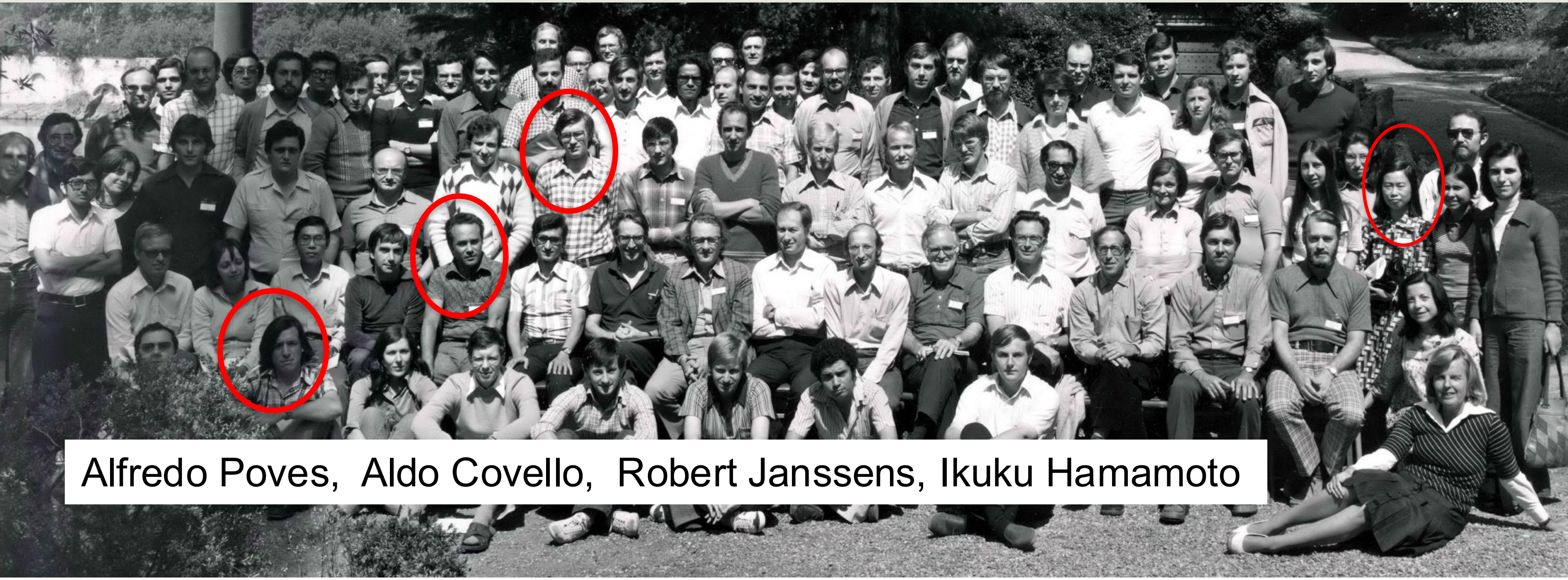
The first 100 years and the next 50 years? of Nuclear Science
A few notes in honor of Robert Janssens

Alex Brown, September 19, 2025

1976 Summer School in Varenna, Italy



Alfredo Poves, Aldo Covello, Robert Janssens, Ikuku Hamamoto

Arthur Kerman
Ricardo Broglia
Aage Bohr (*)
Igal Talmi (100 this year)
Ben Mottelson (*)
Hobson Wildenthal
Ray Satchler

* 1975 Nobel Prize for the nuclear collective model

Matan Talmi's Post

Matan Talmi

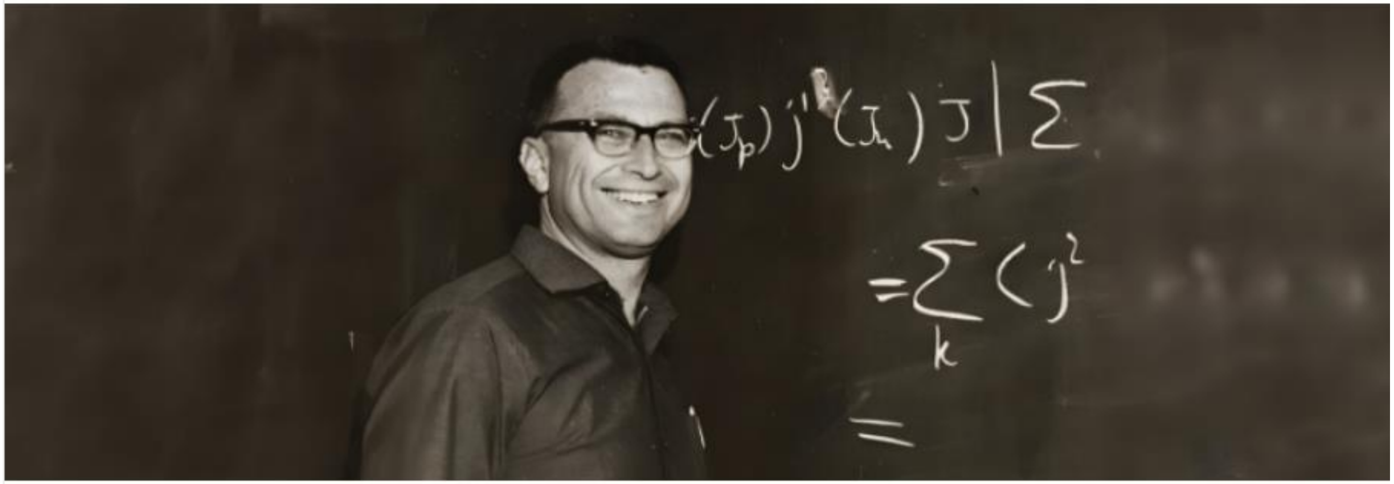
7mo · Edited

...

Jan 31, 2025

My grandpa, Igal Talmi, turned 100 today! ❤️
A nuclear physics pioneer whose breakthroughs in nuclear shell theory hold strong till this day, and as important - a role model of knowledge, optimism and humility who continues to inspire generations of fellow scientists, family and anyone lucky enough to cross his path.

Article in Hebrew, English wiki page in the comments



CIRCULAR

Name: JANSSENS Robert

Date of Birth: 7/8/51

Student: X

Observer:

Institution: Institut de Physique Corpusculaire
2 Chemin du Cyclotron
1348 Louvain-la-Neuve

Brief description of researcher experience (mention also institutions with which you have been associated):

- in beam γ-ray spectroscopy. ~~...~~ (Coincidence measurements, angul. distribution etc.) applied on Deformed Nuclei (Dy^{156}, Os^{178}, Hf^{168}, Er^{164})
- interference between Coulomb and Nuclear force (Collaboration Louvain-la-Neuve - München group of J. De Boer)
- (electron) conversion measurements ~~on~~ deformed nuclei (measurements done at IKO (Amsterdam and Groningen)
- lifetimes and g factor measurements in rare earth nuclei.

Current main research interests:

- High Spin states in nuclei
- Experimental techniques for measuring ~~...~~ short lifetimes, short living states etc..

Mention topics that you would especially like to have discussed:

- High spin isomers
- Triaxial shapes: a review.
- Coexistence of vibrational and rotational spectra

1925 Quantum Mechanics

1925 Pauli invents the Pauli Principle

1928 Dirac predicts anti-particles

1928 Three elementary particles - proton, electron and photon

1928 Two types of fundamental interactions - Coulomb and Gravitational *

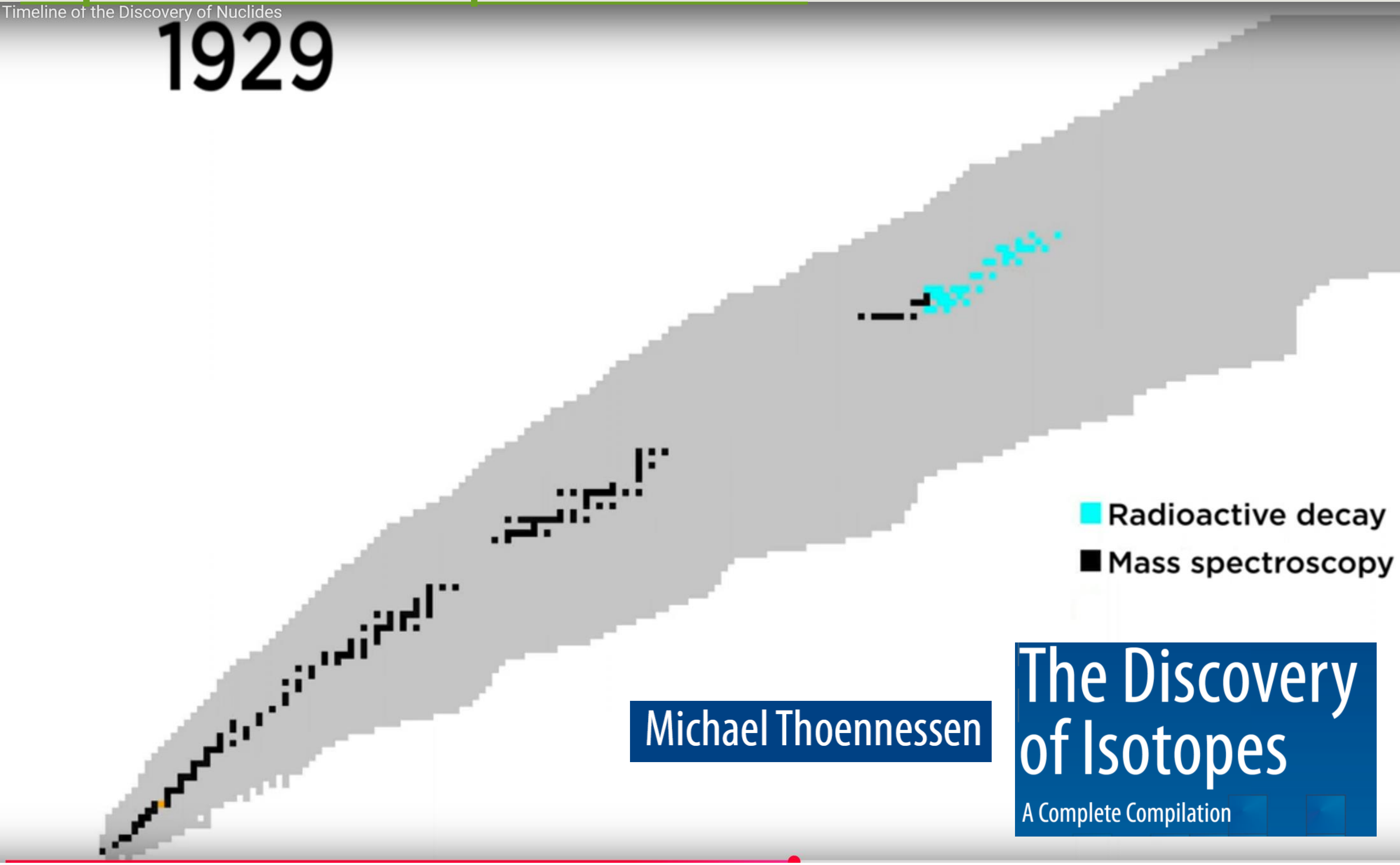
The quantum law of matter

Nature | Vol 639 | 13 March 2025

From strange beginnings, the Pauli exclusion principle has become a gift that keeps on giving. **By Olival Freire Jr and Thiago Hartz**

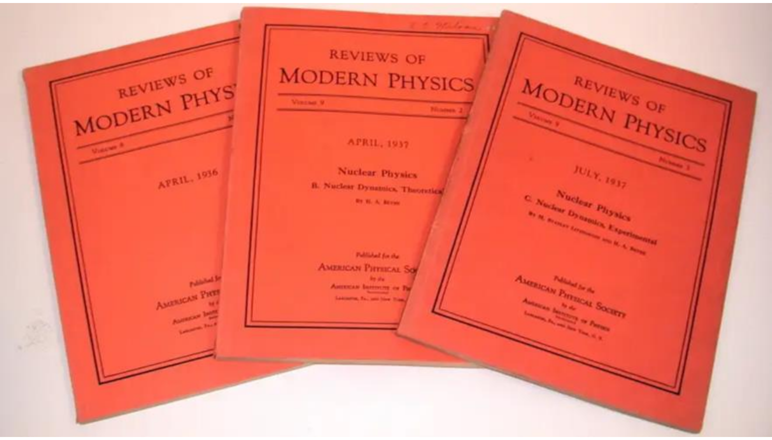
* Albert Einstein, "Einheitliche Feldtheorie von Gravitation und Elektrizitat." Preussische Akademie der Wissenschaften, Phys. math. Klasse, Sitzungsberichte 1925, 414–419. seeTilman Sauer, https://philsci-archive.pitt.edu/3293/1/uft.pdf

Michael Thoennessen: Timeline of the Discovery of Nuclides
https://frib.msu.edu/public/nuclides



1932 Chadwick discovers the neutron
1932 The nucleus is made up of protons and neutrons

KUENZIG BOOKS
IMPORTANT BOOKS IN SCIENCE, TECHNOLOGY AND ENGINEERING
ARTIFACTS OF SCIENCE AND TECHNOLOGY



"During the 1930s, Hans Bethe made many of his major contributions to nuclear physics. The first was a series of three lengthy papers in the Journal Reviews of Modern Physics in 1936 and 1937 comprising almost 500 pages of a comprehensive review of experimental and theoretical nuclear physics...The three papers...were so comprehensive that together they became known as the Bethe Bible and 50 years later [were] republished as a book by the American Institute of Physics...The significance of his work in theoretical physics was underscored by Professor O. Klein...[who mentioned Bethe's Bible] at the presentation of the Nobel Prize to Hans Bethe on December 11, 1967. (see L'Annunziata, Radioactivity, Elsevier, 2007)

