What can transitions in atomic nuclei teach us?

Martin Venhart

Vice-President of Slovak Academy of Sciences

President-elect

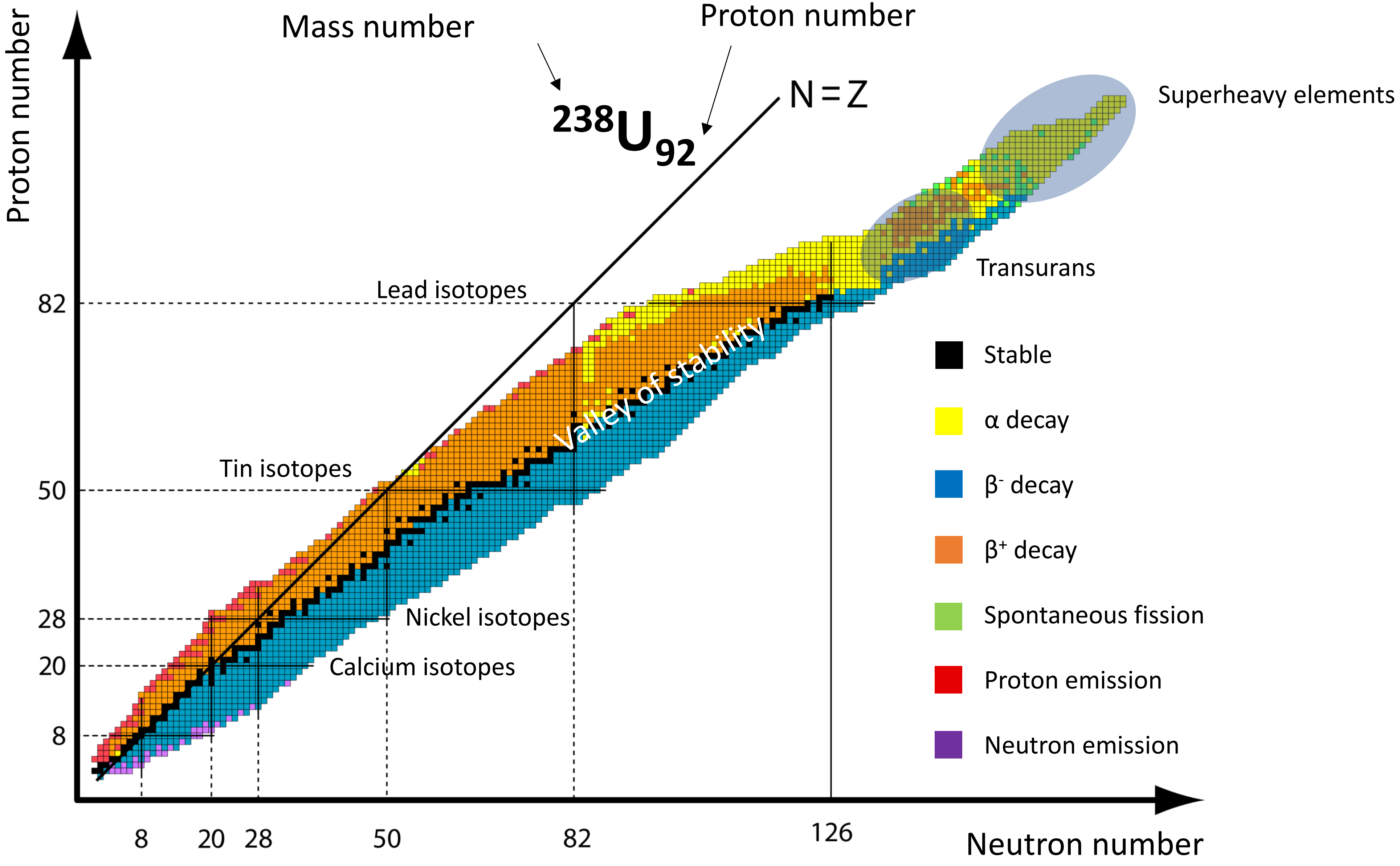
History of studies of atomic nuclei

- Discovery of radioactivity: 1896 by Henri Becquerel
- Discovery of electron: 1897 by J. J. Thomson
- Discovery of radium and polonium 1898 by Maria et Pierre Curie
- Radium committee in Manchester – search for applications of radium
- Discovery of atomic nucleus: 1911 by Ernest Rutherford – gold foil experiment
- Discovery of proton: 1925 by Ernest Rutherford
- Discovery of neutron: 1932 by James Chadwick
- Discovery of deuterium: 1932 by Harold D. Urey
- Discovery of transmutation of elements and artificial radioactivity: 1933 Irene et Frank Joliot-Curie

Periodic table – excellent for chemistry, but insufficient for nuclei

1 H Vodík																	2 He Hélium
3 Li Lítium	4 Be Berýlium											5 B Bór	6 C Uhlík	7 N Dusík	8 O Kyslík	9 F Fluór	10 Ne Neón
11 Na Sodík	12 Mg Horčík											13 Al Hliník	14 Si Kremík	15 P Fosfor	16 S Síra	17 Cl Chlór	18 Ar Argón
19 K Draslík	20 Ca Vápnik	21 Sc Skandium	22 Ti Titán	23 V Vanád	24 Cr Chróm	25 Mn Mangán	26 Fe Železo	27 Co Kobalt	28 Ni Nikel	29 Cu Meď	30 Zn Zinok	31 Ga Gálium	32 Ge Germánium	33 As Arzén	34 Se Selén	35 Br Bróm	36 Kr Kryptón
37 Rb Rubídium	38 Sr Stroncium	39 Y Ytrium	40 Zr Zirkón	41 Nb Niób	42 Mo Molybdén	43 Tc Technécium	44 Ru Ruténium	45 Rh Ródium	46 Pd Paládium	47 Ag Striebro	48 Cd Kadmium	49 In Indium	50 Sn Cín	51 Sb Antimón	52 Te Telúr	53 I Jód	54 Xe Xenón
55 Cs Cézium	56 Ba Bárium	57 La Lantán	72 Hf Hafnium	73 Ta Tantal	74 W Volfrám	75 Re Rénium	76 Os Osmium	77 Ir Irídium	78 Pt Platina	79 Au Zlato	80 Hg Ortuť	81 Tl Tálium	82 Pb Olovo	83 Bi Bizmut	84 Po Polónium	85 At Astát	86 Rn Radón
87 Fr Francium	88 Ra Rádium	89 Ac Aktínium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hásium	109 Mt Meitnérium	110 Ds Darmštátium	111 Rg Röntgénium	112 Cn Kopernícium	113 Nh Nihónium	114 Fl Fleróvium	115 Mc Moskóvium	116 Lv Livermórium	117 Ts Tenés	118 Og Oganesón
			58 Ce Cér	59 Pr Prazeodým	60 Nd Neodým	61 Pm Prométium	62 Sm Samárium	63 Eu Európium	64 Gd Gadolínium	65 Tb Terbium	66 Dy Dysprózium	67 Ho Holmium	68 Er Erbium	69 Tm Túlium	70 Yb Yterbium	71 Lu Lutécium	
			90 Th Tórium	91 Pa Protaktínium	92 U Urán	93 Np Neptúnium	94 Pu Plutónium	95 Am Américium	96 Cm Curium	97 Bk Berkélium	98 Cf Kalifornium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobélium	103 Lr Lawrencium	

Table of isotopes



Origin of isotopes

1. Primordial nucleosynthesis at and soon after Big Bang (0 – 20 minutes): **H, He, Li (small fraction)**
2. Stellar nucleosynthesis (various processes): **C – Bi**
3. Supernovae and neutron-star collisions: **neutron rich stable isotopes, U, Th**
4. Nuclear decay (natural decay chains of U, Th): **Pa, Ac, Ra, Fr, Rn, At, Po**
5. Interactions of cosmic radiation in interstellar space: **Li, Be, B**
6. Man-made elements – some of them are known to exist in the Universe: **Tc, Pm, Z > 92**

Understanding of isotopes is to important to understand our origin!

Youtube: "Ako vznikli chemické prvky vo vesmíre"

Application of isotopes

- Energy production:
  - Fission reactors (very imporant for Slovakia)
  - Nuclear fusion in the future (Fusion reactor under construction in Cadarache, France)

  - **NUCLEAR POWER IS GREEN POWER**
  - **Will be extremely important in reducing carbon dioxide**

- Nuclear medicine:
  - Approximately 30 000 000 patients annually undergo diagnosis procedure using ^{99}Tc isotope
  - Therapy of tumors using various isotopes: astatine or actinium in the future (recent article in Scientific Reports)
  - Positron-emission tomography, Nature article: PET based on quantum entanglement

- Applications in different research:
  - E.g. Stable isotopes in archeology: not only dating, but also location of area of origin of artefacts (stable strontium isotopes)
  - Radiocarbon dating, argon dating in geology
  - National security applications: ^{18}O

Atomic nuclei today

- Presently: approximately 3500 isotopes are known, 118 elements (hydrogen – oganesson)
- Approximately 250 isotopes are stable
- Stable or long-lived?
- E.g. ^{209}Bi, $T_{1/2} = 2 \times 10^{19}$ years (9 orders of magnitude longer than age of the Universe)
- Elements without stable isotopes: Tc (Z = 43), Pm (Z = 61) and all above Z = 82
- Structure of atomic nuclei can be addressed via their excited states
- Aproximately 176 000 excited states are known

Characteristics of excited states

- **Excitation energy:**
  - Relatively easy to measure (nowadays)

  - 2 excited states below 1 keV: ^{229}Th (8.9 eV) and ^{235}U (76 eV)
  - Most of excitations: hundreds of keV
  - Highest known excitations: few tens of MeV

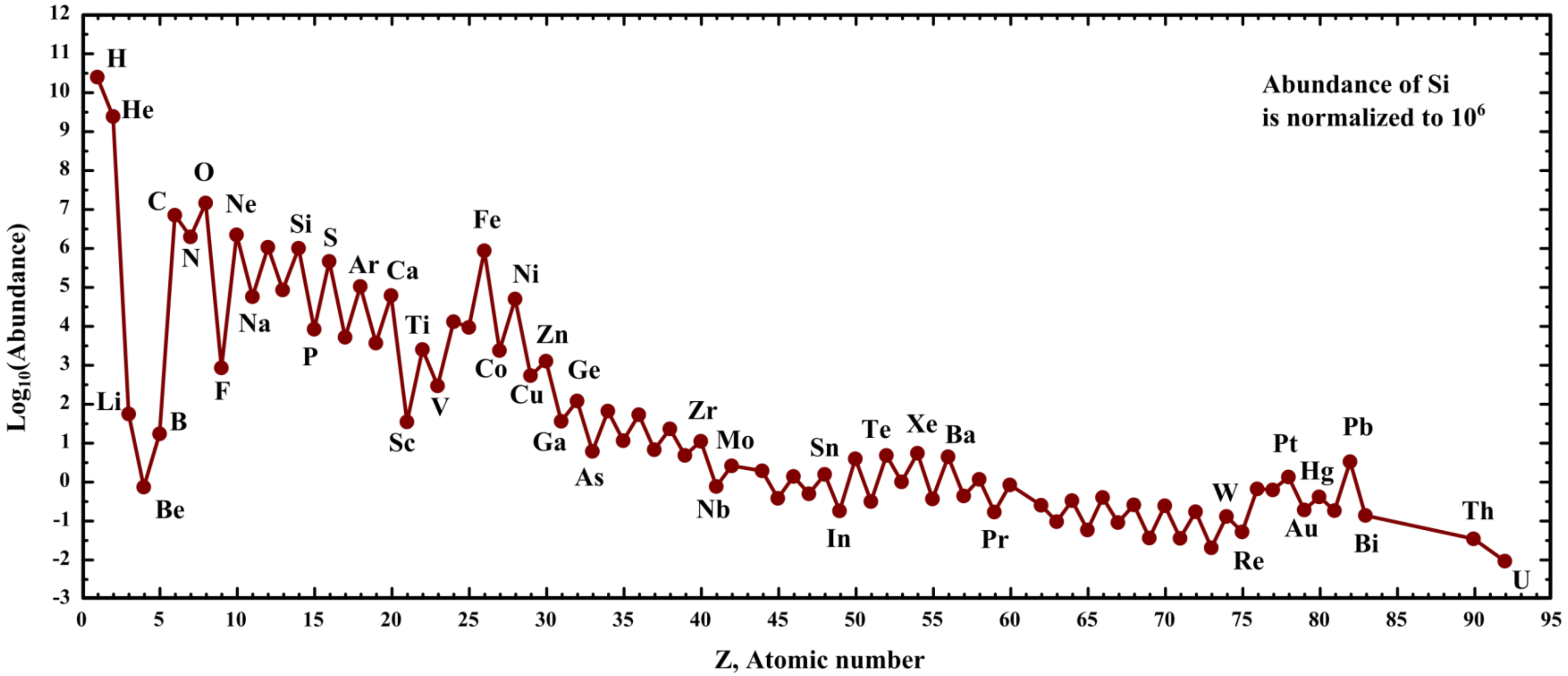
- **Lifetime:**
  - Tens of femtoseconds – 10^{15} years:
    - ^{180}Ta, very rare isotope, the only that exists on Earth in excited state
    - 1 cubic cm of pure tantalum metal stores about 75 kJ of energy

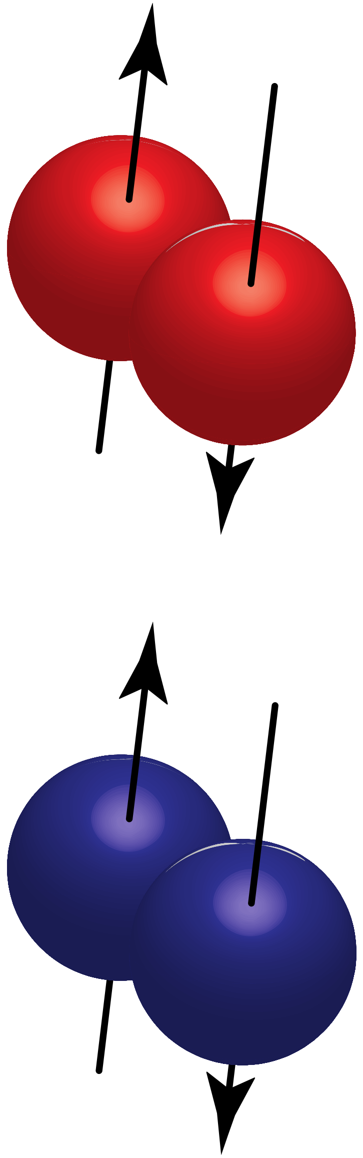
- **De-excitation modes:**
  - Most common: emission of gamma rays
  - Higher-order processes: internal conversion, internal pair creation, two-photon emission...
  - Radioactive processes: emission of particles or clusters
  - Spontaneous fission

