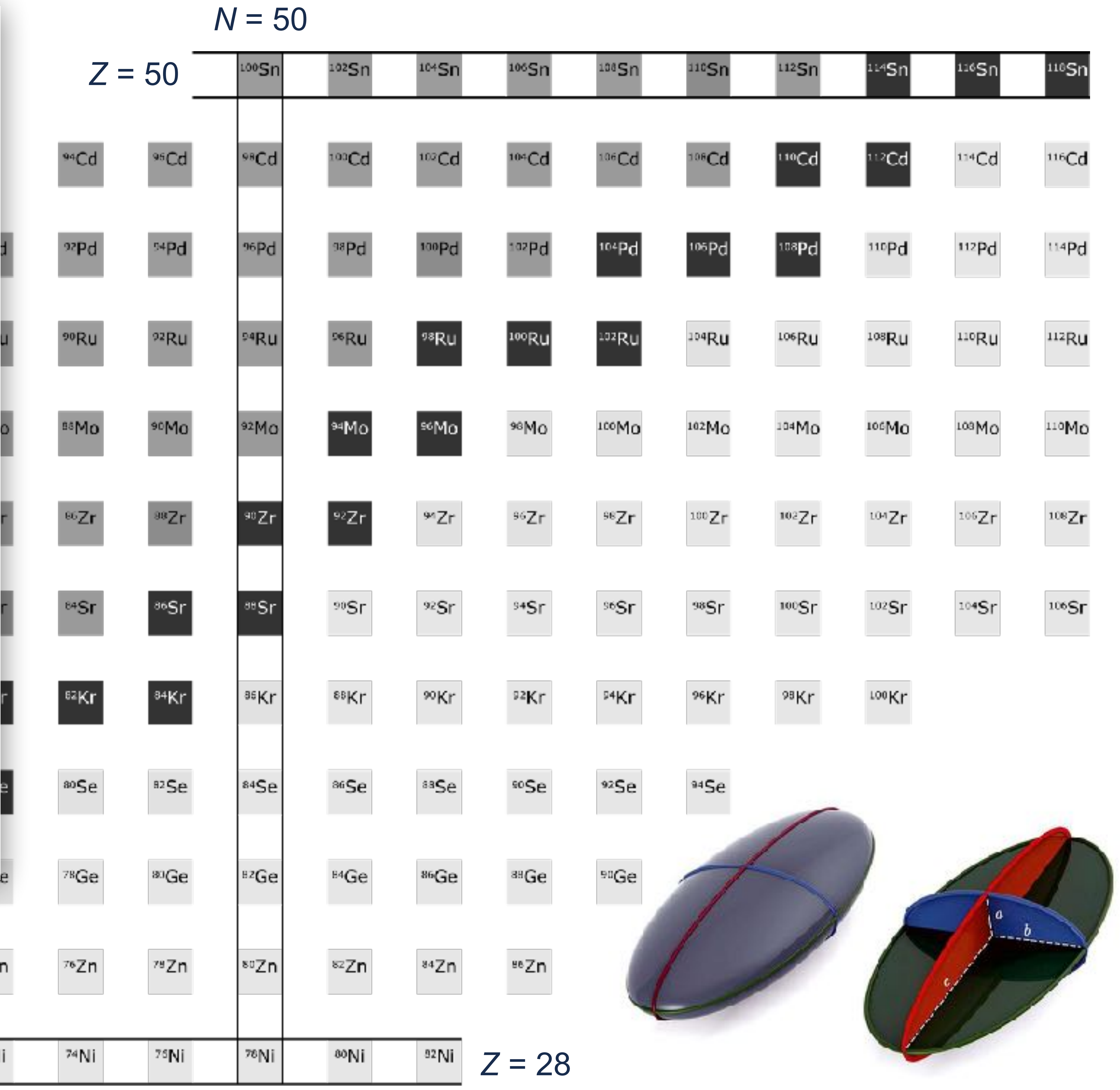
Triaxiality in the Se, Ge and Zn Isotopes



PHYSICAL REVIEW C **103**, 014311 (2021)

Onset of triaxial deformation in ^{66}Zn and properties of its first excited 0^+ state studied by means of Coulomb excitation

M. Rocchini,[1,2,3,*] K. Hadyńska-Klęk,[4,5] A. Nannini,[1,2] A. Goasduff,[6,7] M. Zielińska,[8] D. Testov,[6,7] T. R. Rodríguez,[9] A. Gargano,[10] F. Nowacki,[11] G. De Gregorio,[10,12] H. Naïdja,[13] P. Sona,[1,2] J. J. Valiente-Dobón,[4] D. Mengoni,[6,7] P. R. John,[6,7,14] D. Bazzacco,[6,7] G. Benzoni,[15] A. Boso,[6,7] P. Cocconi,[4] M. Chiari,[1,2] D. T. Doherty,[16] F. Galtarossa,[4] G. Jaworski,[4] M. Komorowska,[5] N. Marchini,[1,17] M. Matejska-Minda,[5,18] B. Melon,[1] R. Menegazzo,[6,7] P. J. Napiorkowski,[5] D. Napoli,[4] M. Ottanelli,[1] A. Perego,[1,2] L. Ramina,[7] M. Rampazzo,[7] F. Recchia,[6,7] S. Riccetto,[19,20] D. Rosso,[4] and M. Siciliano[4,6]



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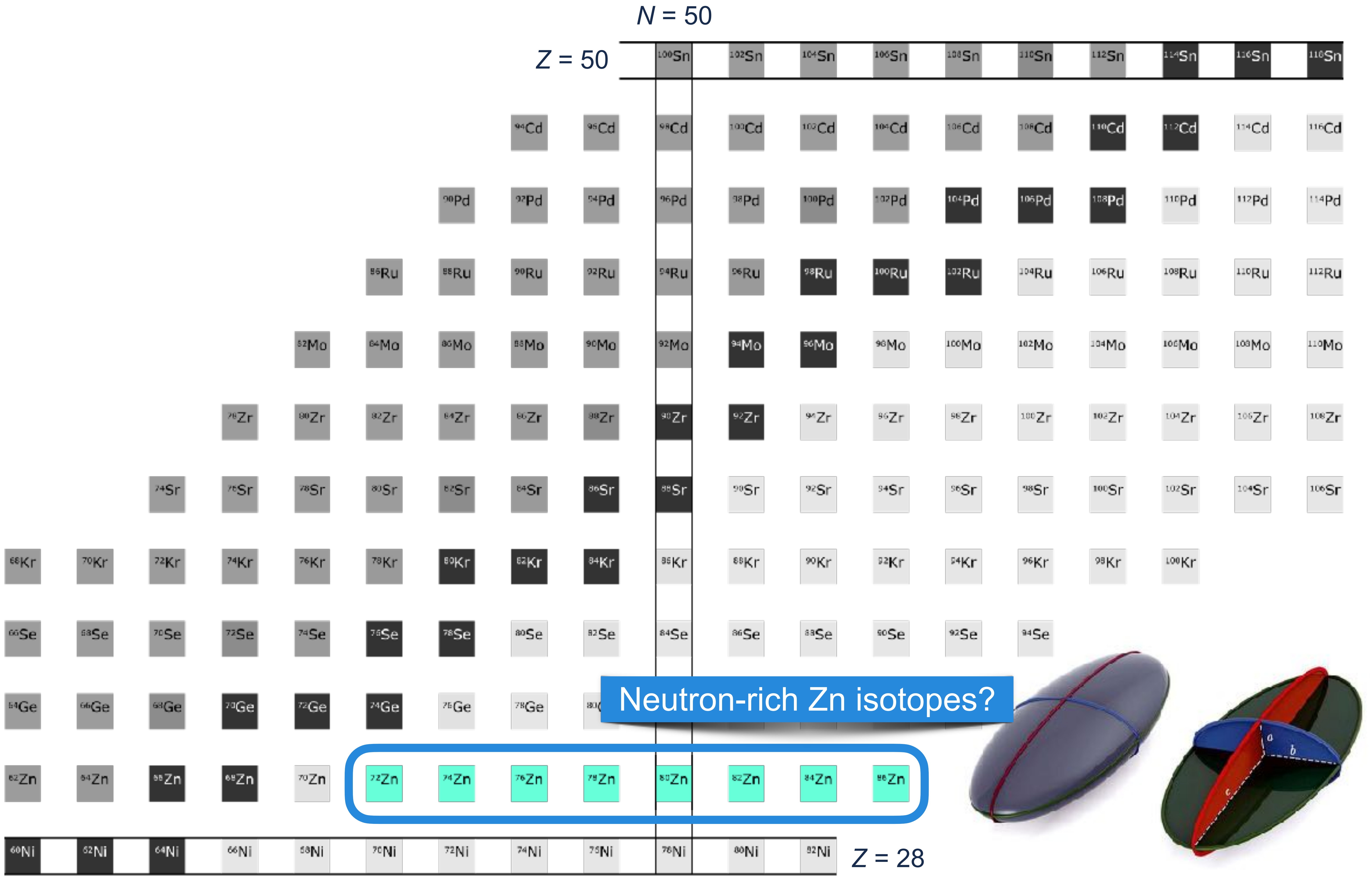

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Triaxiality in the Se, Ge and Zn Isotopes

PRL **97,** 162502 (2006) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2006

Global Calculations of Ground-State Axial Shape Asymmetry of Nuclei

Peter Möller,[1,*] Ragnar Bengtsson,[2] B. Gillis Carlsson,[2] Peter Olivius,[2] and Takatoshi Ichikawa[3]
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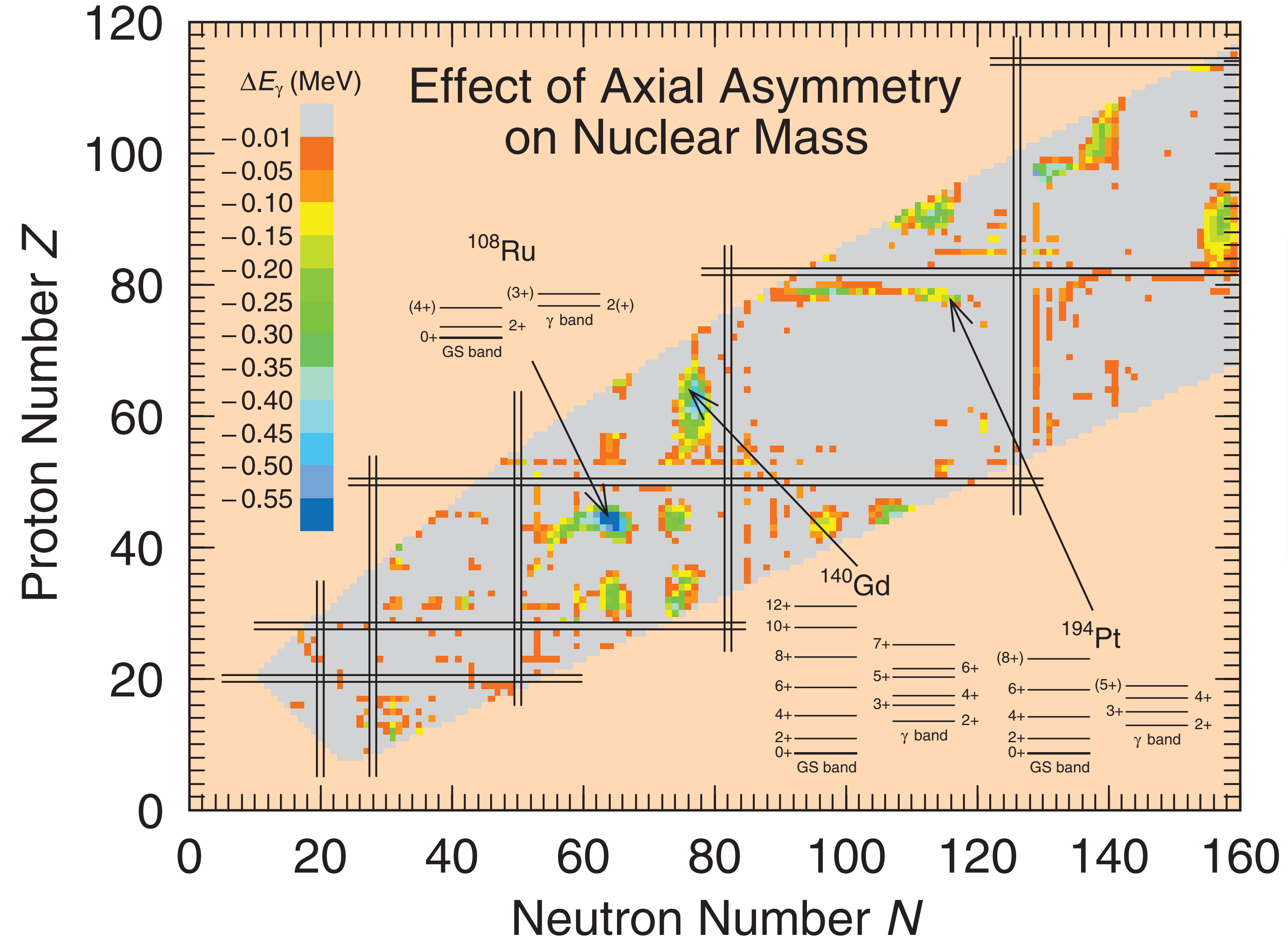
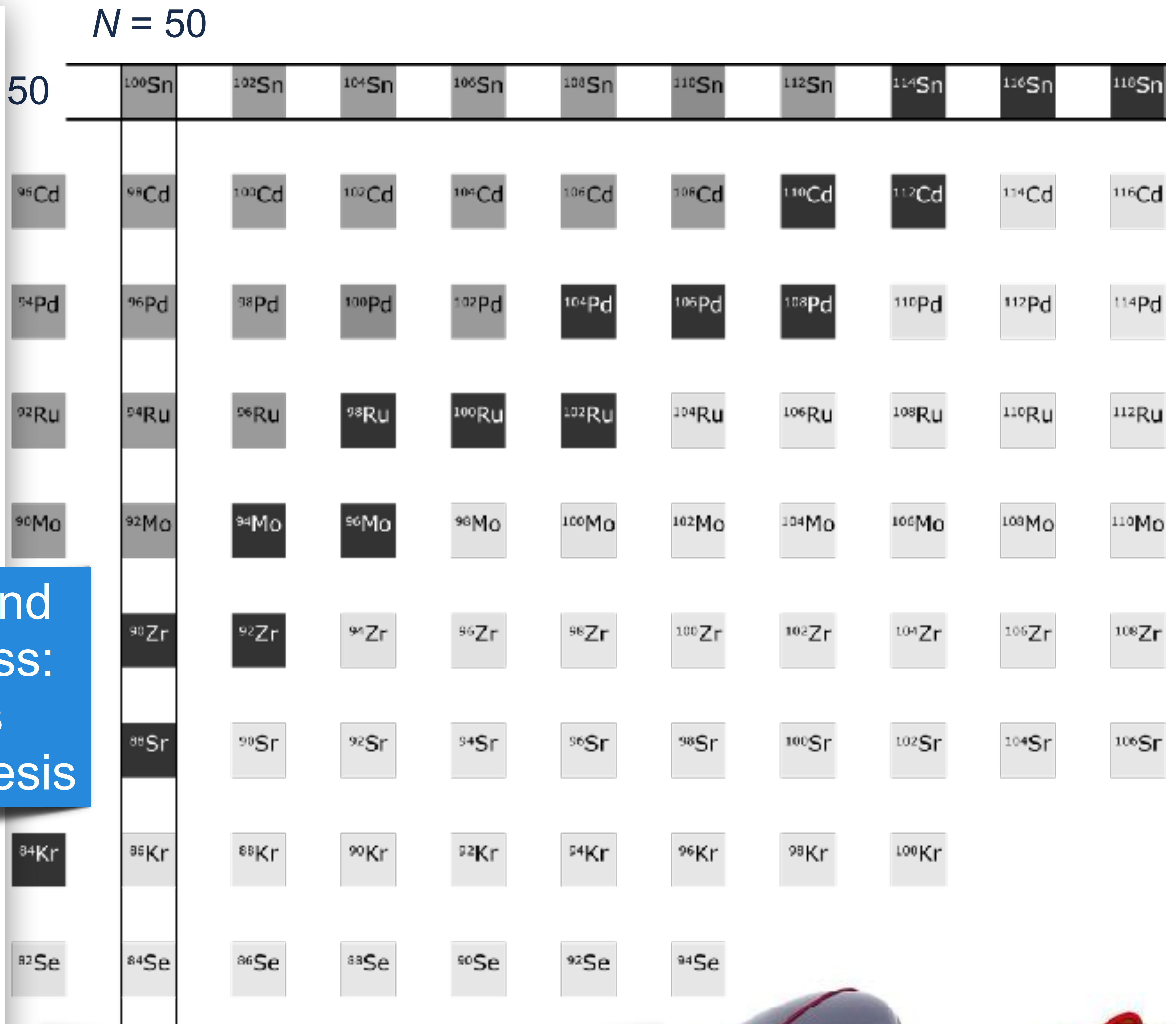
[3]*Advanced Science Research Center, Japan Atomic Energy Agency (JAEA), Tokai-mura, Naka-gun, Ibaraki, 319-1195, Japan*

(Received 21 March 2006; published 17 October 2006)



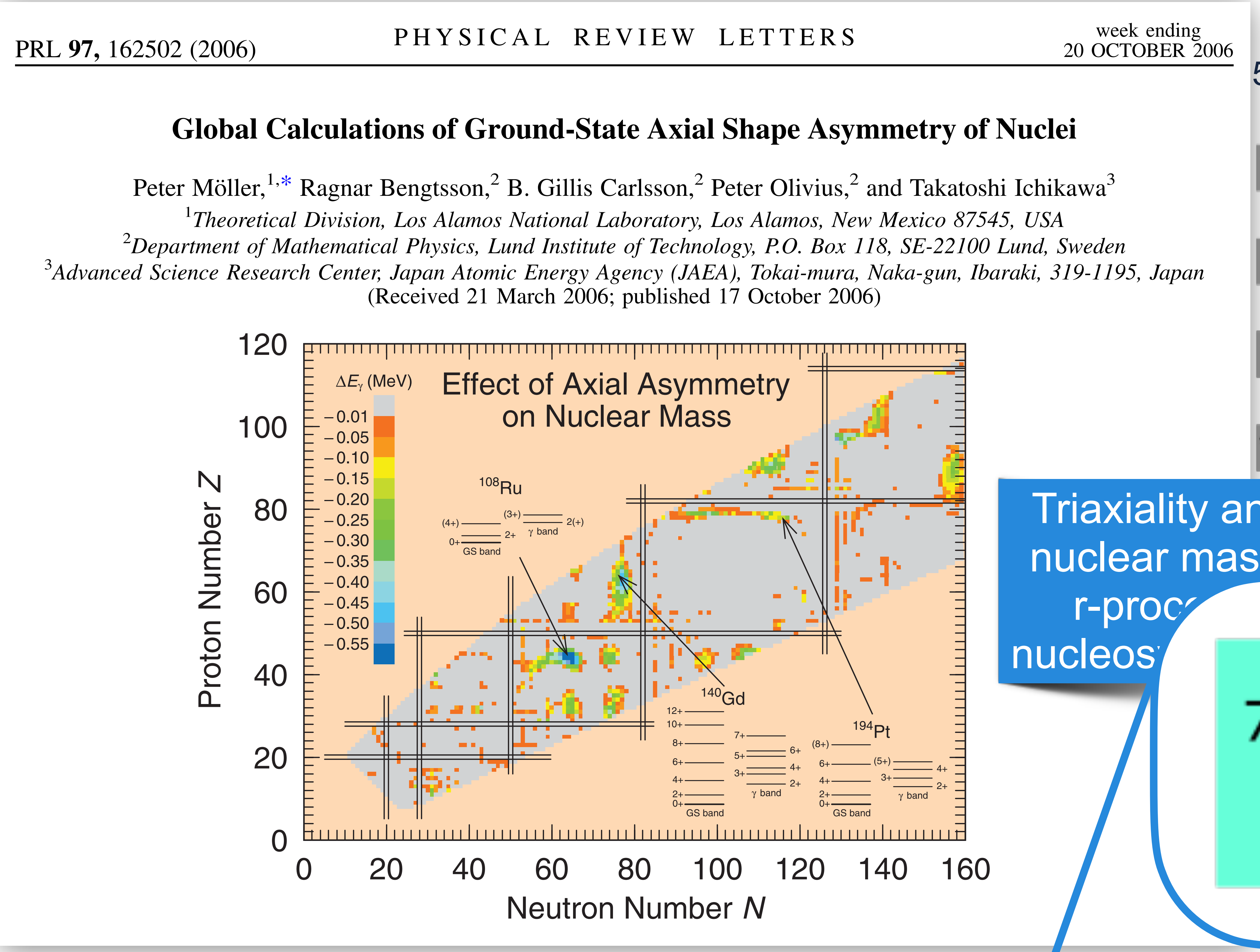
Triaxiality and nuclear mass: r-process nucleosynthesis



Neutron-rich Zn isotopes?

The Colourful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/

Triaxiality in the Se, Ge and Zn Isotopes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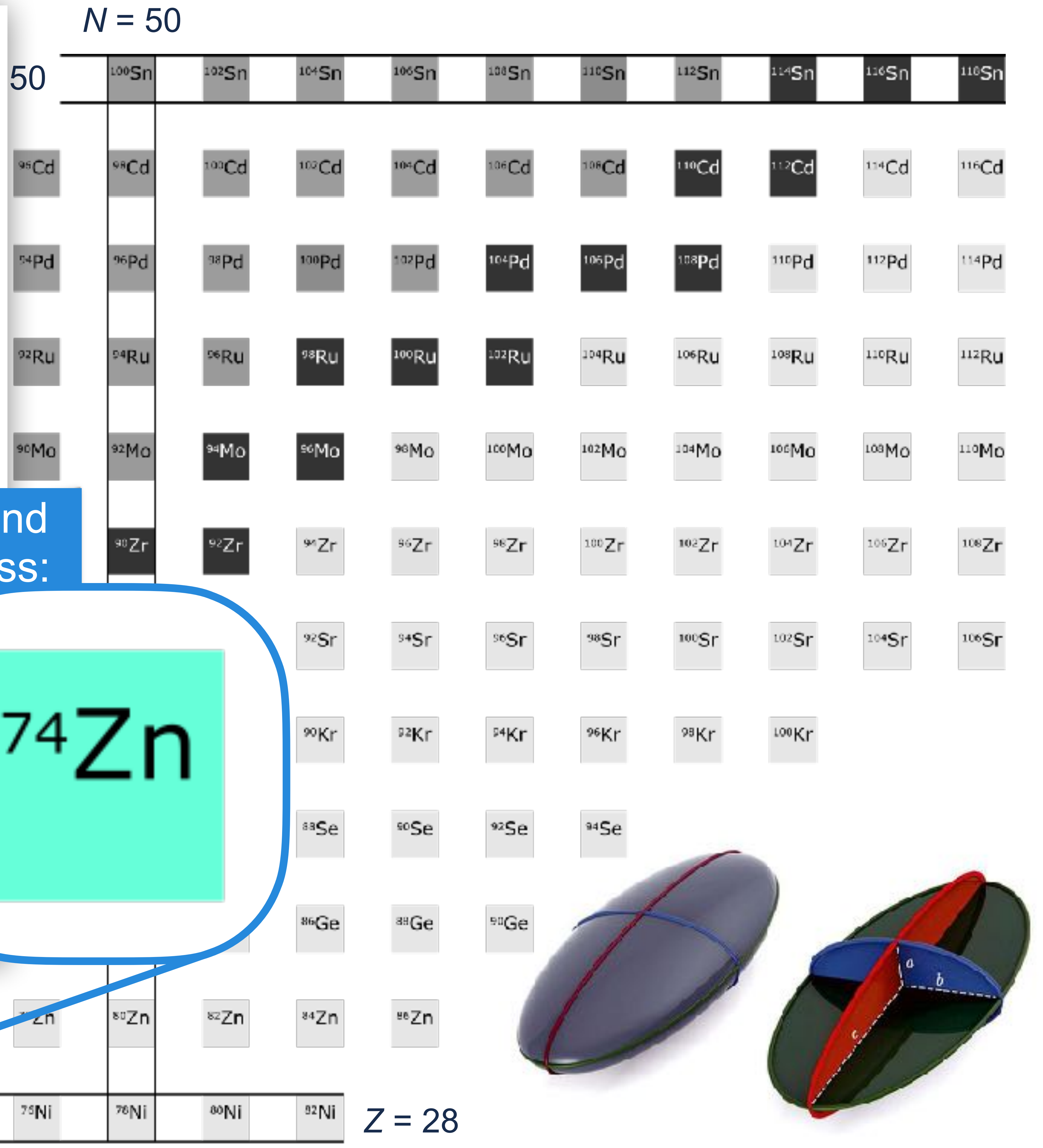

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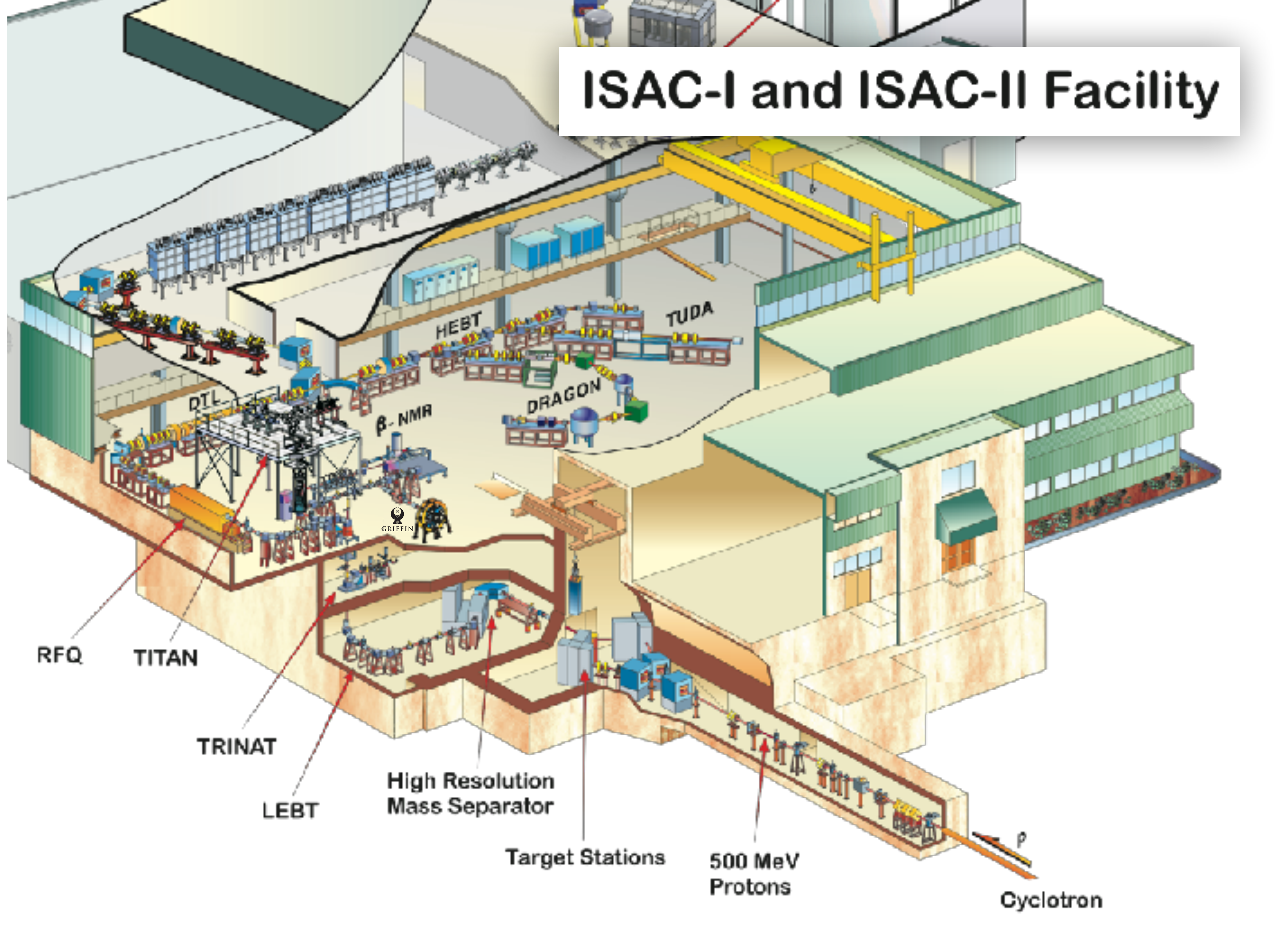
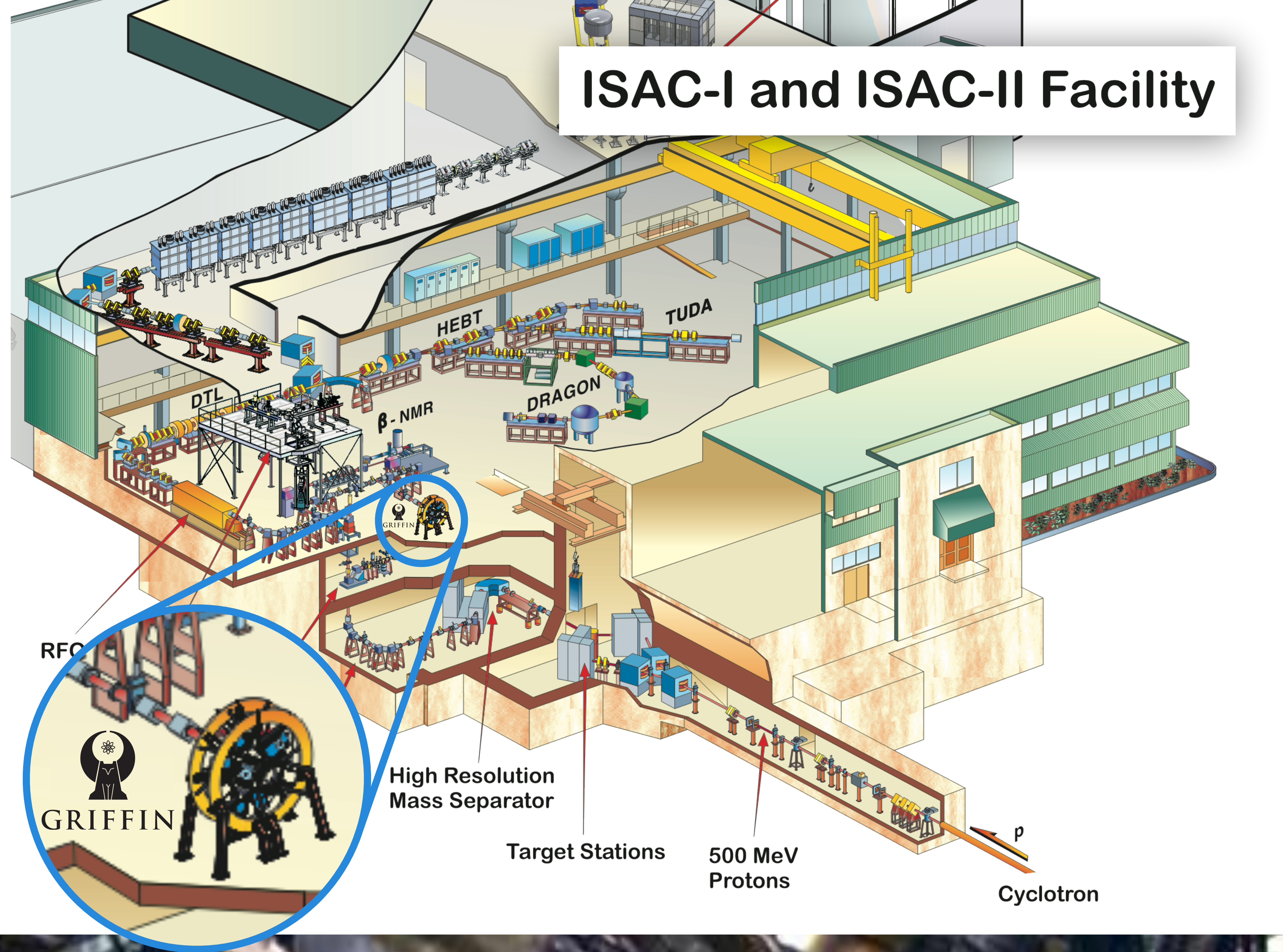