ITEM SOLD

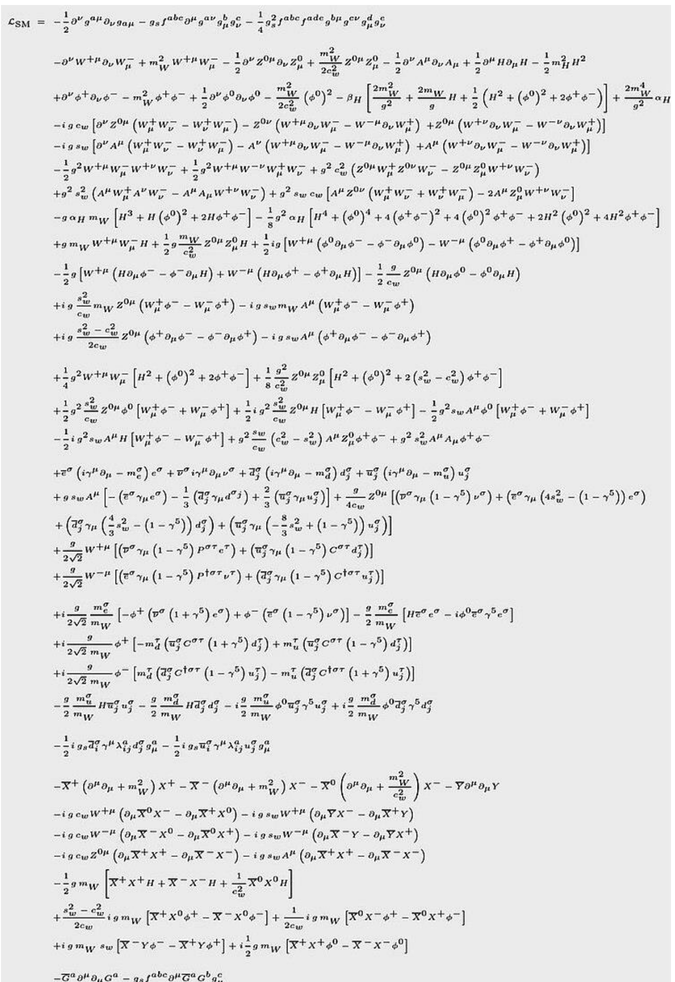
Many energy levels were Observed

1936 Bethe Bible

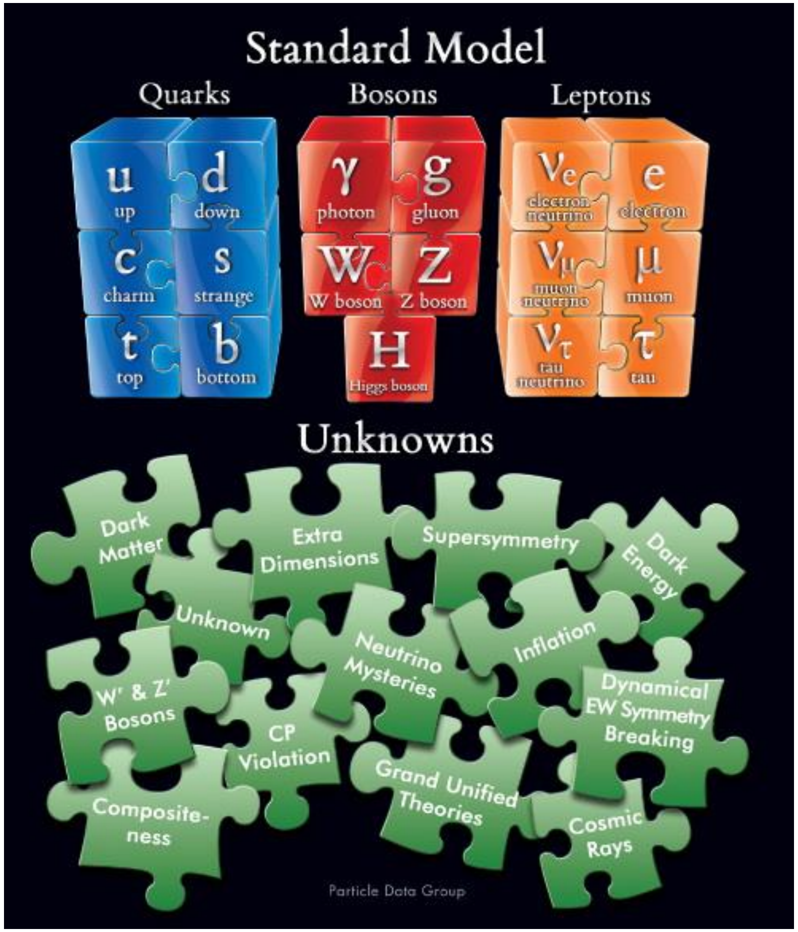
Bethe provided the first models for nuclear levels densities.

Fast forward for particle physics

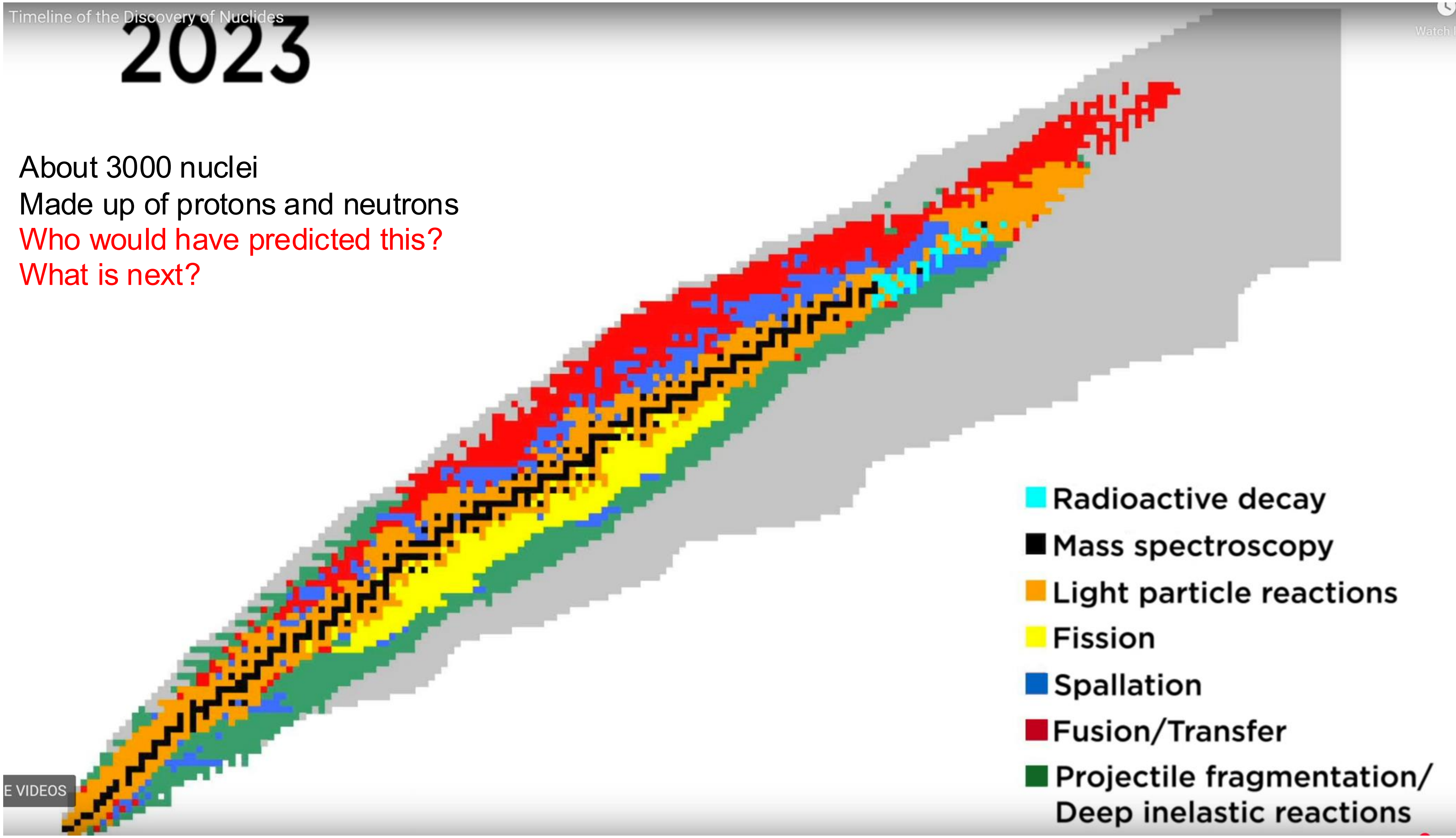
Over 100 hadrons (baryons and mesons) discovered.
Most results explained by 23 elementary particles plus
The “standard model” equations with 26 constants.
Who would have predicted this?
What is next?



Quarks and Leptons have anti-particles (Dirac)

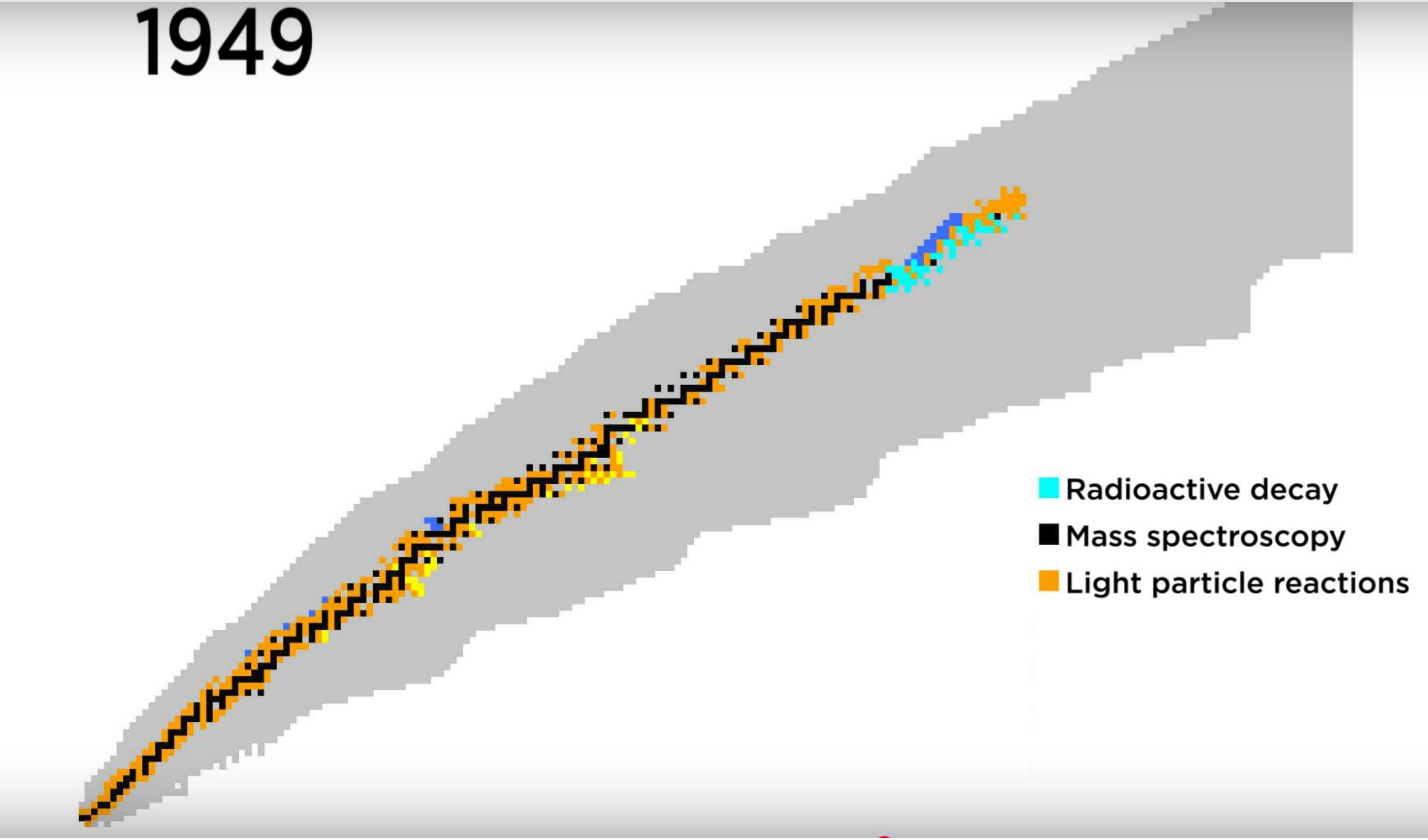


Fast forward for nuclear physics



About 3000 nuclei
Made up of protons and neutrons
Who would have predicted this?
What is next?