- **Spin-parity of the wave function**

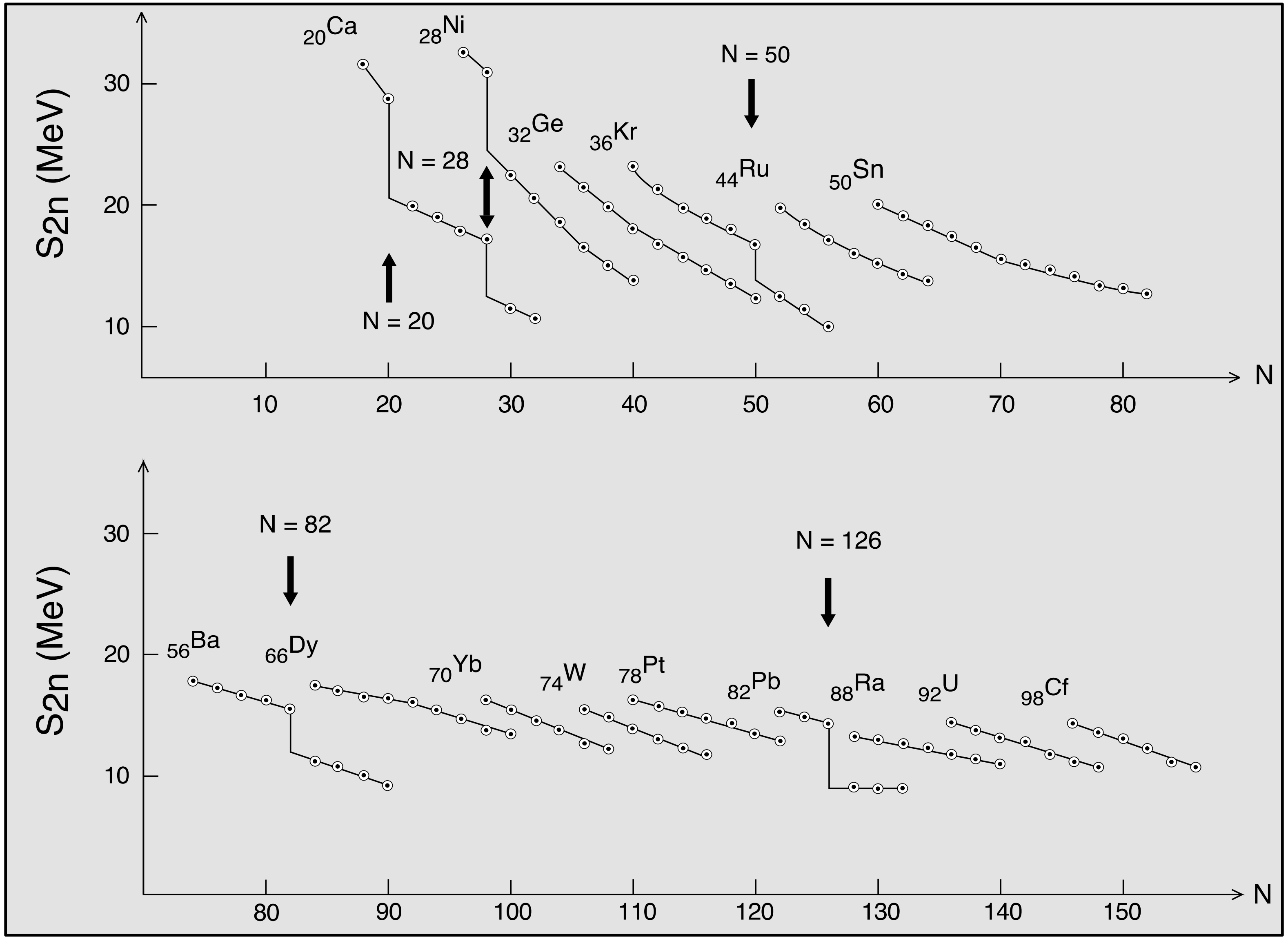
Pairing in nuclei

- Proton-proton, neutron-neutron pairs are formed
- Even-even nuclei have the 0^+ ground state
- Odd-odd nuclei are rarely stable
- Even-Z elements are more abundant in the Universe and have typically more stable isotopes



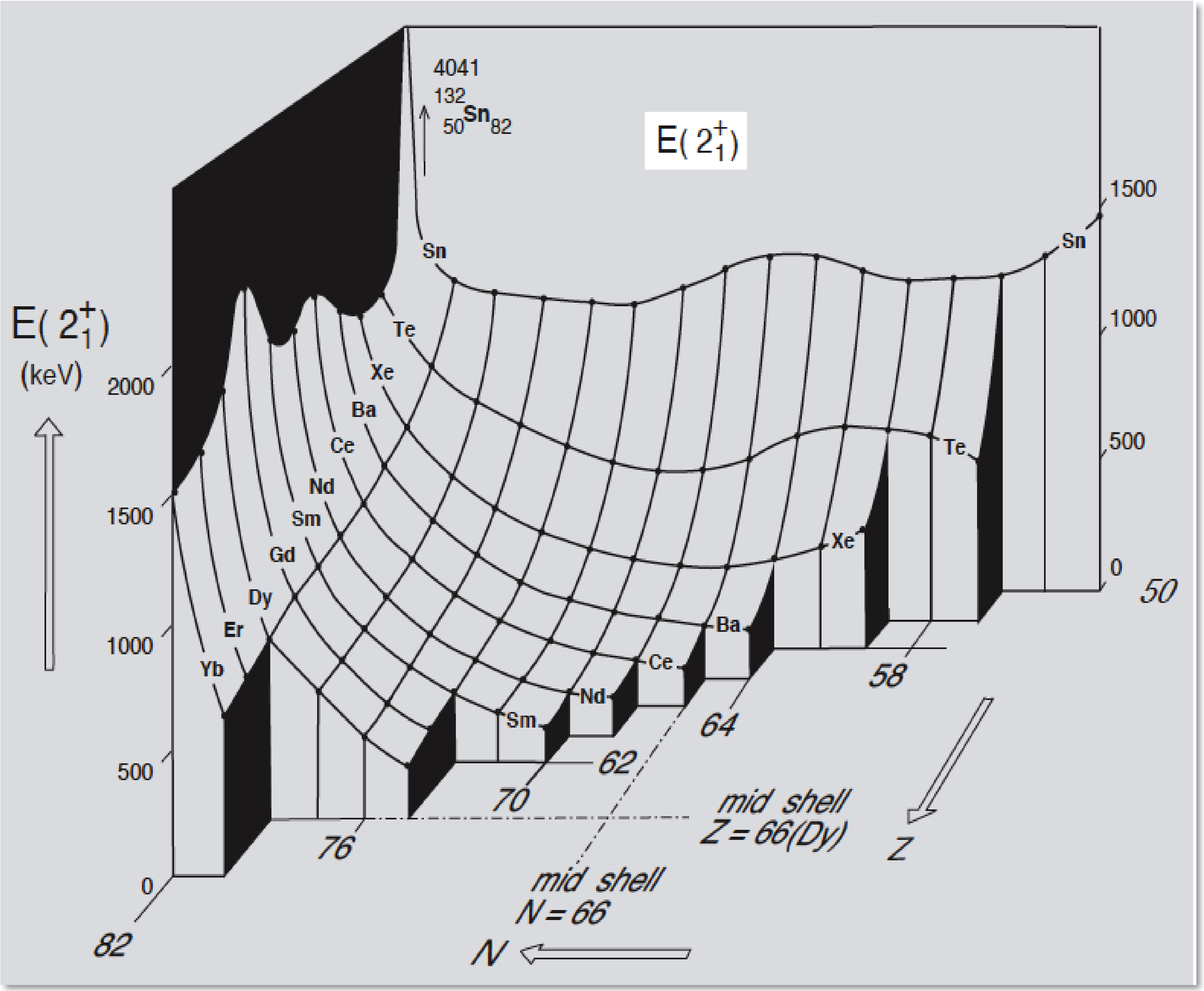


Differences in binding energies reveal nuclear structure



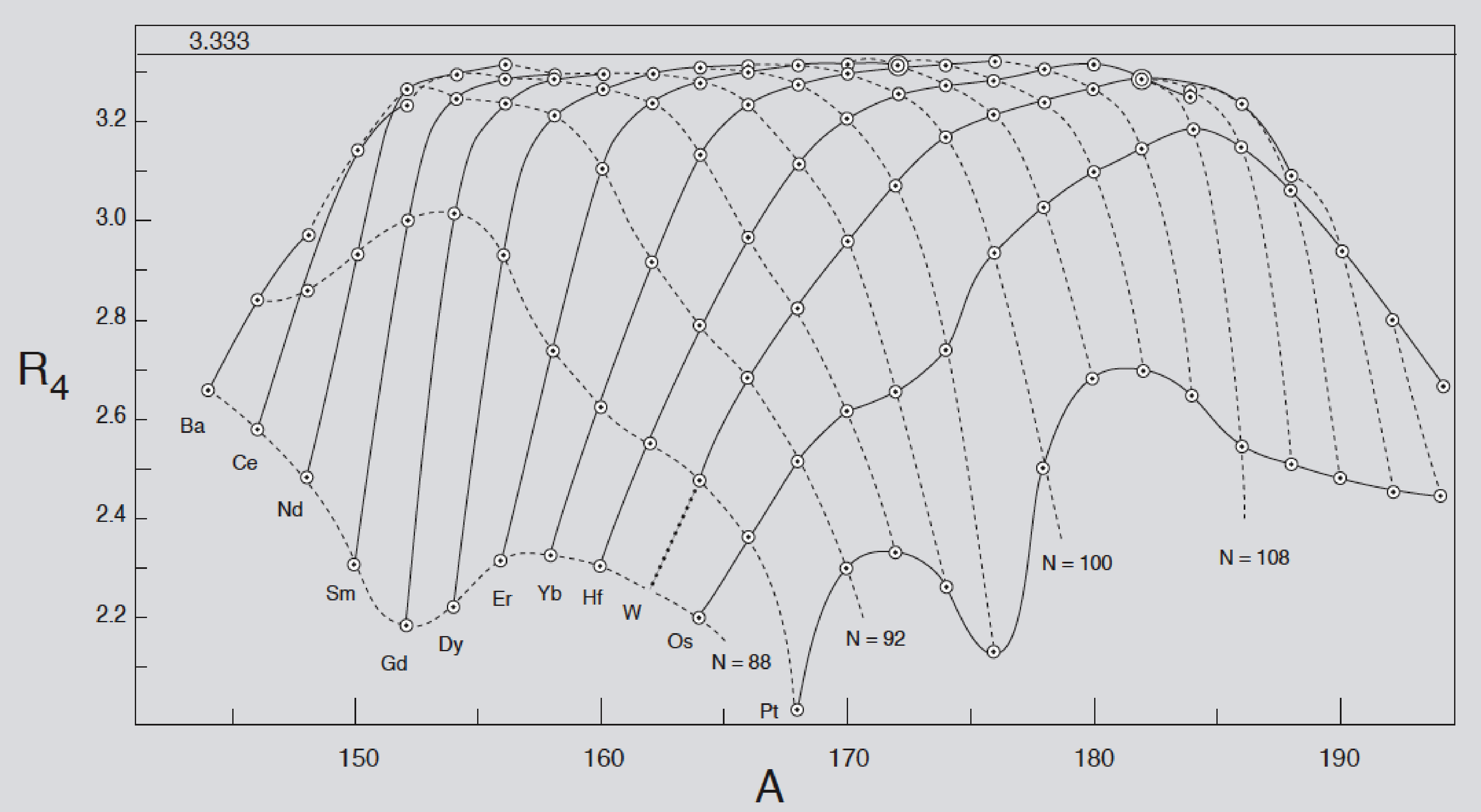
- Magic numbers: 2, 8, 20, 28, 50, 82, 126
- Analogues of noble gases in chemistry
- Magic nuclei are more stable
- Doubly-magic nuclei: magic number of both protons and neutrons

What excited states can tell us?

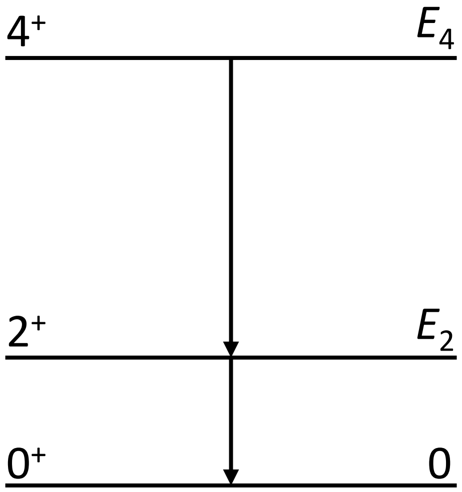


- energy of 2^{+} state in even-even nuclei
- Relatively easy to measure

What excited states can tell us?



- Energy ratio between first 2^+ and 4^+ states
- Also easy to measure

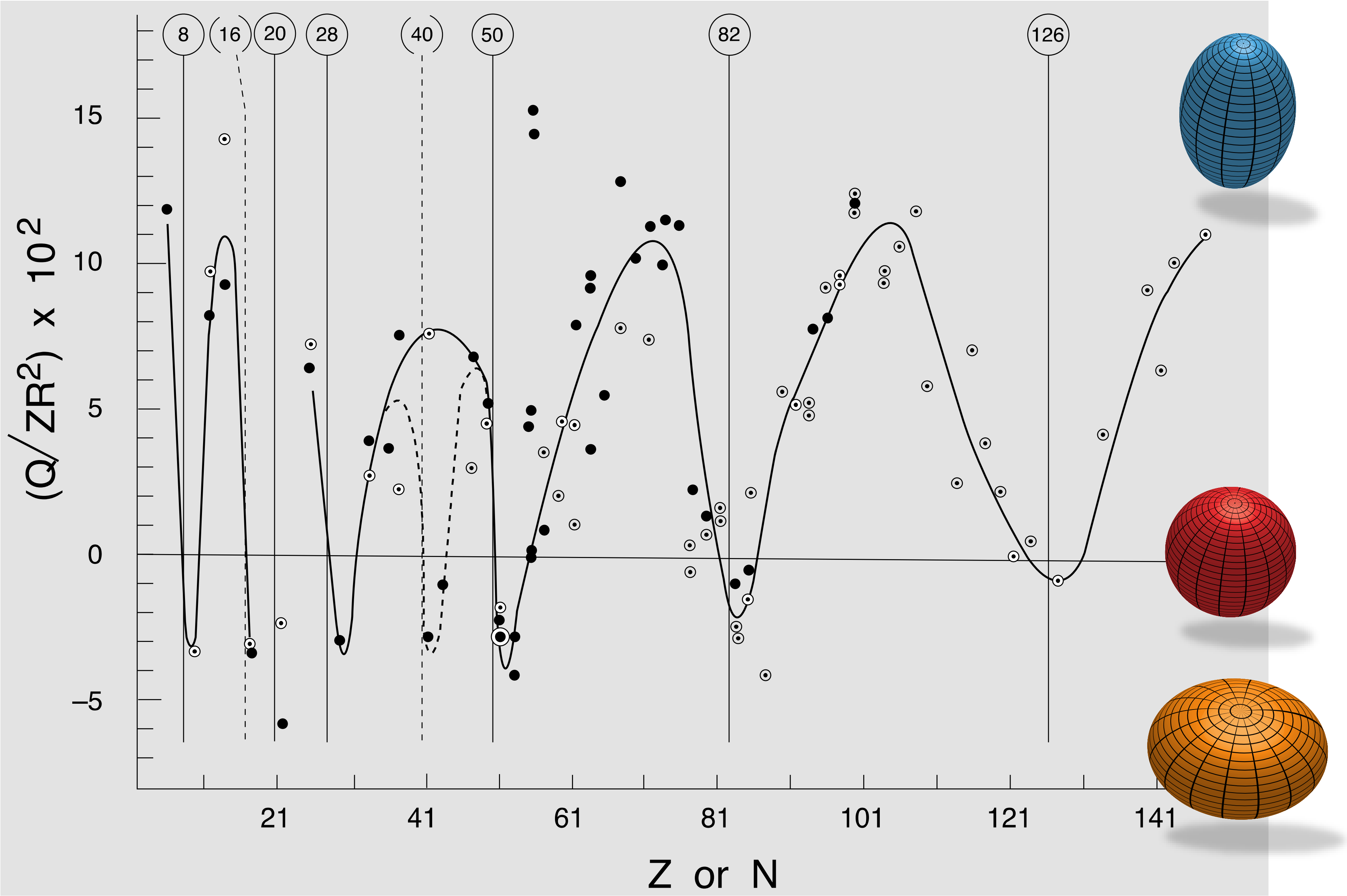


$$R_4 = \frac{E_4}{E_2}$$

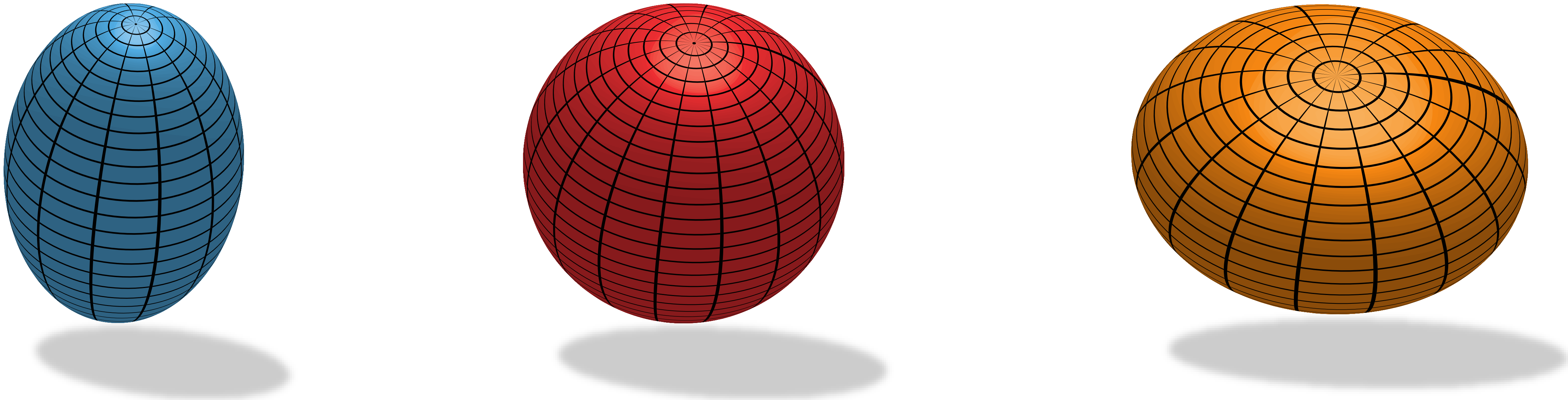
Rotational limit: 3.333

Nuclei have rotational bands. Are they deformed?