ISAC-I and ISAC-II Facility
HEBT
TUDA
DTL
β-NMR
DRAGON
RFQ
TITAN
TRINAT
LEBT
High Resolution Mass Separator
Target Stations
500 MeV Protons
Cyclotron


GRIFFIN


TRIUMF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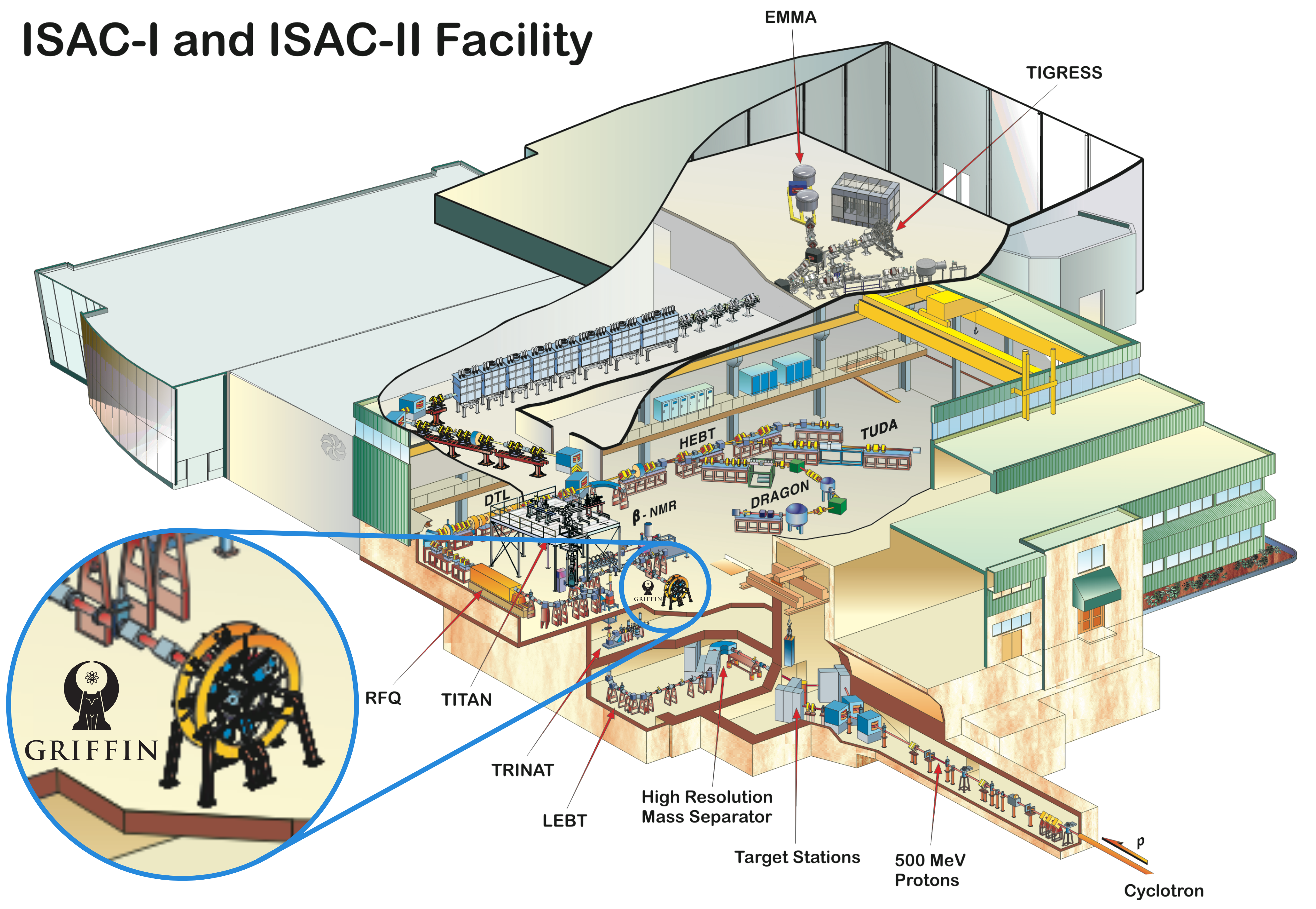
CFBS
GRIFFIN

GRIFFIN @TRIUMF

- ISAC facility: Radioactive Ion Beam production using the ISOL technique
  - ISAC-I ⟹ Non-reaccelerated beams (20-40 keV) ⟹ GRIFFIN
  - ISAC-II ⟹ Post-accelerated beams (up to ~10 MeV/A) ⟹ TIGRESS
- GRIFFIN (Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei): High-efficiency γ-ray spectrometer equipped with many ancillary devices



A.B. Garnsworthy et al., NIMA 918, 9 (2019)

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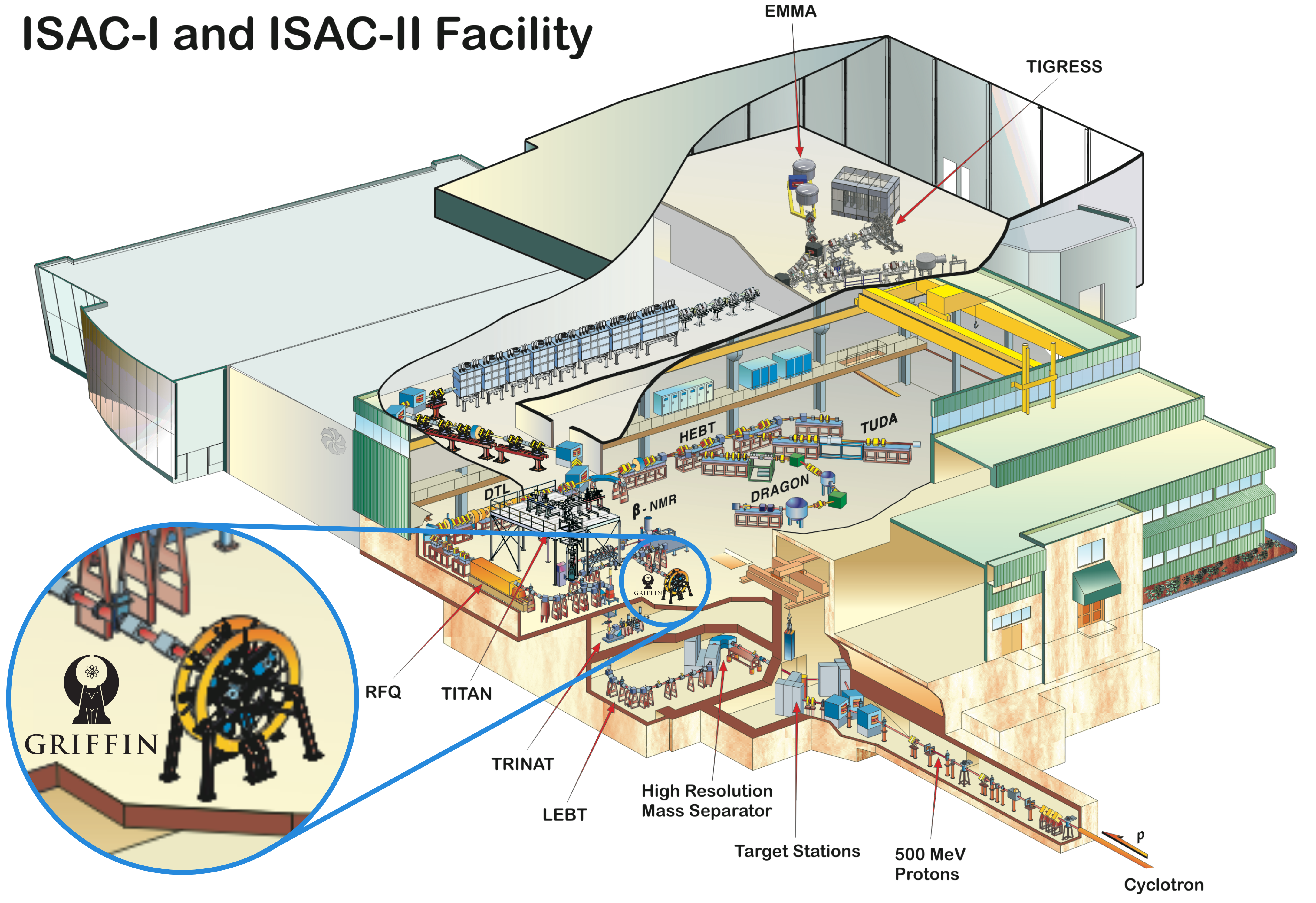

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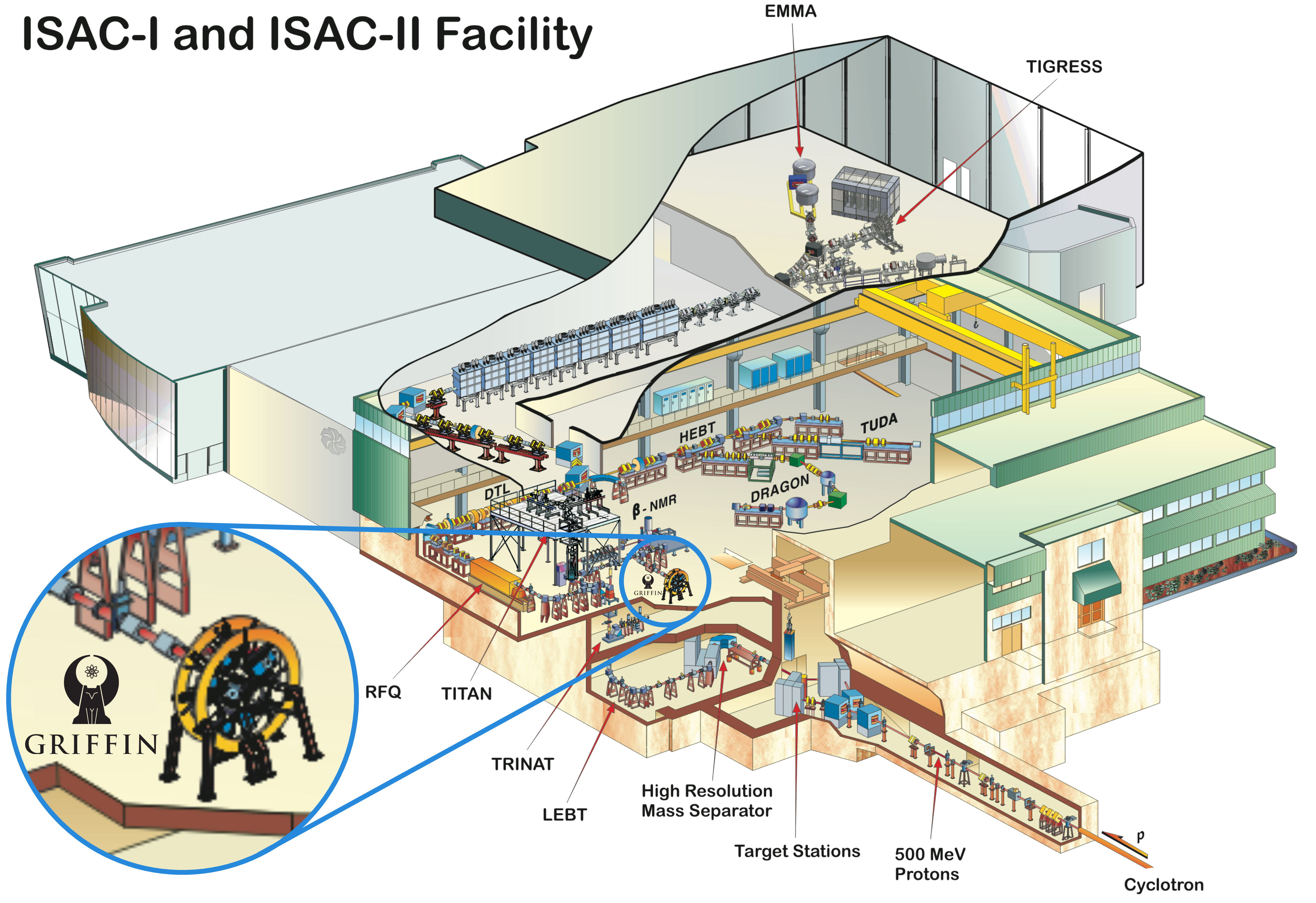

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Axial Shape Asymmetry and Configuration Coexistence in Neutron-Rich ^{74}Zn

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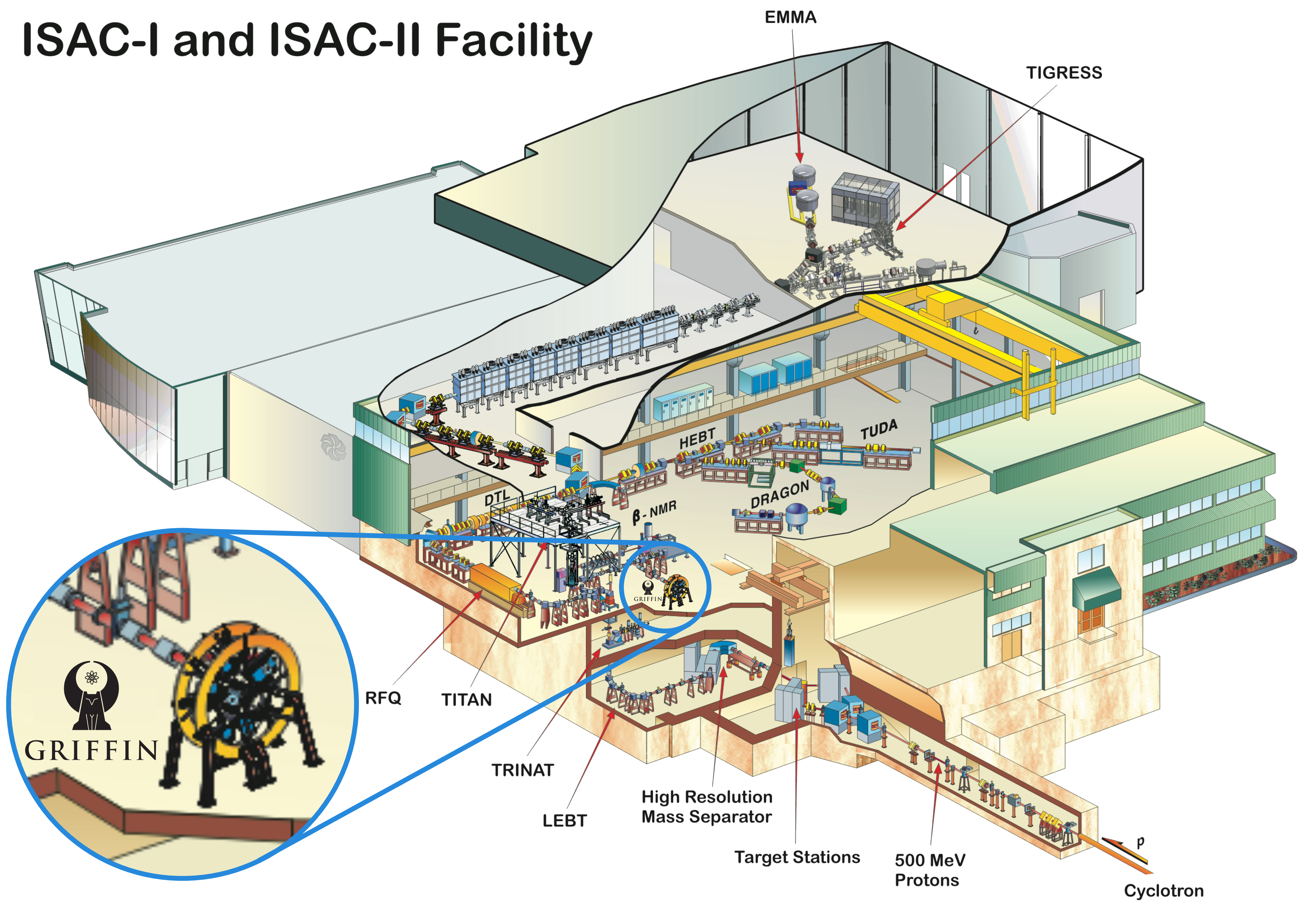

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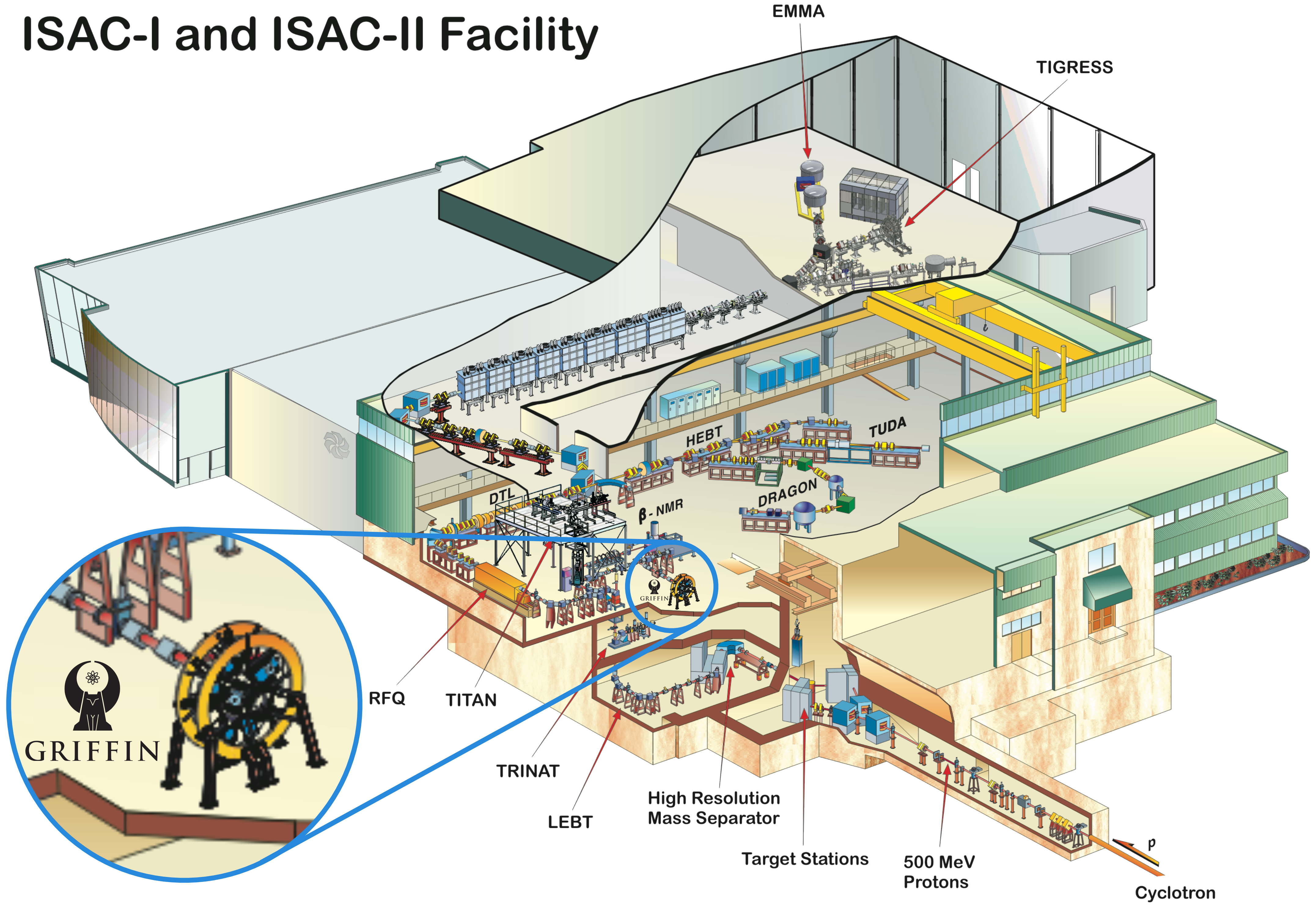

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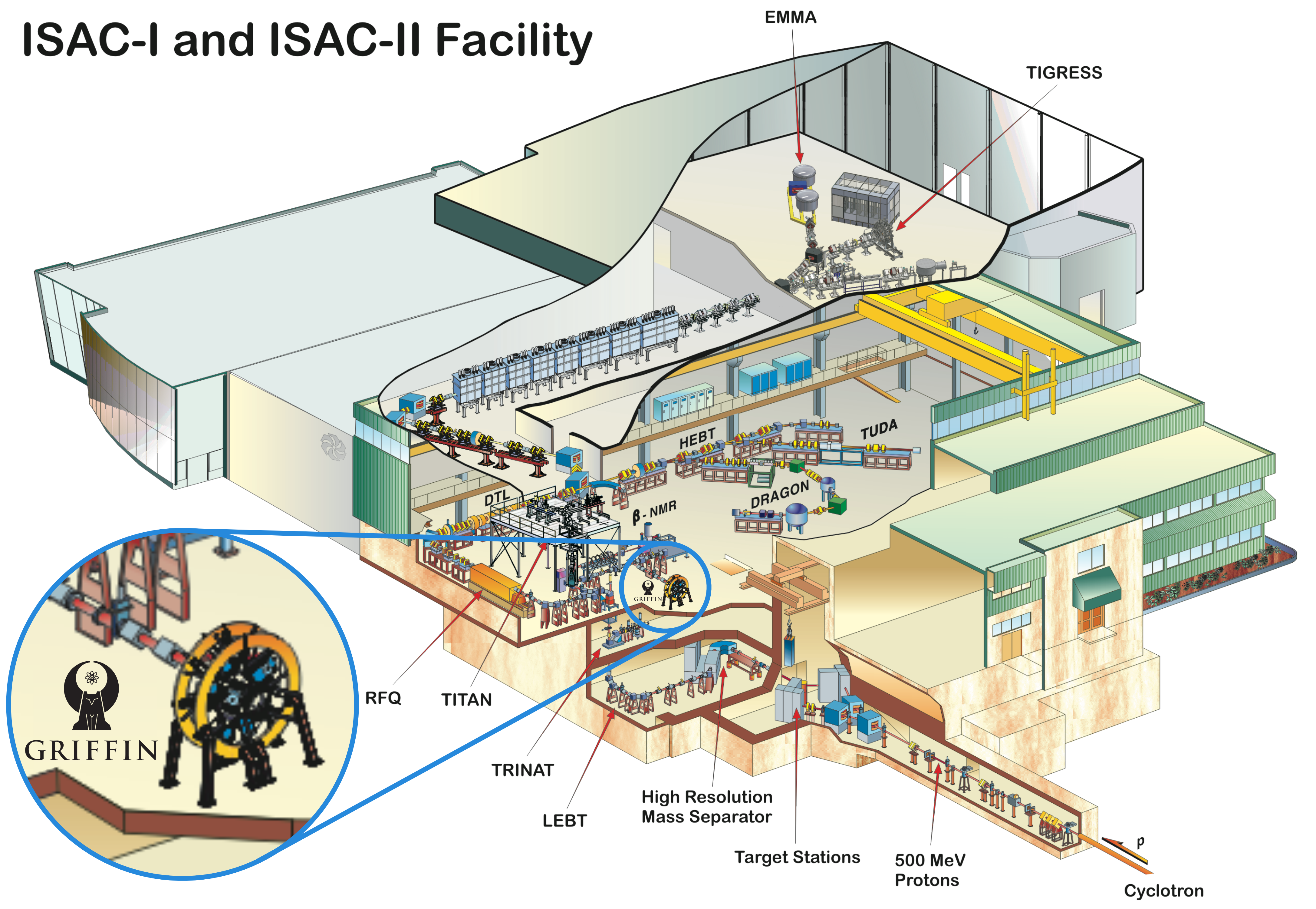