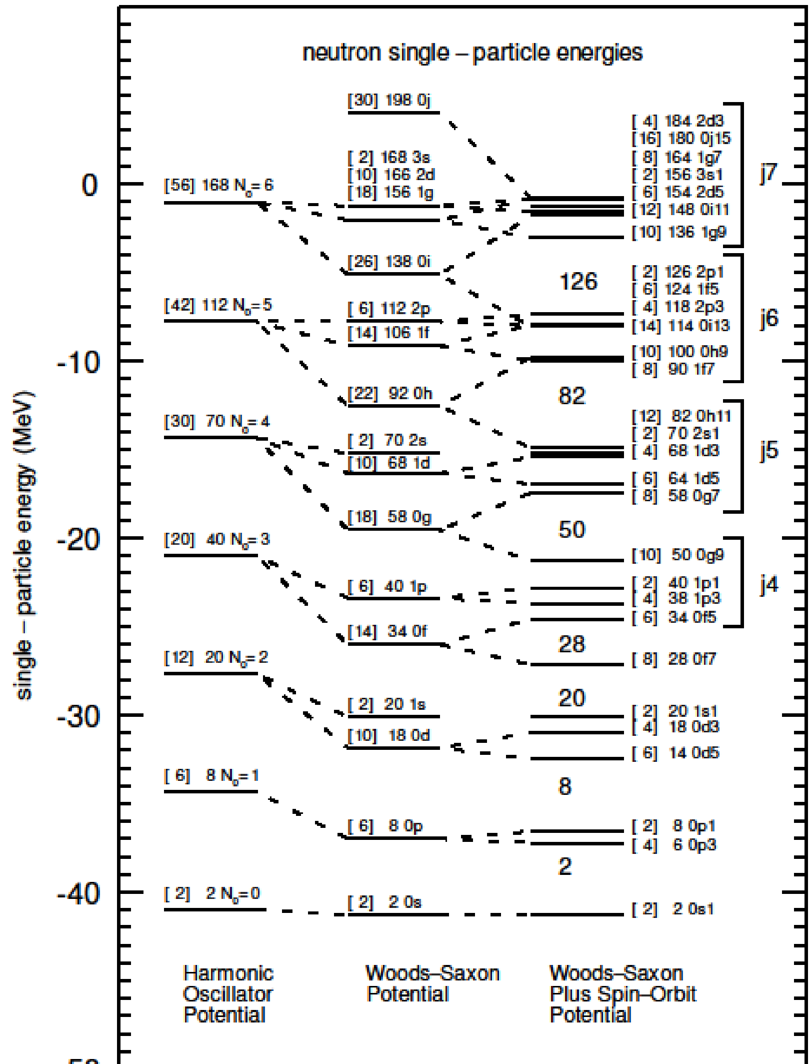
https://frib.msu.edu/public/nuclides



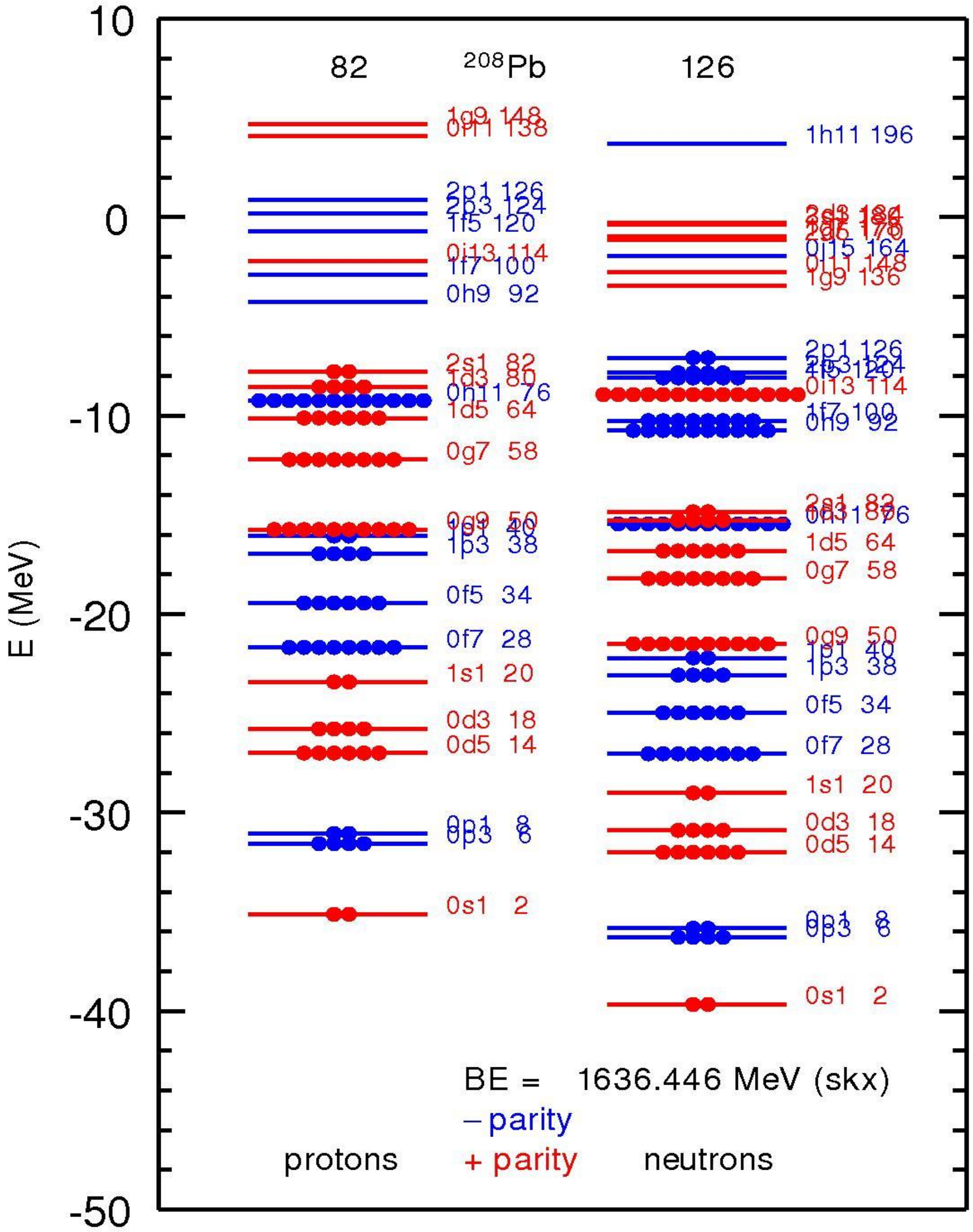
1949-1950 The nuclear shell model was discovered – magic* numbers (2, 8, 20, 28, 50, 82, 126)
1963 Nobel Prize, Mayer and Jensen

Binding energies
Excited states energies
Energies of 2^+ state
J^π values

Maria Goeppert Mayer



* It was Eugene Paul Wigner who coined the term "magic number". Steven A. Moszkowski, who was a student of Maria Goeppert-Mayer, in a talk presented at the American Physical Society meeting in Indianapolis, 4 May 1996 said: "Wigner believed in the liquid drop model, but he recognized, from the work of Maria Mayer, the very strong evidence for the closed shells. It seemed a little like magic to him, and that is how the words 'Magic Numbers' were coined".



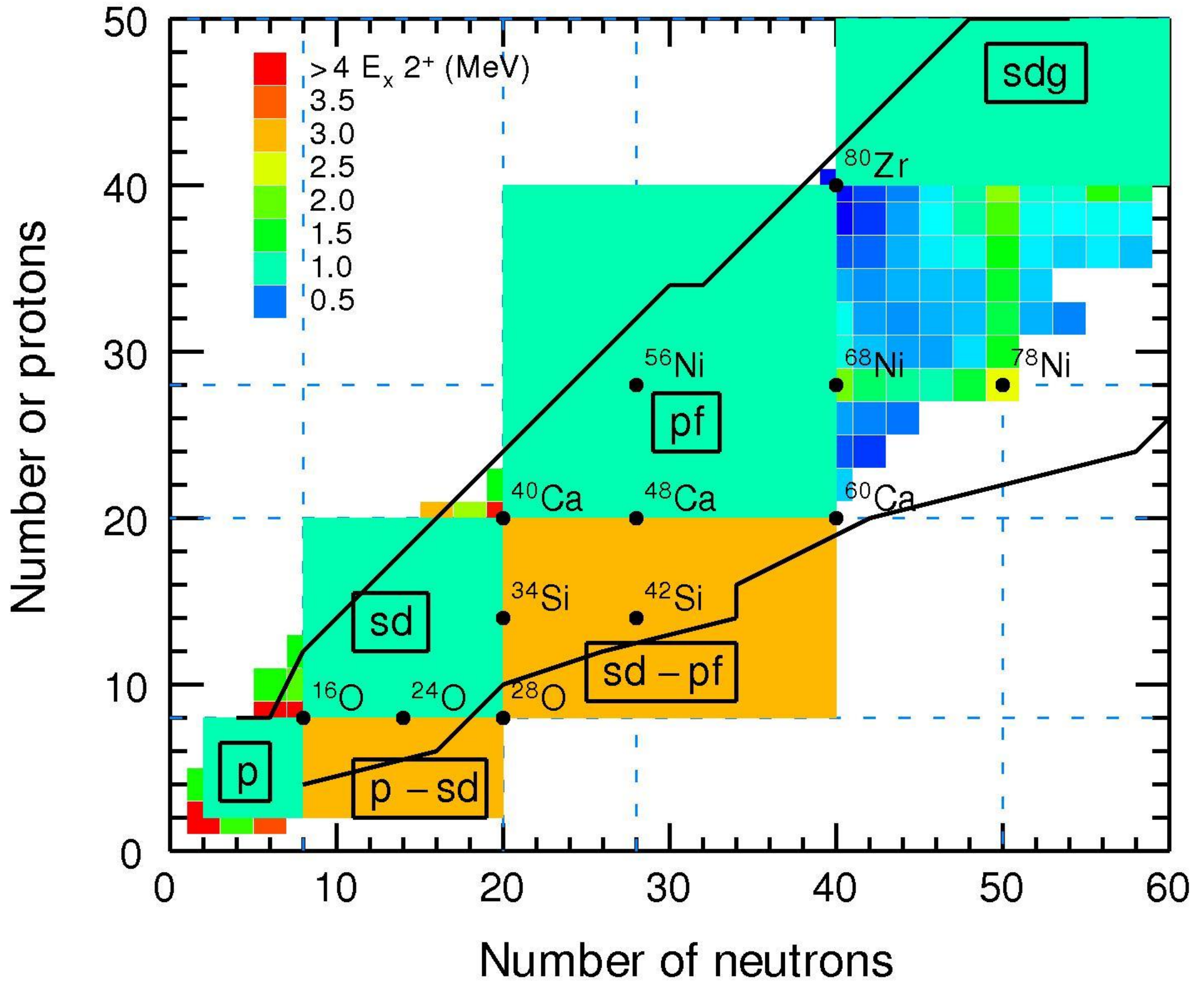
^{208}Pb

Filling of lowest energy quantum states according to the Pauli principle *.

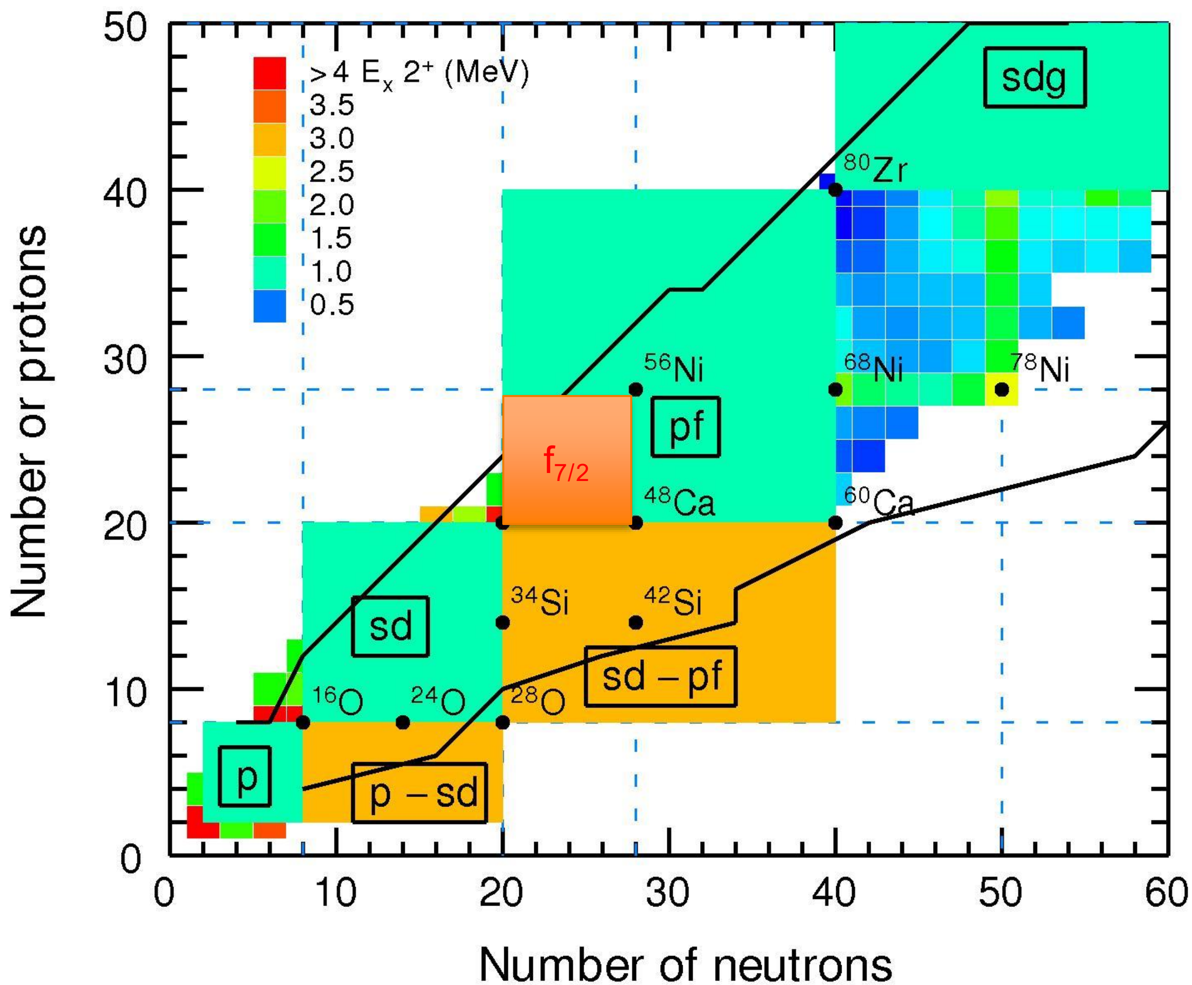
Only one type of fermion can occupy a given quantum state

* This is the dominant configuration of the ^{208}Pb ground state. In addition there are an infinite number of smaller components made up of configurations where the nucleons are excited from filled orbitals to higher orbitals.