Nuclei are deformed

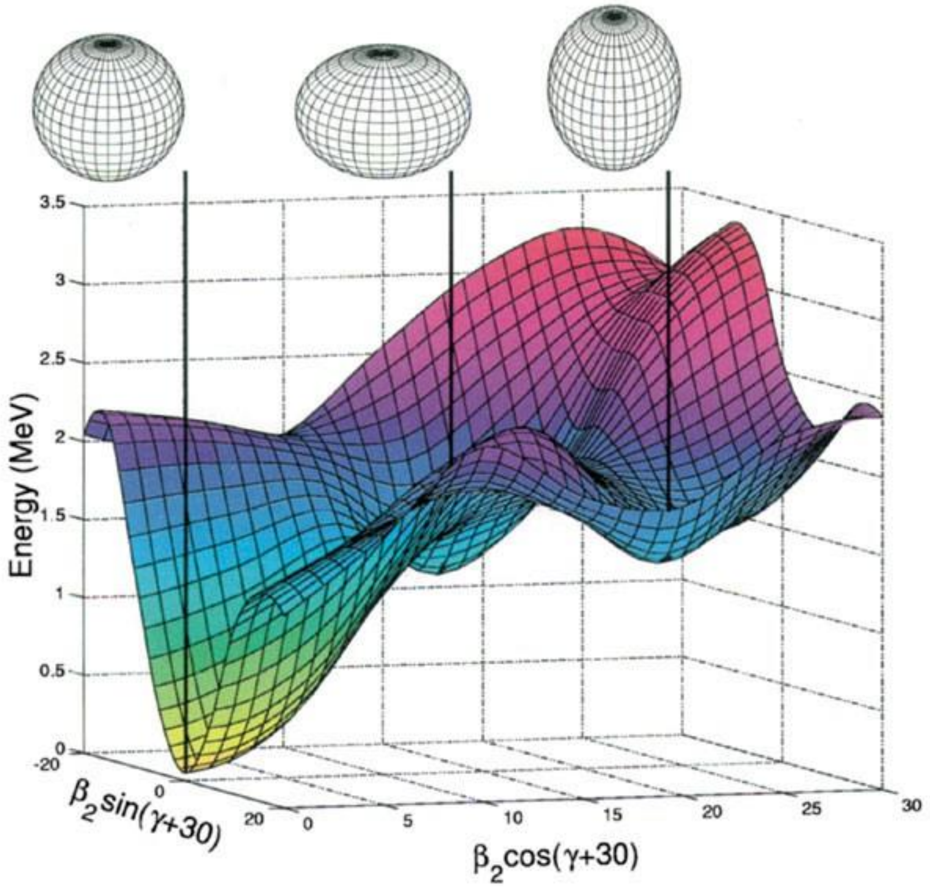


Known fact: Atomic nuclei are not spherical

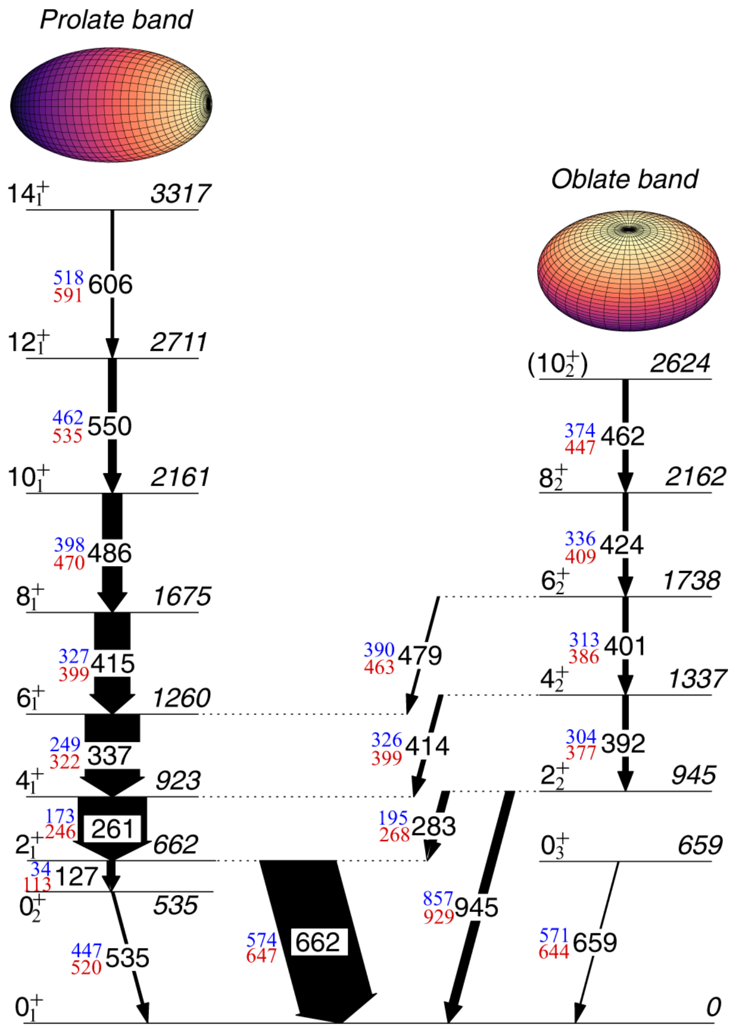


- **Atomic nuclei are naturally deformed**
- **Multiple shapes occur in a single nucleus**

Multiple shapes in atomic nuclei



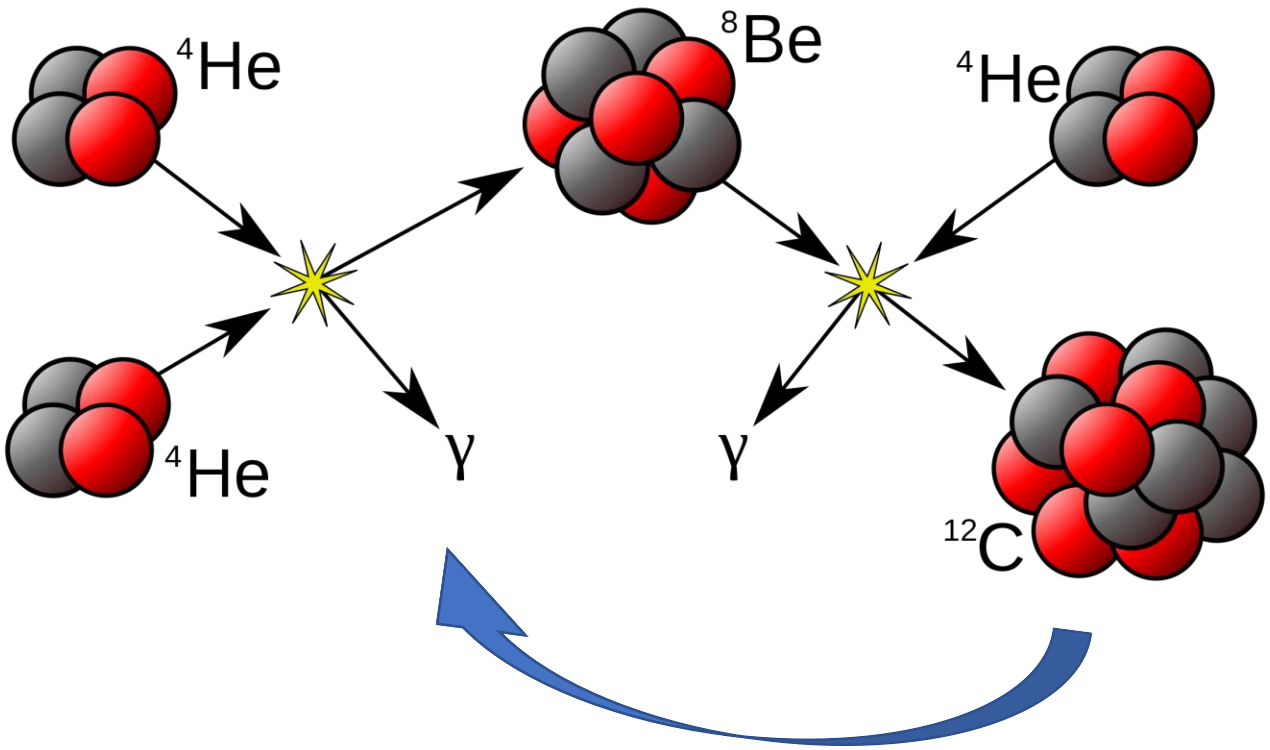
A. N. Andreyev et al., Nature **405**, 430 (2000).



J. Ojala *et al.*, Communications Physics **5**, 213 (2022).

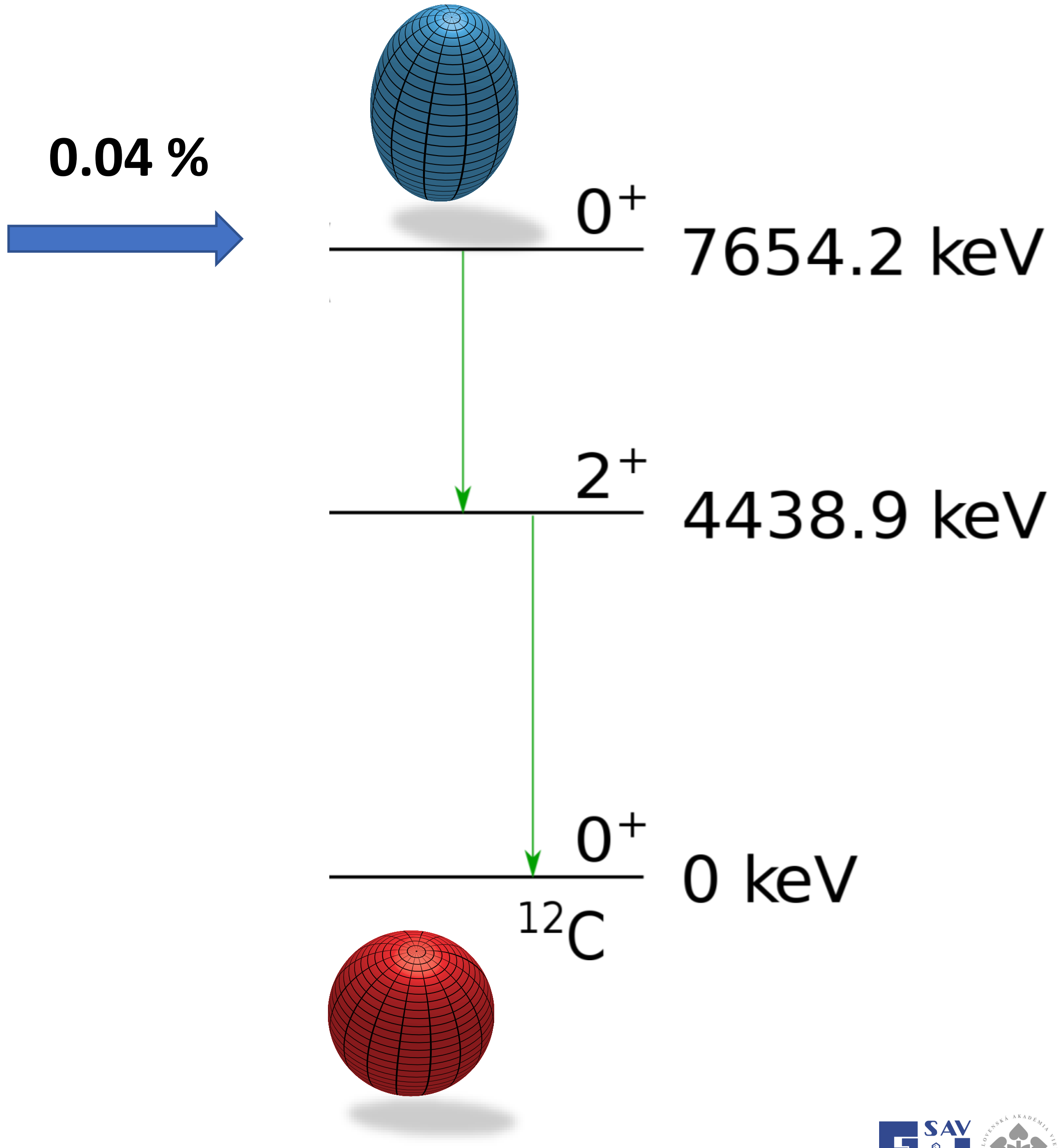
Illustrative Example of multiple shapes: Hoyle state in ^{12}C

6.7 x 10^{-17} s



Back decay: 99.96 % cases

0.04 %



Fundamental relevance *of multiple shapes:*
^{12}C for **stellar nucleosynthesis**