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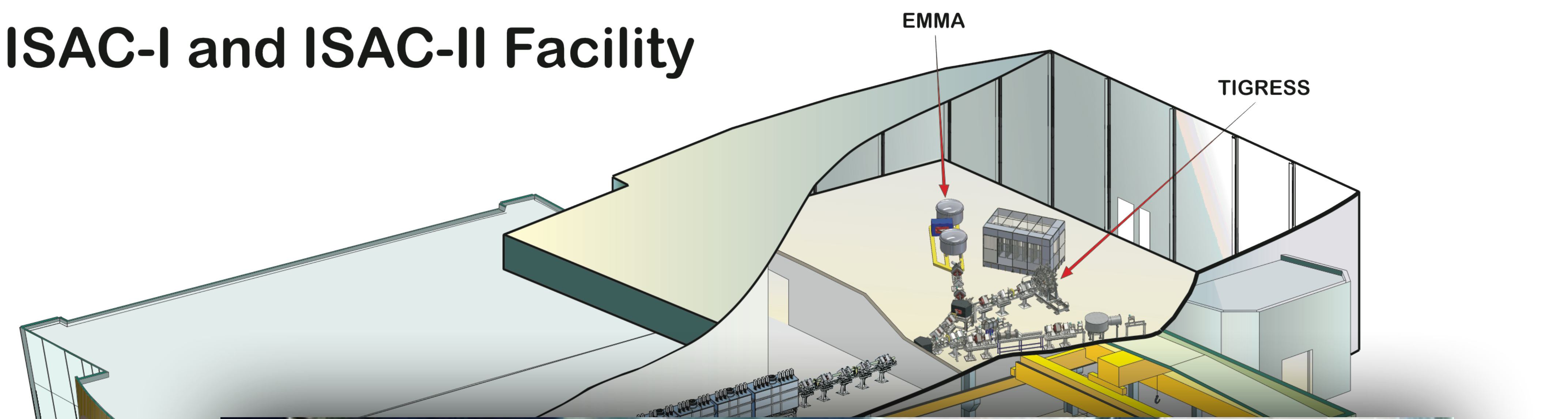
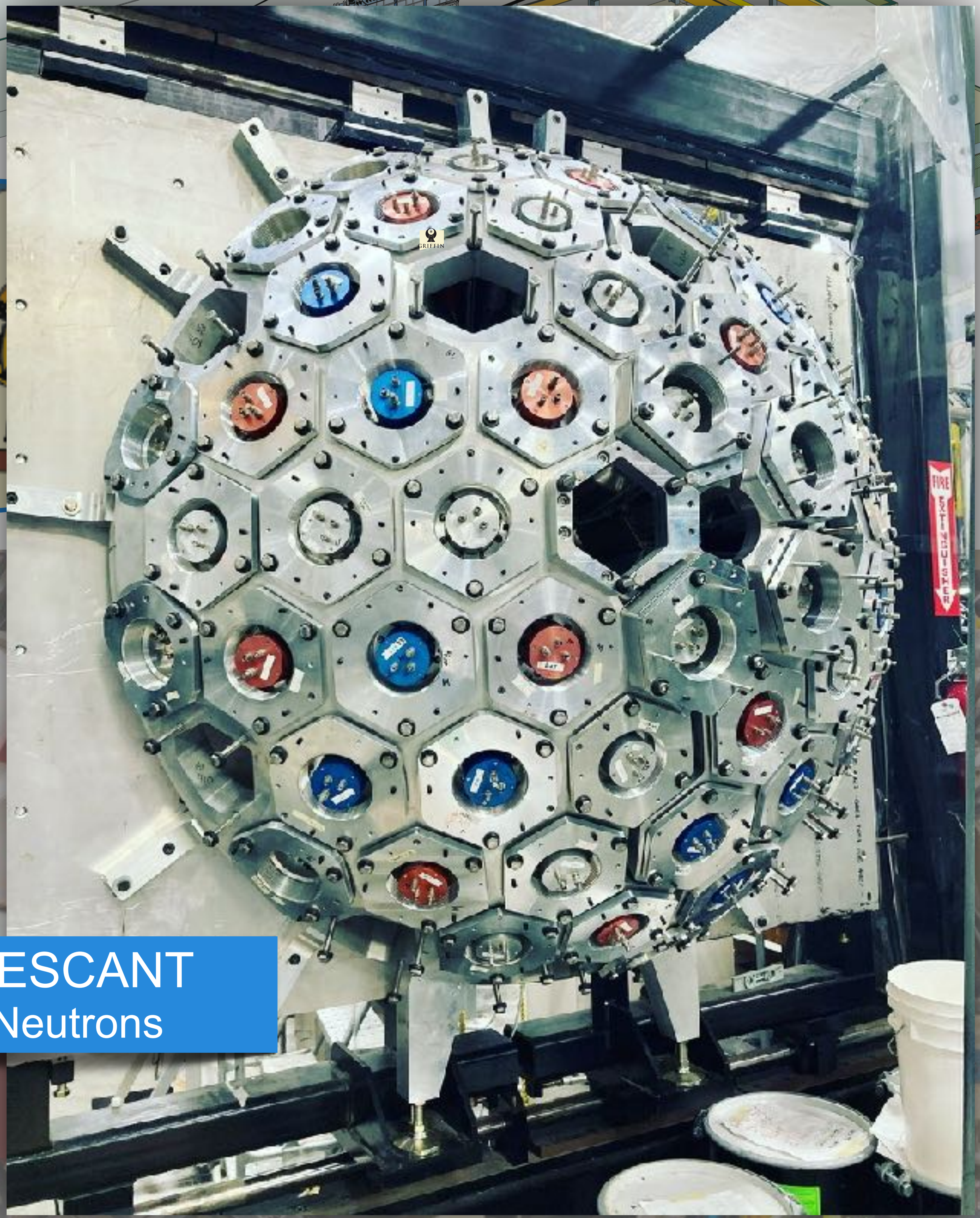
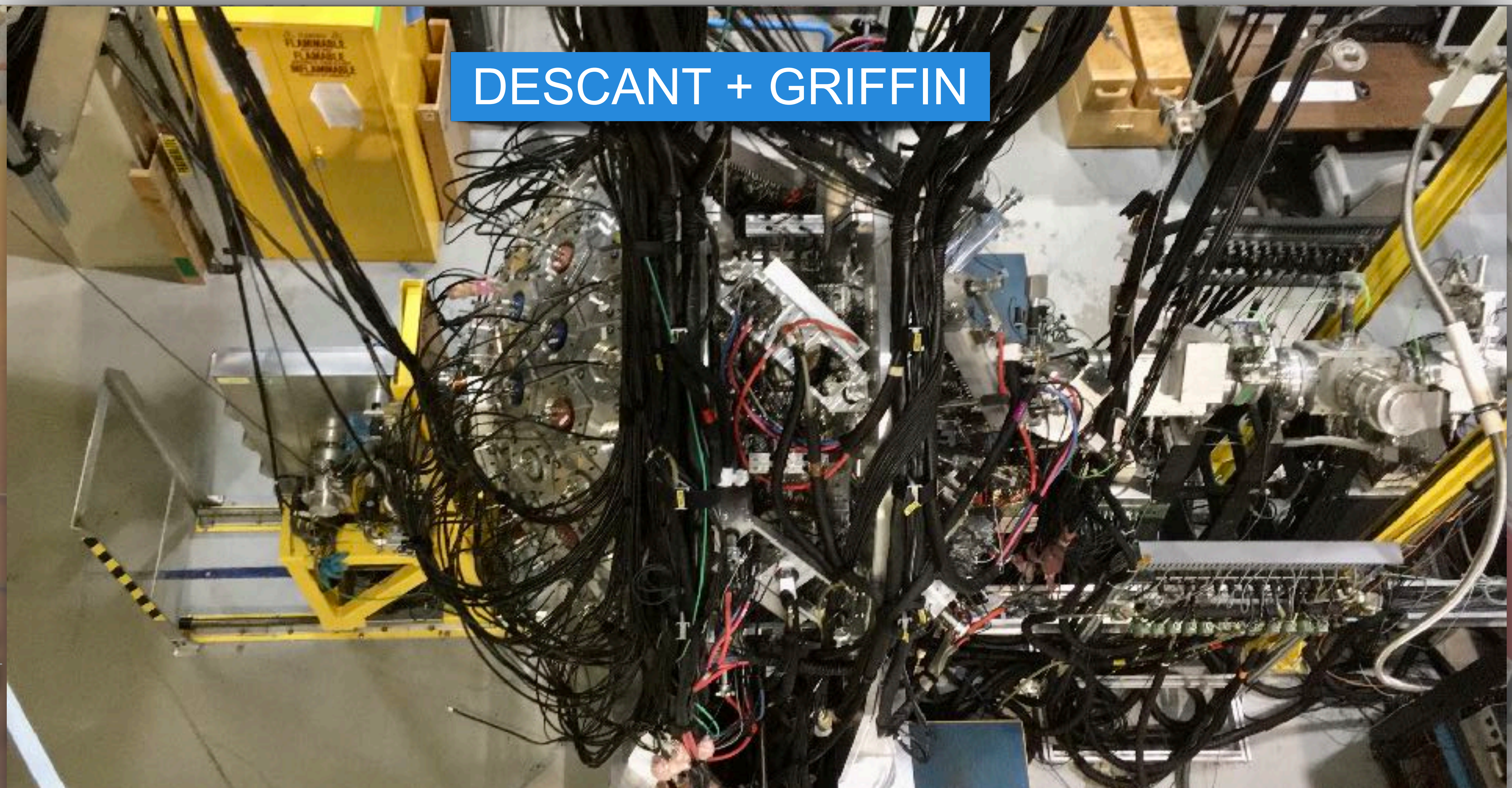
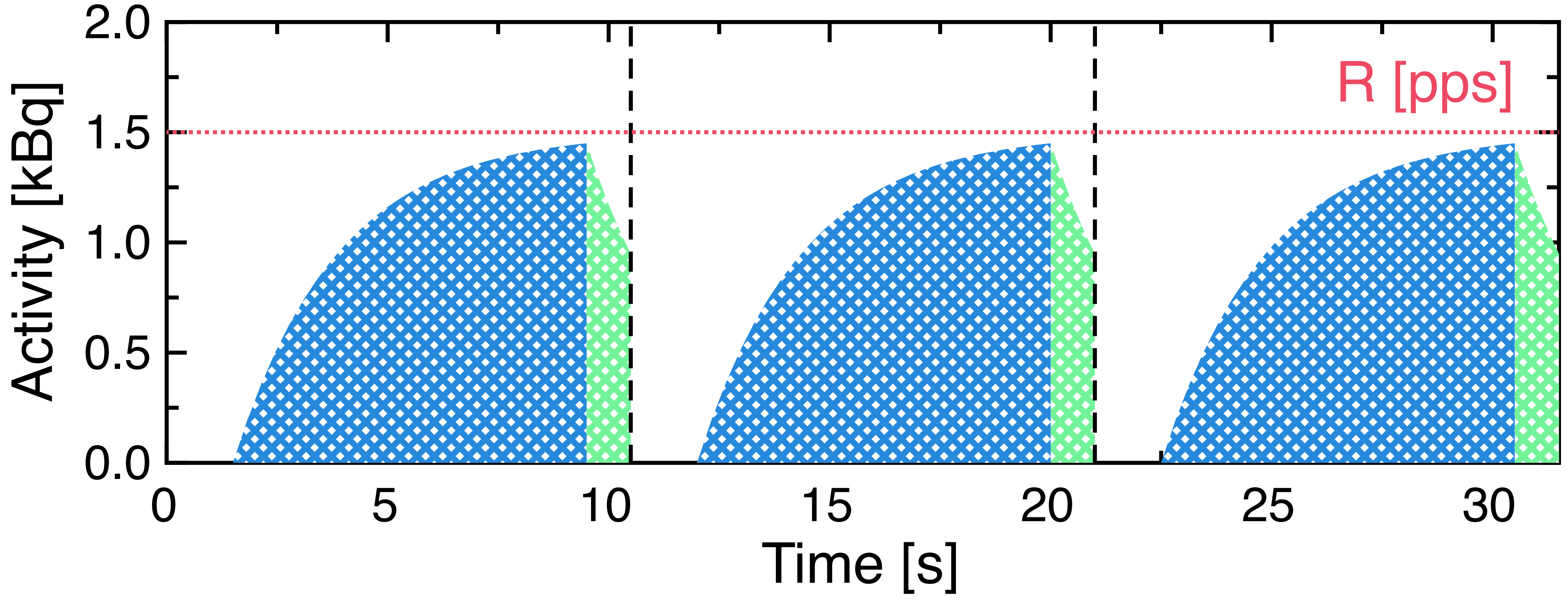


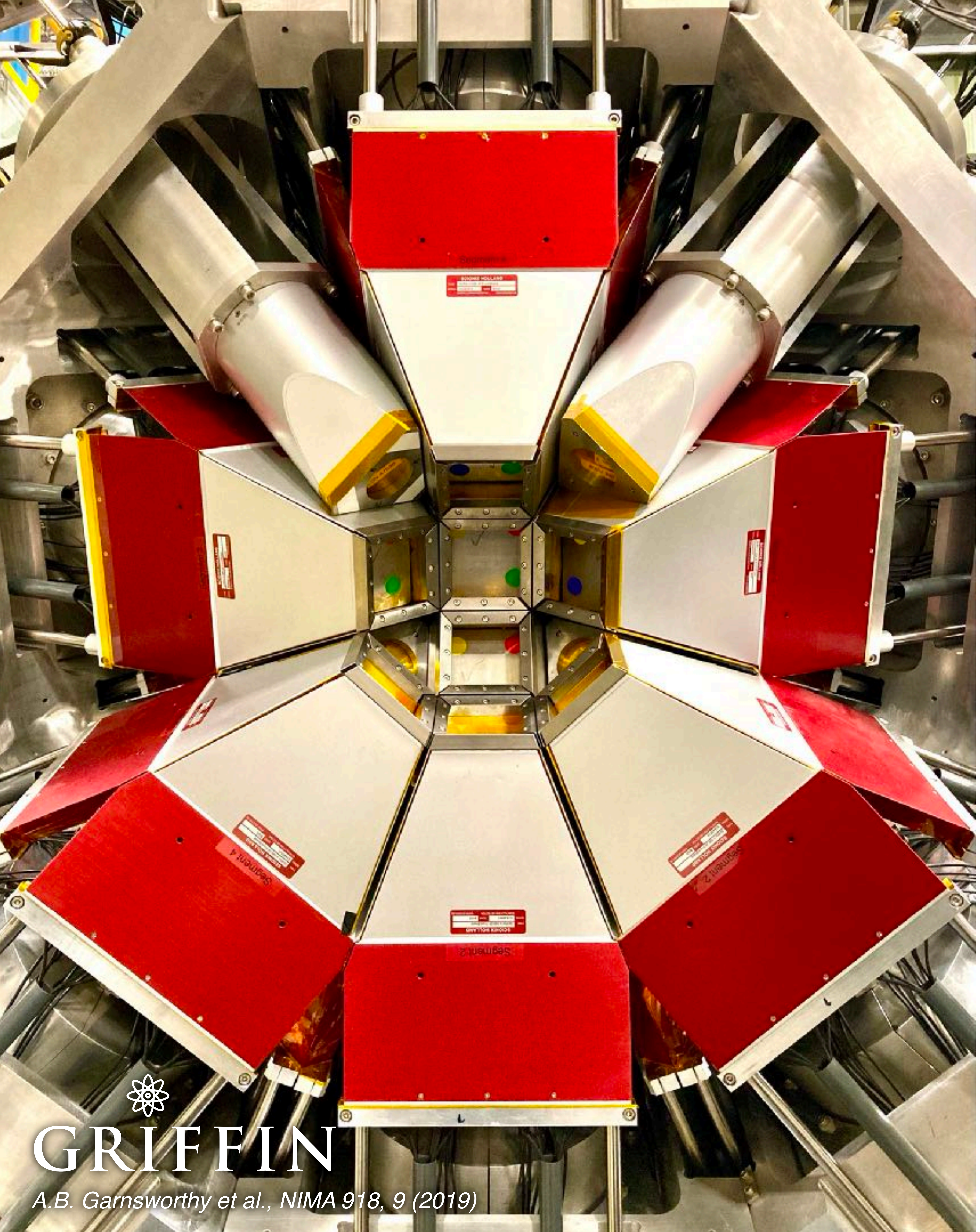




Our Experiment on ^{74}Zn with GRIFFIN

- ^{74}Zn via ^{74}Cu β-decay [$T_{1/2}$ = 1.63(5) s], Beam intensity ≈ $1.5 \cdot 10^3$ pps
- GRIFFIN: 12 of 16 available clovers at 14.5 cm from the target
  - ε_γ(1332.5 keV) = 7.8%, ε_γ(300 keV) = 16.6%
  - P/T (addback + BGO suppressors) = 45.5%
- Tape cycle: 5 $T_{1/2}$ on, 1 s off, 0.5 s background, 1 s tape movement

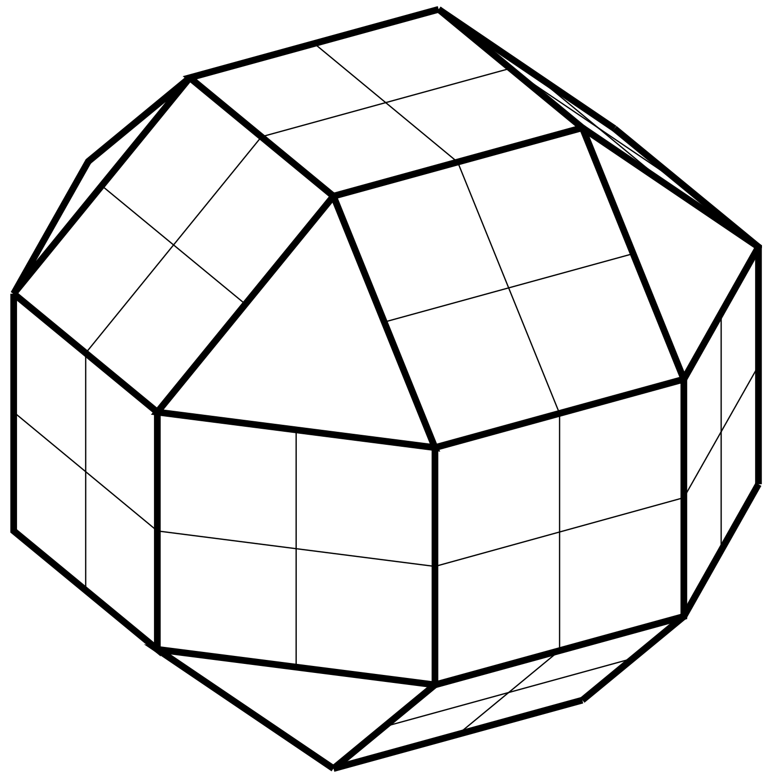




A.B. Garnsworthy et al., NIMA 918, 9 (2019)

γ-γ Angular Correlations

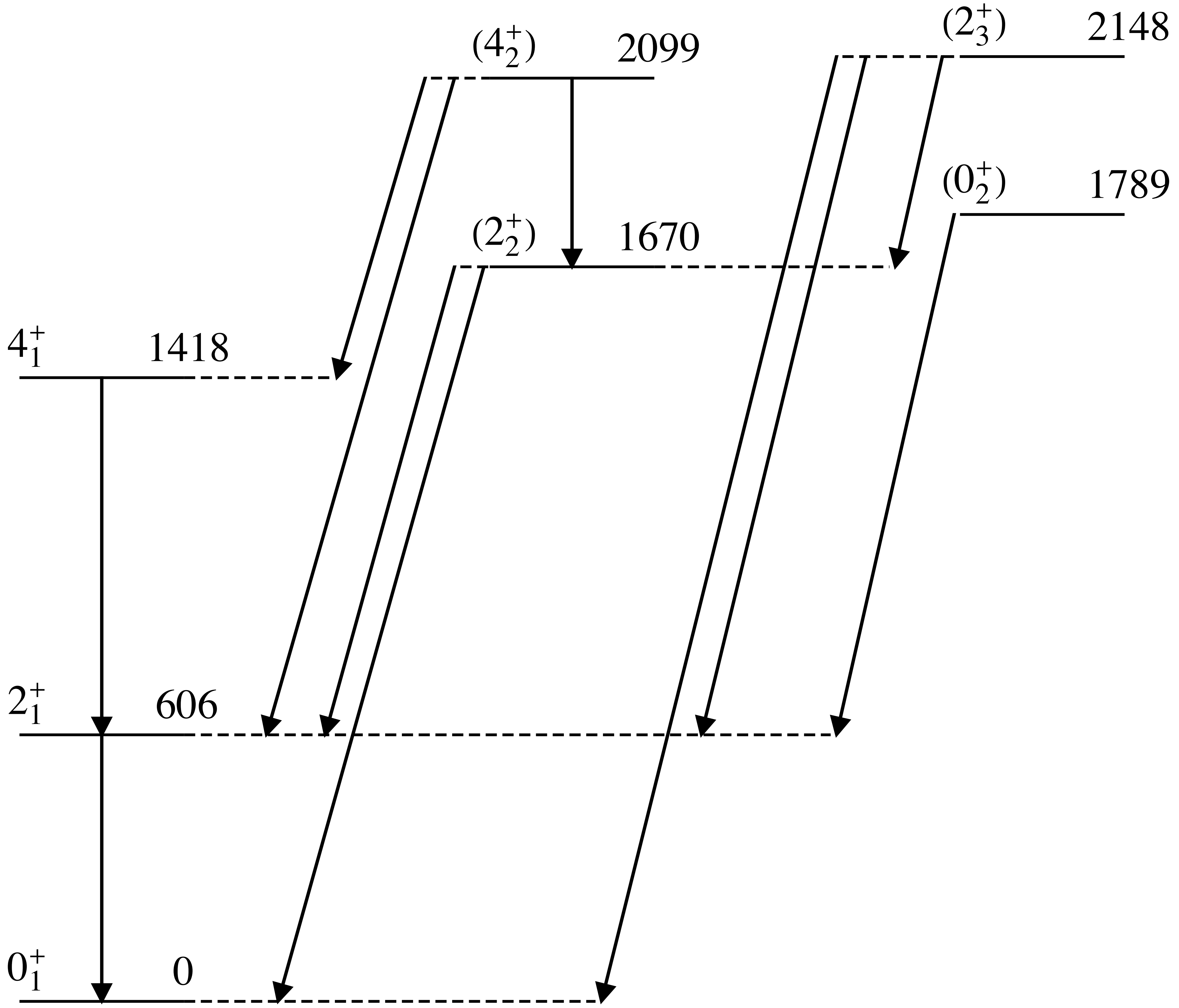
- γ-γ Angular Correlations with GRIFFIN:
  J.K. Smith et al., NIMA 922, 47 (2019)
  - Rhombicuboctahedron geometry ⇒ Up to 52 opening angles



  - Event mixing technique ⇒ No need to know # of pairs for each opening angle and relative efficiencies of the detectors
  - Finite sizes of the detectors ⇒ Detailed GEANT4 simulations
  - Definitive spin assignments at the 99% CL

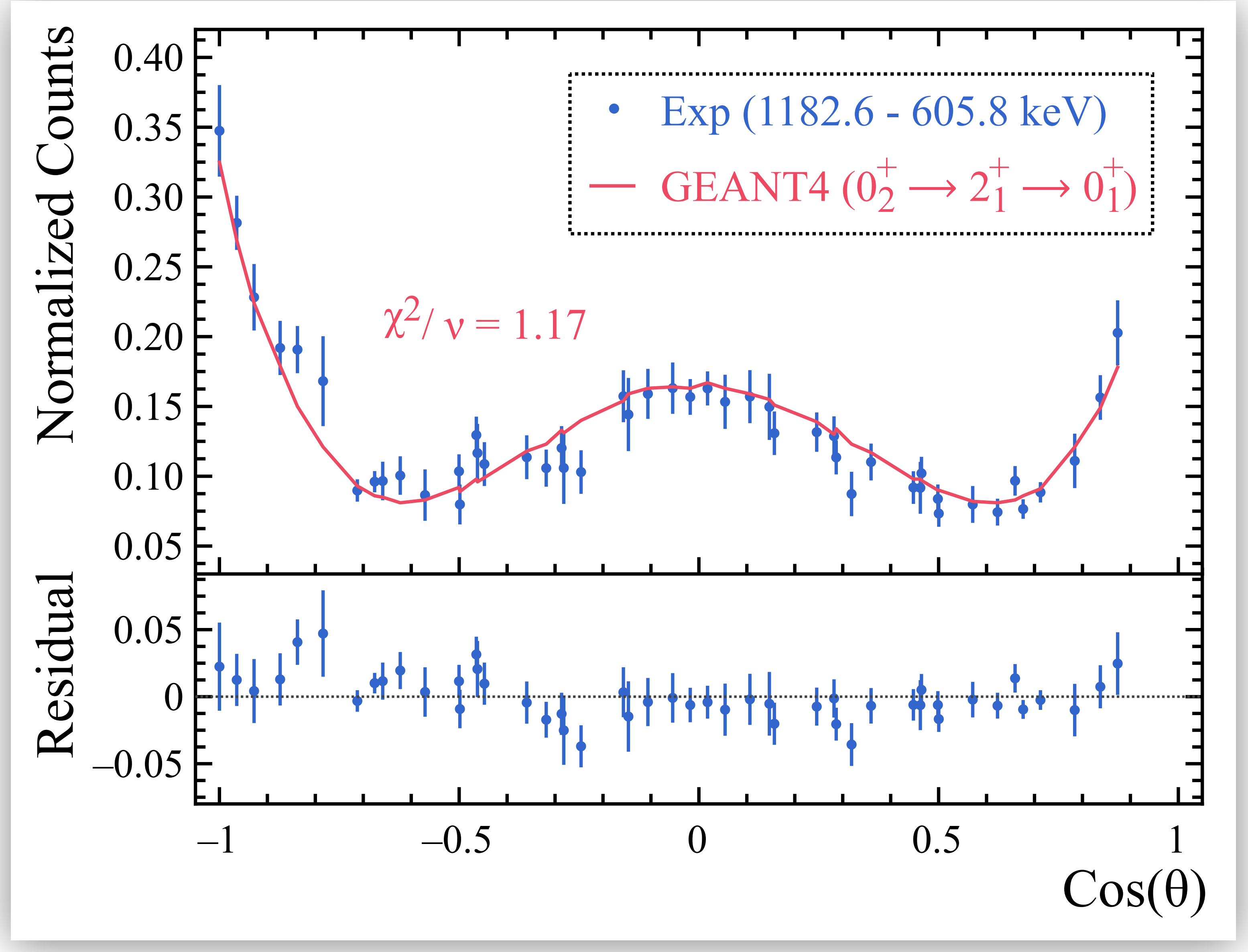
Previous Knowledge

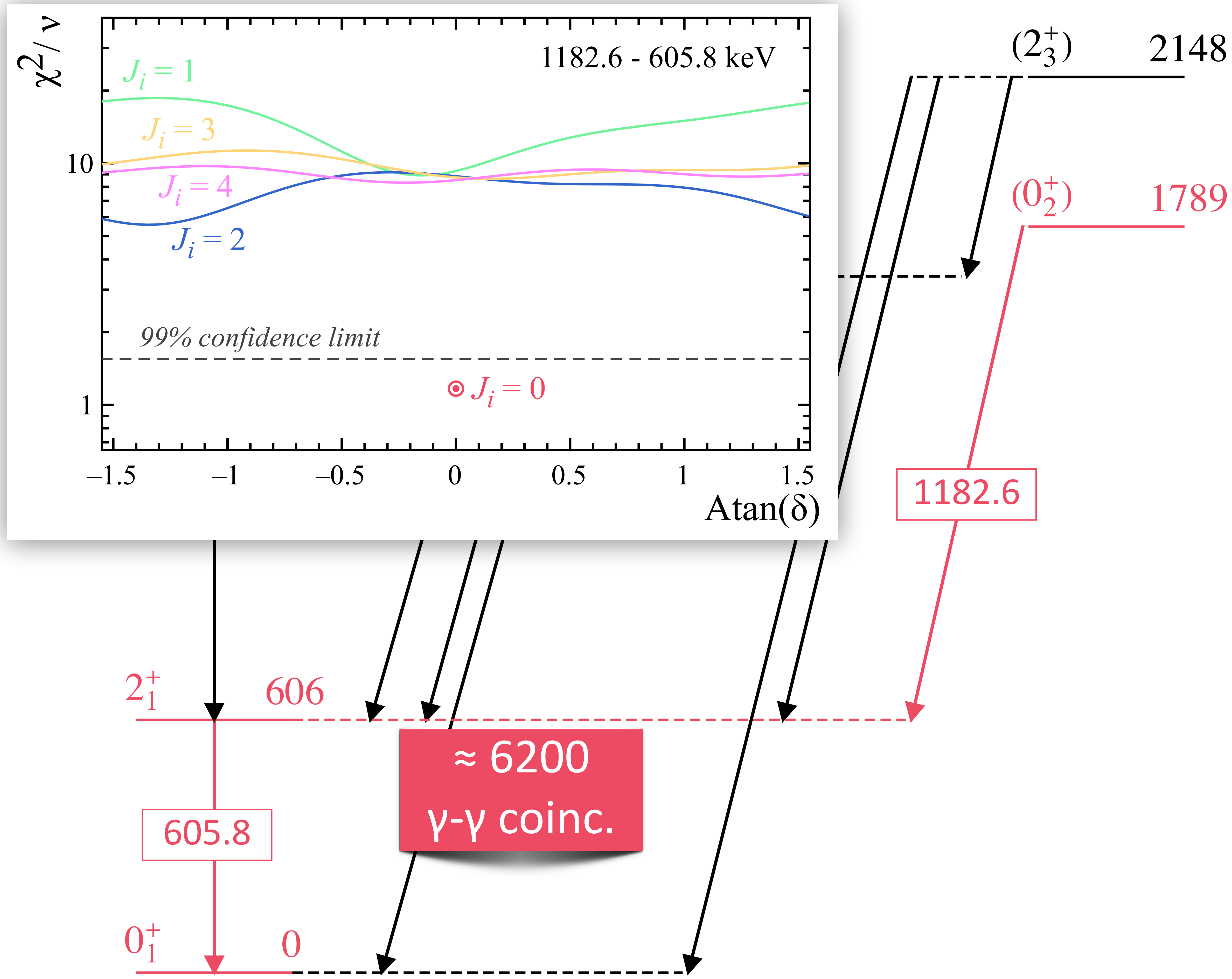
- ^{74}Cu β-decay @ORNL, 3 clovers
  J.L. Tracy Jr. et al., PRC 98, 034309 (2018)
  - 170 γ-rays
  - 50 levels (29 new)
  - log(ft) values
  - Tentative spin assignments based on decay patterns, intensities, log(ft) values, and in a few cases model predictions (shell model and vibrational model)



γ-γ Angular Correlations: the (0_2^+)