The nuclear chart can be divided into “territories” where only a few orbitals dominate the low-lying structure in a given mass region



The nuclear chart can be divided into "territories" where only a few orbitals dominate the wavefunctions of low-lying states

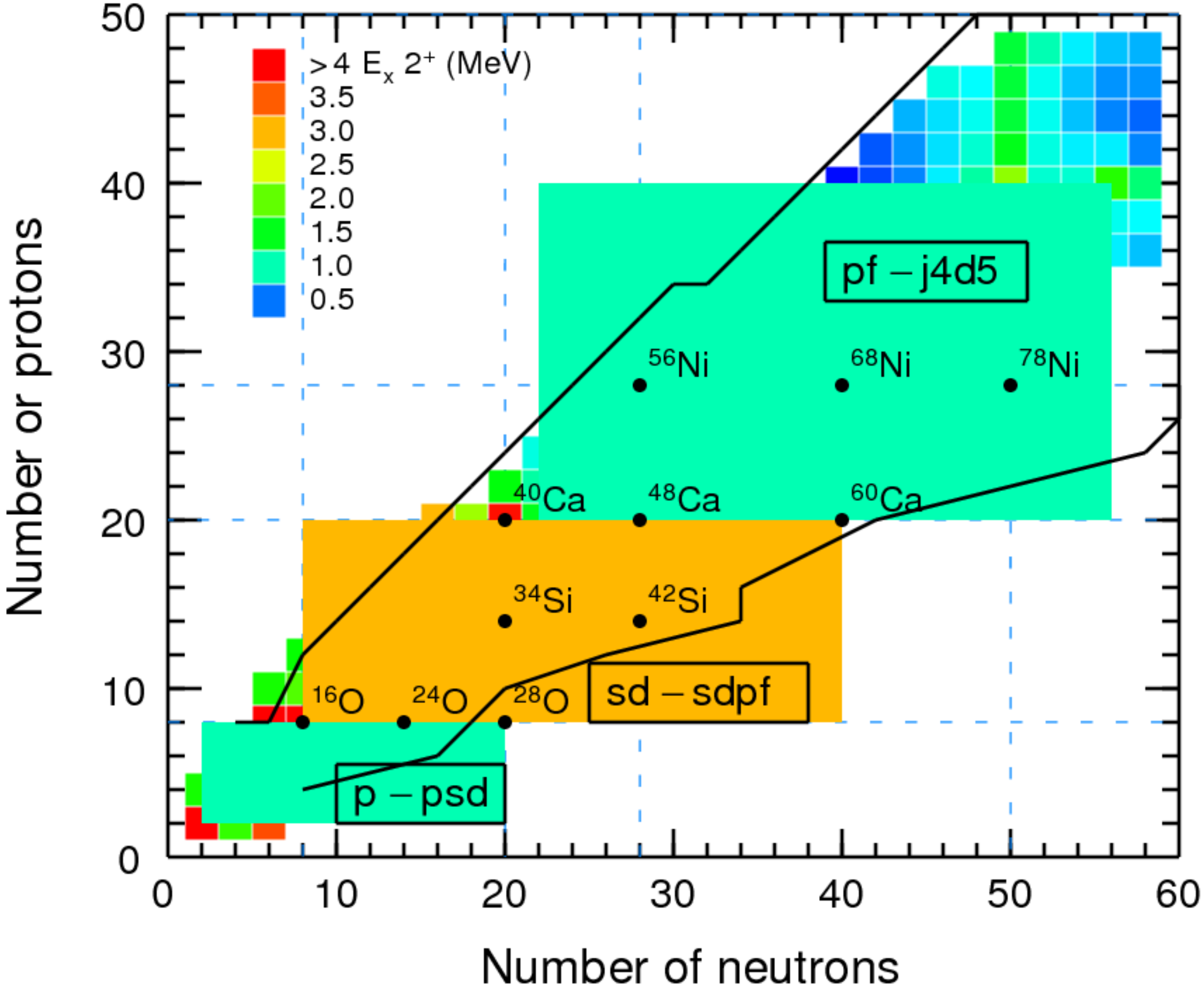


The $f_{7/2}$ shell and many other simple orbital configuration examples started in the 1950s by Talmi et al.
1963 book defined much of the terminology we use today.

The "p" shell in the 1960s by Cohen-Kurath is now replaced by ab-initio methods

The "sd" shell started in the 1970s by Brown-Wildenthal is still providing unique predictions

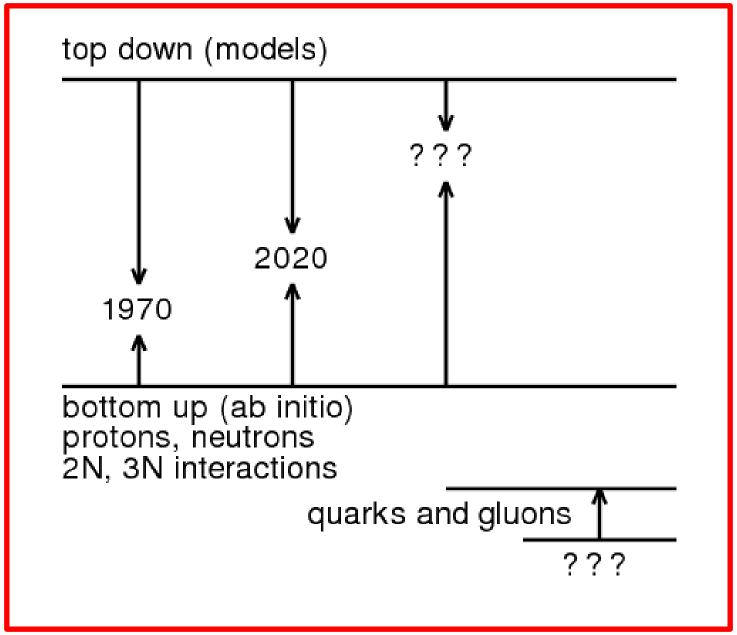
With islands of inversion, more orbitals must be considered and the "territories" enlarged – to be enlarged over the next 50 years.



With the shell-model we have a language within which one can understand everything at many levels of detail

Provides basis states for all ab-initio models (e.g. harmonic oscillator)

We have a top-down language in which everything can be discussed



Next 50 years – can nuclear properties be calculated in a basis that has nothing to do with the shell model?

Calculate all energies to an uncertainty of 1 MeV, 100 keV, 1 keV?

.

An early joint paper

ELSEVIER

Physics Letters B 546 (2002) 55–62

PHYSICS LETTERS B

www.elsevier.com/locate/npe

Structure of ^{52,54}Ti and shell closures in neutron-rich nuclei above ^{48}Ca

R.V.F. Janssens [a,*], B. Fornal [b], P.F. Mantica [c,d], B.A. Brown [c,e], R. Broda [b], P. Bhattacharyya [f], M.P. Carpenter [a], M. Cinausero [g], P.J. Daly [f], A.D. Davies [c,e], T. Glasmacher [c,e], Z.W. Grabowski [f], D.E. Groh [c,d], M. Honma [h], F.G. Kondev [a], W. Królas [b], T. Lauritsen [a], S.N. Liddick [c,d], S. Lunardi [i], N. Marginean [g], T. Mizusaki [j], D.J. Morrissey [c,d], A.C. Morton [c], W.F. Mueller [c], T. Otsuka [k], T. Pawlat [b], D. Seweryniak [a], H. Schatz [c,e], A. Stolz [c,e], S.L. Tabor [l], C.A. Ur [i], G. Viesti [i], I. Wiedenhöver [a,l], J. Wrzesiński [b]

[a] *Argonne National Laboratory, Argonne, IL 60439, USA*

Experiment and theory working together

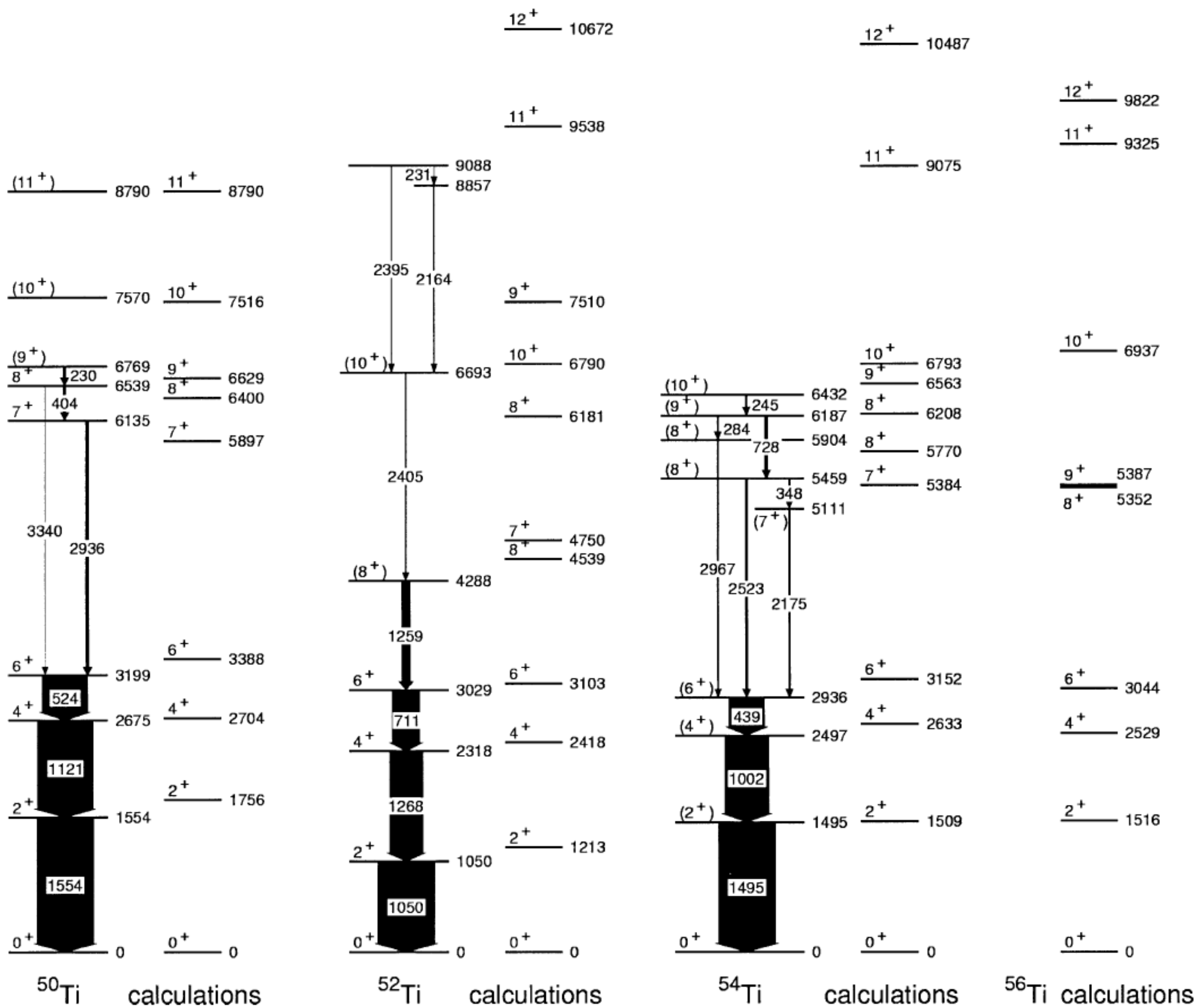


Fig. 3. Comparisons between shell-model calculations with the GXPF1 Hamiltonian and data for the even–even $^{50-54}$Ti isotopes. All the data for ^{54}Ti are from the present experiment as are those for $I \geqslant 8$ in ^{52}Ti. The width of the arrows is proportional to the measured intensities. The energy uncertainty for the strongest transitions in each nucleus is 0.2 keV, and increases to 0.6 keV for the weakest lines.

Experiment and theory working together

Empirical shell-model Hamiltonians rely on a subset of energy data to determine the evolution of the single-particle energies and to constrain some two-body matrix elements

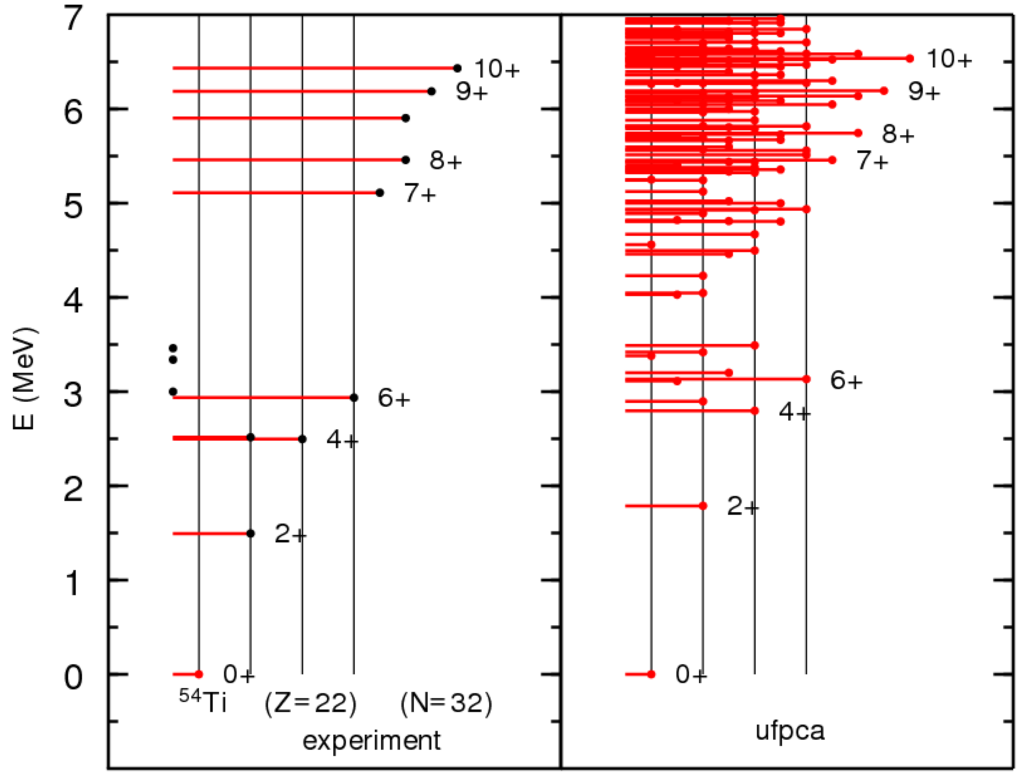
The GFPX1A Hamiltonian obtained in this way was used to predict the yrast spectrum of Ti that agreed with new data om 2002.

The agreement was good enough to use theory to suggest J-pi assignments

But are we sure?