Open questions related to multiple shapes in atomic nuclei

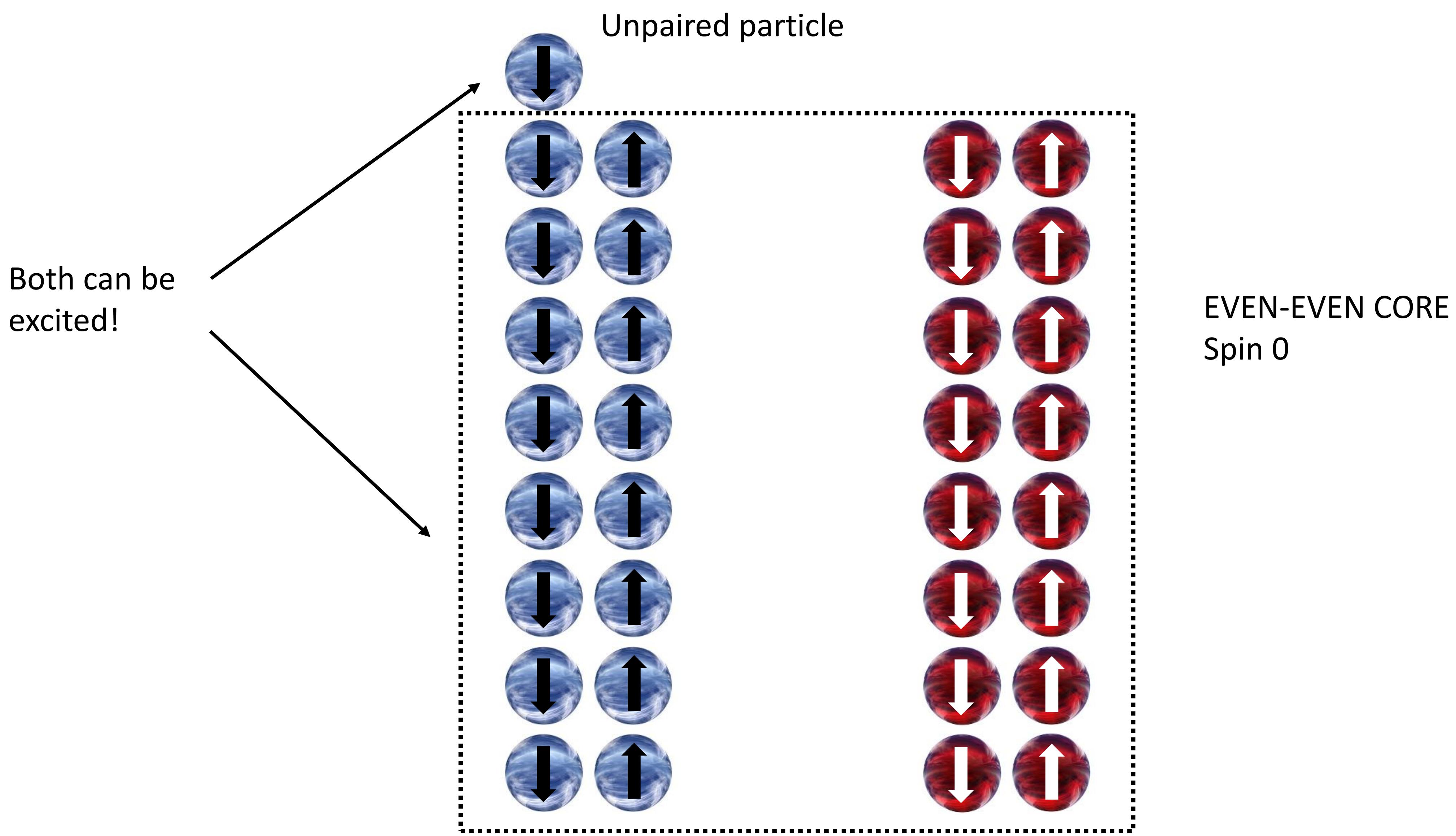
1. How many shapes can occur in a single nucleus?

2. What is evolution of shape parameters with changing proton and neutron number?

3. What physics mechanism is beyond the occurrence of nuclear deformation in general?

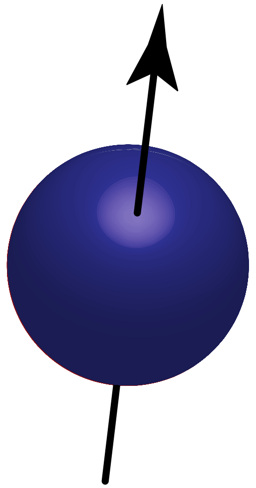
My vision: To use neutron-deficient odd-mass Au isotopes as a laboratory to address the above questions

What is odd-mass nucleus?



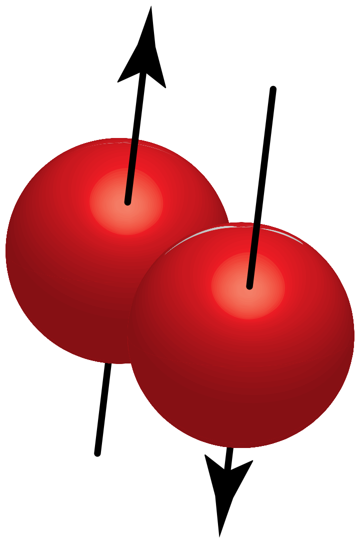
Why odd-mass Au (Z – 79) isotopes?

1. Excited states of unpaired particle act as a probe of deformation parameters
This information cannot be achieved with even nucleus



2. Many coexisting structures are foreseen at low excitation energies in Au isotopes

3. Isotopes can be produced in sufficient amounts at radioactive-ion beam facilites and cyclotrons (unique combination)



Aage Bohr: parametrization of nuclear deformation

$$R(\theta,\phi) = R_0\left(1 + \sum_{\lambda=0}^{\infty}\sum_{\mu=-\lambda}^{\lambda} a_{\lambda\mu}Y_{\lambda\mu}(\theta,\phi)\right)$$

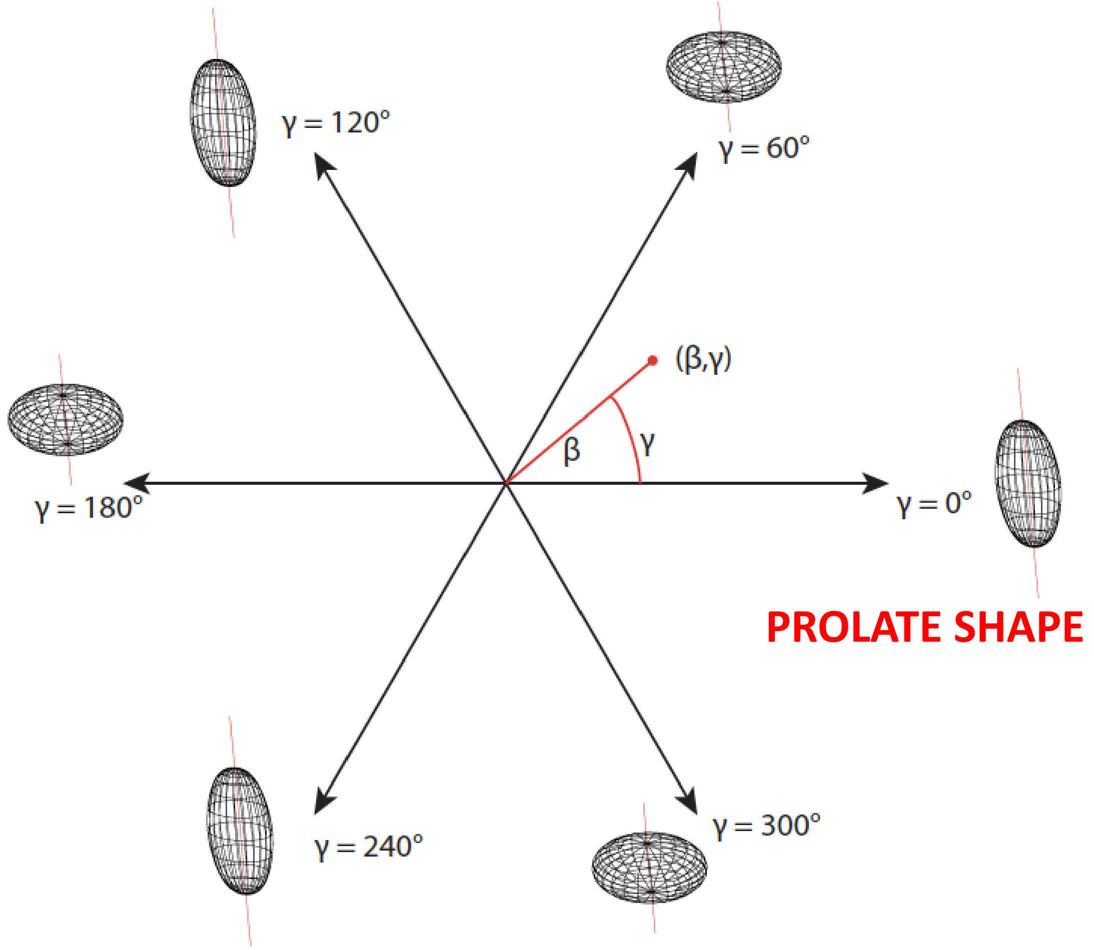
If only quadrupole deformation is considered:

$$a_{22} = a_{2-2}$$
$$a_{21} = a_{2-1} = 0$$

Model with angular momentum properties: quadrupole moments defined on spherical-tensor basis

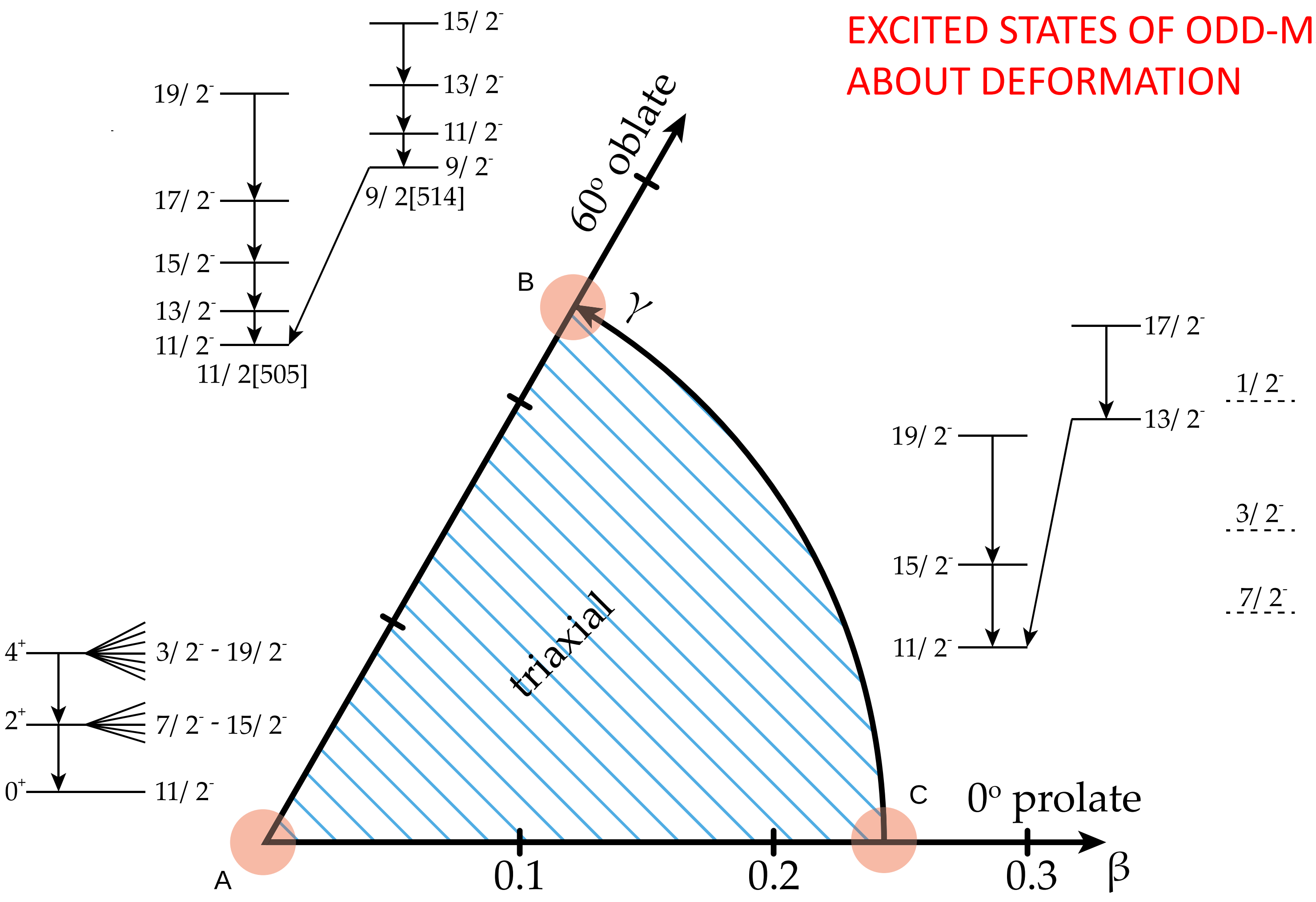
Polar coordinates used in 5-dimensional space:

$$a_{20} = \beta\cos\gamma$$
$$a_{22} = \frac{1}{\sqrt{2}}\beta\sin\gamma$$



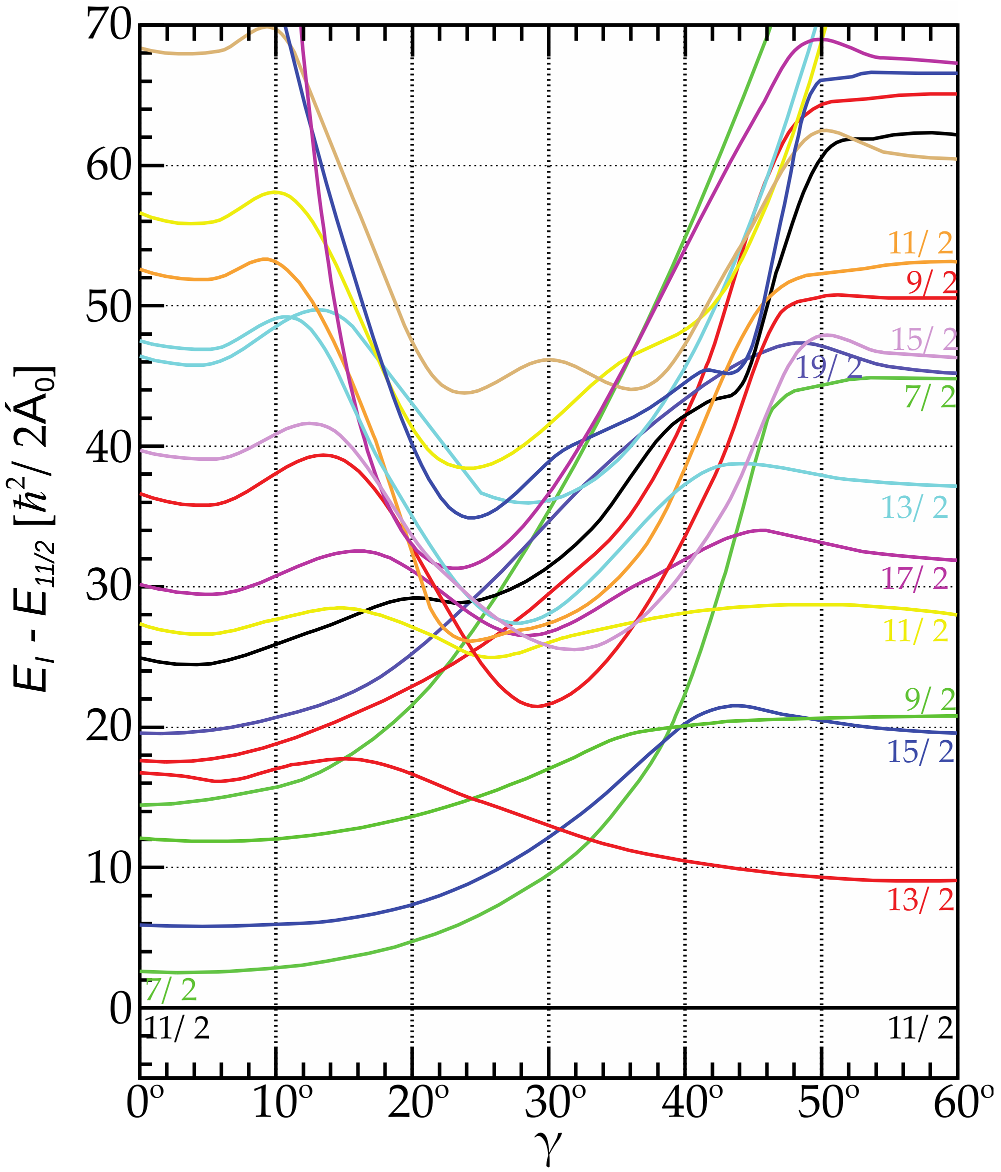
Particle-core coupling approach

EXCITED STATES OF ODD-MASS NUCLEI TELL US ABOUT DEFORMATION

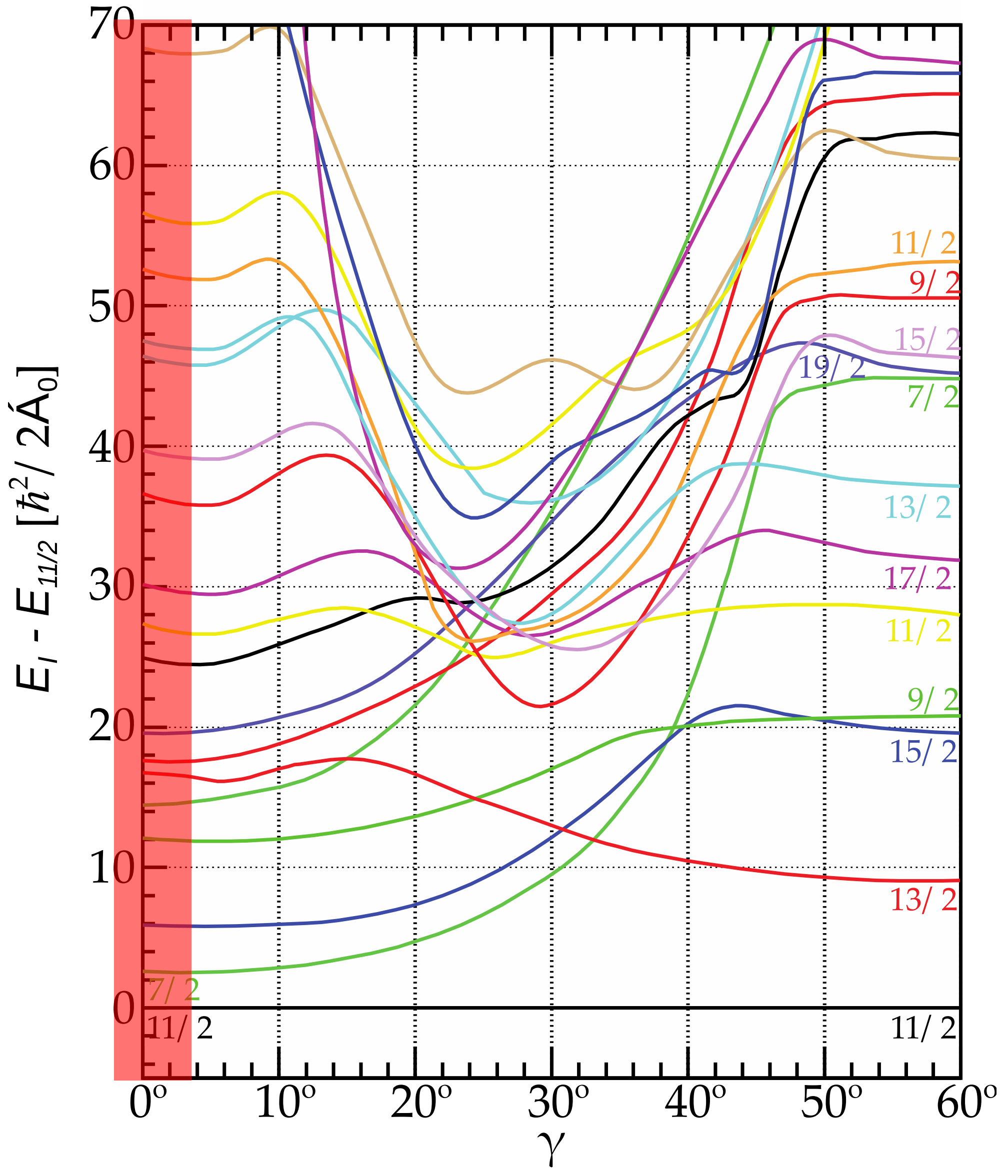


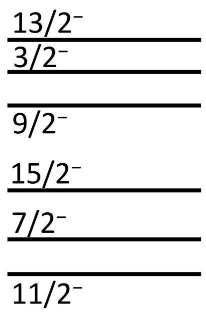
J. Meyer-ter-Vehn *et al.*, Phys. Rev. Lett. **32**, 1383 (1974).

Particle-core coupling approach: Meyer-ter-Vehn model



Particle-core coupling approach: Meyer-ter-Vehn model





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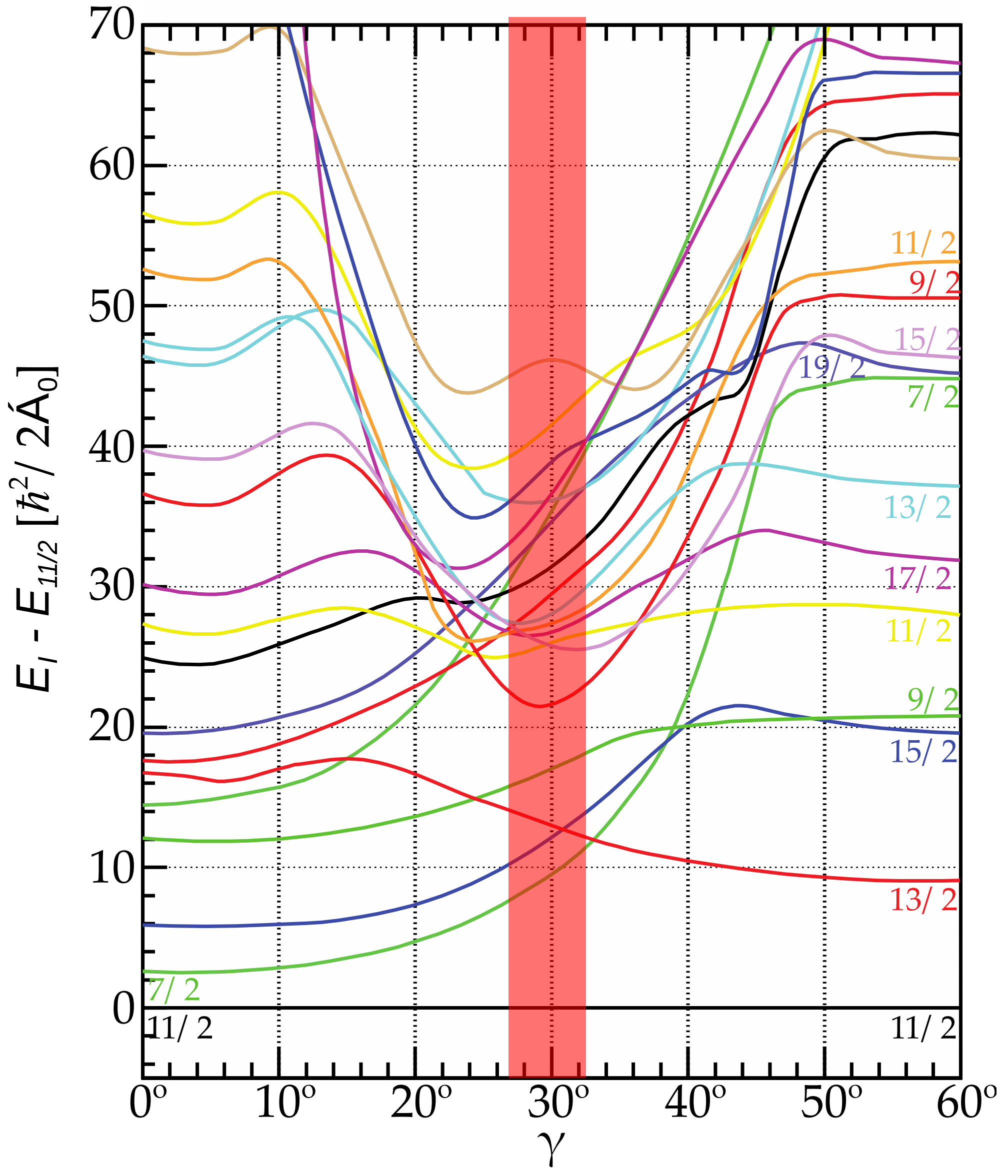

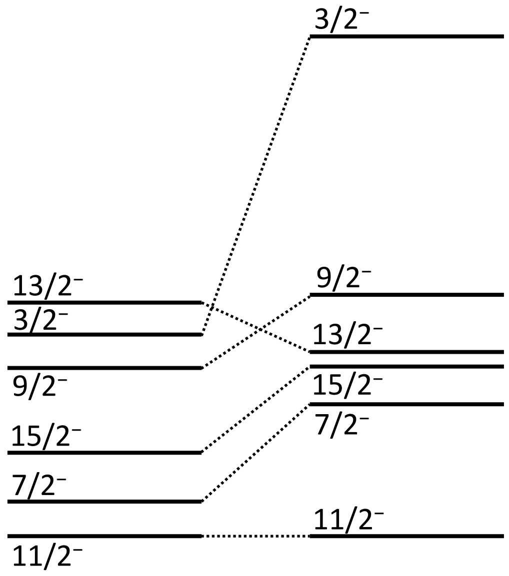

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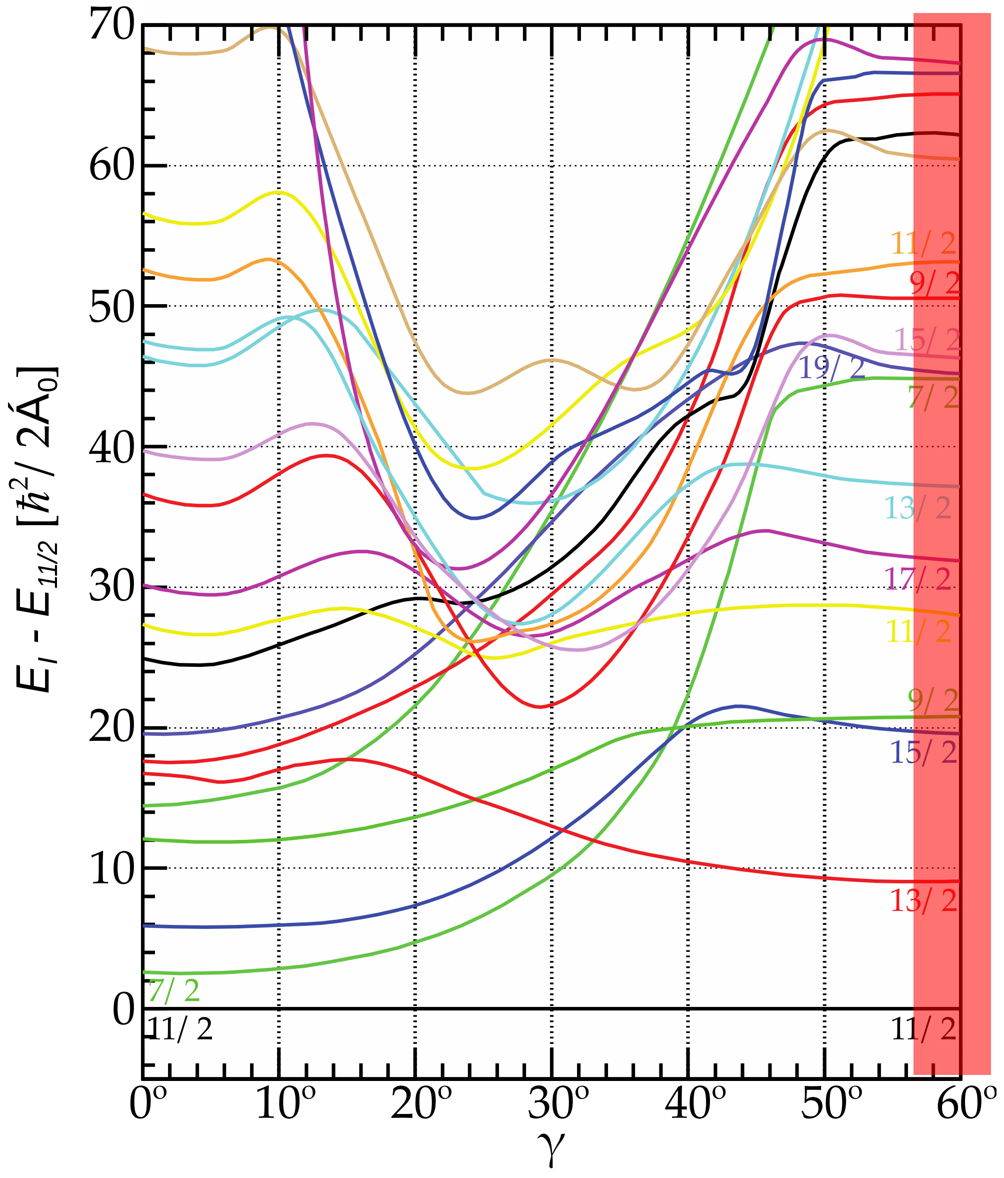
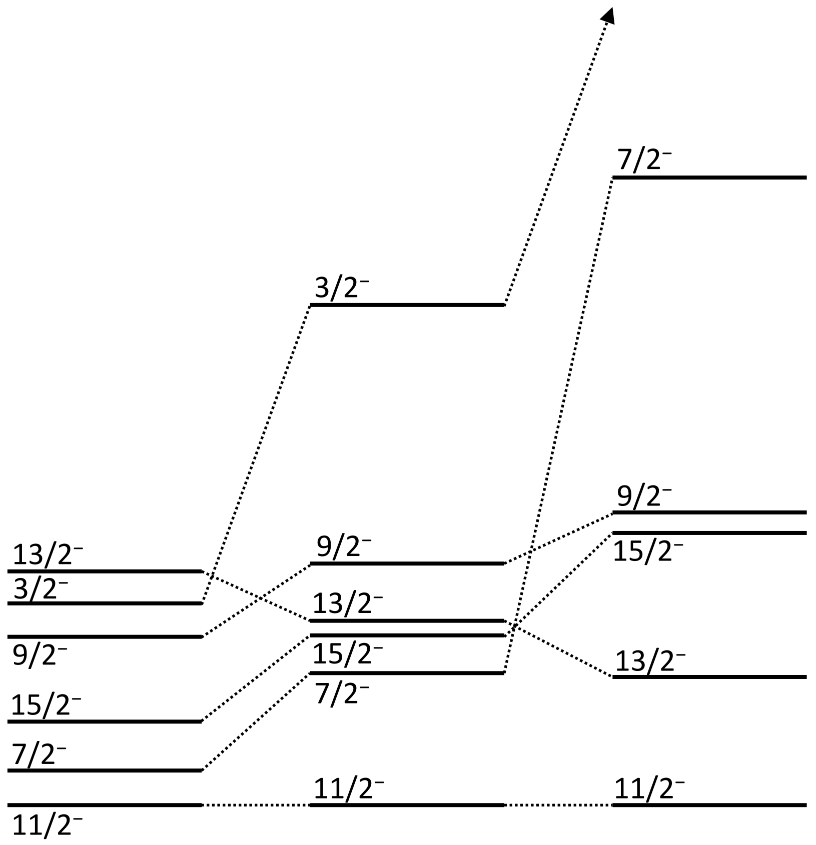
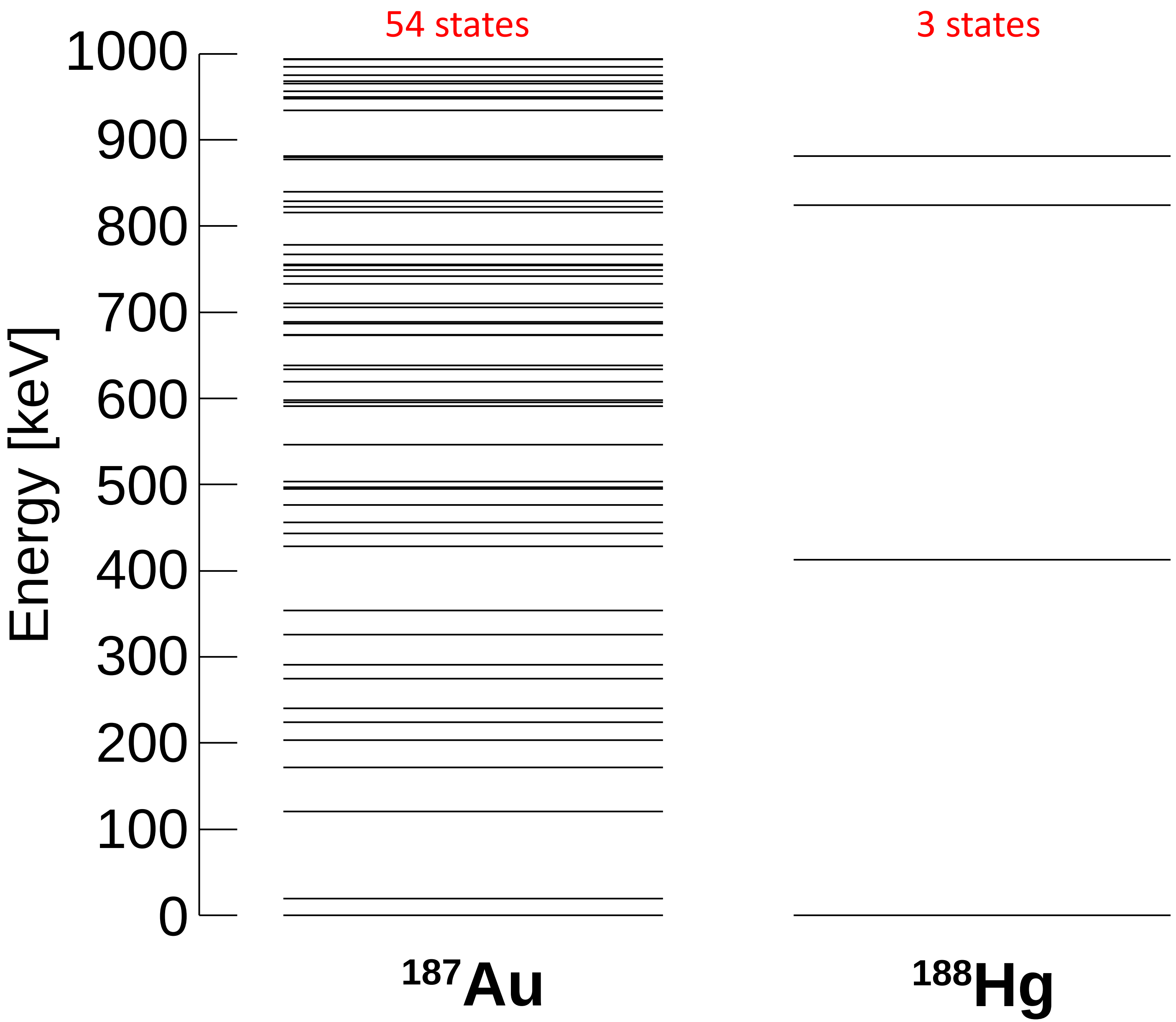