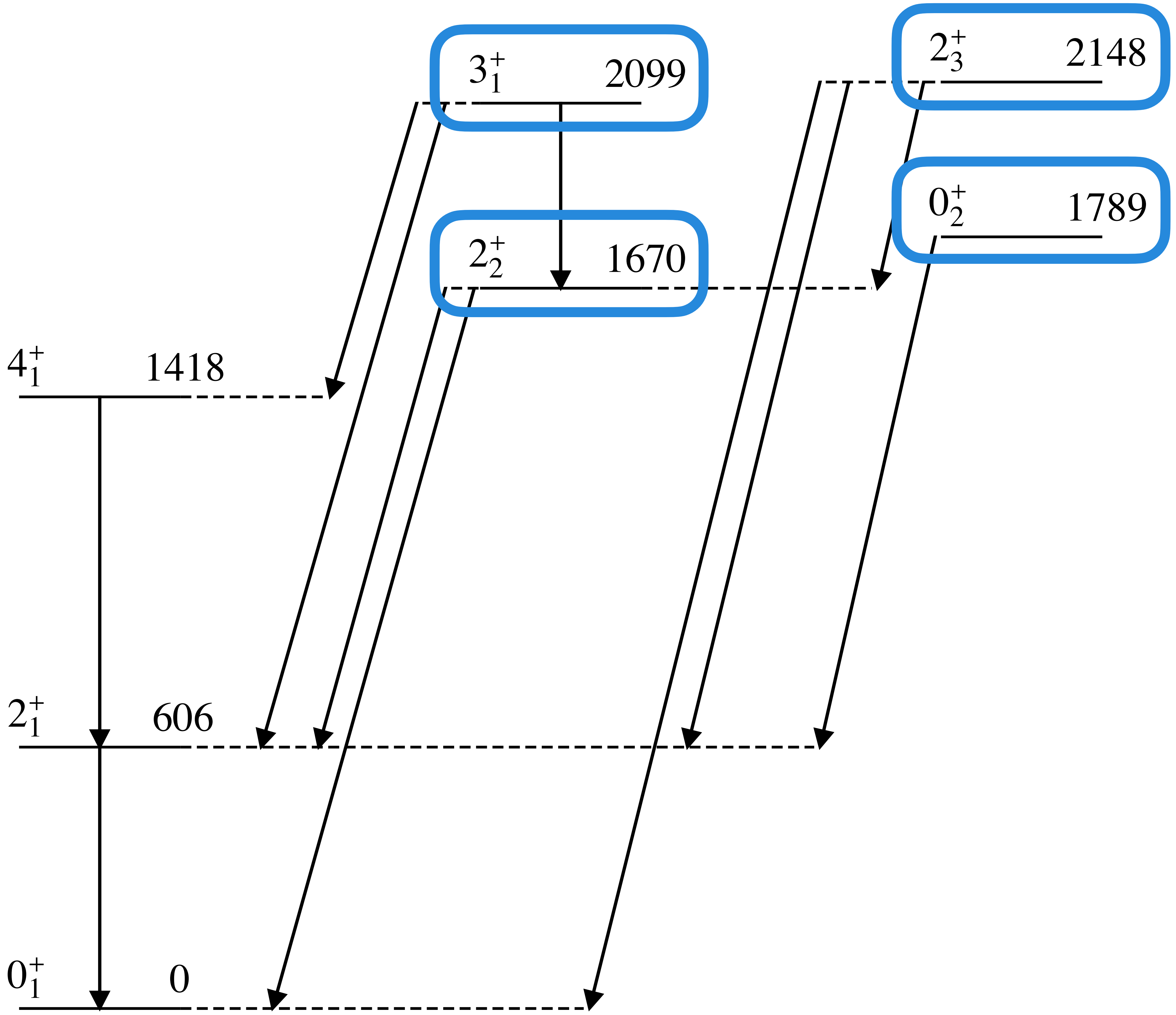
- The state at 1789 keV is firmly established as the first excited 0^+ state





Experimental Results in a Nutshell

- New, definitive spin assignment for:
  - 2_2^+, 0_2^+, 3_1^+, 2_3^+ states



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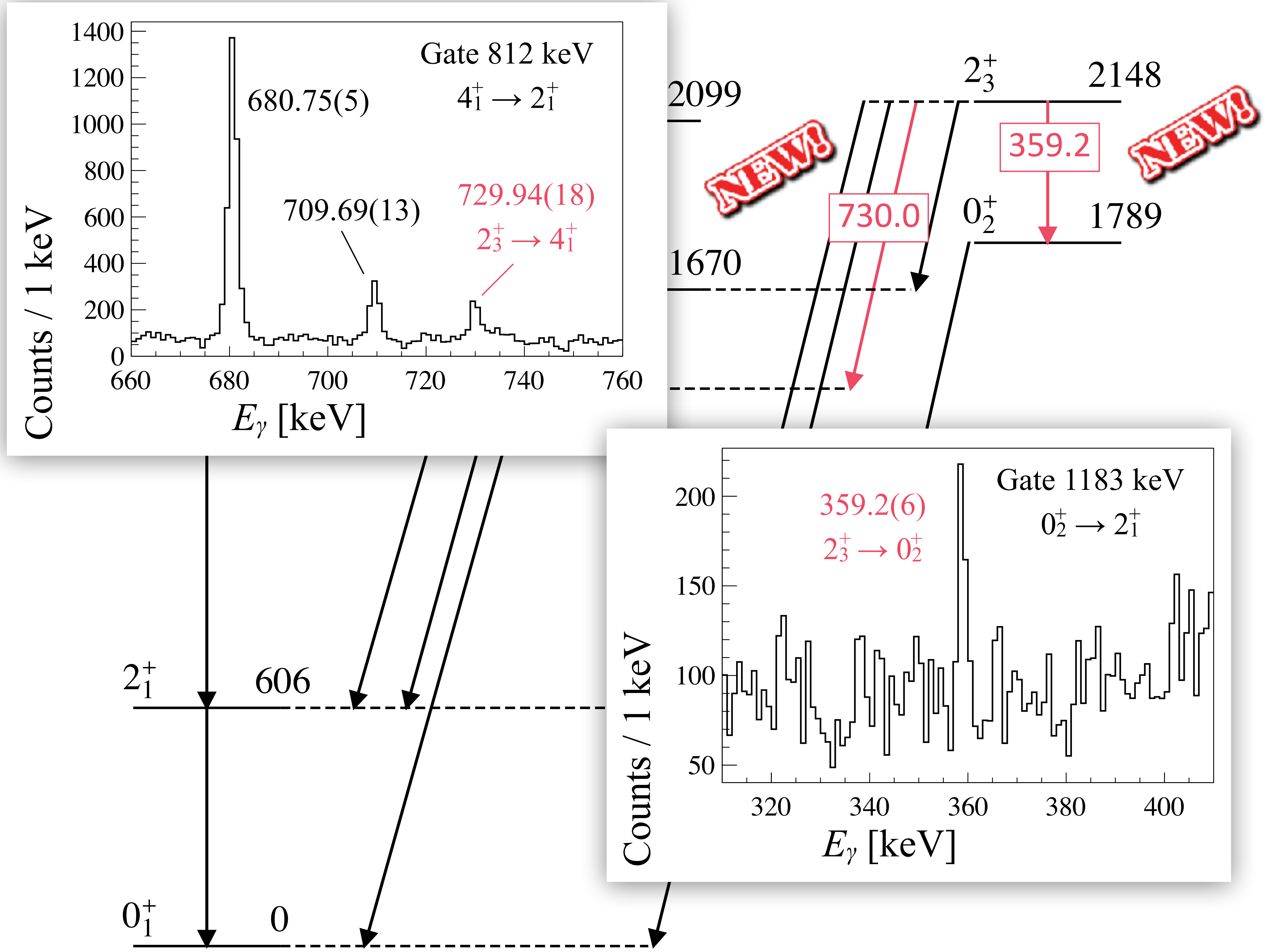

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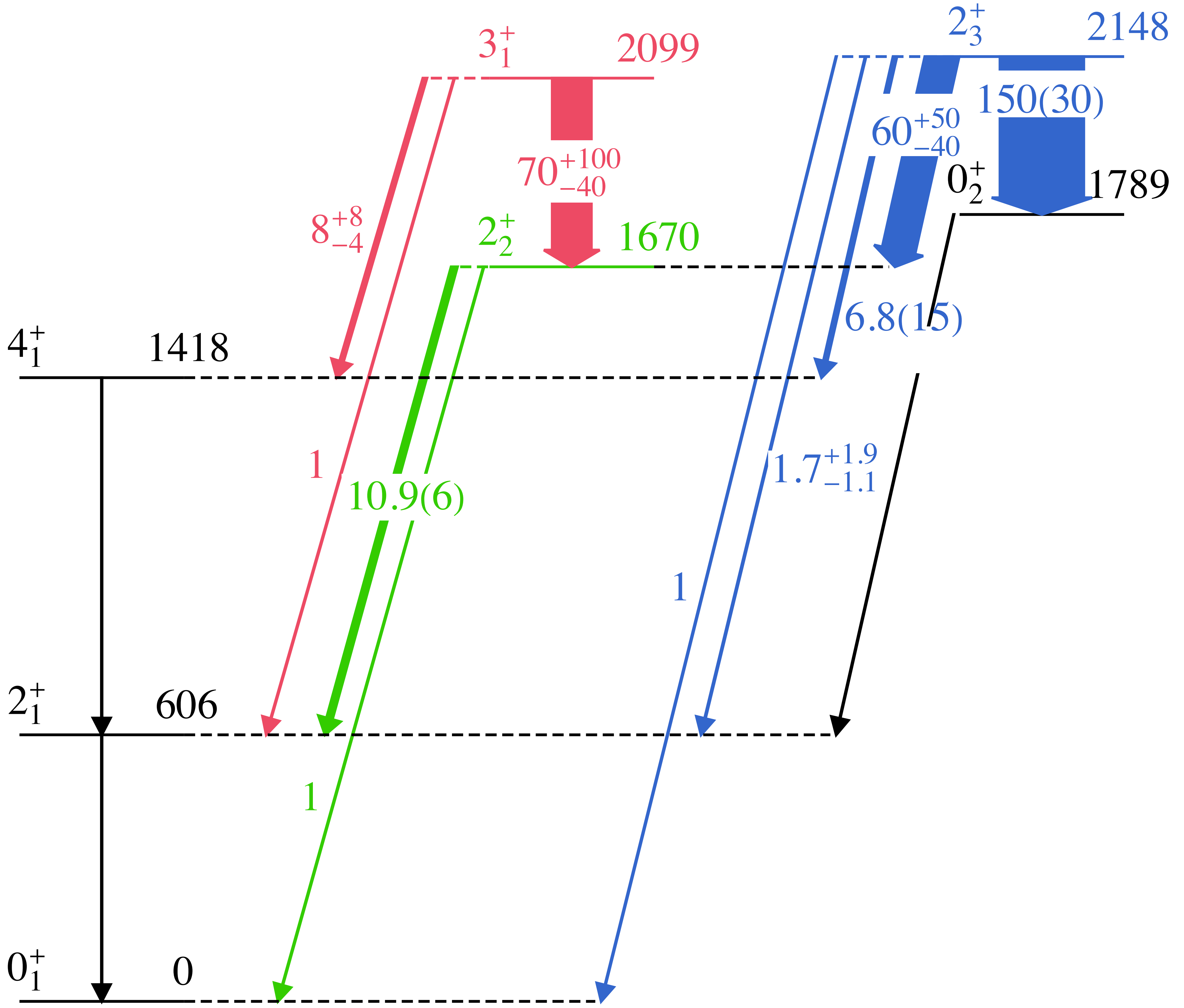
- From measured branching ratios and δ(E2/M1) mixing ratios ⇒ Relative B(E2) values



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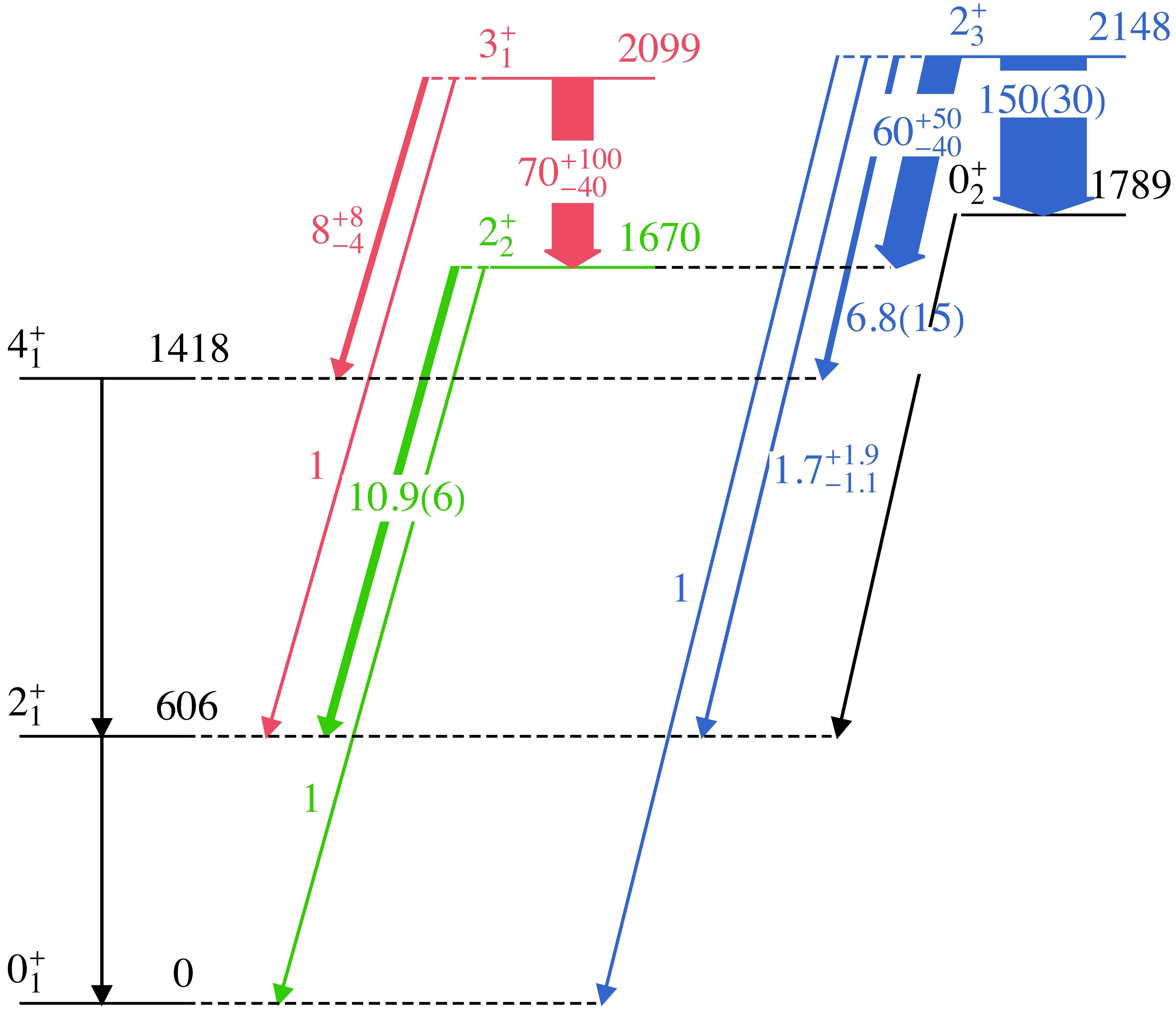
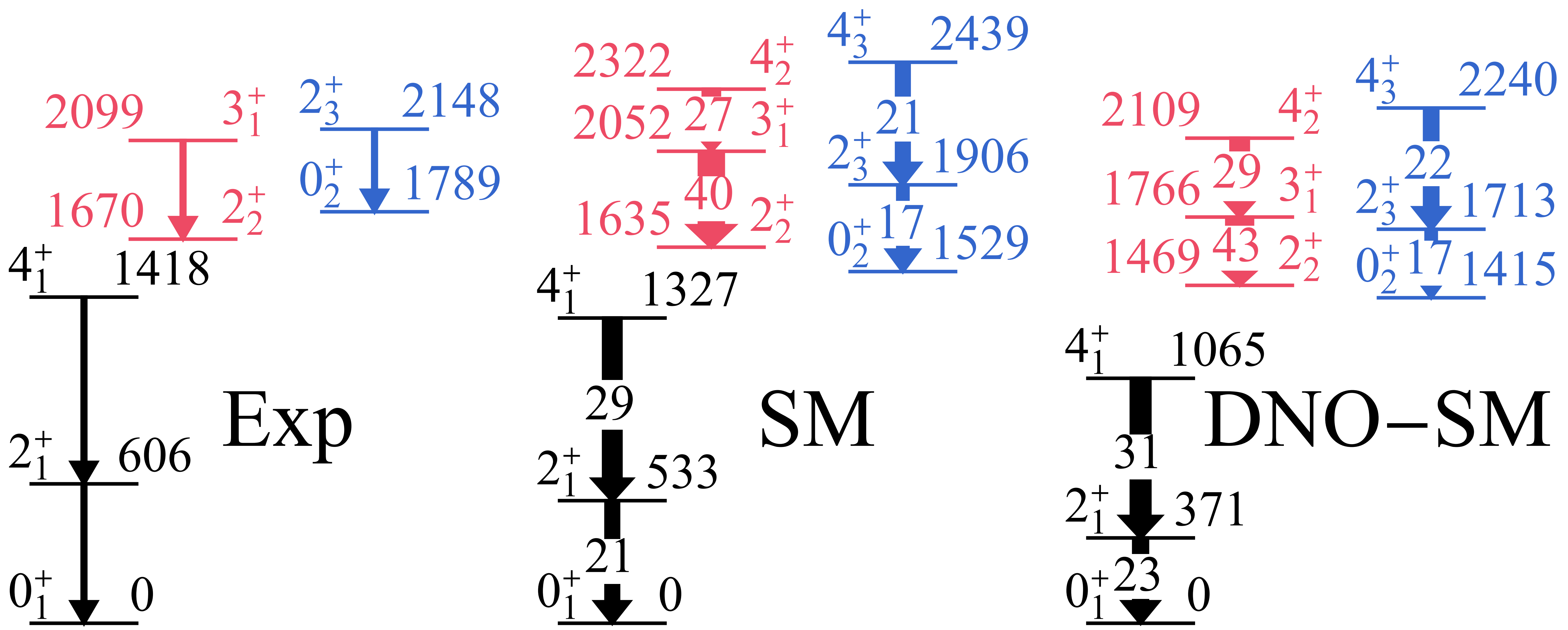
Strong transitions observed, indicative of band structures at low-spin in ^{74}Zn



New Large-Scale Shell-Model Calculations

- By Silvia Lenzi, Frédéric Nowacki, Duc D. Dao
- LNPS interaction, *pf* shell for protons, $1p_{3/2}0f_{5/2}1p_{1/2}0g_{9/2}1d_{5/2}$ orbitals for neutrons
- DNO-SM: Constrained Hartree-Fock shell-model calculations
  D.D. Dao and F. Nowacki, PRC 105, 054314 (2022)
- Excellent agreement both for the spectra and the relative B(E2) values



In-band transitions in the calculated spectrum are labelled with the respective B(E2) values in Weisskopf units

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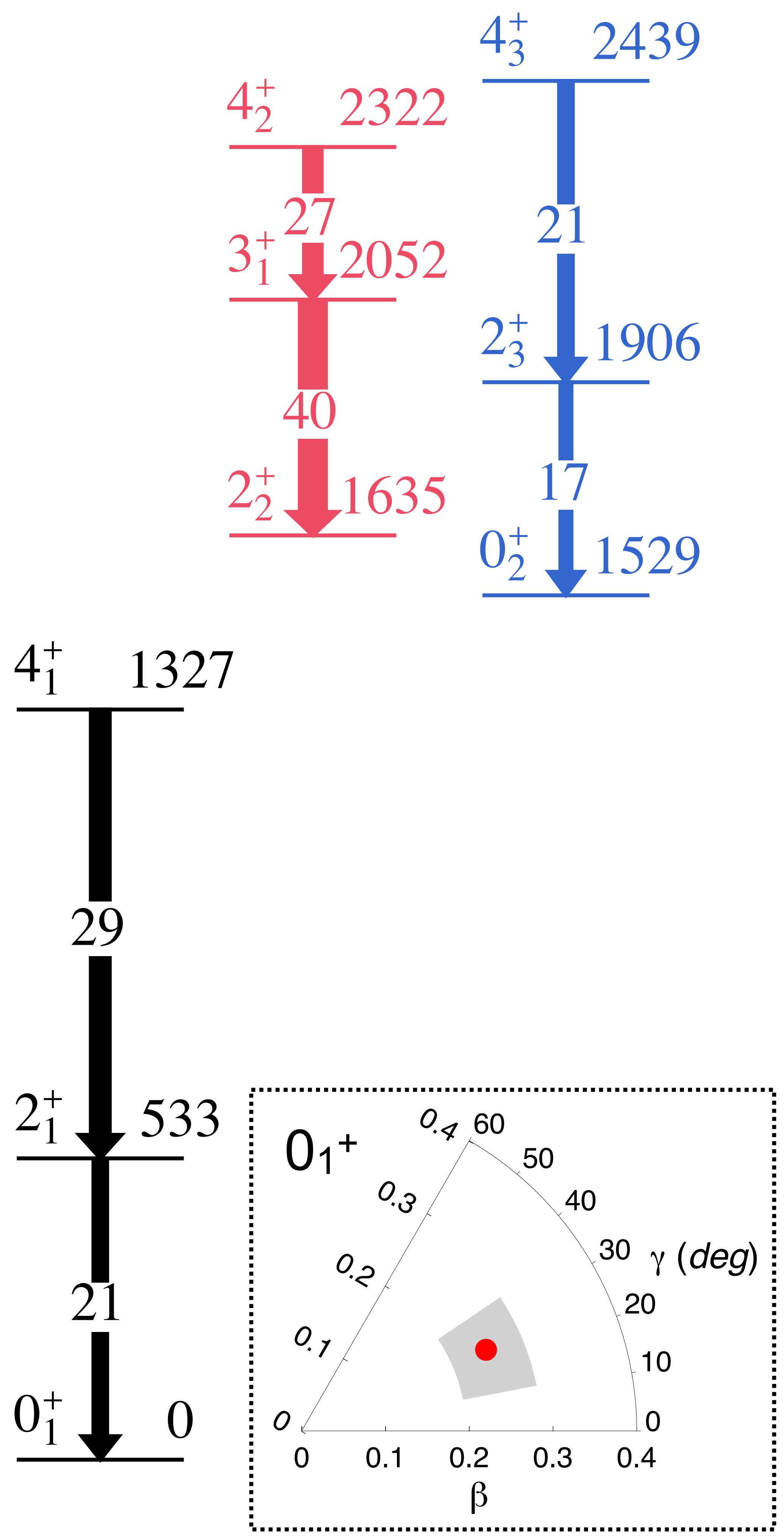
TABLE I. Energies E_γ, branching ratios I_γ, mixing ratios $\delta(E2/M1)$, and relative $B(E2)$ values $B_{\rm rel}(E2)$ measured in the present Letter, together with branching ratios from Ref. [40]. Relative and absolute $B(E2)$ values obtained from the present LSSM calculations (full diagonalization) are also given. Relative $B(E2)$ values of 100 are assumed for normalizing transitions.

$J_i^\pi \to J_f^\pi$	E_γ (keV)	I_γ	$I_\gamma^{\rm prev}$ [40]	$\delta(E2/M1)$	$B_{\rm rel}^{\rm exp}(E2)$	$B_{\rm rel}^{\rm SM}(E2)$	$B_{\rm abs}^{\rm SM}(E2)$ (W.u.)
$2_2^+ \to 2_1^+$	1064.32(10)	100.0(12)	100.0(6)	−1.13(6)	100(5)	100	9.7
$2_2^+ \to 0_1^+$	1670.07(20)	49.3(10)	49.4(4)		9.24(19)	22	2.1
$3_1^+ \to 2_2^+$	428.73(18)	6.5(4)	9.3(4)	$-0.8^{+0.2}_{-1.5}$	100^{+120}_{-30}	100	40
$3_1^+ \to 4_1^+$	680.75(15)	7.10(19)	10.5(4)	$-1.0^{+0.3}_{-0.8}$	14^{+7}_{-5}	7.8	3.1
$3_1^+ \to 2_1^+$	1493.2(3)	100.0(18)	100.0(11)	$-0.57^{+0.06}_{-0.07}$	$1.9^{+0.4}_{-0.3}$	8.8	3.5
				−2.7(5)[a]	6.8(4)		
$2_3^+ \to 0_2^+$	359.2(6)	2.0(4)			100(20)	100	17
$2_3^+ \to 2_2^+$	478.13(15)	6.8(7)	6.5(10)	$+0.9^{+0.8}_{-0.3}$	37^{+24}_{-15}	15	2.6
$2_3^+ \to 4_1^+$	729.94(19)	3.1(7)			4.5(10)	2.4	0.4
$2_3^+ \to 2_1^+$	1542.5(3)	37(3)	29.4(14)	$+2.4^{+1.8}_{-1.0}$	$1.09^{+0.15}_{-0.26}$	0.18	0.03
$2_3^+ \to 0_1^+$	2148.73(16)	100(8)	100.0(27)		0.66(5)	0.18	0.03

[a]Second solution.

Calculated Shapes from Shell Model

- Shapes of the 0_1^+, 0_2^+ states calculated from quadrupole sum rules
  A. Poves, F. Nowacki, and Y. Alhassid, PRC 101, 054307 (2020)



Calculated Shapes from Shell Model

IoIs, Shape Coexistence and Triaxiality

GRIFFIN @TRIUMF

Our Experiment on ^{74}Zn

γ-γ Angular Correlations

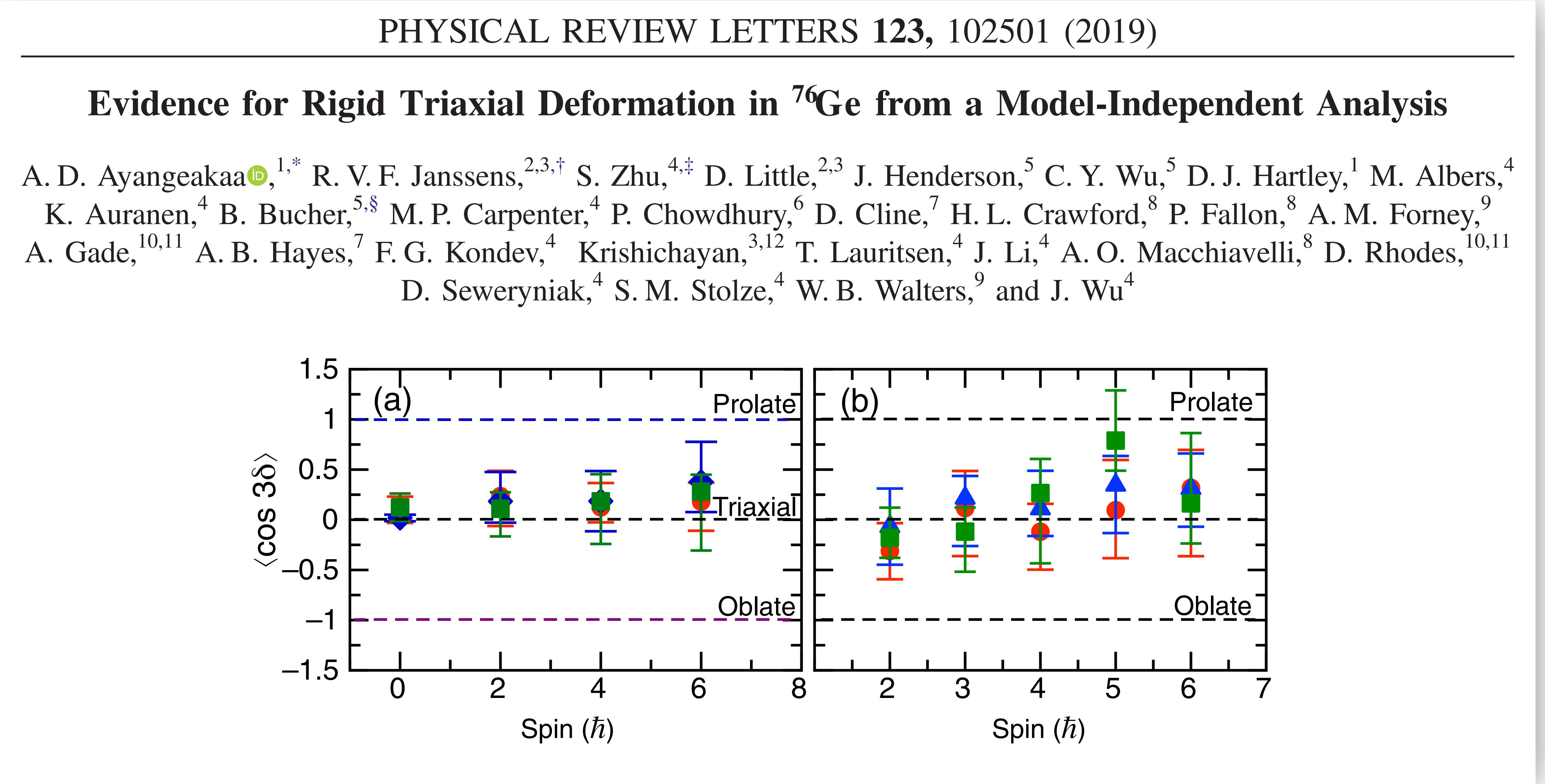
Experimental Results

LSSM Calculations

Shapes and Occupations

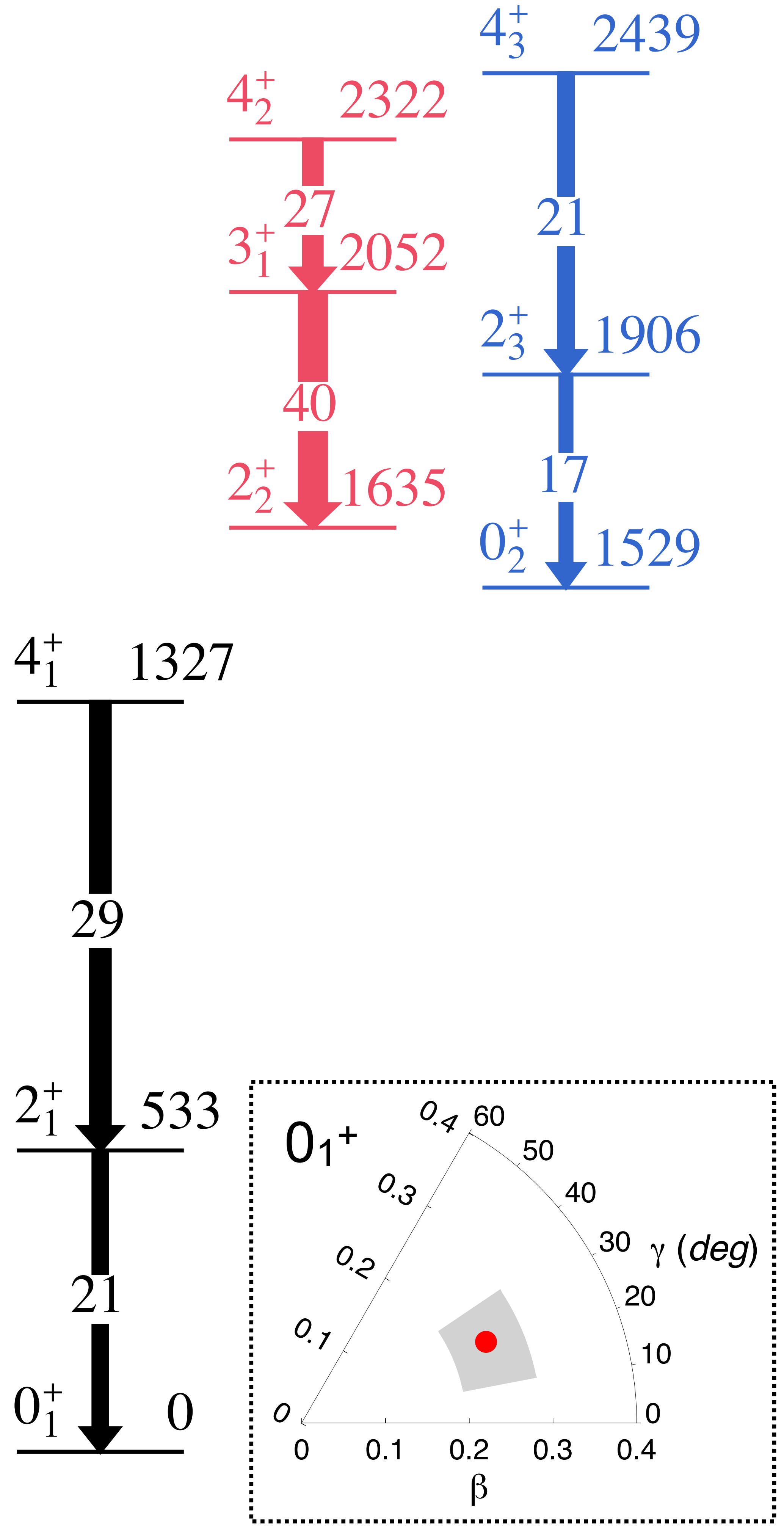
Conclusions

- Shapes of the 0_1^+, 0_2^+ states calculated from quadrupole sum rules
  A. Poves, F. Nowacki, and Y. Alhassid, PRC 101, 054307 (2020)
  - Triaxial ground state (similar dispersions to those in ^{76}Ge‼)