> at 5111, 5459, 5904, 6187, and 6432 keV. All spin assignments are tentative as no angular correlation information is available due to the weak intensity of this reaction channel. However, the fact that the reaction feeds yrast states preferentially, together with the close correspondence between established and calculated levels (see discussion below) allows one to assign spins with confidence along the sequence.

Let's see if the theory has changed – ^{54}Ti



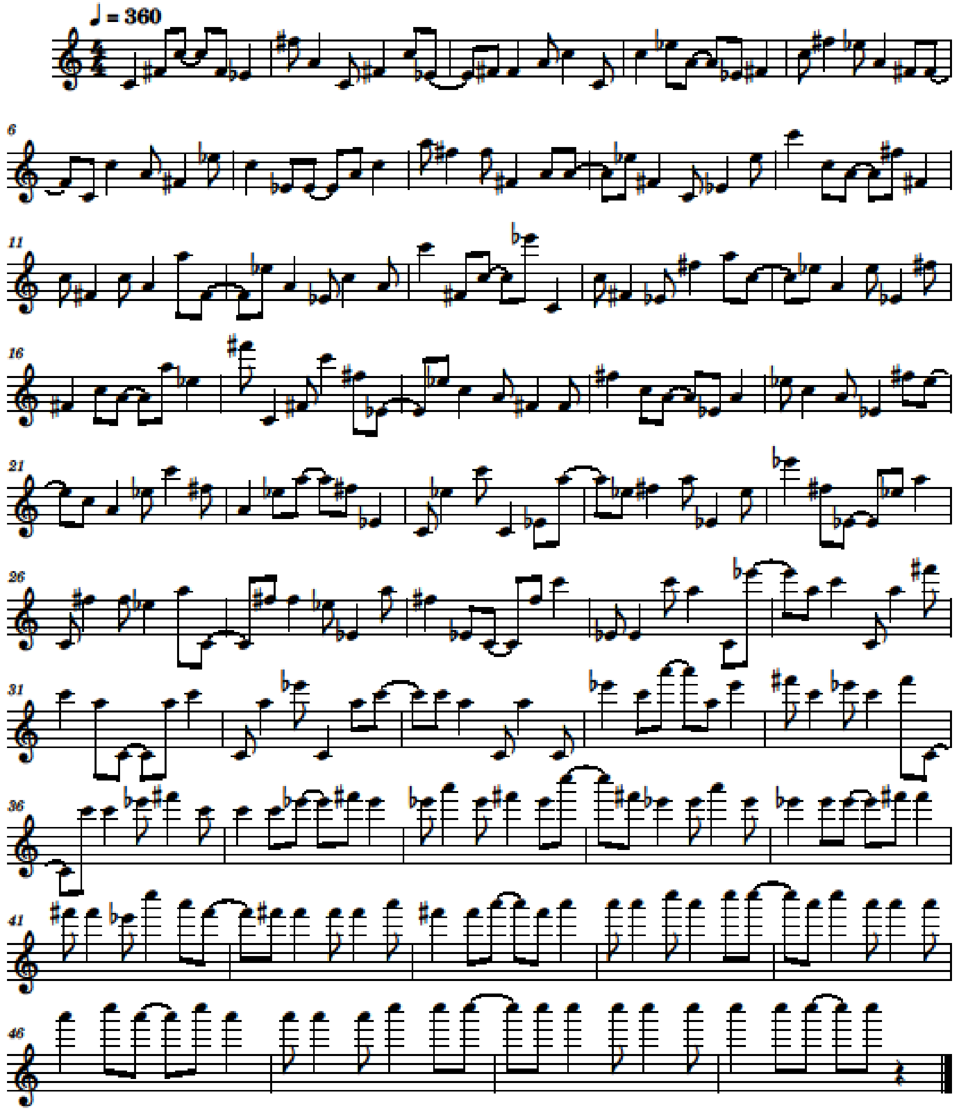
Latest Hamiltonian in the fp model space.

Up to 7 MeV about 100 more levels predicted.
– for most these the only thing of interest is the level density.

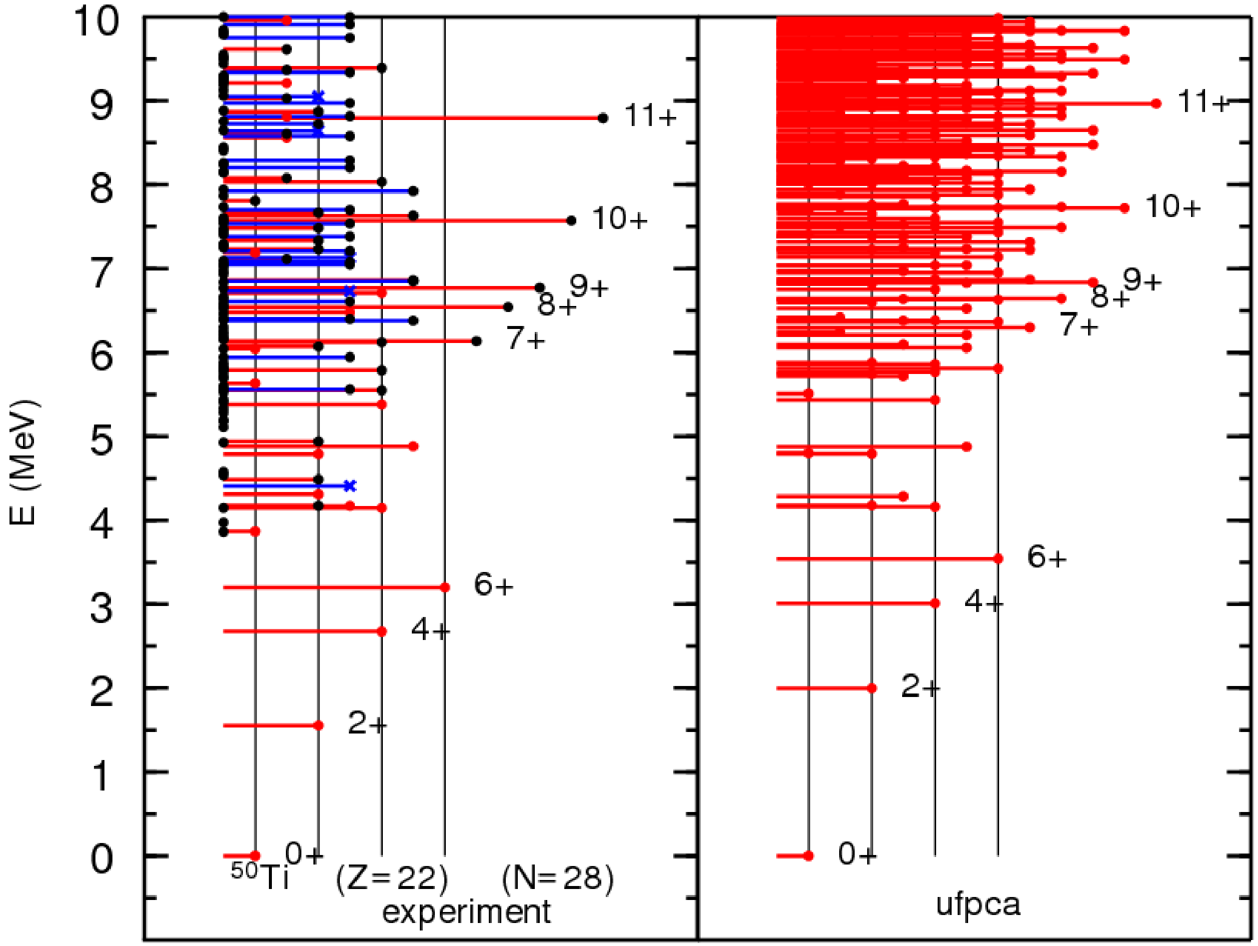
We have great confidence that they are there (within a few hundred keV)

Janssens' Titatium Jig

Alex Brown, September, 2025

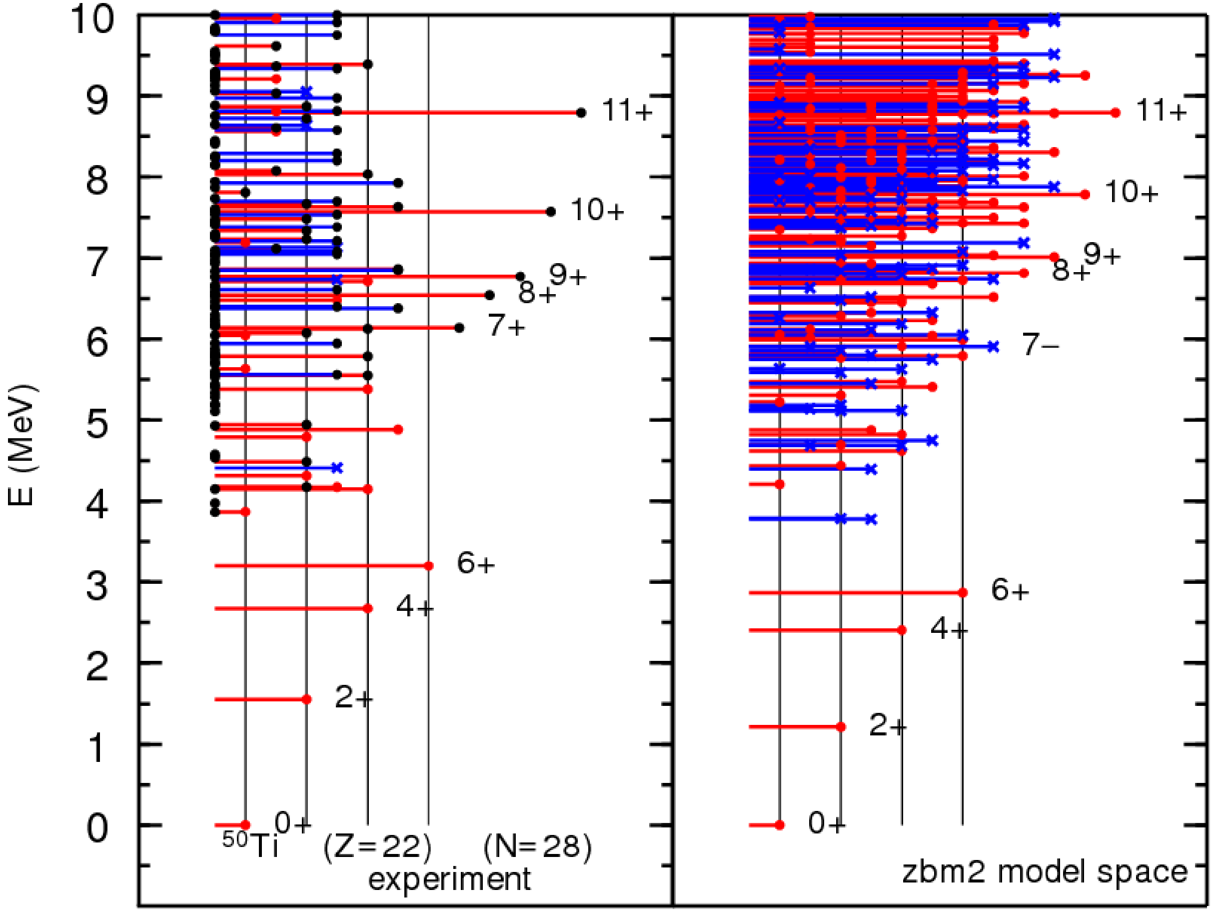


Let's see if the theory has changed – ^{50}Ti



Negative-parity states need a model space that goes beyond fp

Let's see if the theory has changed – ^{50}Ti



ZBM2 model space (d3,s1,f7,p3) is OK

But more orbitals need to be added (d5.p1,f5,g9…)

...... the latest collaborations on ^{74}Ge and ^{68}Zn

PHYSICAL REVIEW C **108**, 024315 (2023)

Testing shell-model interactions at high excitation energy and low spin: Nuclear resonance fluorescence in ^{74}Ge

S. R. Johnson,[1,2,*] R. V. F. Janssens,[1,2] U. Friman-Gayer,[1,2,†] B. A. Brown,[3,4] B. P. Crider,[5] S. W. Finch,[6,2] Krishichayan,[6,2] D. R. Little,[1,2] S. Mukhopadhyay,[7,‡] E. E. Peters,[7] A. P. D. Ramirez,[7,§] J. A. Silano,[8] A. P. Tonchev,[6,8] W. Tornow,[6,2] and S. W. Yates[7]

From the Ground State to the Particle Emission Threshold:
Nuclear Resonance Fluorescence in 68Zn - Thesis of Samantha Johnson

Uses nuclear resonance fluorescence (NRF) with the
High-Intensity Gamma-Ray Source (HIγS) Facility to select 1- and 1+ states.

Good news – the number and spacing of low-lying levels in the jj44 model space (0f5, 1p3, 1p1, 0g9) is OK

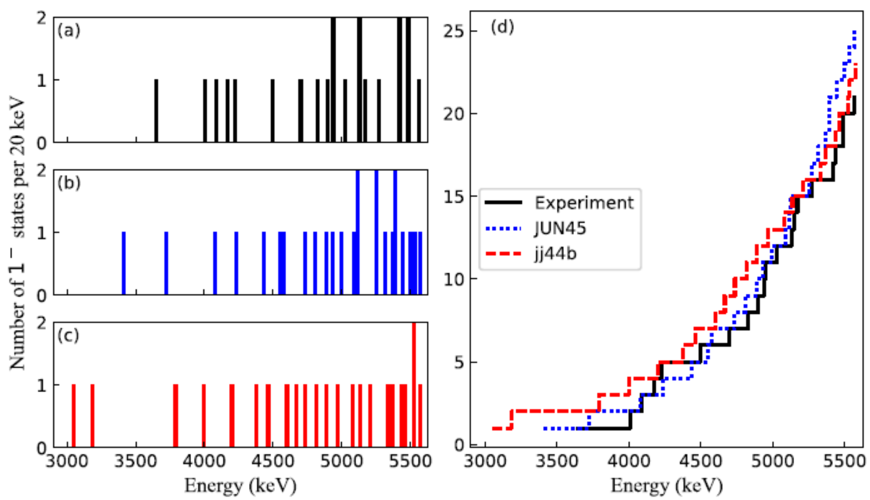


FIG. 4. Distribution of 1^- states (a) experimentally and calculated using (b) the JUN45 interaction and (c) the jj44b interaction. (d) shows a running sum of the number of states.