Density of excited states: challenge related to odd-mass studies



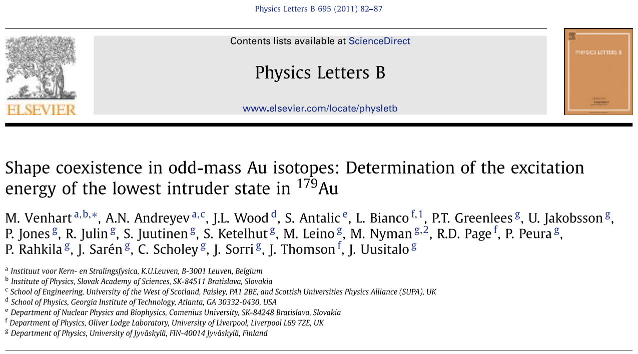
Start of the Au saga at KU Leuven, Belgium

- Discovery of isomeric state in ^{179}Au – gift from Nature

- **Completely by chance:**
  - Analysis of un-succesfull experiment at JYFL
  - Data from ISOLDE, taken for different purpose

- Starting of collaboration with John Wood – topic for Hollywood drama

- **I returned to Bratislava with clear vision on research program on Au isotopes**



Physics Letters B 695 (2011) 82–87

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Shape coexistence in odd-mass Au isotopes: Determination of the excitation energy of the lowest intruder state in ^{179}Au

M. Venhart[a,b,*], A.N. Andreyev[a,c], J.L. Wood[d], S. Antalic[e], L. Bianco[f,1], P.T. Greenlees[g], U. Jakobsson[g], P. Jones[g], R. Julin[g], S. Juutinen[g], S. Ketelhut[g], M. Leino[g], M. Nyman[g,2], R.D. Page[f], P. Peura[g], P. Rahkila[g], J. Sarén[g], C. Scholey[g], J. Sorri[g], J. Thomson[f], J. Uusitalo[g]

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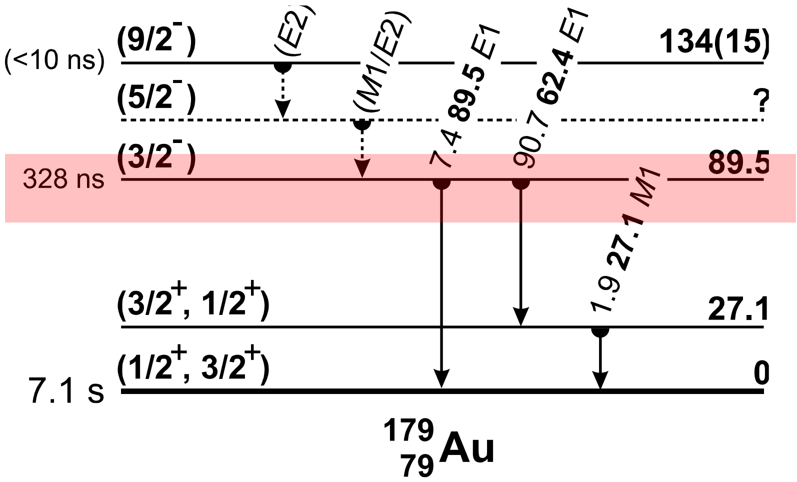
Nuclear physics at 2634 m

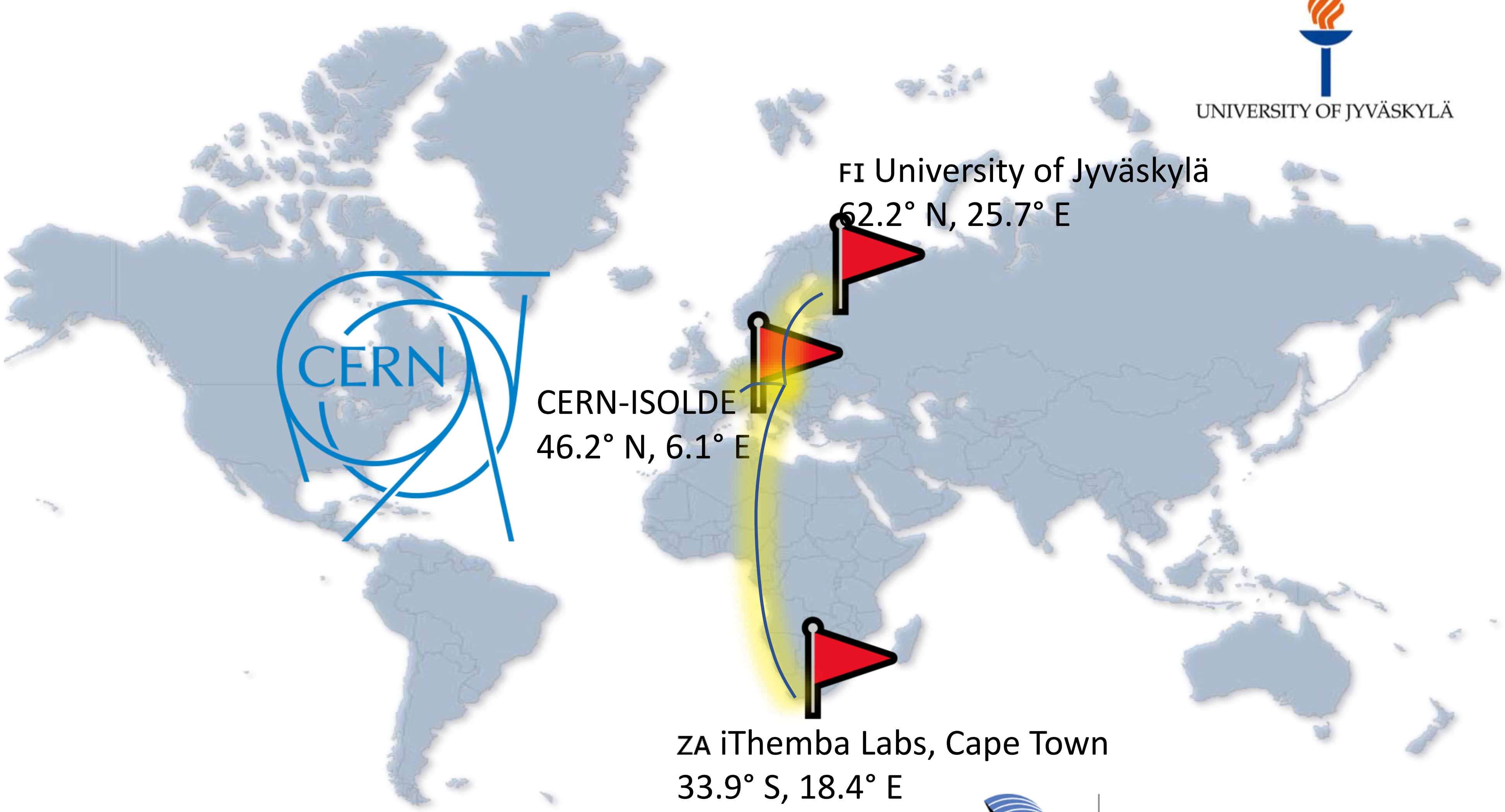


STRONGLY DEFORMED

WEAKLY DEFORMED

Research program at Institute of Physics - experiments

UNIVERSITY OF JYVÄSKYLÄ



NRF National Research Foundation

iThemba LABS Laboratory for Accelerator Based Sciences

Since 2012: 74 days of beam time (as a spokesperson)

SAV

Studies of ^{177,179}Au – Letter publications

Physics Letters B 806 (2020) 135488

Contents lists available at ScienceDirect

Physics Letters B

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Population of a low-spin positive-parity band from high-spin intruder states in ^{177}Au: The two-state mixing effect

M. Venhart[a,*], M. Balogh[a], A. Herzáň[a], J.L. Wood[c], F.A. Ali[b,d], D.T. Joss[b], A.N. Andreyev[e,f], K. Auranen[g], R.J. Carroll[b], M.C. Drummond[b], J.L. Easton[h,i], P.T. Greenlees[g], T. Grahn[g], A. Gredley[b], J. Henderson[e], U. Jakobsson[g,1], R. Julin[g], S. Juutinen[g], J. Konki[g,2], E.A. Lawrie[h,i], M. Leino[g], V. Matoušek[a], C.G. McPeake[b], D. O'Donnell[b,3], R.D. Page[b], J. Pakarinen[g], P. Papadakis[b,4], J. Partanen[g,5], P. Peura[g,6], P. Rahkila[g], P. Ruotsalainen[g], M. Sandzelius[g], J. Sarén[g], B. Saygı[j,k], M. Sedlák[a], C. Scholey[g], J. Sorri[g,7], S. Stolze[g,8], A. Thornthwaite[b], R. Urban[a], J. Uusitalo[g], M. Veselský[l], F.P. Wearing[b],

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RAPID COMMUNICATIONS

PHYSICAL REVIEW C **95**, 061302(R) (2017)

De-excitation of the strongly coupled band in ^{177}Au and implications for core intruder configurations in the light Hg isotopes

M. Venhart,[1,*] F. A. Ali,[2,3,†] W. Ryssens,[4] J. L. Wood,[5] D. T. Joss,[2] A. N. Andreyev,[6,7] K. Auranen,[8] B. Bally,[9] M. Balogh,[1] M. Bender,[10,11] R. J. Carroll,[2] J. L. Easton,[12] P. T. Greenlees,[8] T. Grahn,[8] P.-H. Heenen,[4] A. Herzáň,[2,8] U. Jakobsson,[8] R. Julin,[8] S. Juutinen,[8] D. Kíč,[1] J. Konki,[8] E. Lawrie,[12] M. Leino,[8] V. Matoušek,[1] C. G. McPeake,[2] D. O'Donnell,[2,‡] R. D. Page,[2] J. Pakarinen,[8] J. Partanen,[8] P. Peura,[8] P. Rahkila,[8] P. Ruotsalainen,[8] M. Sandzelius,[8] J. Sarén,[8] B. Sayği,[2] M. Sedlák,[1,13] C. Scholey,[8] J. Sorri,[8] S. Stolze,[8] A. Thornthwaite,[2] J. Uusitalo,[8] and M. Veselský[1]