PHYSICAL REVIEW LETTERS **123**, 102501 (2019)

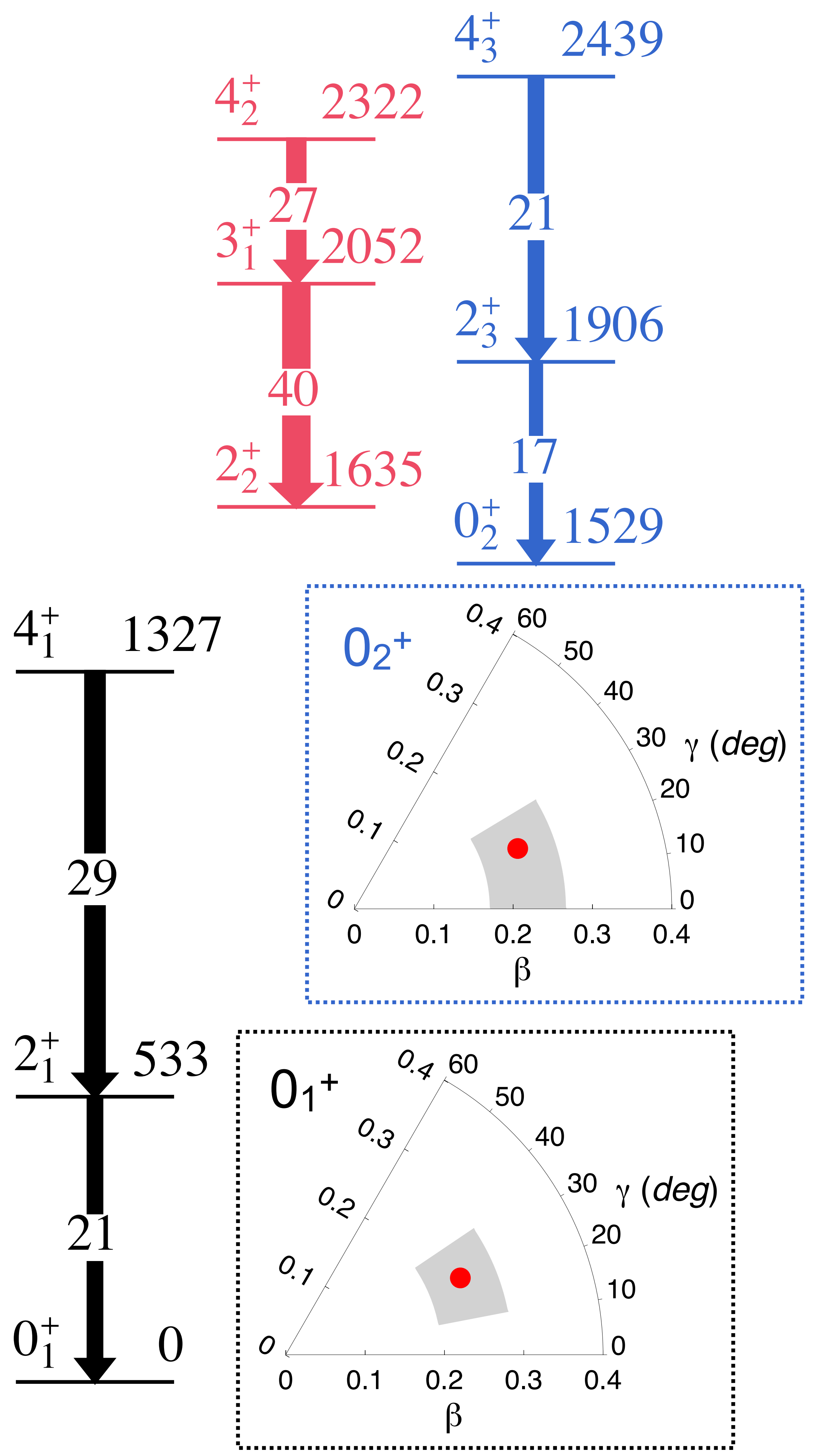
Evidence for Rigid Triaxial Deformation in ^{76}Ge from a Model-Independent Analysis

A. D. Ayangeakaa,[1,*] R. V. F. Janssens,[2,3,†] S. Zhu,[4,‡] D. Little,[2,3] J. Henderson,[5] C. Y. Wu,[5] D. J. Hartley,[1] M. Albers,[4] K. Auranen,[4] B. Bucher,[5,§] M. P. Carpenter,[4] P. Chowdhury,[6] D. Cline,[7] H. L. Crawford,[8] P. Fallon,[8] A. M. Forney,[9] A. Gade,[10,11] A. B. Hayes,[7] F. G. Kondev,[4] Krishichayan,[3,12] T. Lauritsen,[4] J. Li,[4] A. O. Macchiavelli,[8] D. Rhodes,[10,11] D. Seweryniak,[4] S. M. Stolze,[4] W. B. Walters,[9] and J. Wu[4]



Calculated Shapes from Shell Model

- Shapes of the 0_1^+, 0_2^+ states calculated from quadrupole sum rules
  A. Poves, F. Nowacki, and Y. Alhassid, PRC 101, 054307 (2020)
  - Triaxial ground state (similar dispersions to those in ^{76}Ge!!)
  - Different shape for the 0_2^+: Less deformed and more prolate



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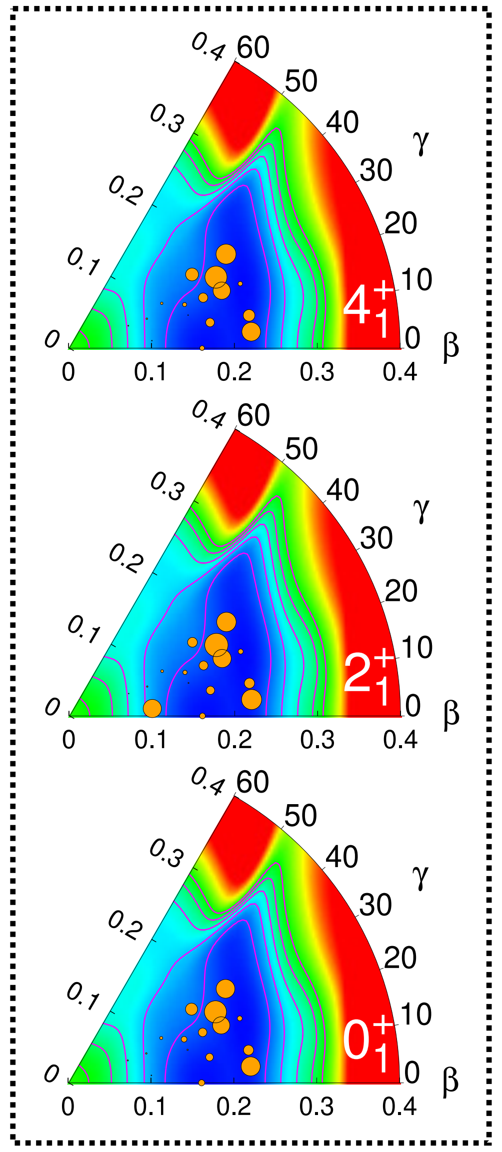
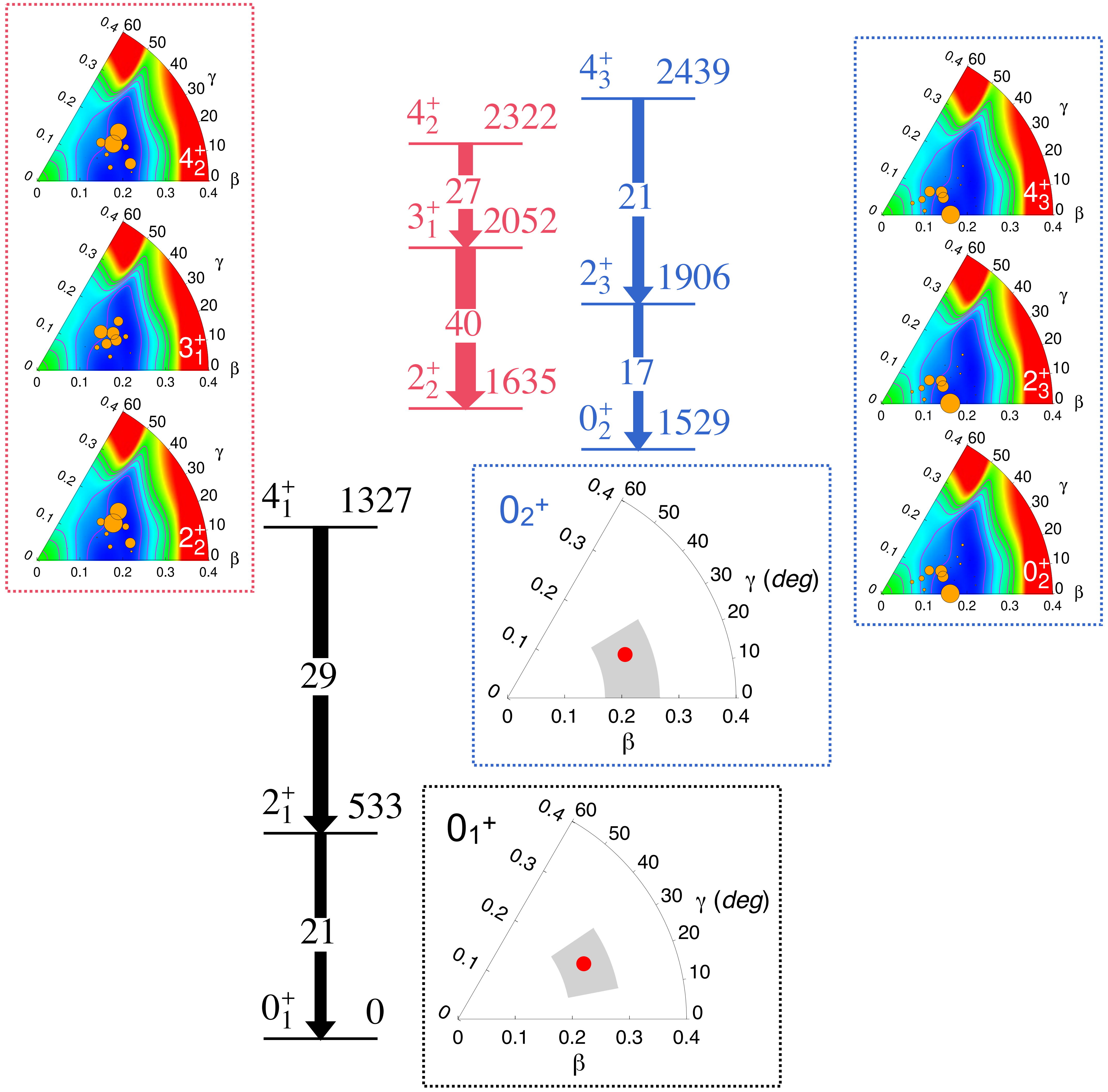
  - Triaxial ground state (similar dispersions to those in ^{76}Ge!!)
  - Different shape for the 0_2^+: Less deformed and more prolate
- "T-Plot"-like analysis: Shape for each individual state
  - Normalized probability to find a deformation (β,γ) superimposed to the potential energy surface (GCM)
  - Results from quadrupole sum rules confirmed





Calculated Shapes from Shell Model

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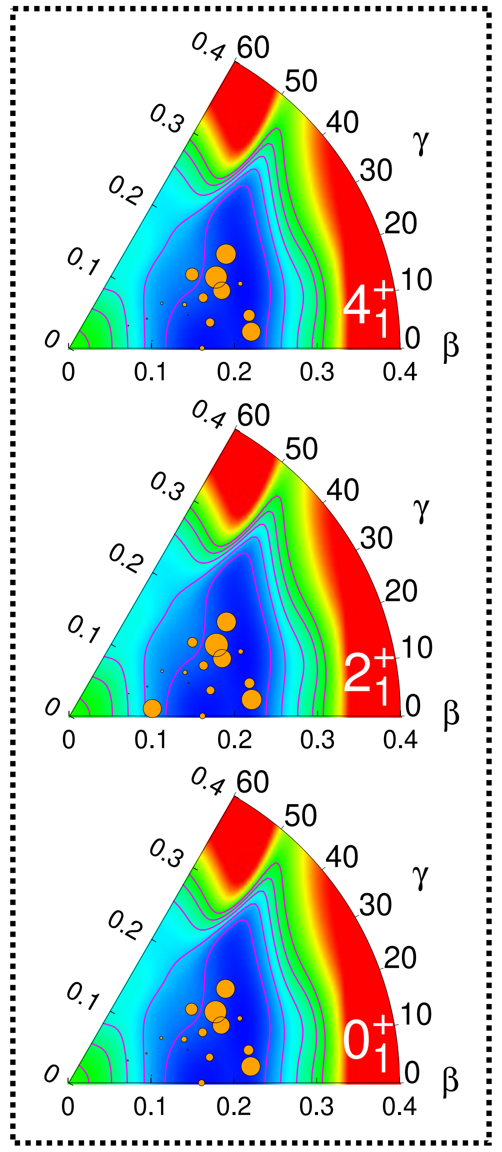
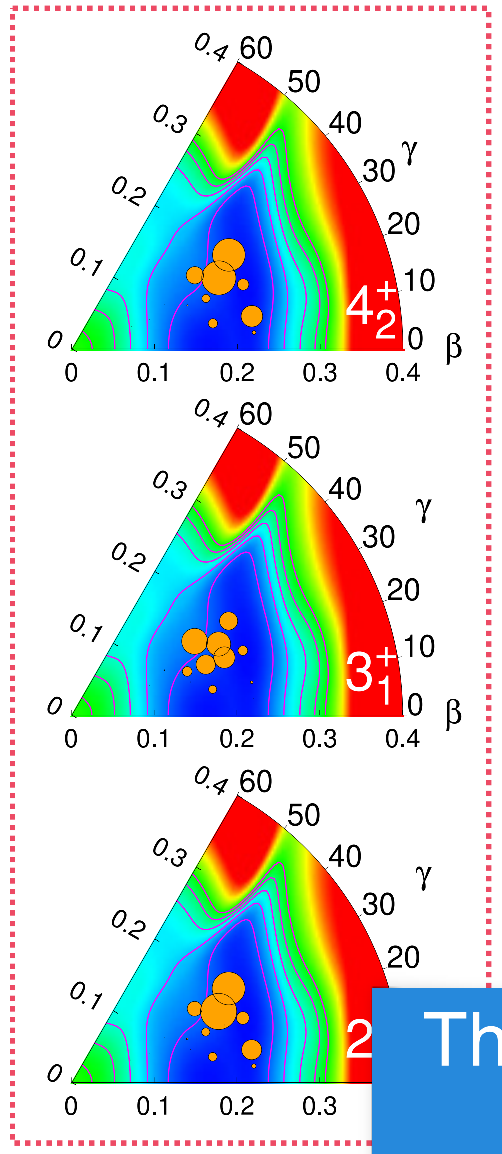
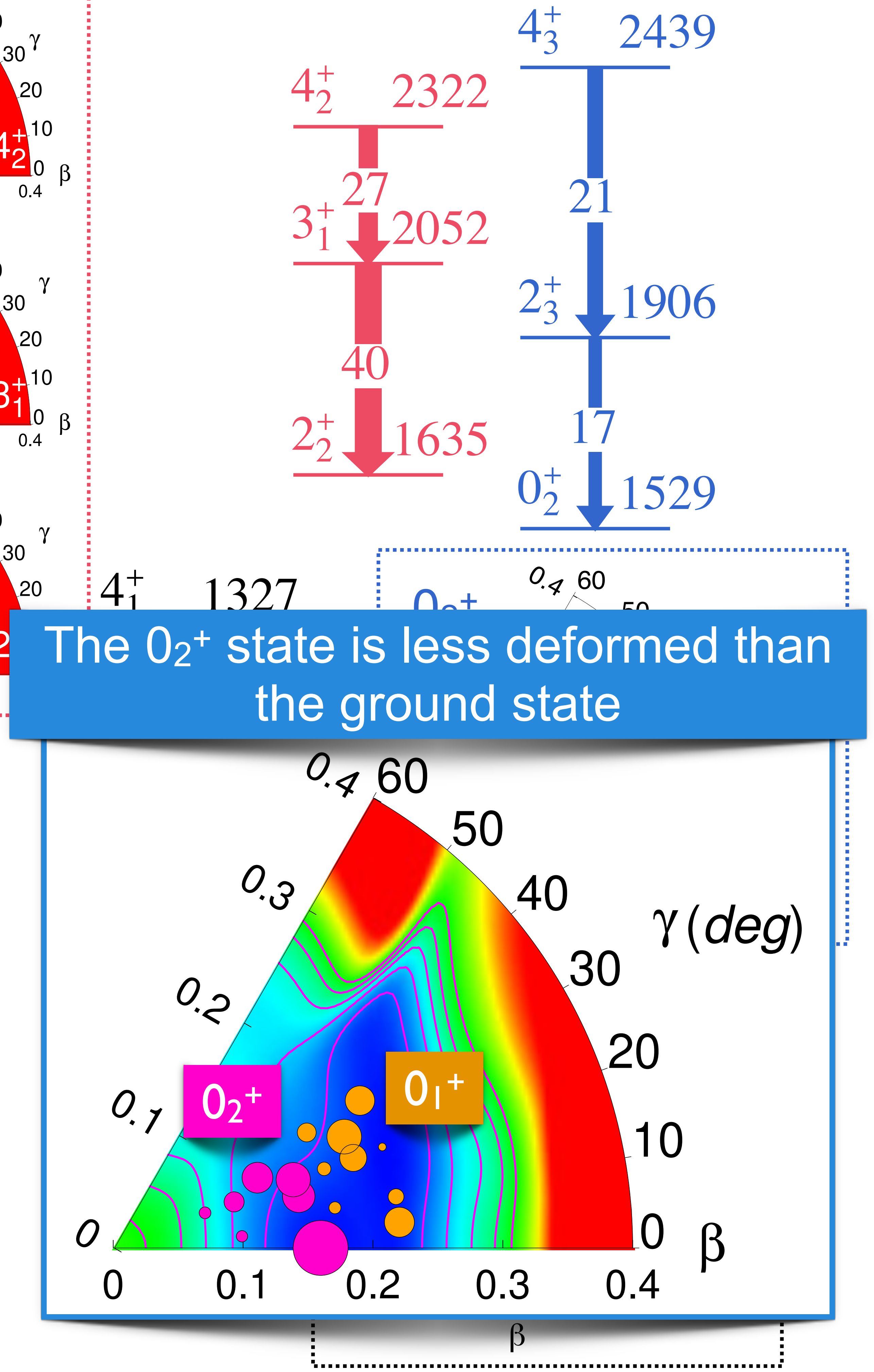
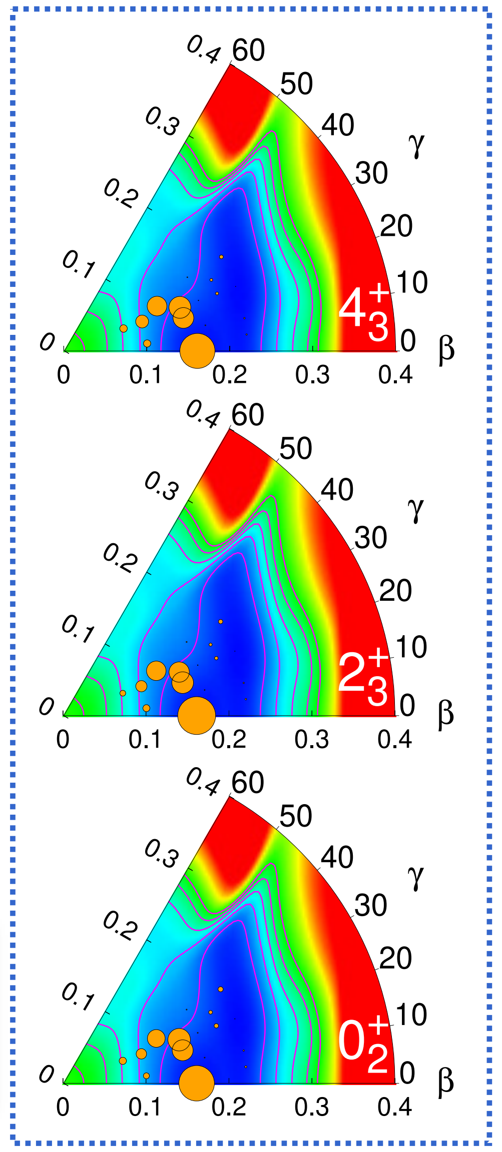




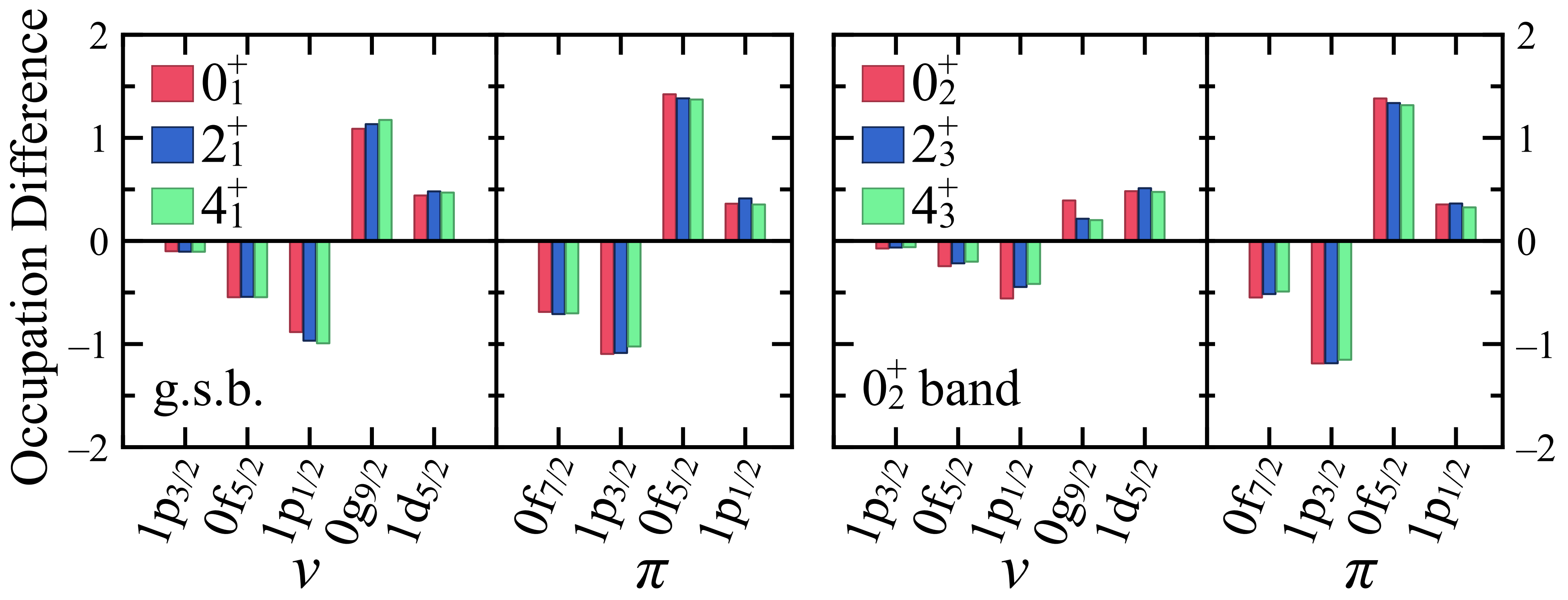


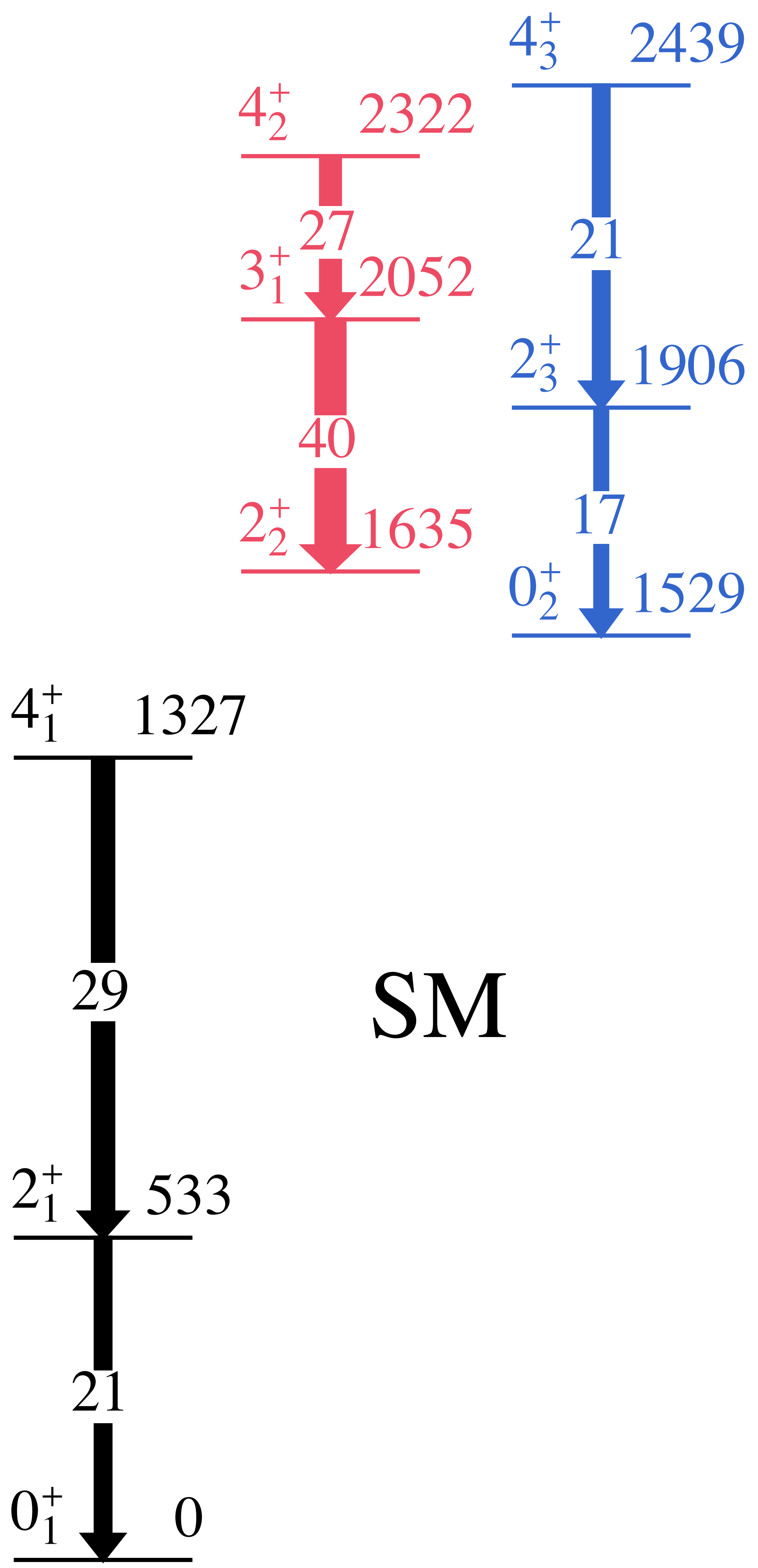
The 0_2^+ state is less deformed than the ground state