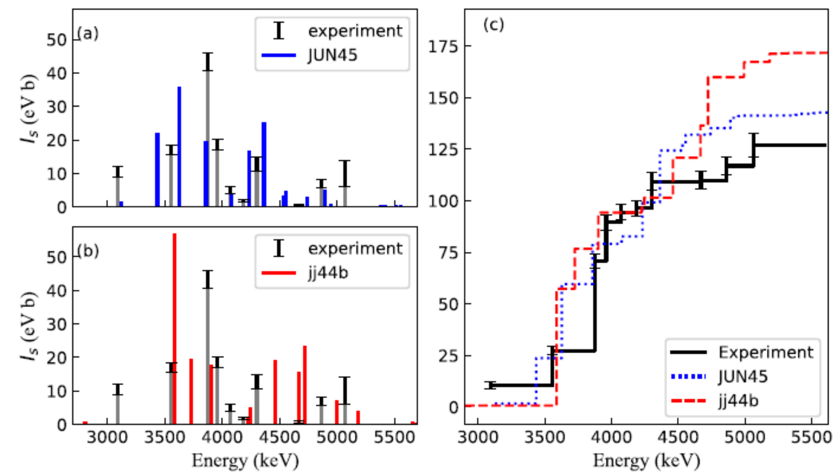
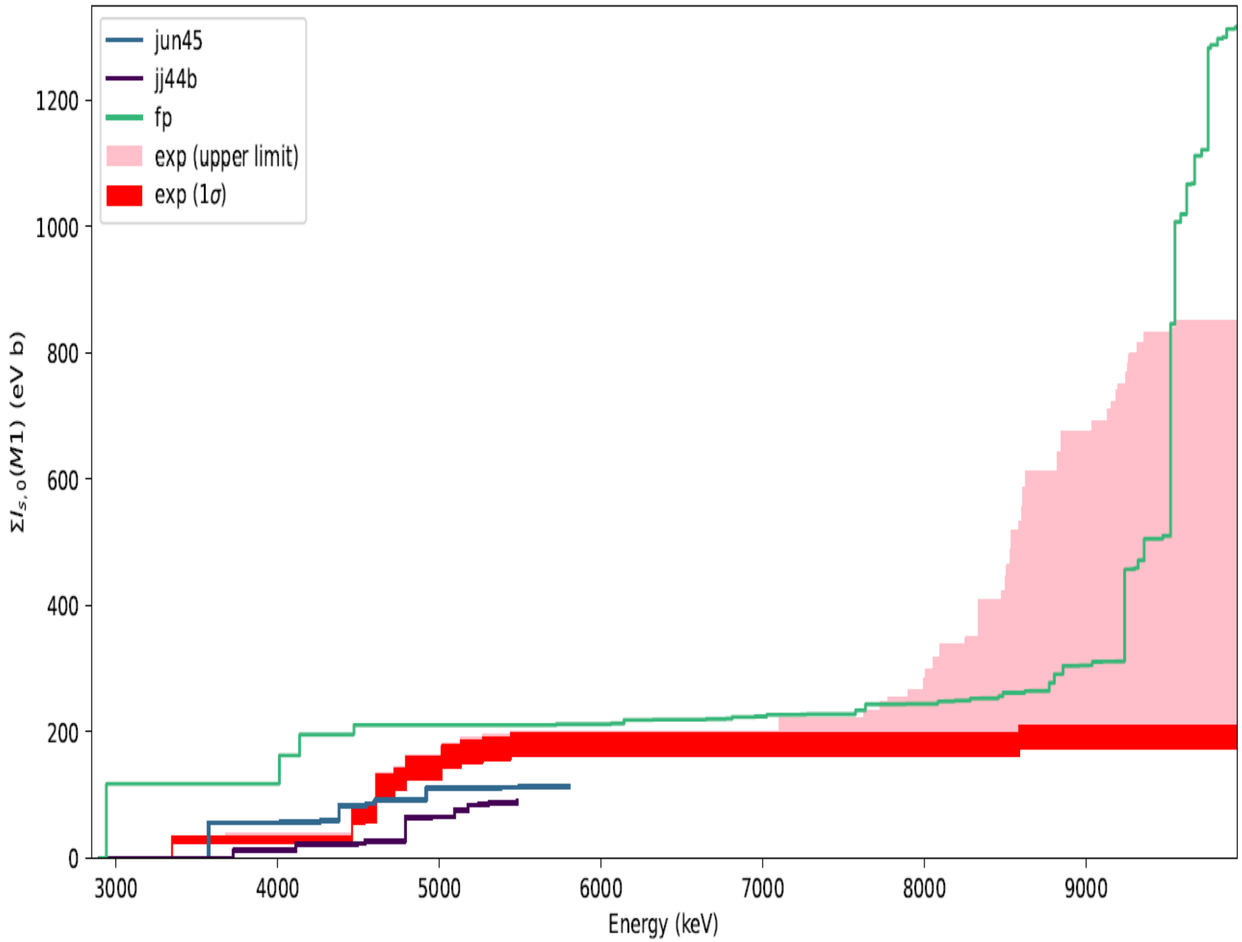


FIG. 5. Distribution of and cross-section values for experimental 1^+ states as compared to those calculated using (a) the JUN45 and (b) the jj44b interaction. (c) provides a running sum of the cross-section values.

Not such good news
the B(M1) strength also requires the 0f7 orbital
one needs the (0f7, 0f5, 1p3, 1p1, 0g9) model space

Results from (0f7, 0f5, 1p3, 1p1) model space



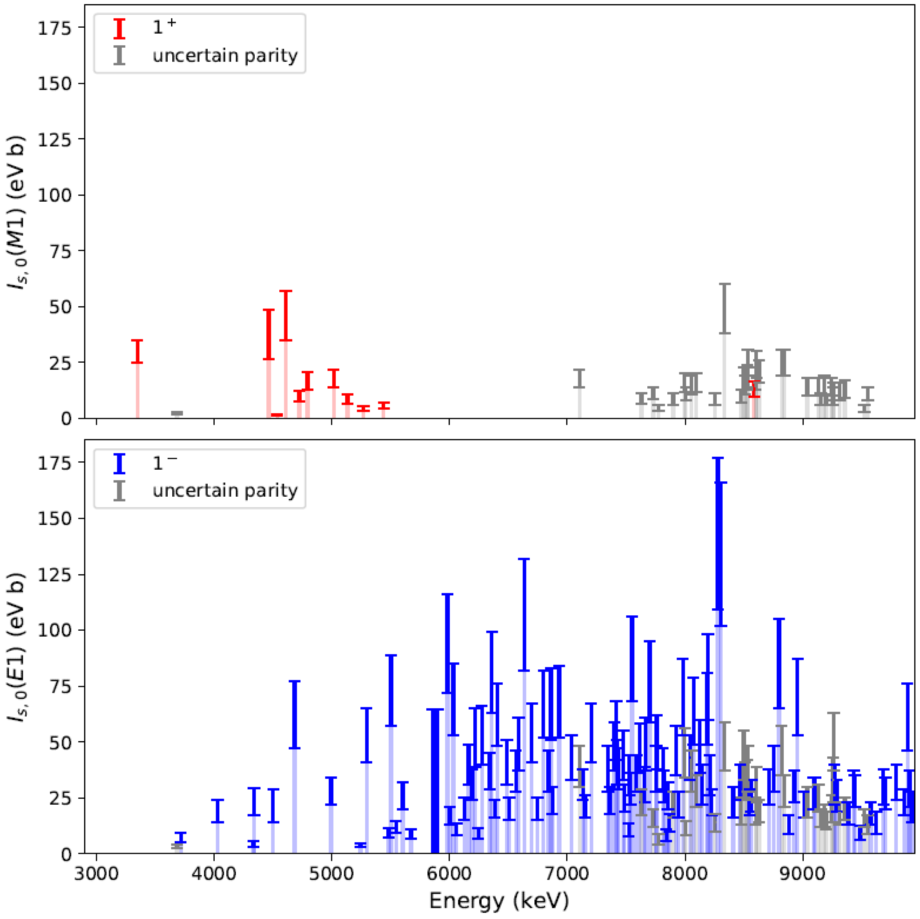
Bad news:

B(E1) = 0 in the jj44 (0f5, 1p3, 1p1, 0g9) model space

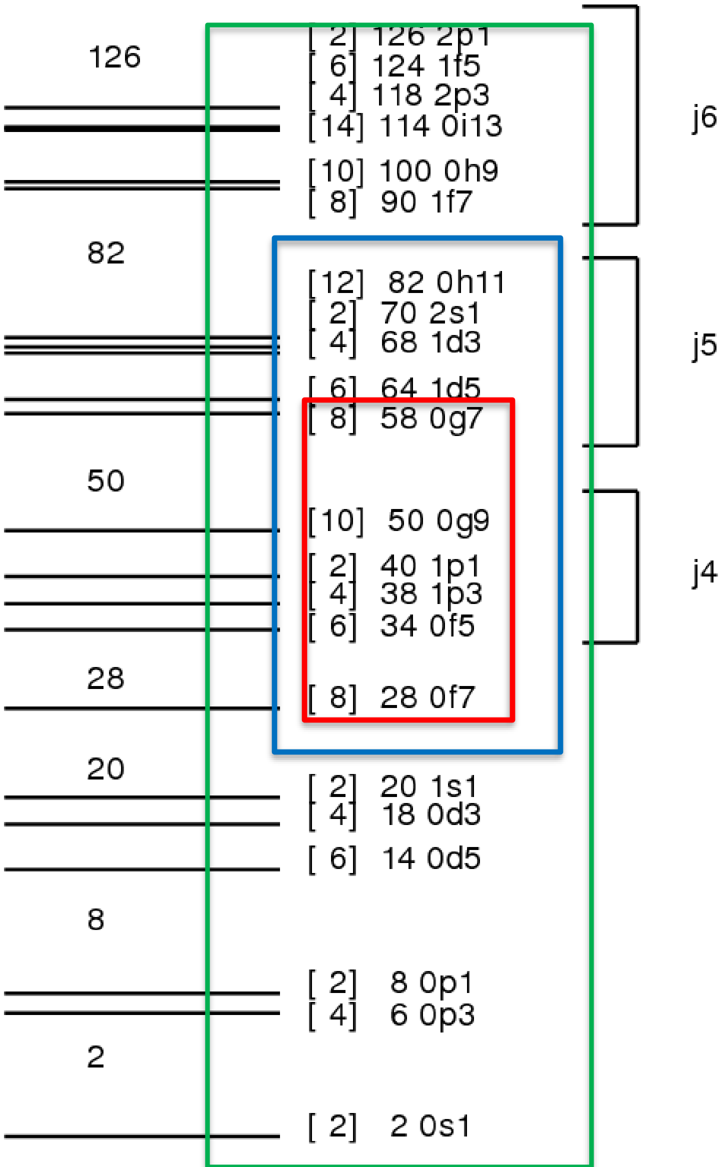
Good news:

B(E1) = 0 in the jj44 (0f5, 1p3, 1p1, 0g9) model space

Experimental B(E1) on the order of 0.0001 WU ??



Vertical vs Horizonal Shell Model Truncations



j4 – horizontal for low-lying collective states (with effective charge).

For full B(M1)

For full B(E1)

At higher energy we are interested in levels density and gamma strength functions

For complete E2 and deformation (no effective charge)

PHYSICAL REVIEW C **112**, 024302 (2025)

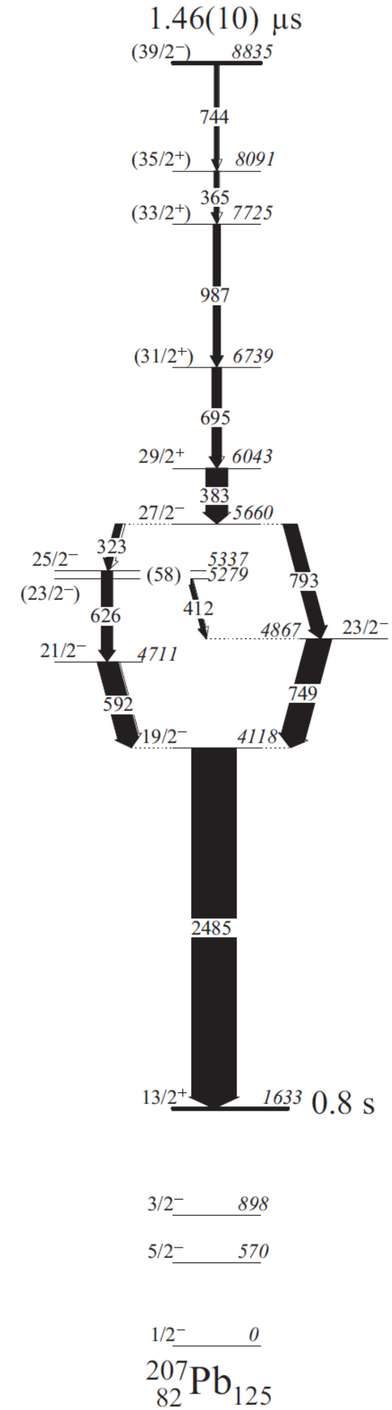
Core-excited microsecond isomer in ^{207}Pb