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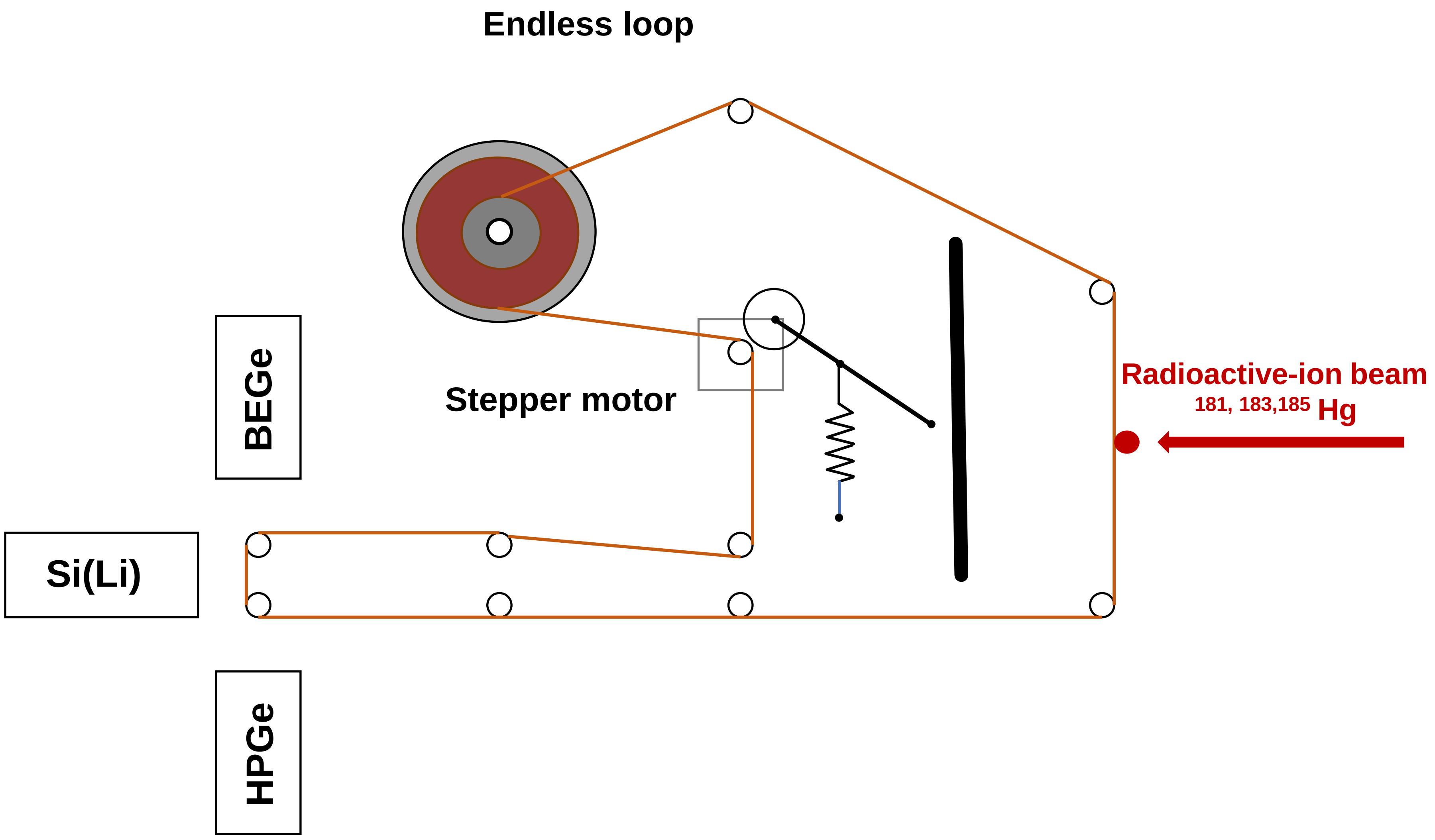
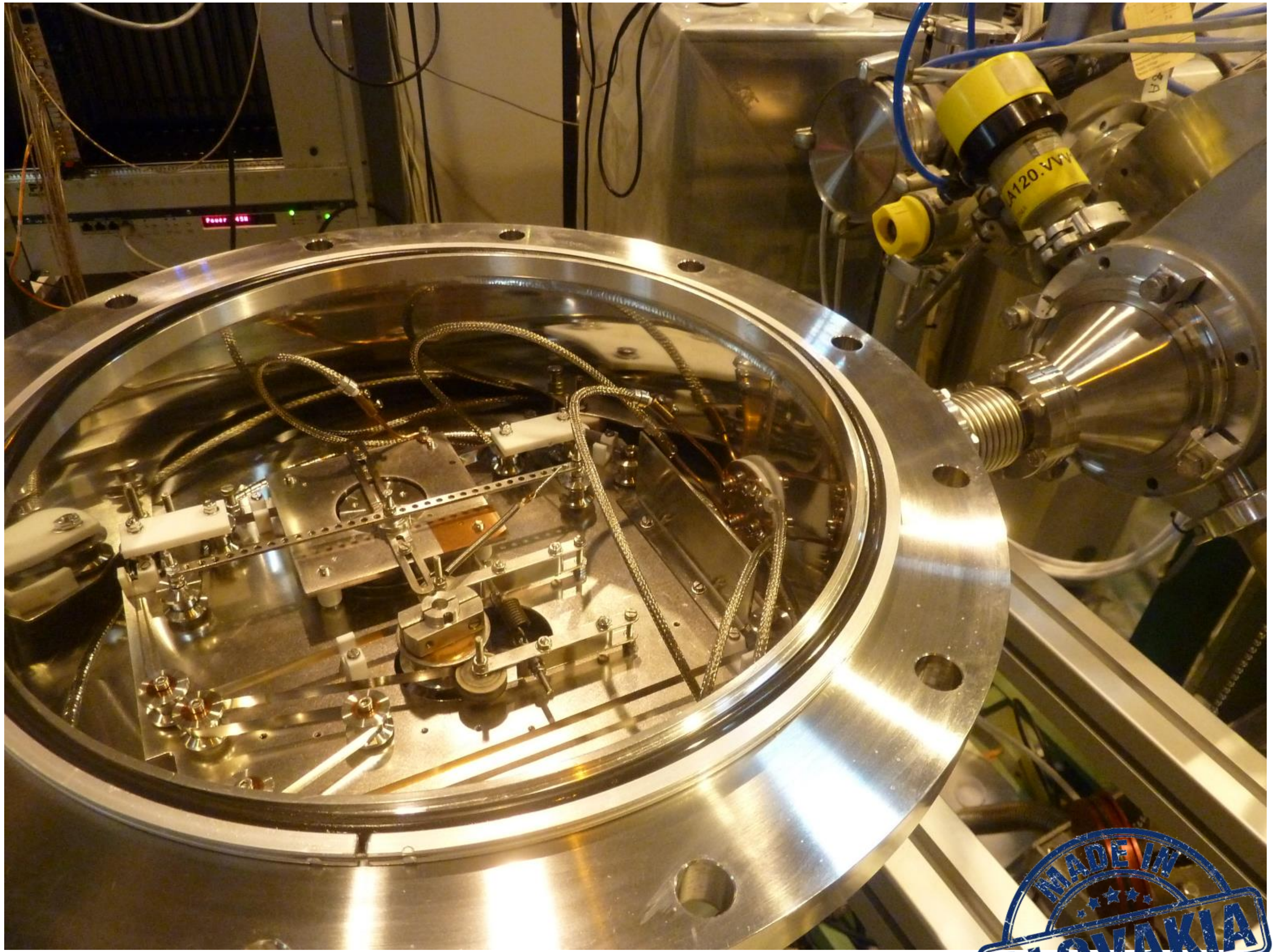
LEADERSHIP OF INTERNATIONAL COLLABORATIONS

Multiple shapes in atomic nuclei

Principle of the IS521 experiment



Experiment IS521 at CERN-ISOLDE: TATRA system

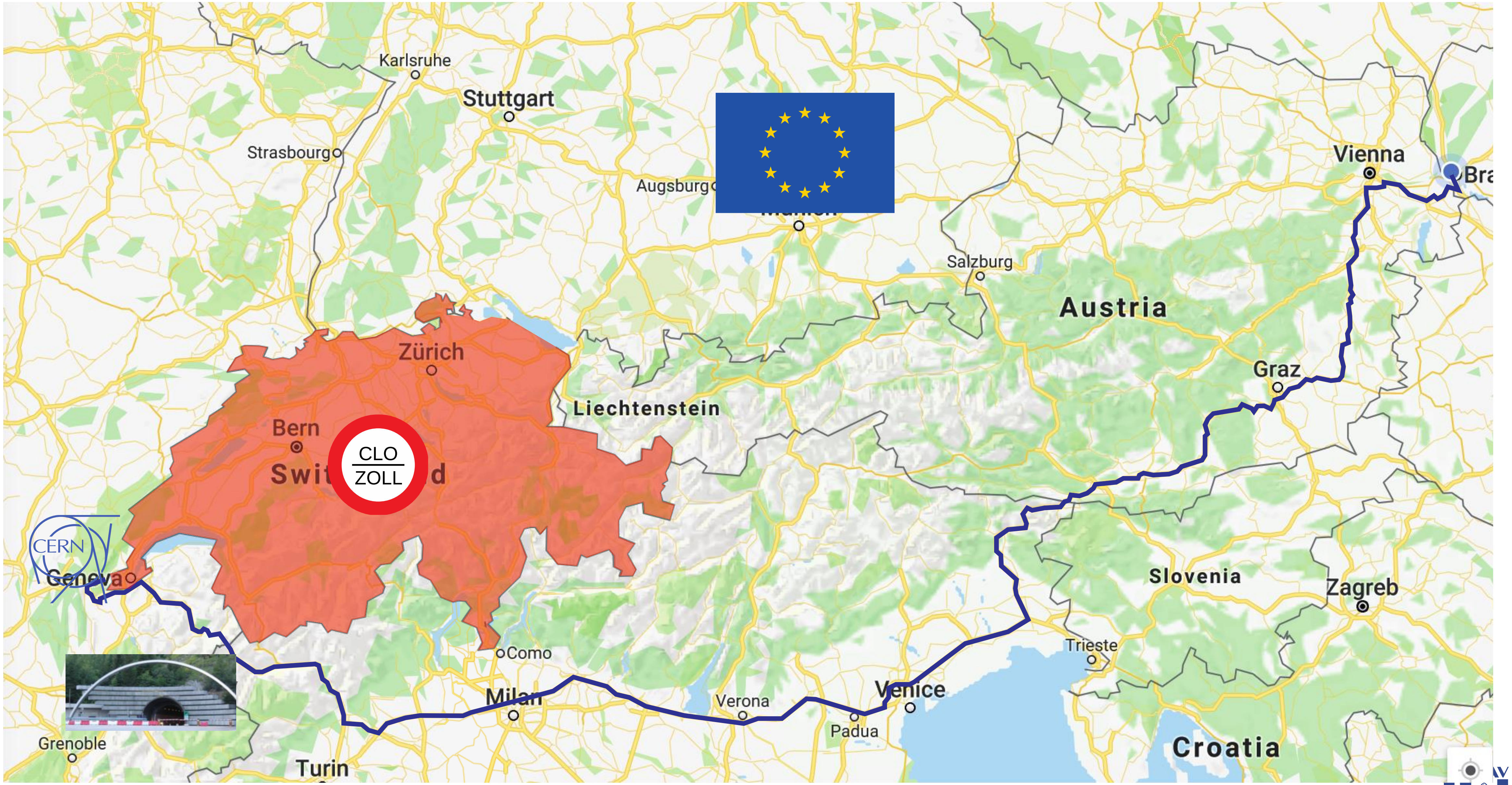


V. Matoušek *et al.*, Nucl. Instrum. And Meth A **812**, 118 (2016).

- **TA**pe **TRA**nsportation system inspired by 8-track tapes
- Rapidly quenched material: metallic glass is used to transport radioactive samples (deposition of ISOLDE beam)
- Operated at 3 x 10^{-8} mbar
- Windowless LN_2 cooled detector was used
- Very good resolution for conversion electrons

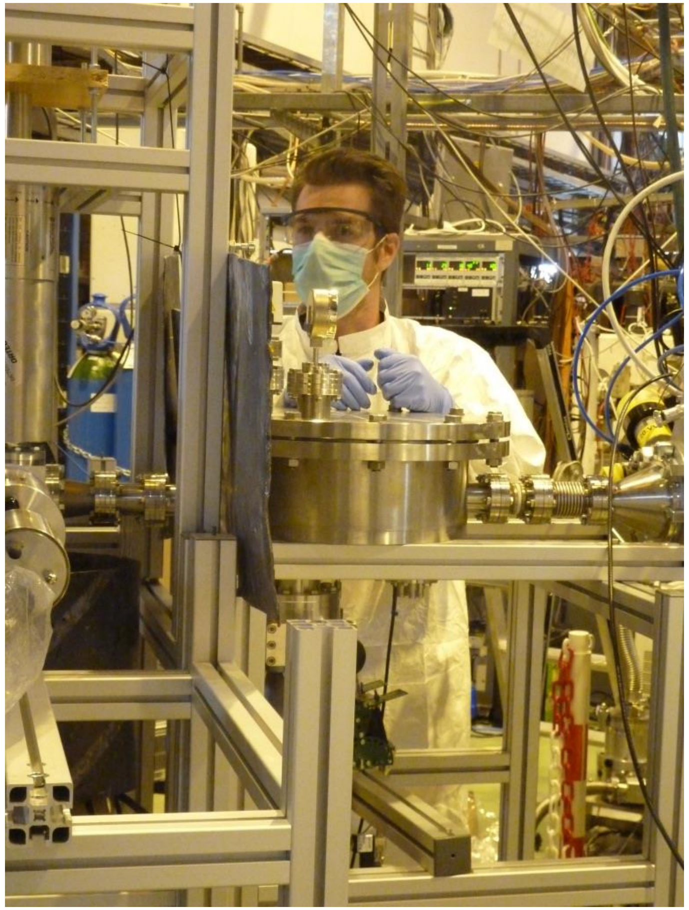
8 track tapes

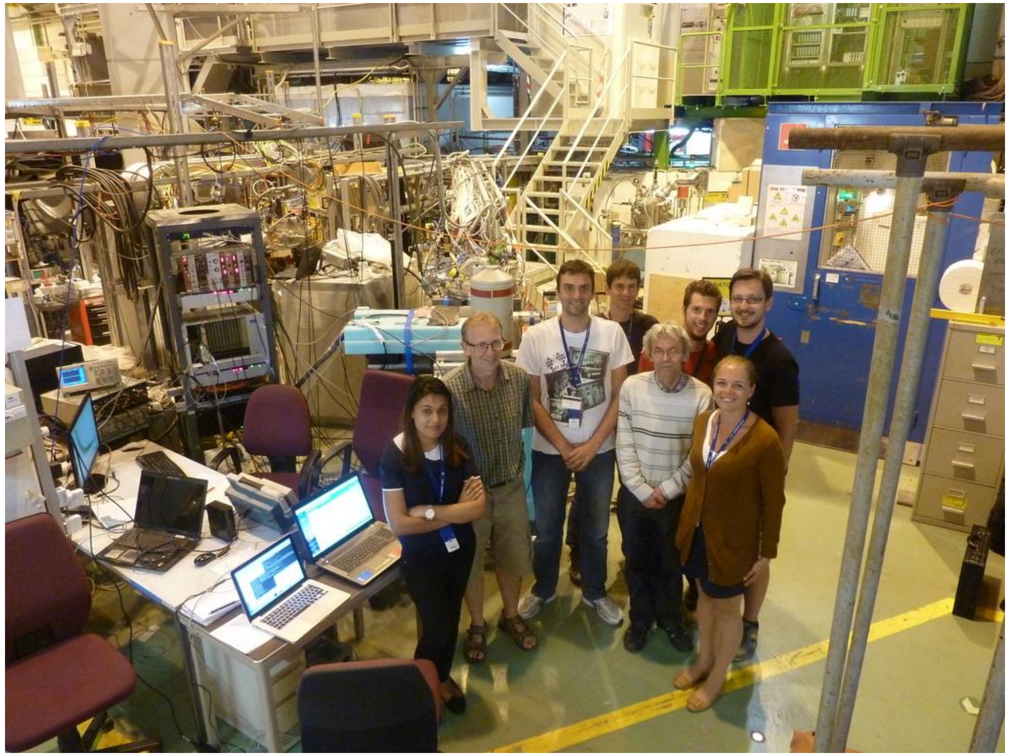
Multiple shapes in atomic nuclei



Experiment IS521 at CERN-ISOLDE: TATRA system

- Work of Vladislav Matoušek and Matúš Sedlák is highlighted – key people of the team for development of the system, electronics and software