Occupation Numbers from Shell Model

- Occupation difference with respect to the Fermi configuration for each orbital in the chosen model space:





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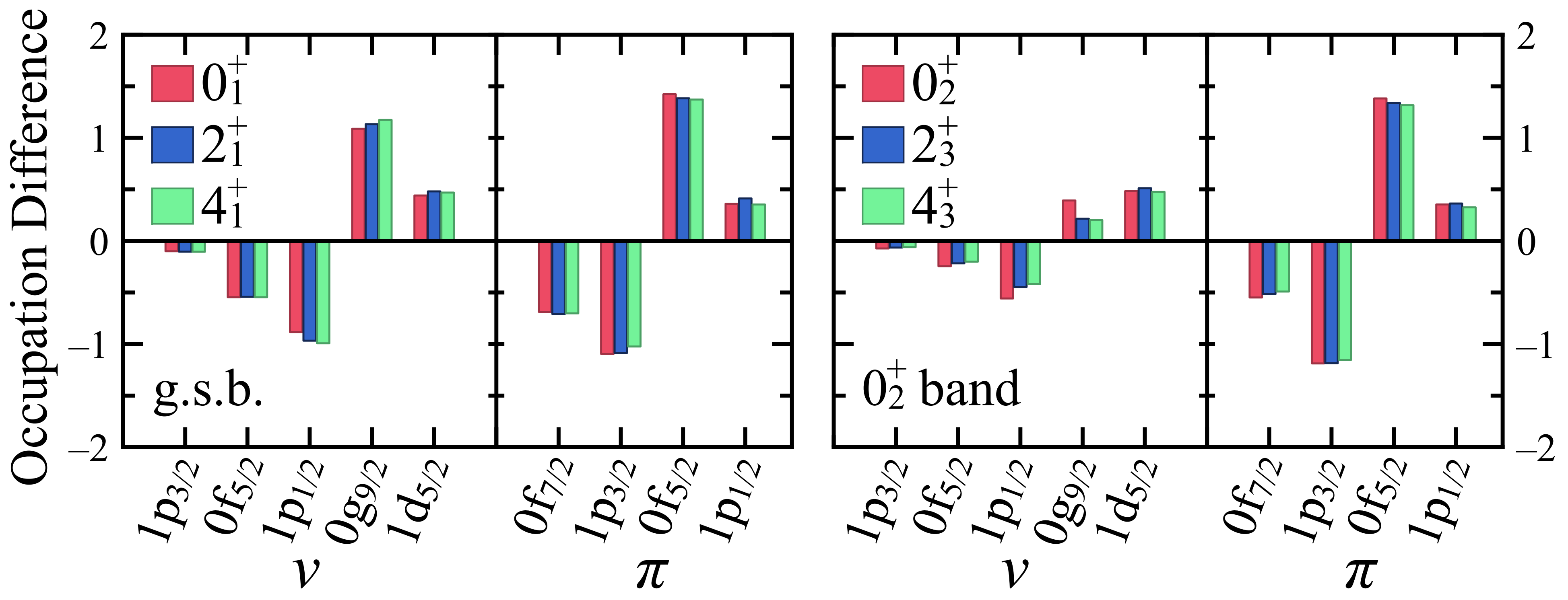
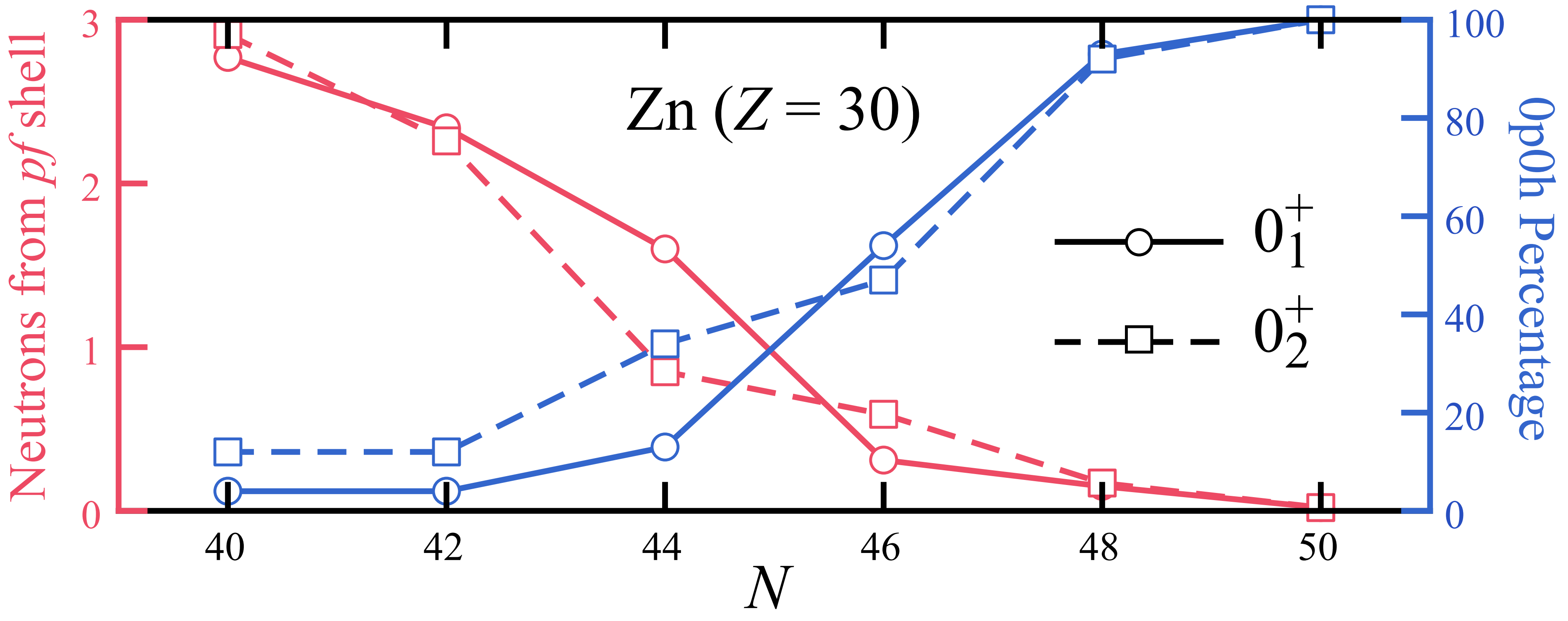
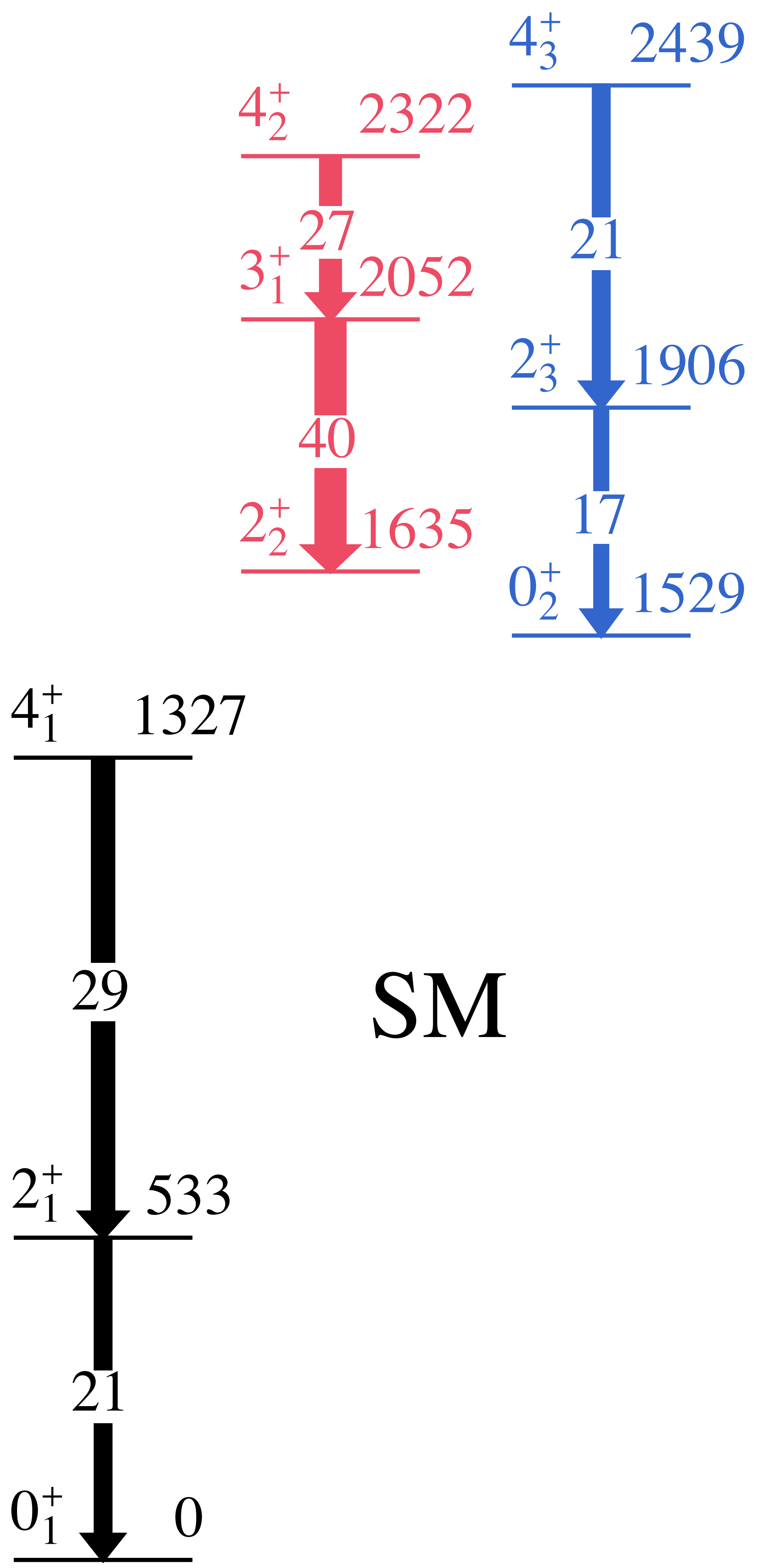


- Which is the intruder state? Neutrons from the *pf* shell and percentage of 0p0h configuration:





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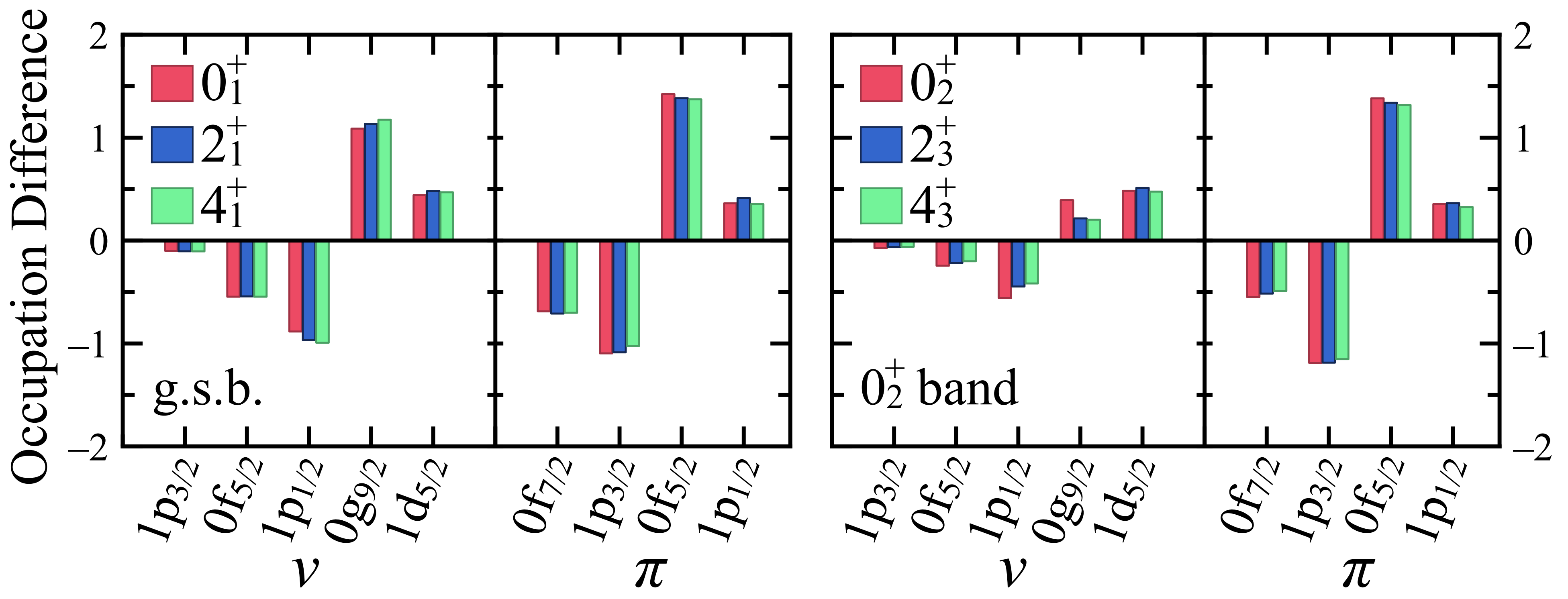

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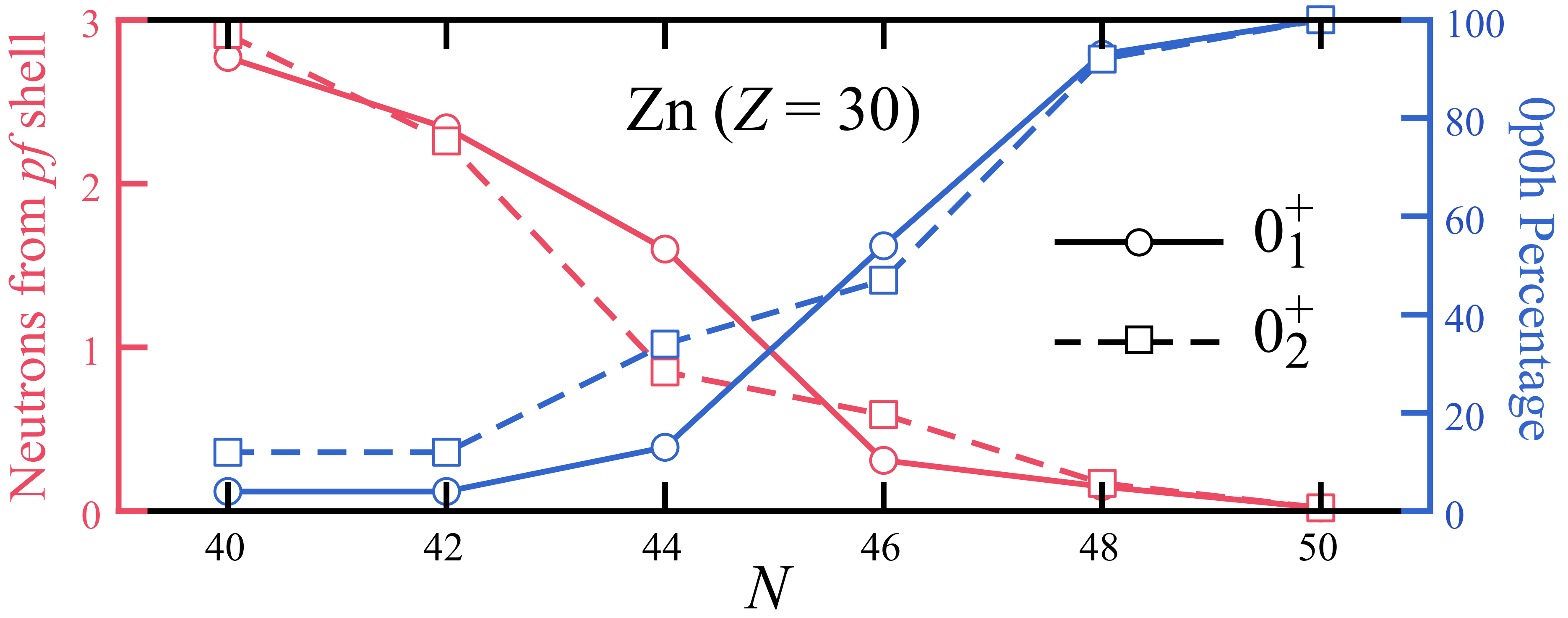
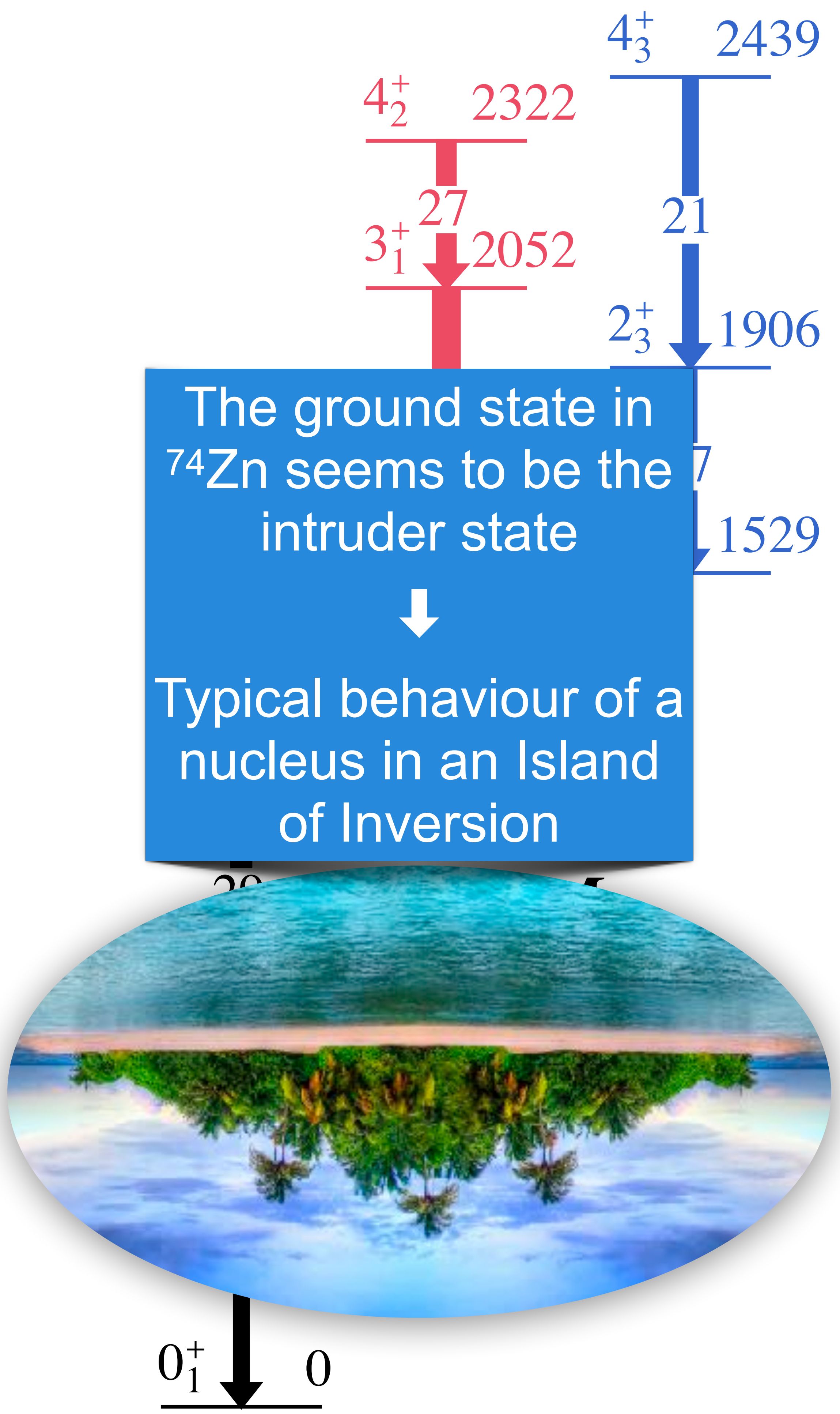




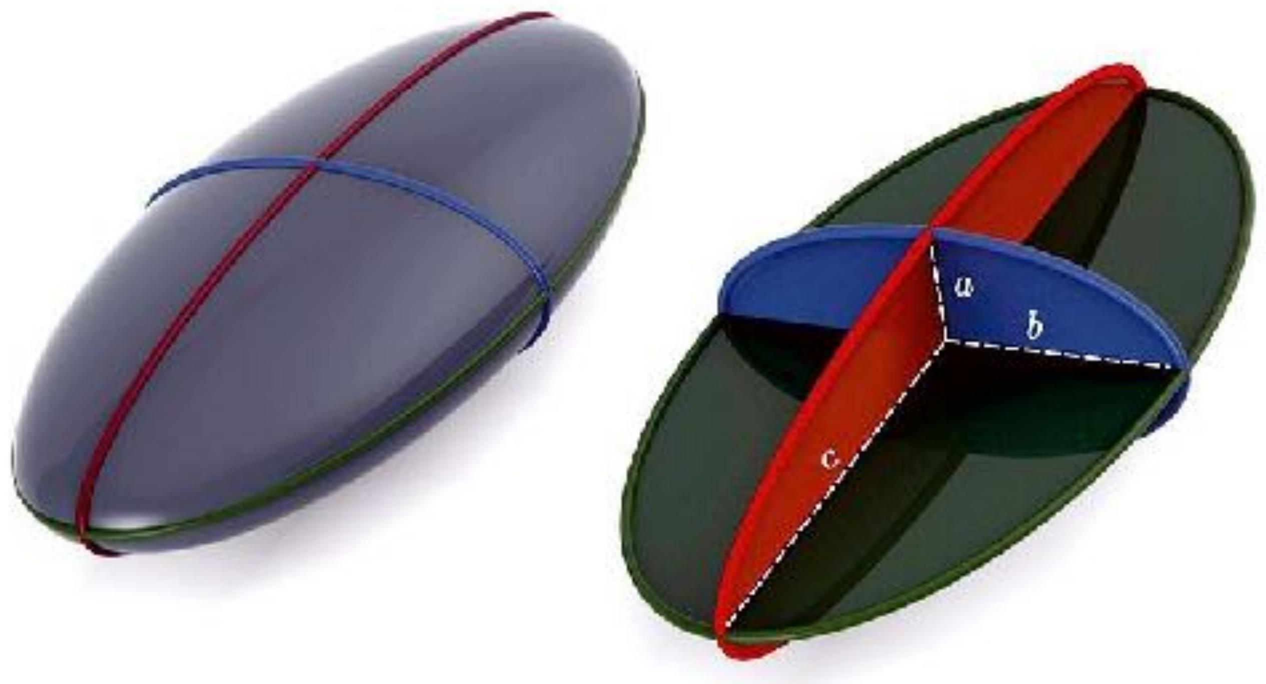
The ground state in ^{74}Zn seems to be the intruder state

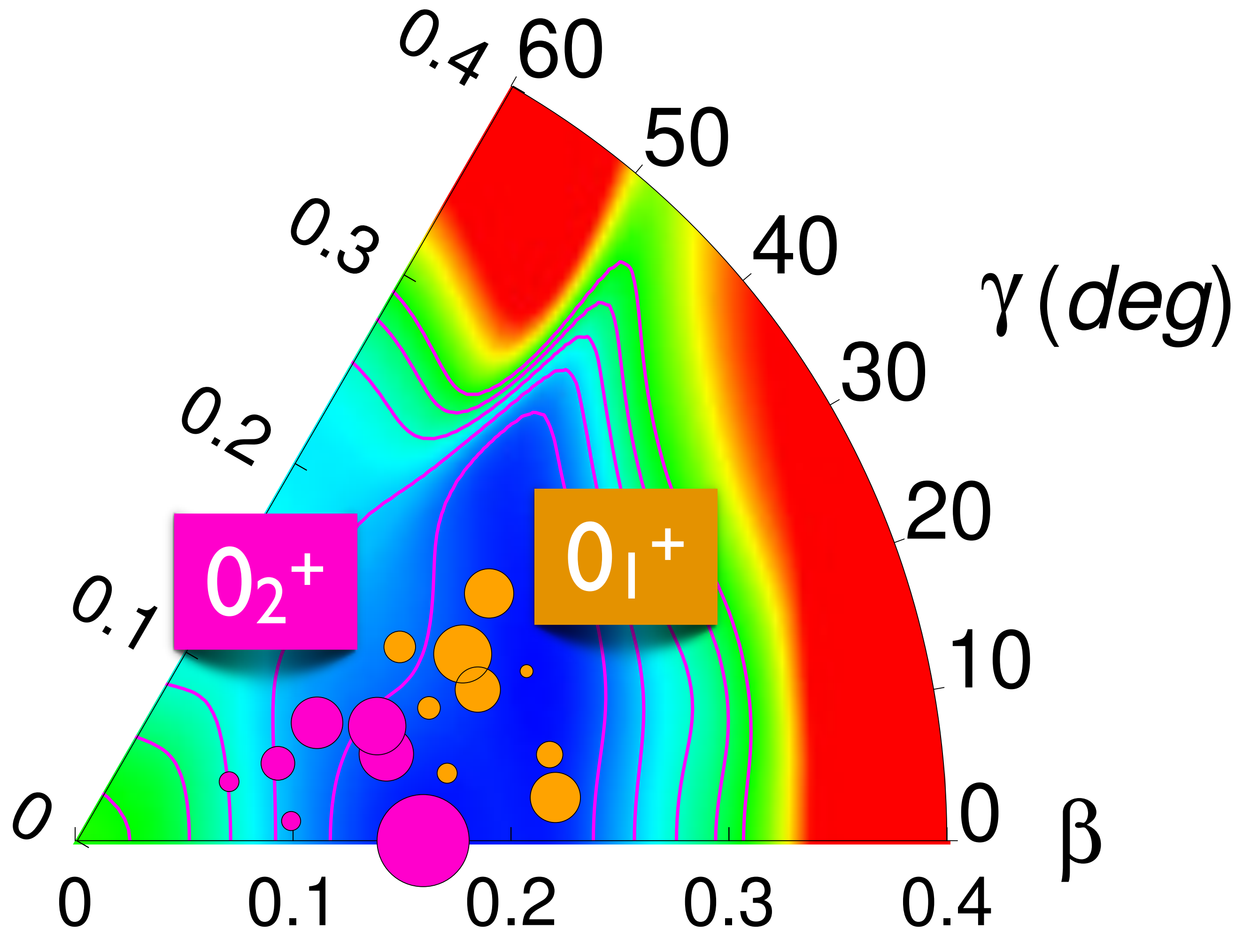
⬇

Typical behaviour of a nucleus in an Island of Inversion

Conclusions

- Strong $2_3^+ \longrightarrow 0_2^+ \Longrightarrow$ Hint of Configuration Coexistence
- Strong $3_1^+ \longrightarrow 2_2^+ \Longrightarrow$ Hint of a quasi γ-band at low excitation energy and Triaxiality
- New Large-Scale Shell-Model calculations support this interpretation
- Inversion of "normal" and intruder configurations $\Longrightarrow$ ^{74}Zn seems to be in the N = 40 Island of Inversion, which extends further north in the chart of the nuclides





PHYSICAL REVIEW LETTERS **130,** 122502 (2023)

First Evidence of Axial Shape Asymmetry and Configuration Coexistence in ^{74}Zn: Suggestion for a Northern Extension of the $N = 40$ Island of Inversion