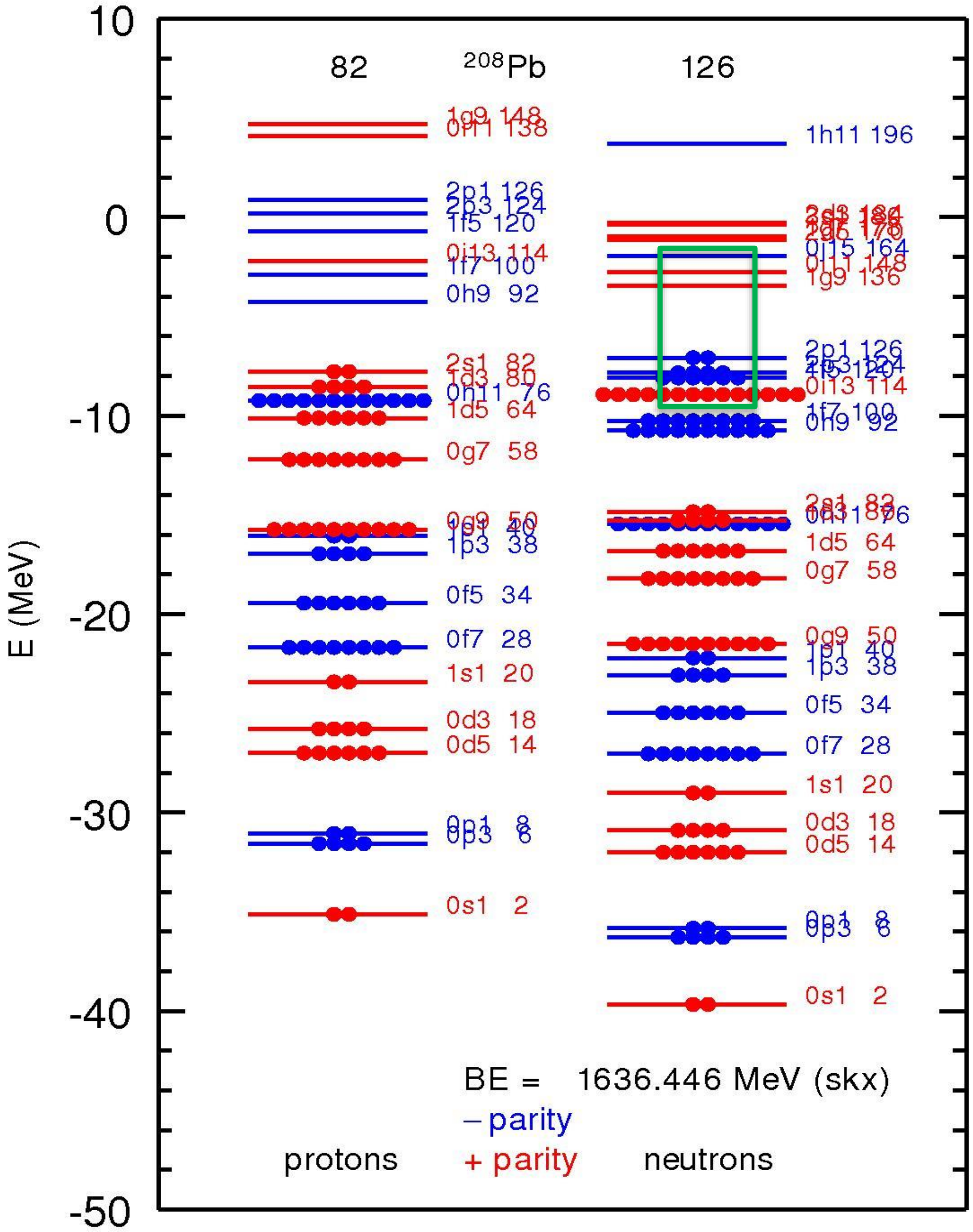
S. K. Tandel,[1,2,*] S. G. Wahid,[2] N. Krishnadev,[3] M. Hemalatha,[4] Subhrajit Sahoo,[5] P. C. S
R. V. F. Janssens,[6,7] F. G. Kondev,[8] M. P. Carpenter,[8] T. Lauritsen,[8] and D. S

TABLE III. Energies and spins of levels in ^{207}Pb from experiment and shell-model calculations (see text for details). The predicted probabilities for the main component of the configuration are listed for each state.

I_i^π	Configuration	Probability (%)	E_{expt} (keV)	E_{SM} (keV)
$21/2^-$	$\nu(i_{13/2}^{-1}, p_{1/2}^{-1}, g_{9/2}^{1})$	61.4	4711	4687
$23/2_1^-$	$\nu(i_{13/2}^{-1}, p_{1/2}^{-1}, g_{9/2}^{1})$	69.2	4867	4840
$23/2_2^-$	$\nu(i_{13/2}^{-1}, f_{5/2}^{-1}, g_{9/2}^{1})$	30.1	5279	5196
$25/2^-$	$\nu(i_{13/2}^{-1}, f_{5/2}^{-1}, g_{9/2}^{1})$	68.9	5337	5258
$27/2^-$	$\nu(i_{13/2}^{-1}, f_{5/2}^{-1}, g_{9/2}^{1})$	93.7	5660	5488
$29/2^+$	$\nu(i_{13/2}^{-1}, p_{1/2}^{-1}, j_{15/2}^{1})$	73.4	6043	6299
$31/2^+$	$\nu(i_{13/2}^{-1}, f_{5/2}^{-1}, j_{15/2}^{1})$	78.6	6739	6618
$33/2^+$	$\nu(i_{13/2}^{-2}, g_{9/2}^{1})$	73.6	7725	6821
$35/2^+$	$\nu(i_{13/2}^{-2}, i_{11/2}^{1})$	91.8	8091	7326
$39/2^-$	$\nu(i_{13/2}^{-2}, j_{15/2}^{1})$	90.4	8835	8255

E. K. Warburton and B. A. Brown, Phys. Rev. C **43**, 602 (1991).





$0j_{15/2}$

$0i_{13/2}$

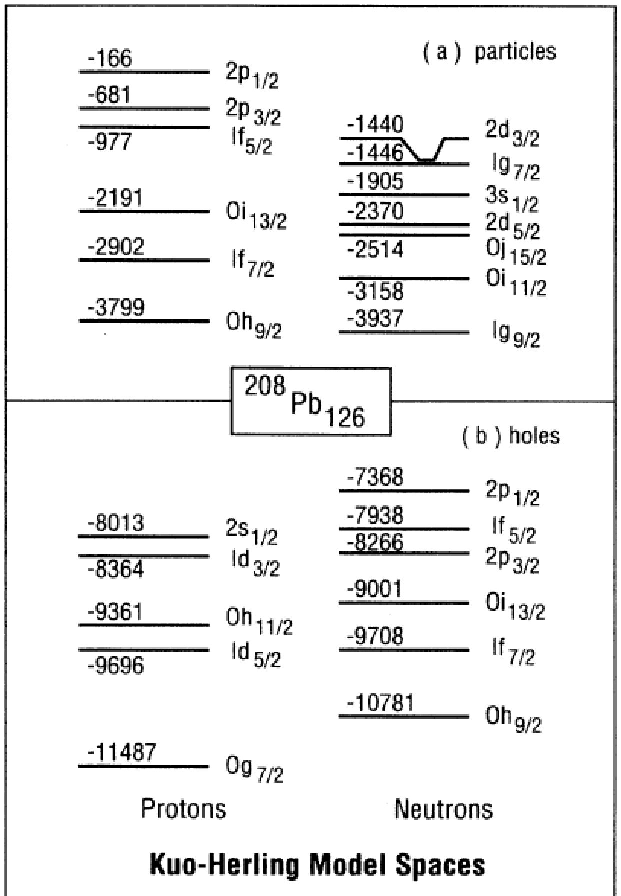
The observed states in ^{207}Pb involve neutron particle-hole excitations within the green box.

PHYSICAL REVIEW C VOLUME 43, NUMBER 2 FEBRUARY 1991

Appraisal of the Kuo-Herling shell-model interaction and application to A=210–212 nuclei

E. K. Warburton
Brookhaven National Laboratory, Upton, New York 11973

B. A. Brown
Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824



These SPE provide about 80% of the spectra of excited states.

For ^{208}Pb they are known from exp. Theory (EDF or ab-iinitio) cannot do better than about 1 MeV.
Next 50 years?

The Kuo-Herrling interaction from the 1970's is old but good enough (when combined with exp SPE) to predict energies within about 100 keV.

MAJOR REPORT • OPEN ACCESS

Motivations for early high-profile FRIB experiments

B Alex Brown, Alexandra Gade, S Ragnar Stroberg, Jutta E Escher, Kevin Fossez, Pablo Giuliani, Calem R Hoffman, Witold Nazarewicz, Chien-Yeah Seng, Agnieszka Sorensen ▾ Show full author list

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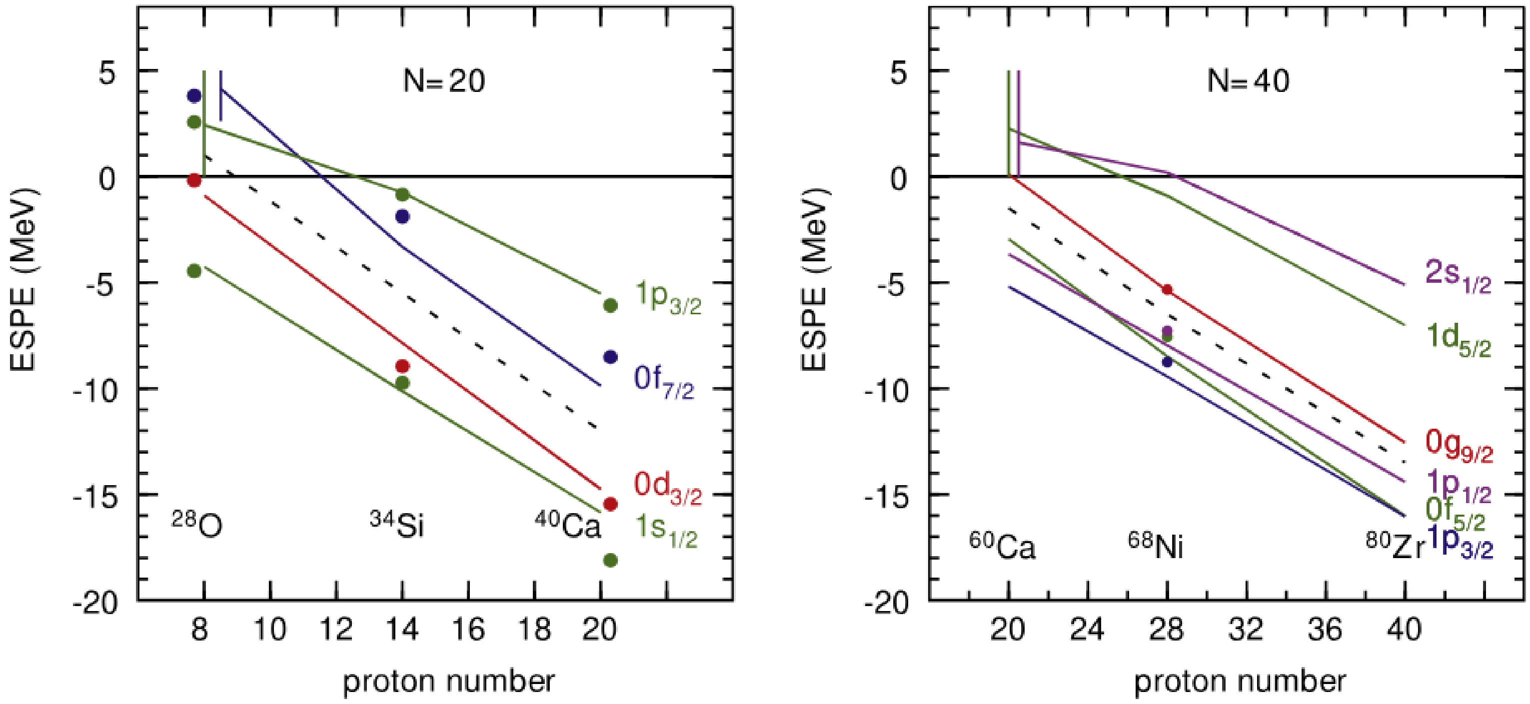
Journal of Physics G: Nuclear and Particle Physics, Volume 52, Number 5

Citation B Alex Brown *et al* 2025 *J. Phys. G: Nucl. Part. Phys.* **52** 050501

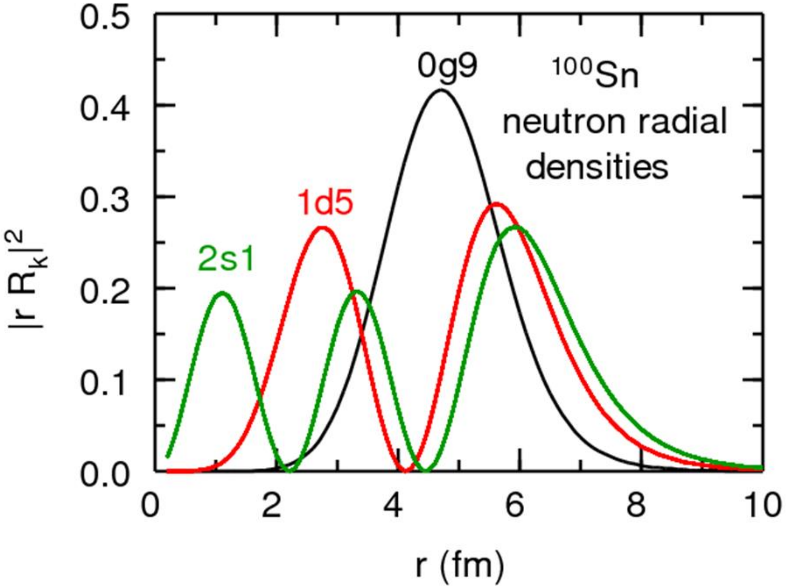
DOI 10.1088/1361-6471/adb449

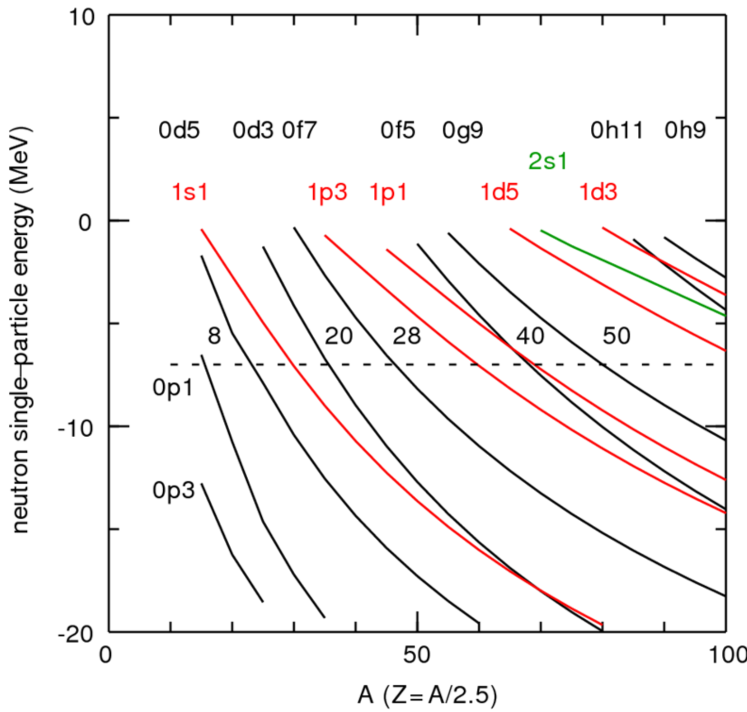


Lines are from Skx Energy Density Functional

N=20 points are the ESPE from the FSU Hamiltonian

Why do the single-particle energy (SPE) gaps change?