M. Rocchini,[1,*] P. E. Garrett,[1] M. Zielińska,[2] S. M. Lenzi,[3,4] D. D. Dao,[5] F. Nowacki,[5] V. Bildstein,[1] A. D. MacLean,[1] B. Olaizola,[6,†] Z. T. Ahmed,[1] C. Andreoiu,[7] A. Babu,[6] G. C. Ball,[6] S. S. Bhattacharjee,[6,‡] H. Bidaman,[1] C. Cheng,[6] R. Coleman,[1] I. Dillmann,[6,8] A. B. Garnsworthy,[6] S. Gillespie,[6] C. J. Griffin,[6] G. F. Grinyer,[9] G. Hackman,[6] M. Hanley,[10] A. Illana,[11] S. Jones,[12] A. T. Laffoley,[1] K. G. Leach,[10] R. S. Lubna,[6,§] J. McAfee,[6,13] C. Natzke,[6,10] S. Pannu,[1] C. Paxman,[6,13] C. Porzio,[6,14,15,||] A. J. Radich,[1] M. M. Rajabali,[16] F. Sarazin,[10] K. Schwarz,[6] S. Shadrick,[10] S. Sharma,[9] J. Suh,[9] C. E. Svensson,[1] D. Yates,[6,17] and T. Zidar[1]

Marco Rocchini
INFN - Istituto Nazionale di Fisica Nucleare
FIRENZE DIVISION

THANK YOU FOR THE ATTENTION

M. Rocchini[1], P.E. Garrett[1], M. Zielińska[2], S.M. Lenzi[3,4], D.D. Dao[5], F. Nowacki[5], V. Bildstein[1], A.D. MacLean[1], B. Olaizola[6,†], Z. Ahmed[1], C. Andreoiu[7], A. Babu[6], G.C. Ball[6], S.S. Bhattacharjee[6,‡], H. Bidaman[1], C. Cheng[6], R. Coleman[1], I. Dillmann[6,8], A.B. Garnsworthy[6], S. Gillespie[6], C. Griffin[6], G.F. Grinyer[9], G. Hackman[6], M. Hanley[10], A. Illana[11], S. Jones[12], A.T. Laffoley[1], K.G. Leach[10], R.S. Lubna[6,§], J. McAfee[6,13], C. Natzke[6,10], S. Pannu[1], C. Paxman[6,13], C. Porzio[6,14,15,¶], A.J. Radich[1], M. Rajabali[12], F. Sarazin[10], K. Schwarz[6], S. Shadrick[10], S. Sharma[9], J. Suh[9], C.E. Svensson[1], D. Yates[6,16], and T. Zidar[1]

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[7] Simon Fraser University, Burnaby, Canada [8] University of Victoria, Victoria, Canada [9] University of Regina, Regina, Canada [10] Colorado School of Mines, Golden, USA
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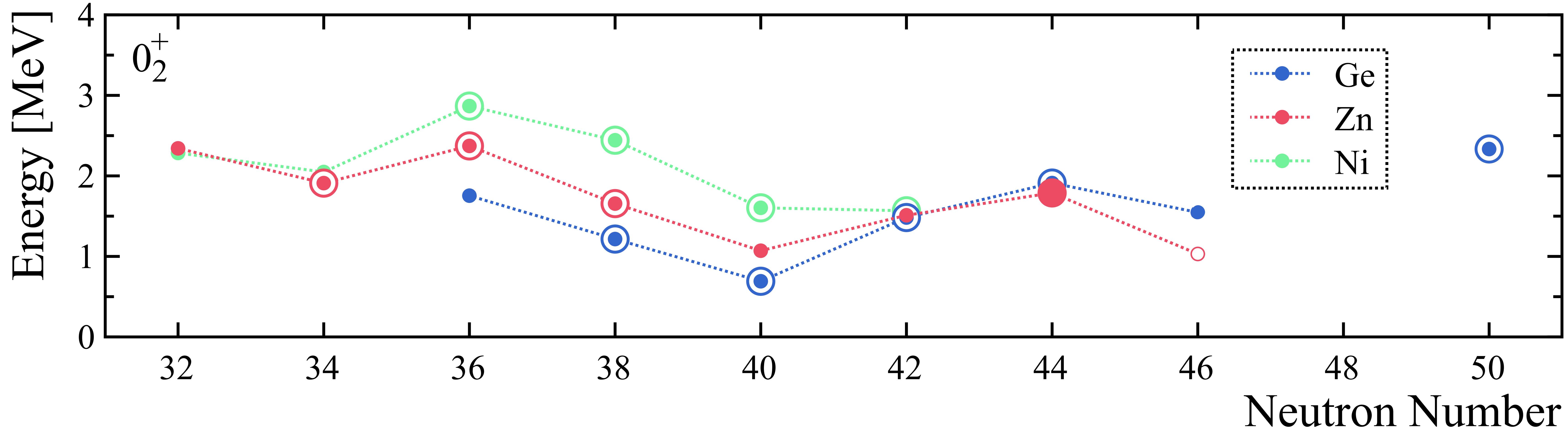
BACKUP

0_2^+ States in the Ge, Zn and Ni Isotopes

- Stable Ge (N = 38 - 44) ⟹ ν excitations across N = 40, small-deformation
  M. Honma, T. Otsuka, T. Mizusaki, and M. Hjorth-Jensen, PRC 80, 064323 (2009)

- Radioactive ^{82}Ge ⟹ ν excitations across N = 50, large-deformation
  J. K. Hwang et al., PRC 84, 024305 (2011)

Multitude of p-h excitations across shell and sub shell gaps, with different features and deformations



Small, filled dots: firm J^π assignment

Open dots: tentative J^π assignment

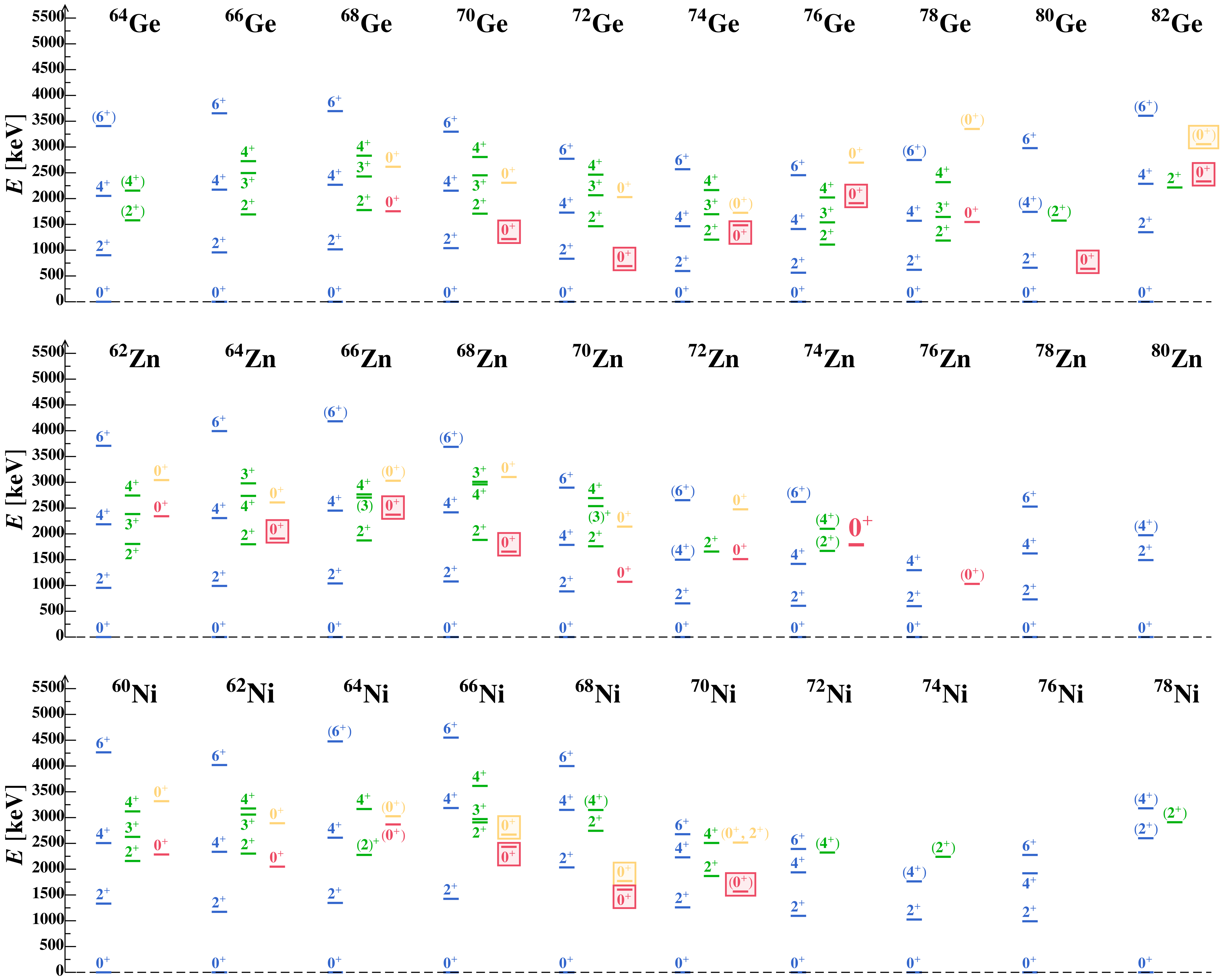
Circled dots: evidence or suggestions for Shape Coexistence

Large, filled dots: our new results

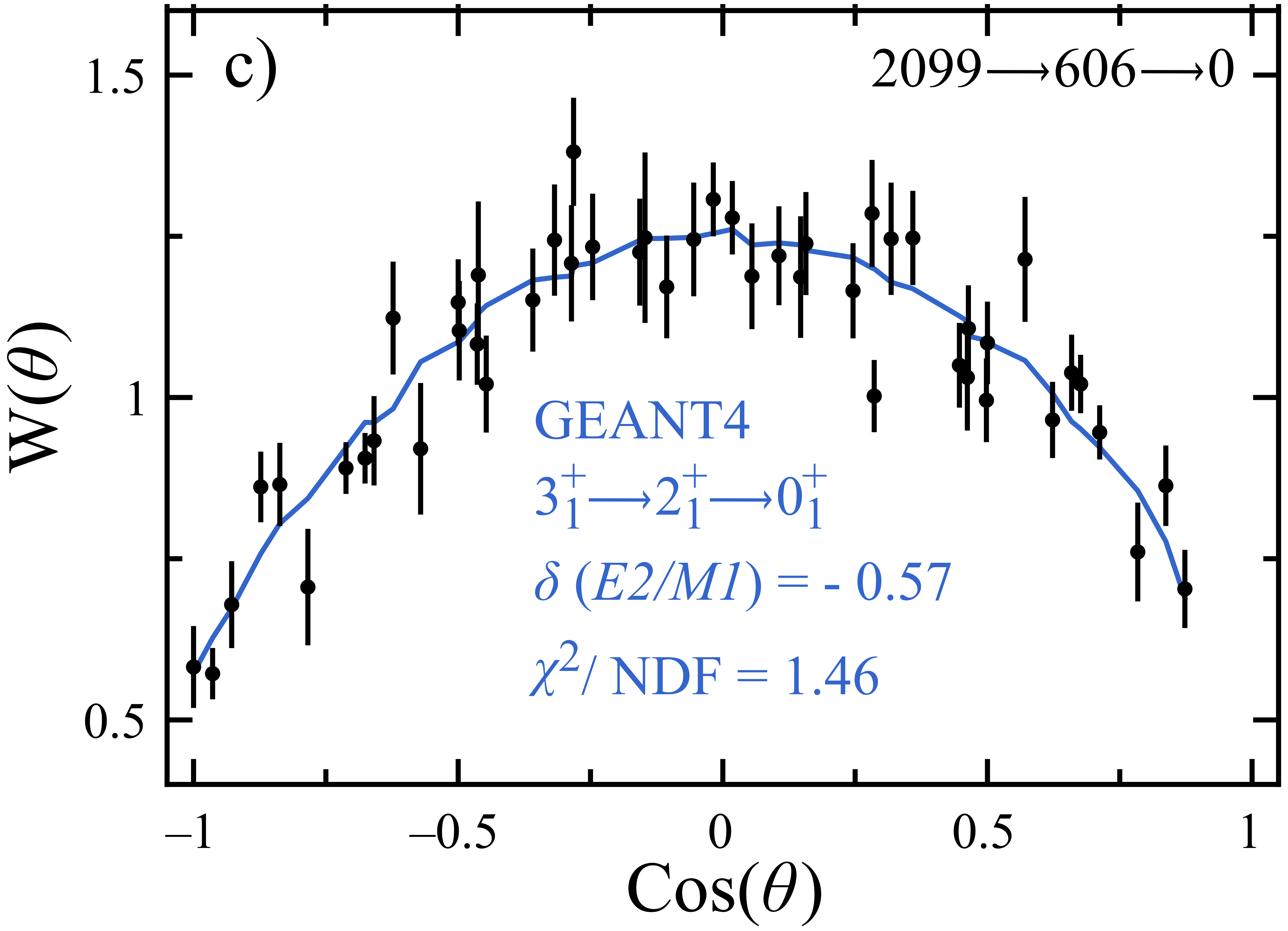
Data from NNDC Brookhaven ENSDF and XUNDL databases

- Ni (N = 36 - 42), Multiple Shape Coexistence:
  S. Leoni et al., PRL 118, 162502 (2017) - S. Leoni et al., Acta Physica Polonica B 50, 605 (2019) - N. Marginean et al., PRL 125, 102502 (2020)
  - 0_2^+ in ^{64,66,68}Ni ⟹ ν excitations across N = 40, small-deformation
  - 0_4^+ in ^{64,66}Ni, 0_3^+ in ^{68}Ni, 0_2^+ in ^{70}Ni ⟹ π excitations across Z = 28, large-deformation

Energy Systematics



$3_1^+ \rightarrow 2_1^+ \rightarrow 0_1^+$



Extension of the N=40 IoI

TABLE I: Occupation of the neutron intruder orbitals and percentage of particle-hole excitations across the $N = 40$ gap in the ground states and first excited 0^+ states of the Zinc isotopes.The red bold number indicates places where the extra intruder population is larger than 1 particule in average in the ground state and delimits the contour of the Island of Inversion.

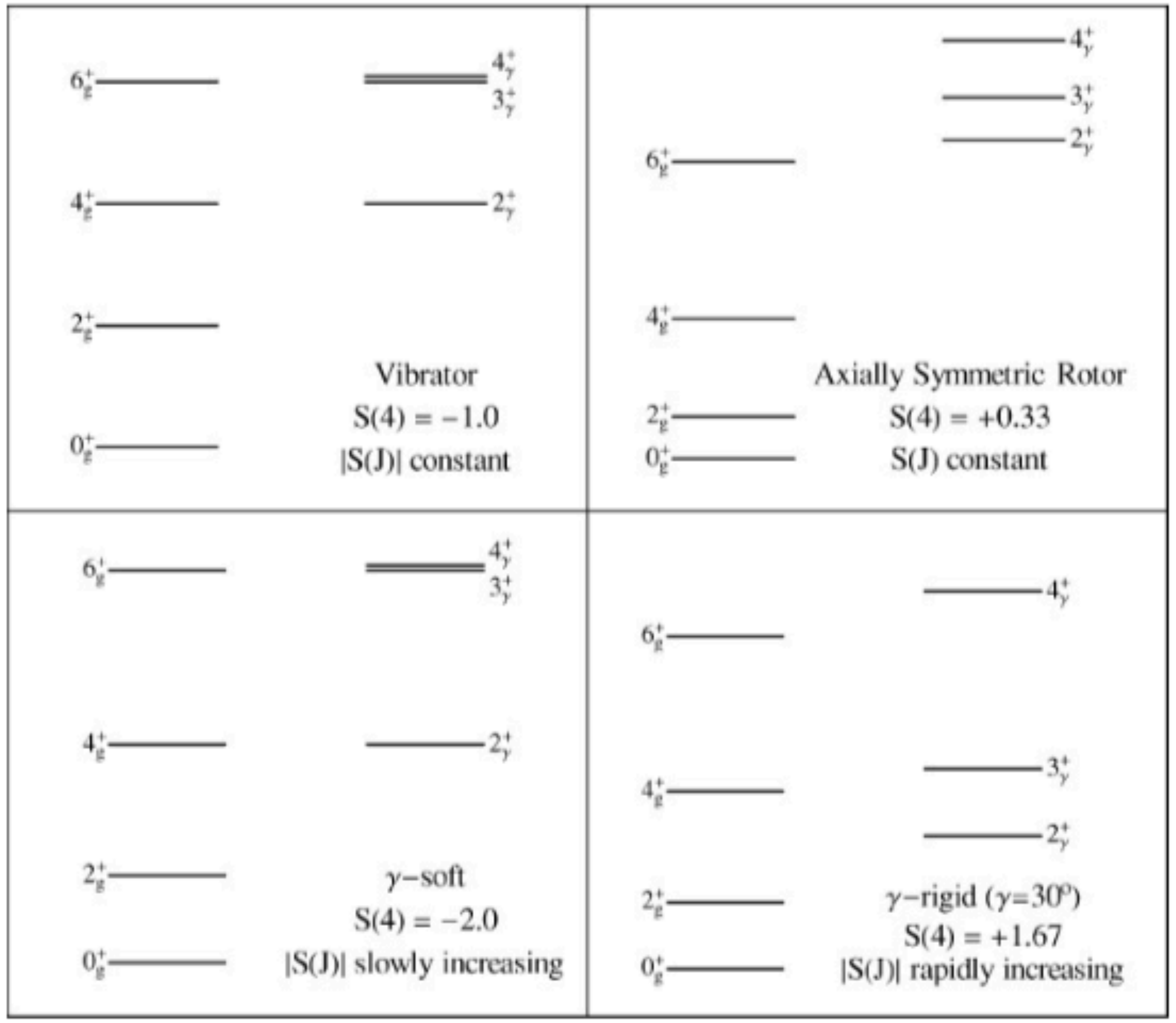
Nucleus	state	IPM $\nu g_{9/2}$	IPM $\nu d_{5/2}$	SM $\nu g_{9/2}$	SM $\nu d_{5/2}$	0p0h
^{68}Ni	0_1^+	0	0	0.80	0.10	62
	0_2^+	0	0	2.10	0.10	17
^{70}Ni	**0_1^+**	**2**	**0**	**2.86**	**0.17**	**55**
	0_2^+	2	0	4.47	0.41	21
^{72}Ni	0_1^+	4	0	4.52	0.34	61
	0_2^+	4	0	5.18	0.18	12
^{74}Ni	0_1^+	6	0	5.96	0.43	58
	0_2^+	6	0	5.65	0.73	44
^{76}Ni	0_1^+	8	0	7.84	0.36	90
	0_2^+	8	0	7.39	0.77	92
^{78}Ni	0_1^+	10	0	9.83	0.19	99
	0_2^+	10	0	7.79	2.33	94
^{70}Zn	**0_1^+**	**0**	**0**	**2.60**	**0.17**	**4**
	0_2^+	0	0	2.66	0.25	12
^{72}Zn	**0_1^+**	**2**	**0**	**3.99**	**0.35**	**4**
	0_2^+	2	0	3.97	0.29	12
^{74}Zn	**0_1^+**	**4**	**0**	**5.13**	**0.47**	**13**
	0_2^+	4	0	4.35	0.50	34
^{76}Zn	0_1^+	6	0	5.79	0.52	54
	0_2^+	6	0	6.12	0.47	47
^{78}Zn	0_1^+	8	0	7.67	0.48	93
	0_2^+	8	0	7.73	0.44	92
^{80}Zn	0_1^+	10	0	9.72	0.30	100
	0_2^+	10	0	9.74	0.28	100

TABLE II. Occupation number n^ν of neutron intruder orbitals from the shell-model calculations (SM) of this work compared to the independent particle model (IPM). The percentage of particle-hole excitations across the $N = 40$ gap in the ground state of Cr isotopes is also given. The last column features the pairing correlations energy differences $\Delta E^*_{\mathrm{Pairing}}$ (in MeV) evaluated between the ground state and the 2_1^+ state.

Nucleus	$n^\nu(g_{9/2}+d_{5/2})$ IPM	$n^\nu(g_{9/2}+d_{5/2})$ SM	$0p0h$	$2p2h$	$4p4h$	$6p6h$	$\Delta E^*_{\mathrm{Pairing}}$
^{60}Cr	0	1.8	14	75	7	0	1.84
^{62}Cr	0	3.5	1	25	71	3	1.49
^{64}Cr	0	4.3	0	8	71	20	1.25
^{66}Cr	2	5.2	0	40	56	3	1.13
^{68}Cr	4	6.0	6	79	11	0	1.24

Staggering

$$S(J) = \frac{\{E(J^+_\gamma) - E[(J-1)^+_\gamma]\} - \{E[(J-1)^+_\gamma] - E[(J-2)^+_\gamma]\}}{E(2^+_1)},$$



N = 40

PHYSICAL REVIEW C **80**, 064323 (2009)

New effective interaction for f_5pg_9-shell nuclei

M. Honma,[1] T. Otsuka,[2,3,4] T. Mizusaki,[5] and M. Hjorth-Jensen[6]

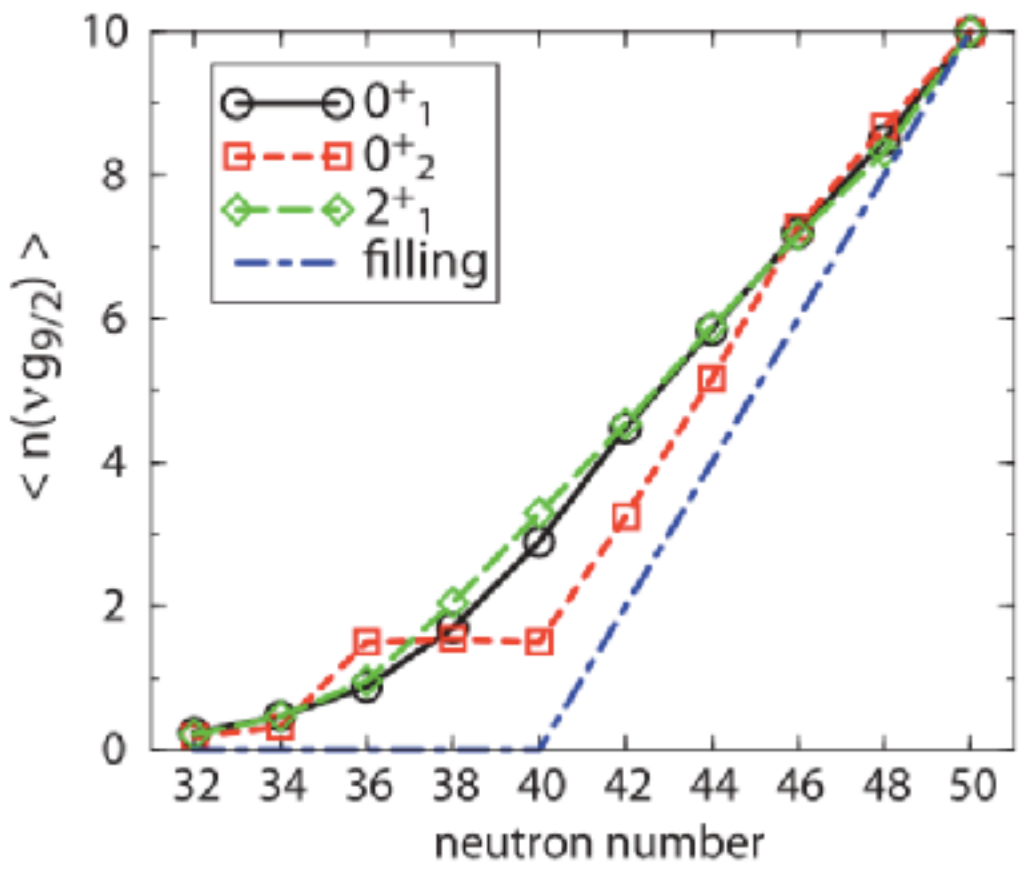


FIG. 24. (Color online) Occupation numbers of the neutron $g_{9/2}$ orbit in the shell-model wave functions. The filling configuration corresponds to the dot-dashed line.

VOLUME 88, NUMBER 9 PHYSICAL REVIEW LETTERS 4 MARCH 2002

$^{68}_{28}\mathrm{Ni}_{40}$: Magicity versus Superfluidity

O. Sorlin,[1] S. Leenhardt,[1] C. Donzaud,[1] J. Duprat,[1] F. Azaiez,[1] F. Nowacki,[2] H. Grawe,[3] Zs. Dombrádi,[4] F. Amorini,[5] A. Astier,[6] D. Baiborodin,[7] M. Belleguic,[1] C. Borcea,[8] C. Bourgeois,[1] D.M. Cullen,[9,*] Z. Dlouhy,[7] E. Dragulescu,[8] M. Górska,[3] S. Grévy,[10] D. Guillemaud-Mueller,[1] G. Hagemann,[11] B. Herskind,[11] J. Kiener,[12] R. Lemmon,[13] M. Lewitowicz,[14] S.M. Lukyanov,[15] P. Mayet,[3] F. de Oliveira Santos,[14] D. Pantalica,[7] Yu.-E. Penionzhkevich,[15] F. Pougheon,[1] A. Poves,[16] N. Redon,[6] M.G. Saint-Laurent,[14] J.A. Scarpaci,[1] G. Sletten,[11] M. Stanoiu,[14] O. Tarasov,[15,†] and Ch. Theisen[17]

TABLE II. Shell-model and experimental energies of the first excited state $E(2^+)$ [MeV], calculated $B(E2\uparrow; 0_1^+ \to 2^+)$ [e^2 fm^4], and the number $\langle n_{9/2}\rangle_{\mathrm{extra}}$ of excessive neutrons occupying the $g_{9/2}$ orbit are compiled.

	^{62}Ni	^{64}Ni	^{66}Ni	^{68}Ni	^{70}Ni	^{72}Ni	^{74}Ni
$E(2^+)_{\mathrm{calc}}$	1.11	1.24	1.49	1.73	1.50	1.42	1.33
$E(2^+)_{\mathrm{exp}}$	1.173	1.346	1.425	2.033	1.259		
$B(E2\uparrow)_{\mathrm{calc}}$	775	755	520	265	410	505	690
$\langle n_{9/2}\rangle_{\mathrm{extra}}$	0.24	0.43	0.67	1.19	0.73	0.45	0.27

^{66}Zn Coulex

PHYSICAL REVIEW C **103**, 014311 (2021)

Onset of triaxial deformation in ^{66}Zn and properties of its first excited 0^+ state studied by means of Coulomb excitation

M. Rocchini,[1,2,3,*] K. Hadyńska-Klęk,[4,5] A. Nannini,[1,2] A. Goasduff,[6,7] M. Zielińska,[8] D. Testov,[6,7] T. R. Rodríguez,[9] A. Gargano,[10] F. Nowacki,[11] G. De Gregorio,[10,12] H. Naïdja,[13] P. Sona,[1,2] J. J. Valiente-Dobón,[4] D. Mengoni,[6,7] P. R. John,[6,7,14] D. Bazzacco,[6,7] G. Benzoni,[15] A. Boso,[6,7] P. Cocconi,[4] M. Chiari,[1,2] D. T. Doherty,[16] F. Galtarossa,[4] G. Jaworski,[4] M. Komorowska,[5] N. Marchini,[1,17] M. Matejska-Minda,[5,18] B. Melon,[1] R. Menegazzo,[6,7] P. J. Napiorkowski,[5] D. Napoli,[4] M. Ottanelli,[1] A. Perego,[1,2] L. Ramina,[7] M. Rampazzo,[7] F. Recchia,[6,7] S. Riccetto,[19,20] D. Rosso,[4] and M. Siciliano[4,6]

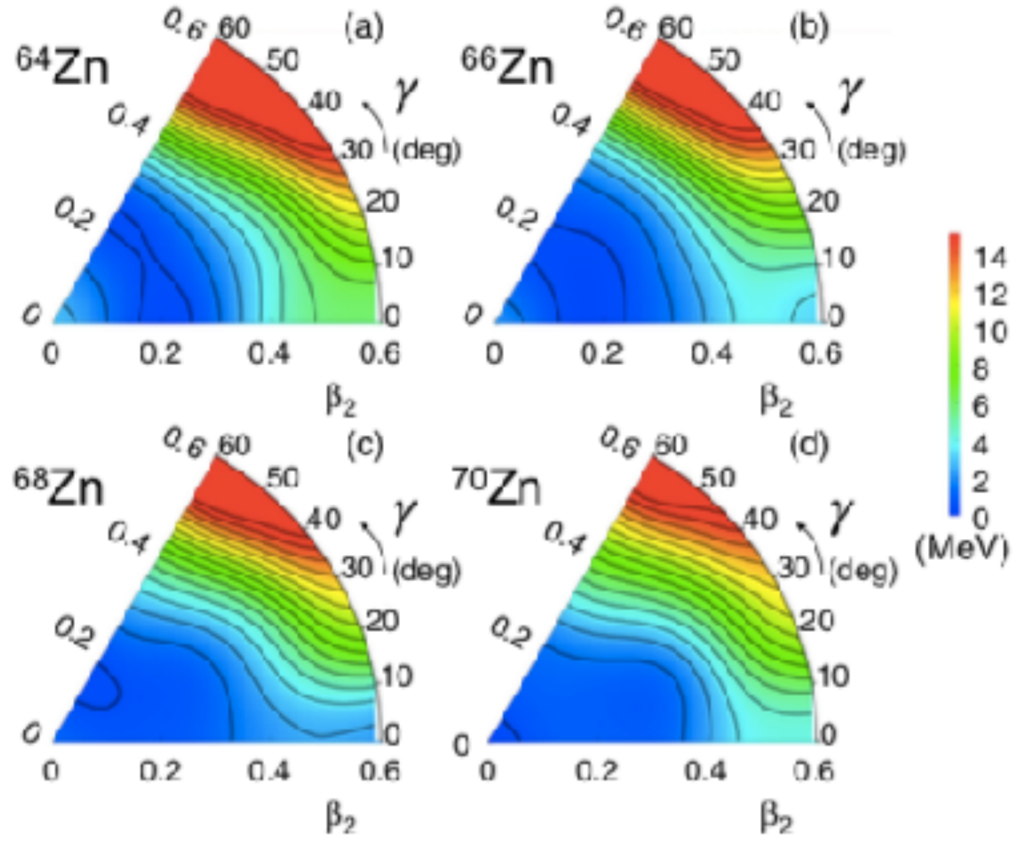


FIG. 8. Potential energy surfaces for stable Zn isotopes resulting from deformation-constrained Hartree-Fock calculations with the particle number projection method (PN-VAP) and Gogny D1S interaction.

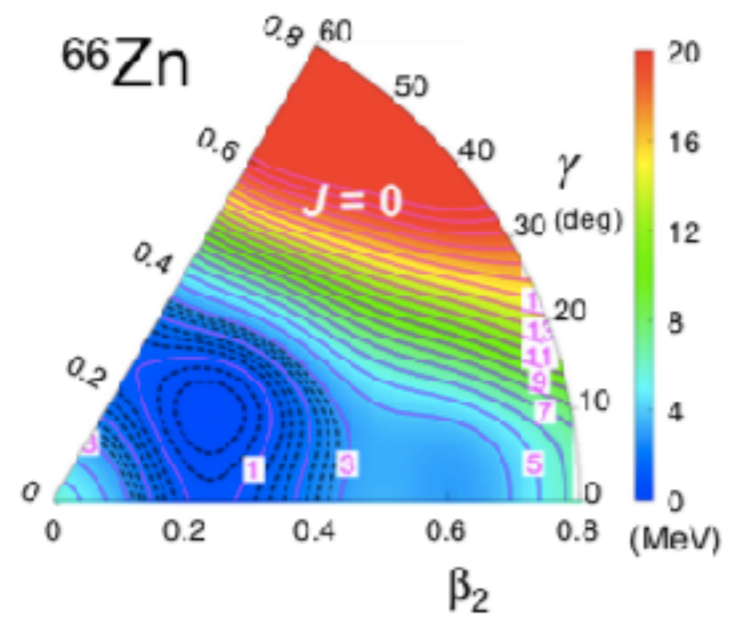


FIG. 9. Same as Fig. 8 for ^{66}Zn after projecting onto angular momentum $J = 0$. A triaxial shape with a finite dispersion characterize the isotope and a second prolate minimum results from the calculation.

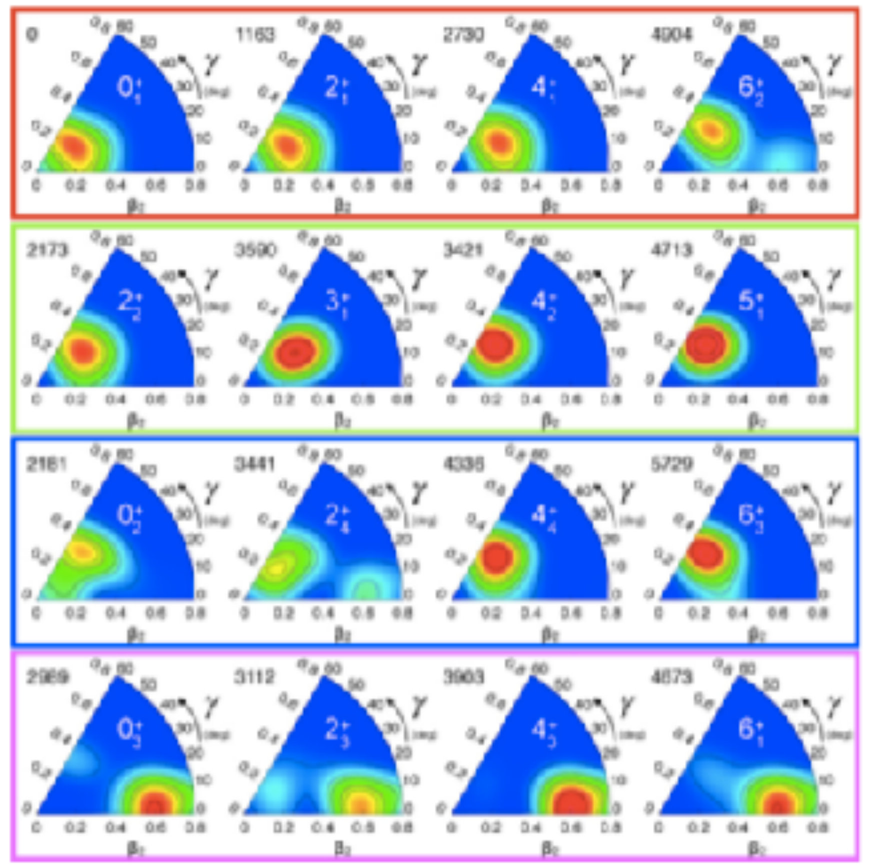


FIG. 11. Collective wave functions for selected states in ^{66}Zn, obtained within the SCCM framework. The energy of each state (in keV) is given on topleft of each CFW. The colored frames are used to present the suggested band assignments.

Zn: Relativistic Mean-Field

Eur. Phys. J. A 25, 29–39 (2005)
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Relativistic mean-field study for Zn isotopes

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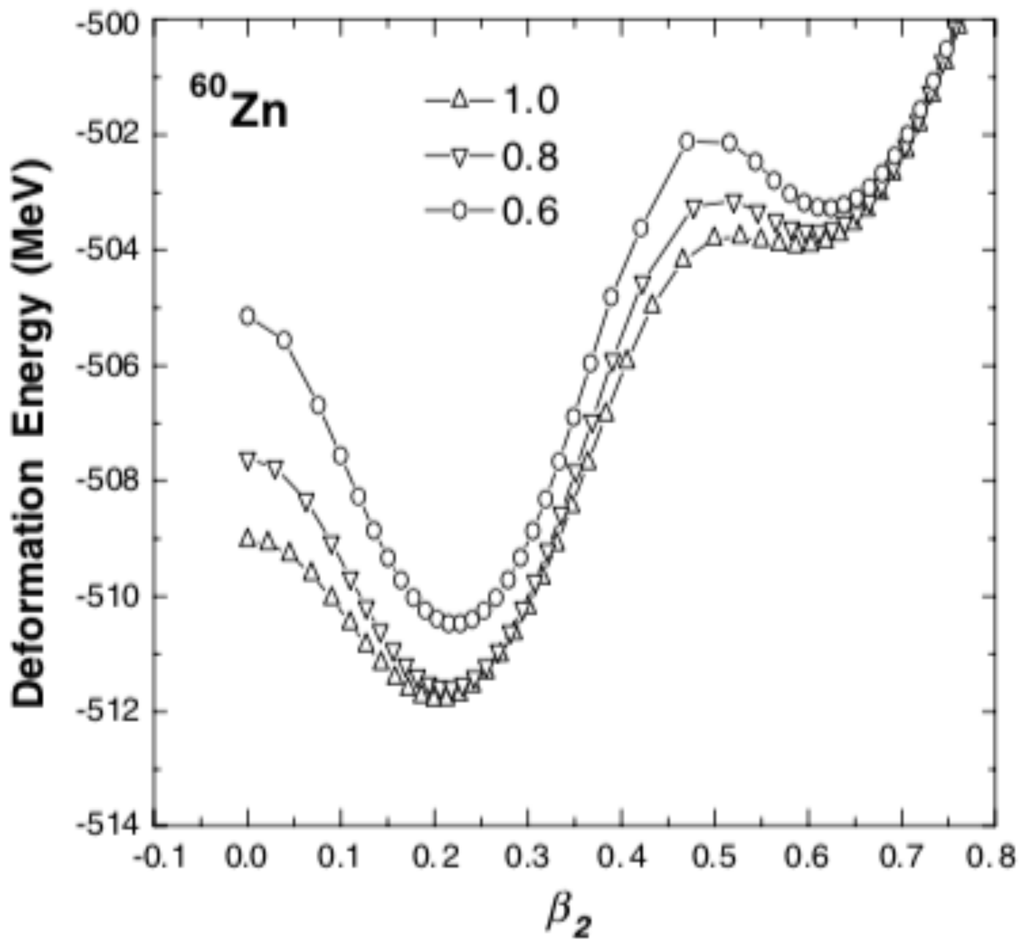

Fig. 8. The Routhian for ^{60}Zn with respect to the quadrupole deformation with the NL-SH set. The coefficient labeled in the figure is the reduction factor of the pairing gap constant. The coefficient 1.0 means no reduction.

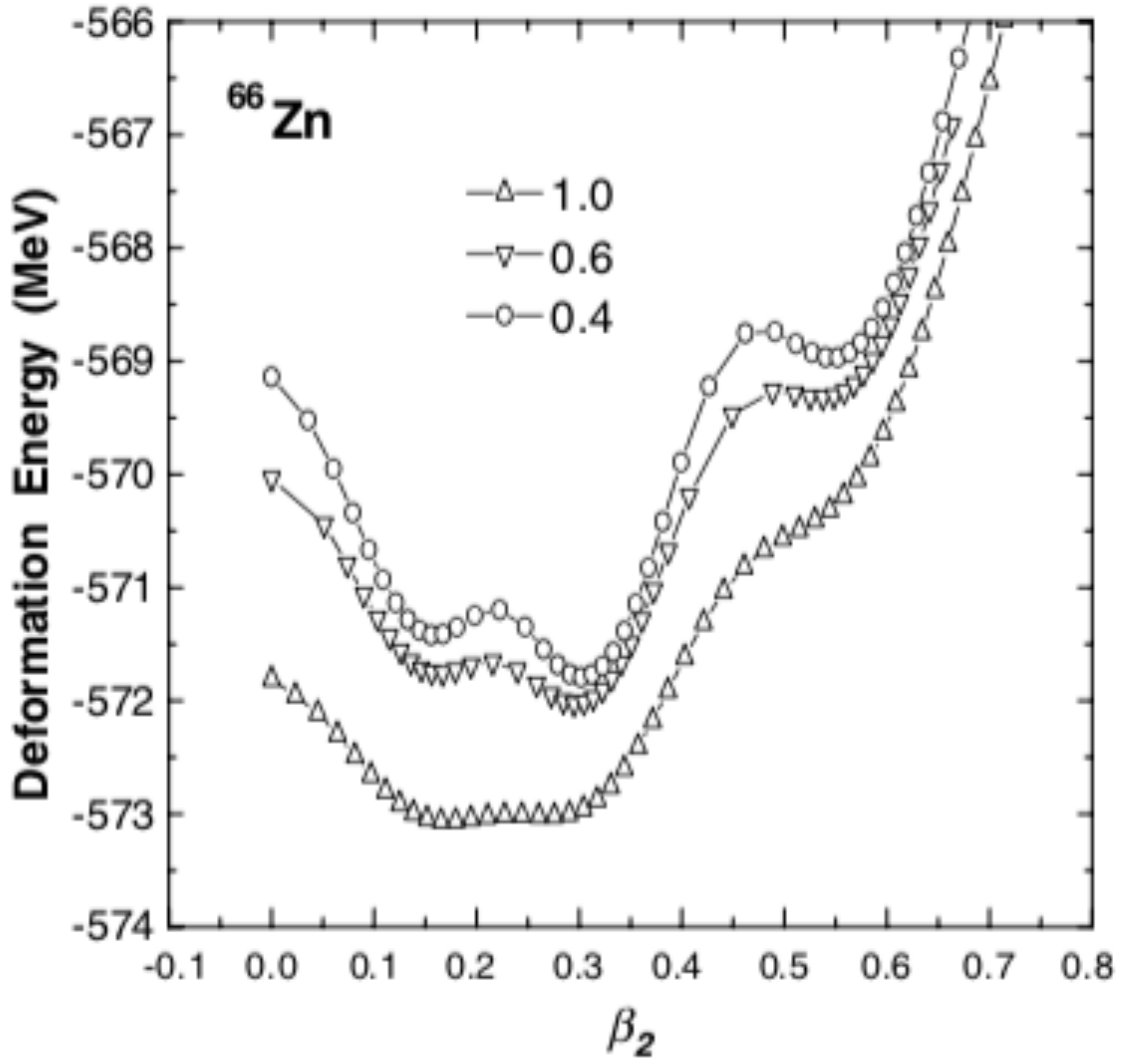

Fig. 9. The same as shown in fig. 8, but for ^{66}Zn.

Zn: Covariant Density Functional theory

PHYSICAL REVIEW C **101**, 064322 (2020)

Ground state properties of Zn, Ge, and Se isotopic chains in covariant density functional theory

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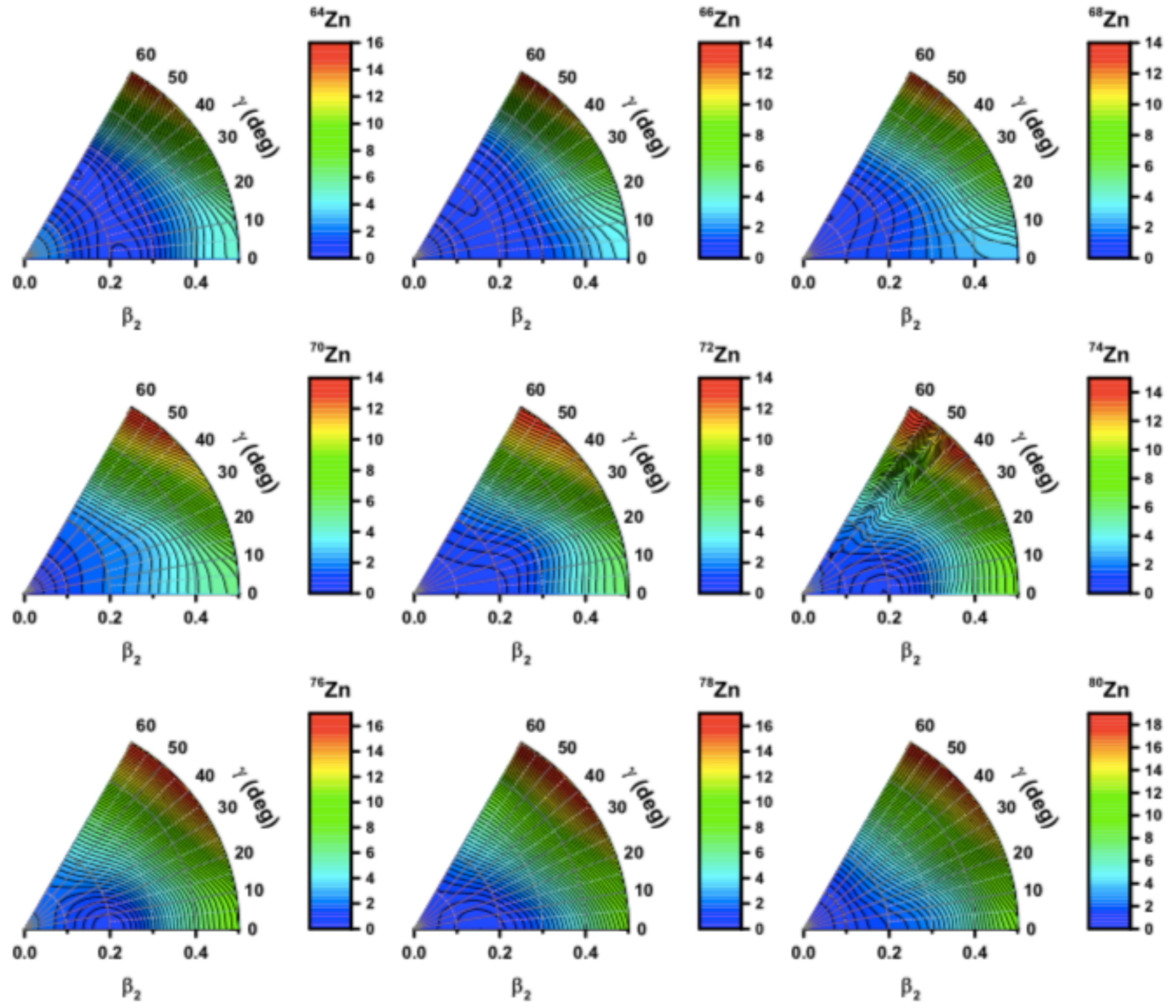

Ni Isotopes & Z = 28

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **89**, 031301(R) (2014)

Novel shape evolution in exotic Ni isotopes and configuration-dependent shell structure

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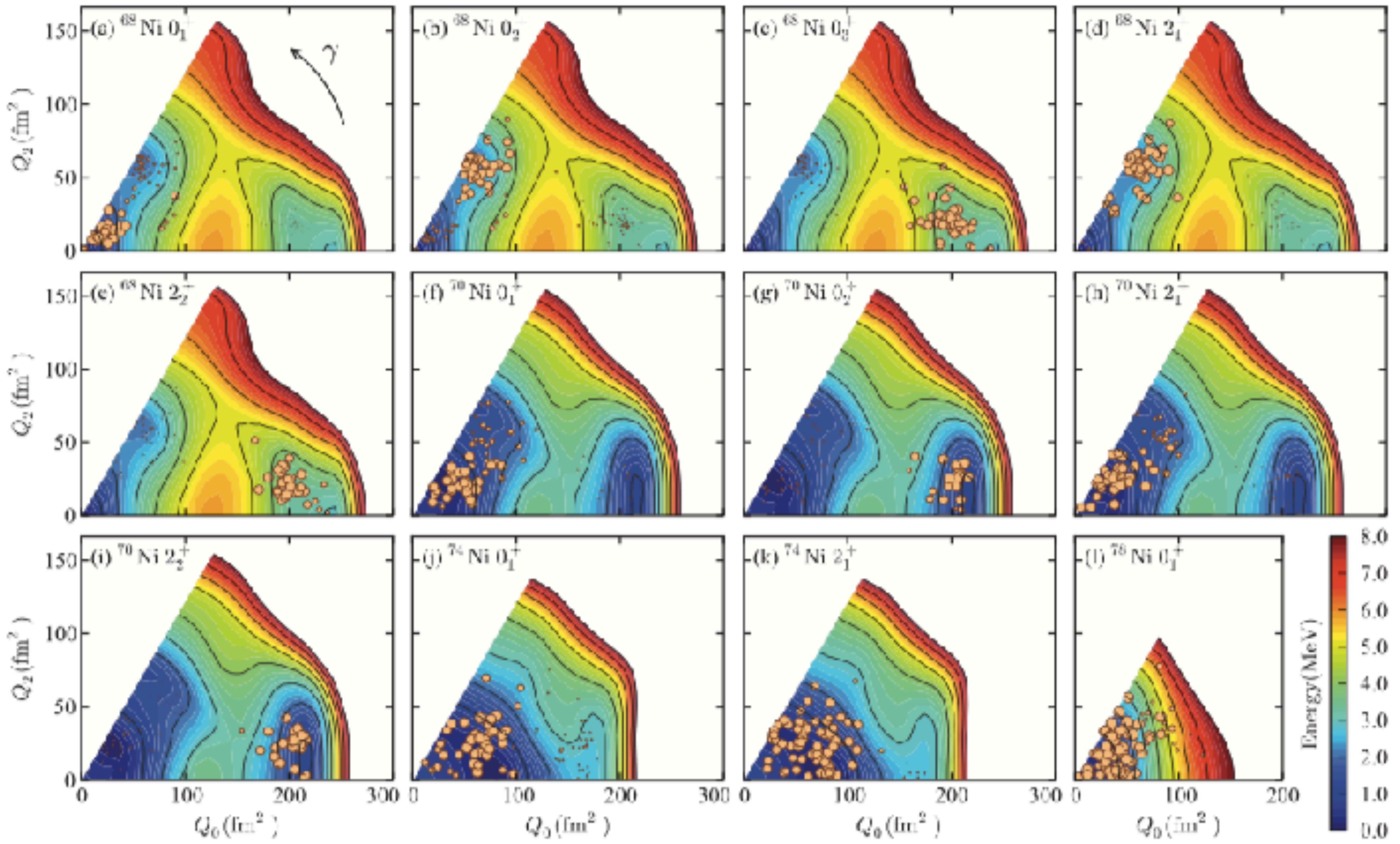
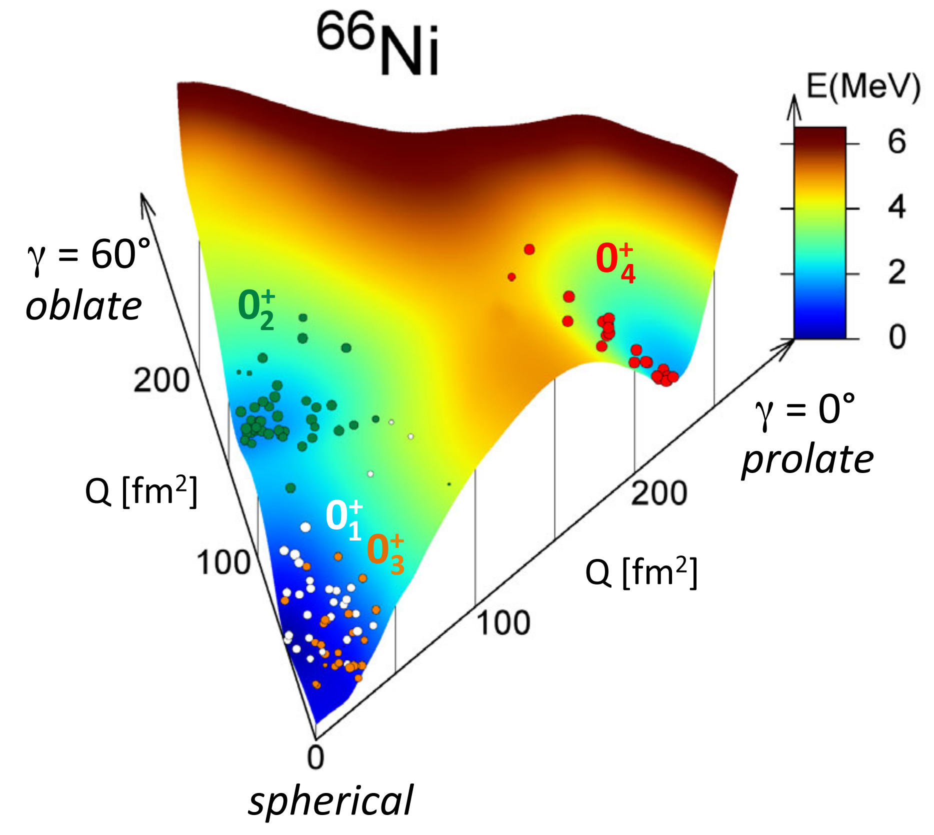


FIG. 3. (Color online) Potential energy surfaces (PESs) of Ni isotopes, coordinated by the usual Q_0 and Q_2 (or γ). The energy relative to the minimum is shown by contour plots. Circles on the PES represent shapes of MCSM basis vectors (see the text).



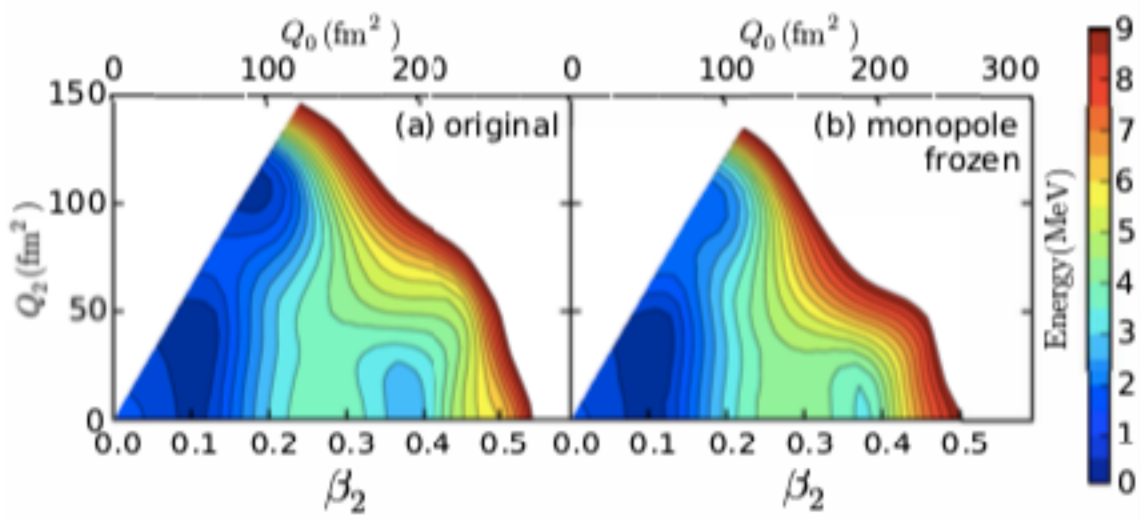


FIG. 4: ^{64}Ni potential energy surfaces with (a) full, original interaction used in MCSM calculations [11], and (b) monopole-frozen interaction (i.e., the monopole component is subtracted from the proton-neutron interaction, and single-particle energies are adjusted to original effective values of the spherical minimum [6]).

^{82}Ge

PHYSICAL REVIEW C **84**, 024305 (2011)

Possible excited deformed rotational bands in ^{82}Ge

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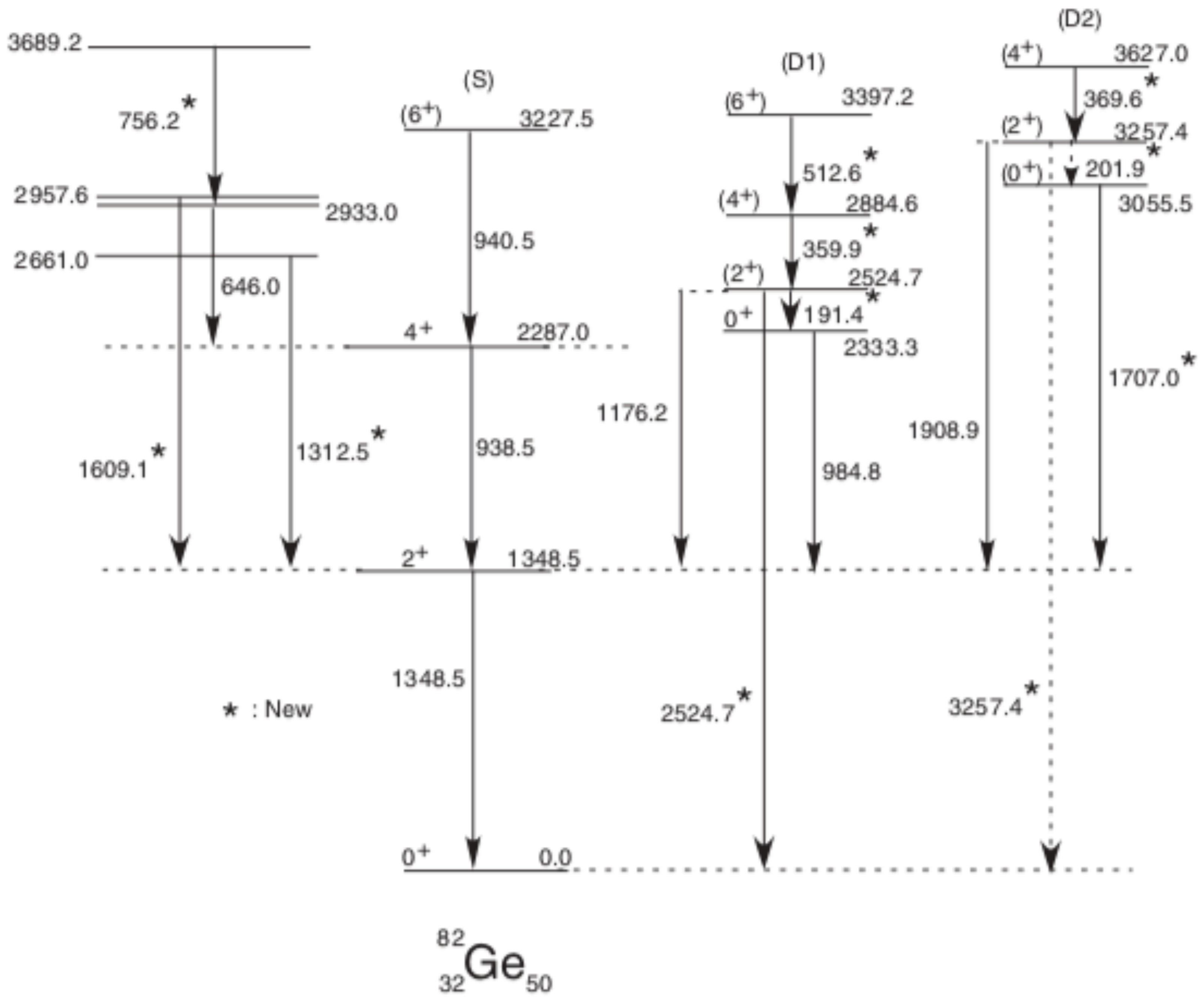

0^+ States in Ni Isotopes

S. Leoni et al., Acta Physica Polonica B 50, 605 (2019)