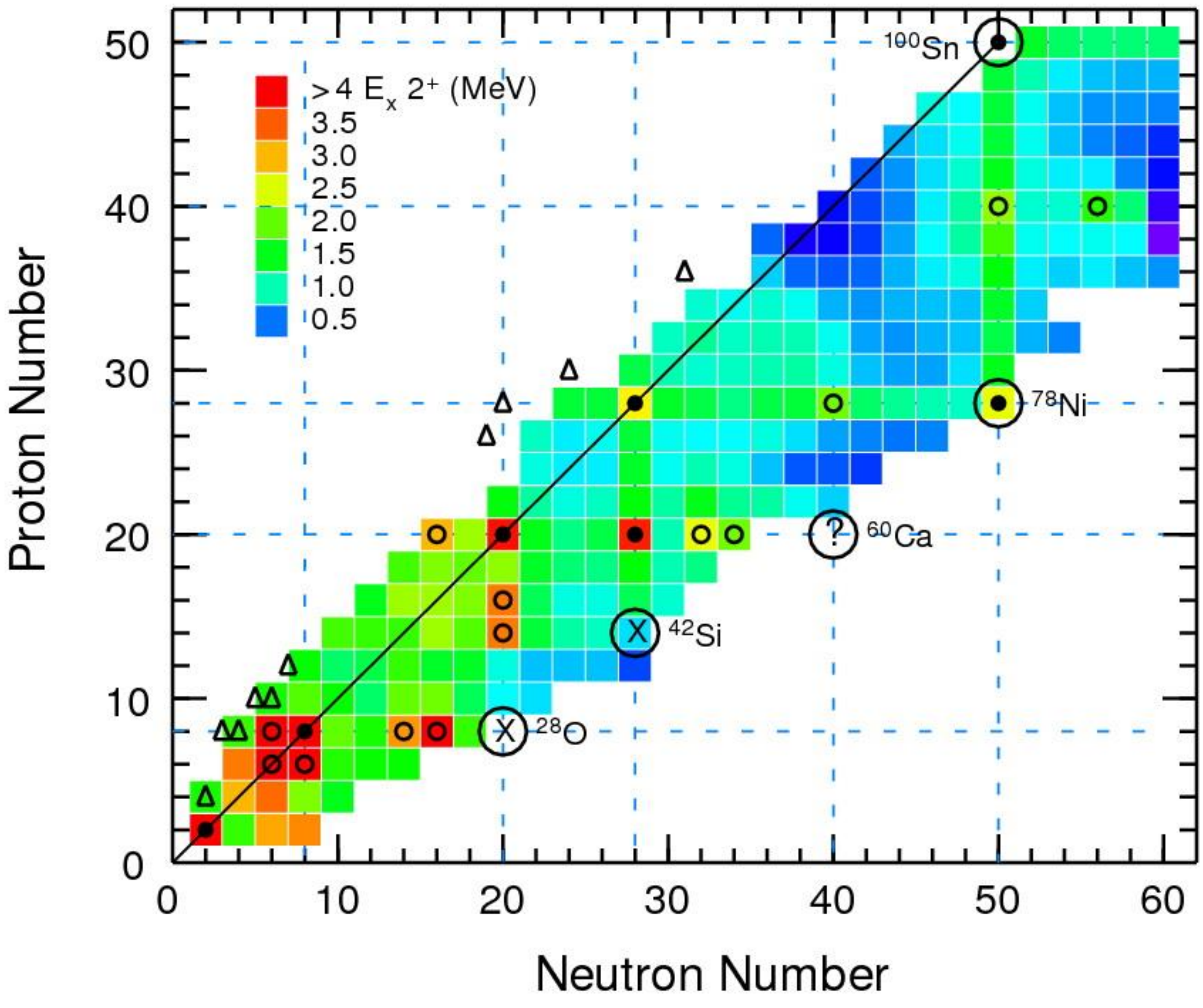


Neutron-drip line

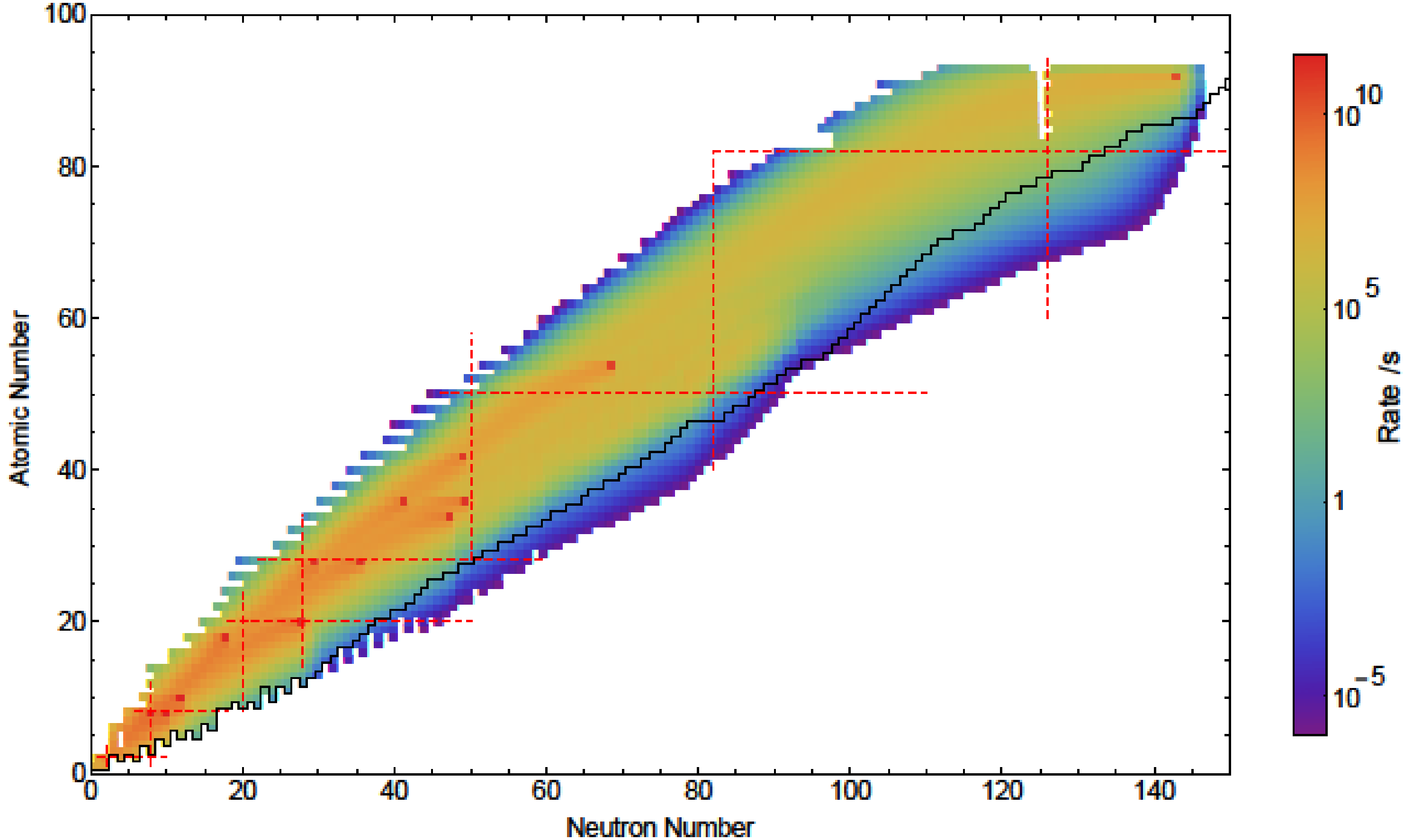
Near stability

As one decreases the SPE in a potential well
All SPE with n=1 bend down compared to those with n=0
the SPE with n=2 ($2s_{1/2}$) bends down even more
The $1s_{1/2}$, $2s_{1/2}$ … (s-states) become extended - halos (no centrifugal barrier)

Nuclear Structure from JPG paper



FRIB 2024: 10 kW → 400 kW



Picture will be about the same, but the rate/s scale will increase a factor of 40
With FRIB, other facilities and their additions we will have the experimental capabilities over the next 50 years.

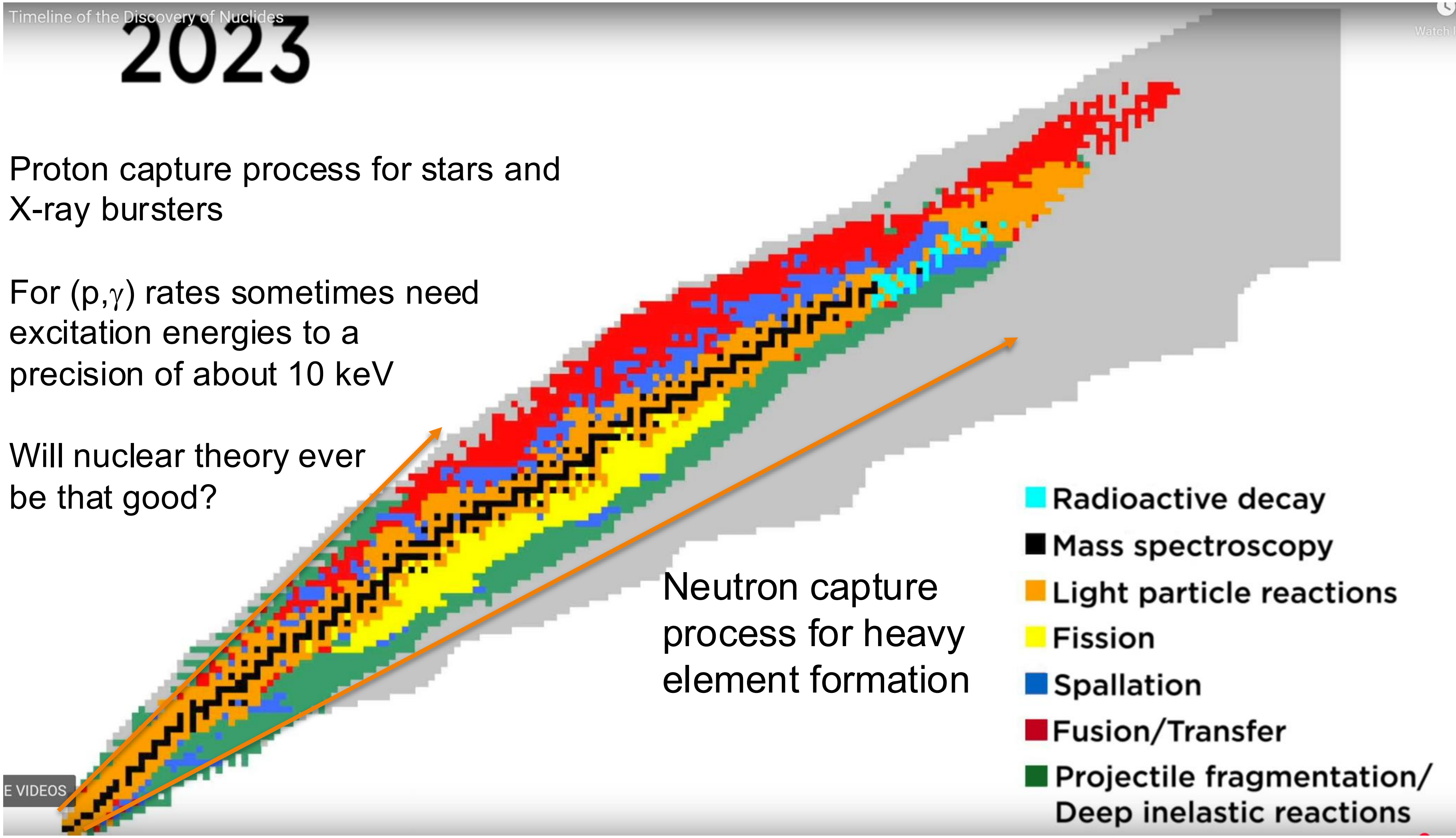
Nuclear Astrophysics

Proton capture process for stars and X-ray bursters

For (p,γ) rates sometimes need excitation energies to a precision of about 10 keV

Will nuclear theory ever be that good?

Neutron capture process for heavy element formation



100 + 50 years

Over the past 100 years - experiment and theory have been intertwined

Designed and built facilities with for new ways of making nuclei.
Designed and built detectors for “seeing” what nuclei are like.
Found connections between nuclear properties and nuclear astrophysics.
Applied top-down implications of quantum mechanics for understanding what we see.
Understood the bottom-up connections with nucleons and particle physics.
Made use of the exponential increase in computation.

Over the next 50 years - experiment and theory will be intertwined

FRIB and other facilities will be used, and they will be upgraded and changed.
New experimental detectors will be designed and used.
Top-down and bottom-up theory understandings will be merged.
Computational and AI advances will be used in ways that we cannot imagine.

Thank you, Robert, for your immense contributions to bring us to this point.