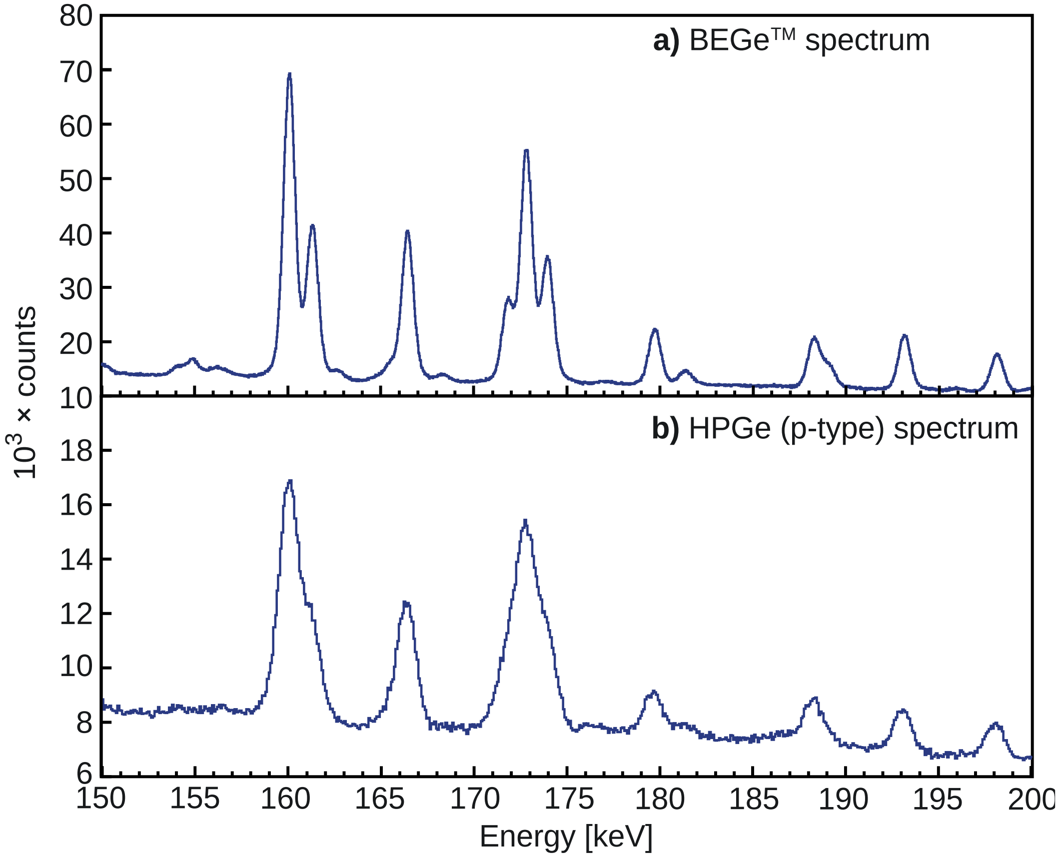




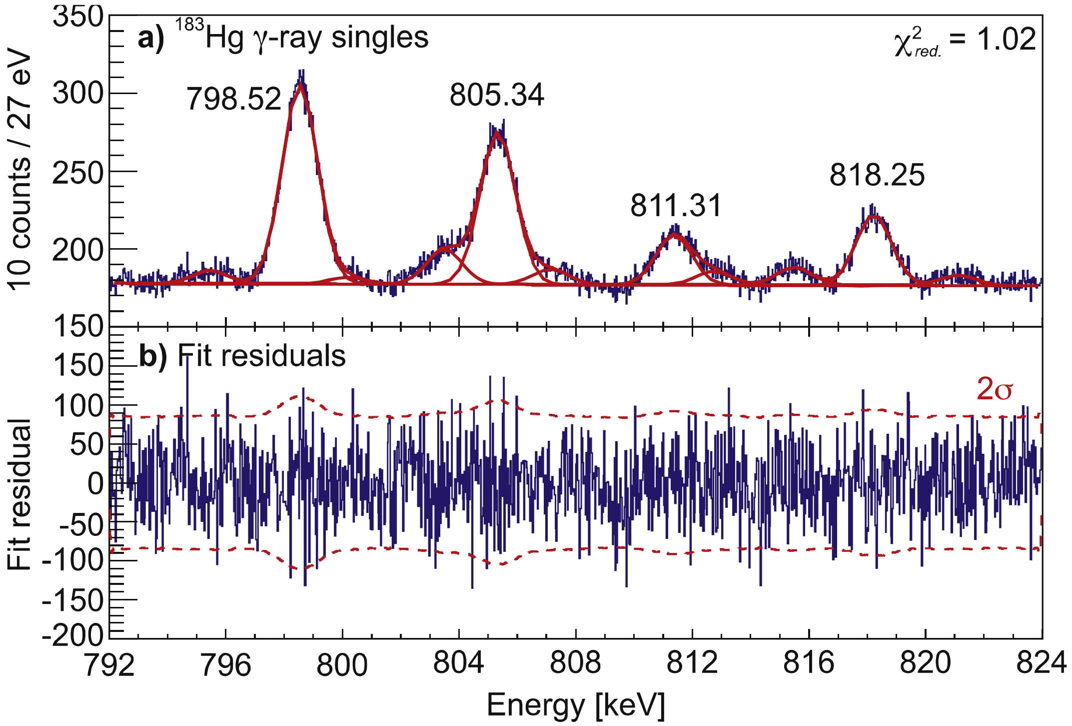
BEGe^{TM} detector: reason of success of TATRA

- Excellent resolution, nearly ideal gaussian peak shape

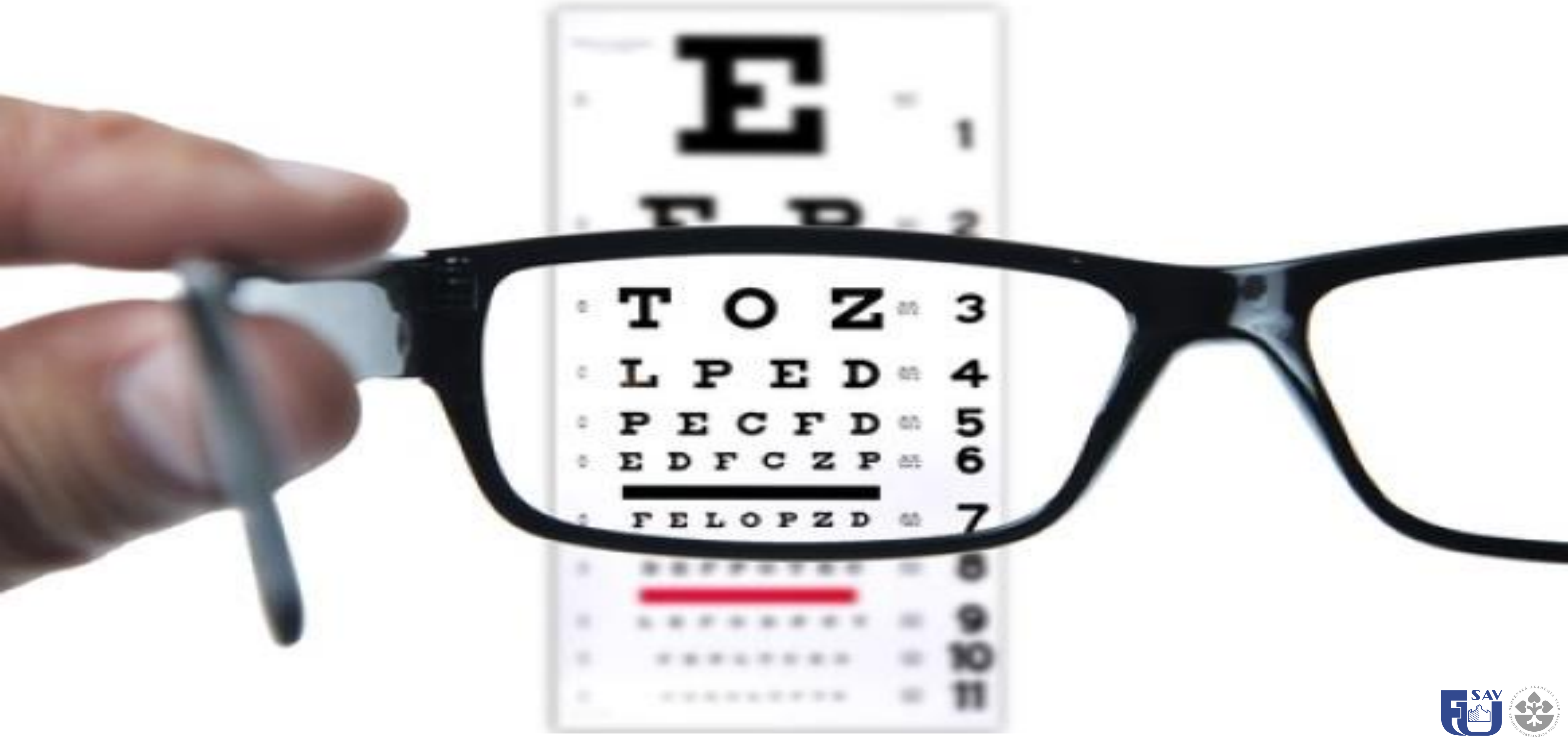
Note a difference in resolution



Peak shape and linear background

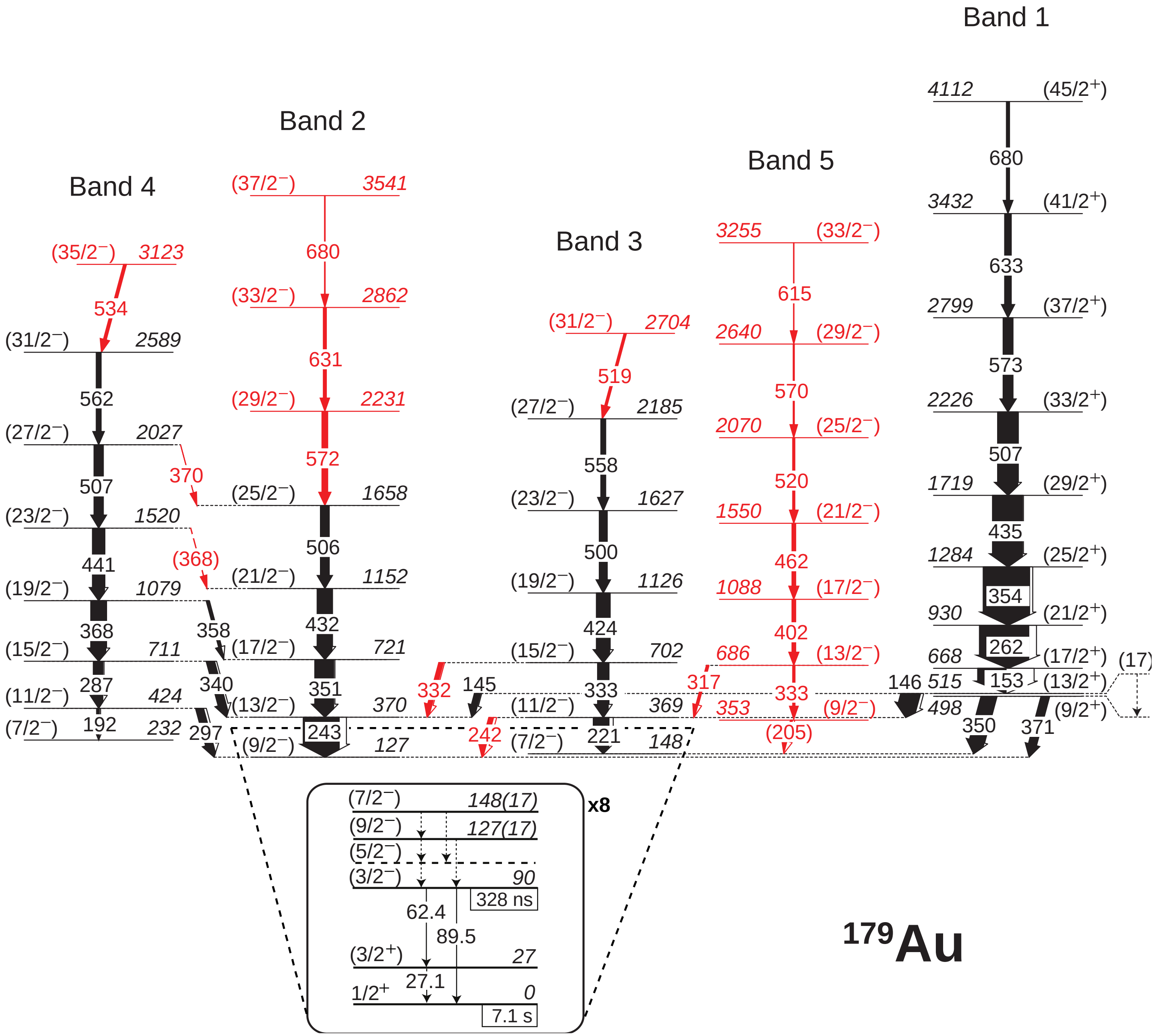


BEGe: a pair of new eyes for odd-mass nuclei



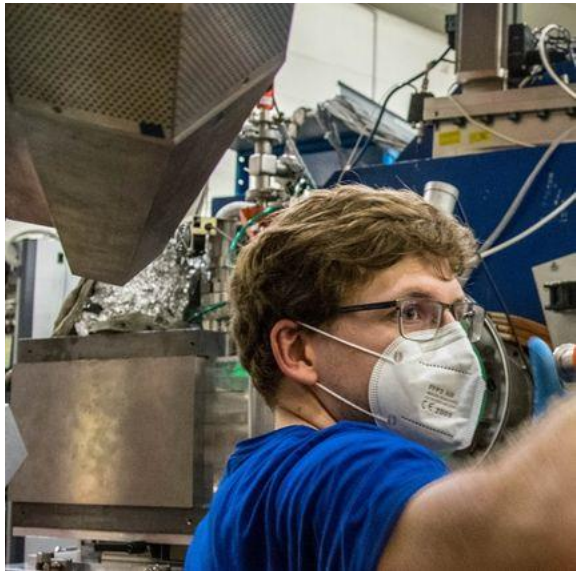
BEGe: a pair of new eyes for odd-mass nuclei

Rotational band in ^{179}Au: Triaxiality



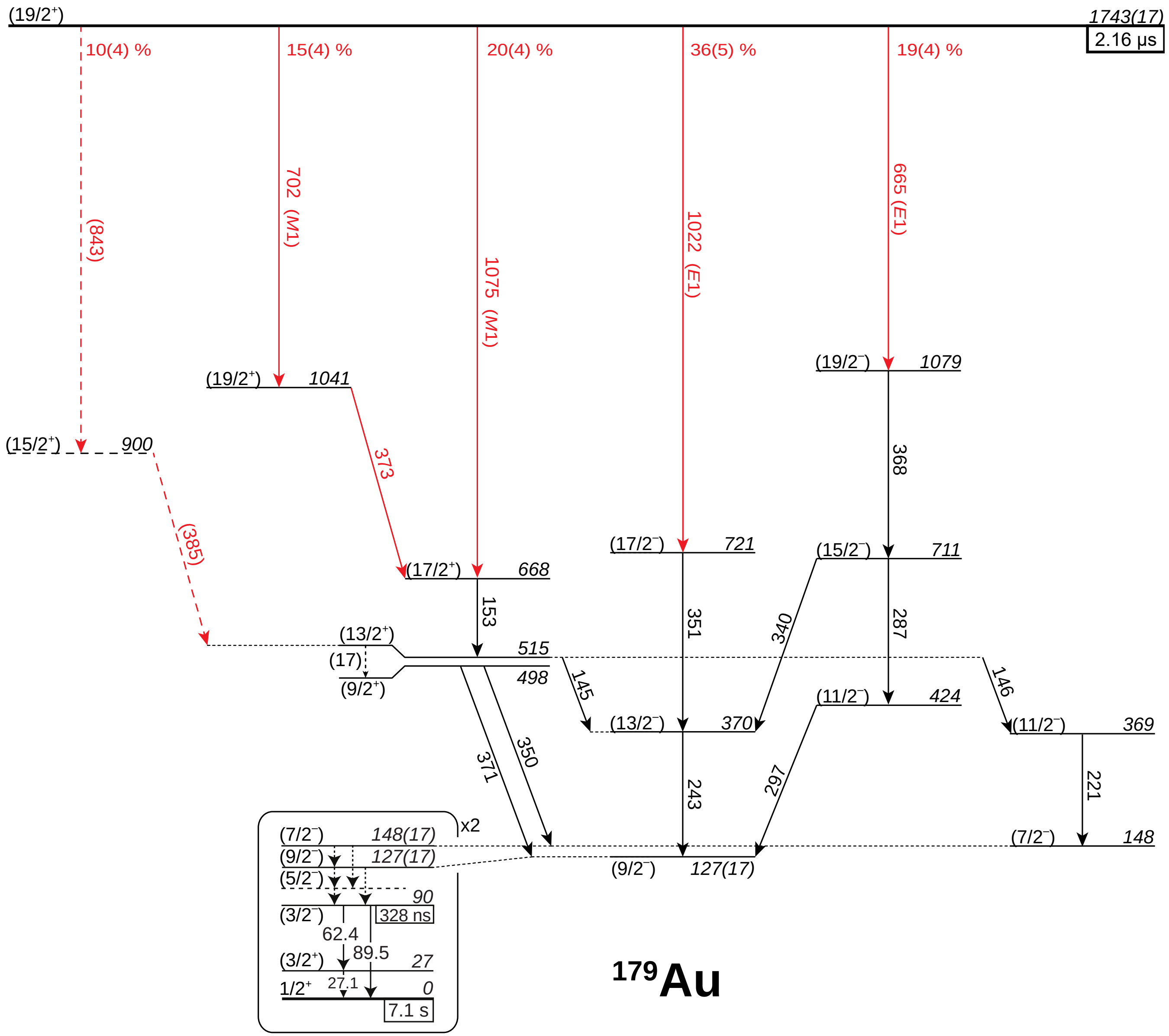
Analysis by **Matúš Balogh**:

- Brilliant mind
- Thorough identification of weak transitions
- Very few people would be able to do it
- New band has population intensity of about 3 %



M. Balogh *et al.*, Phys. Rev. C **106**, 064324 (2022).

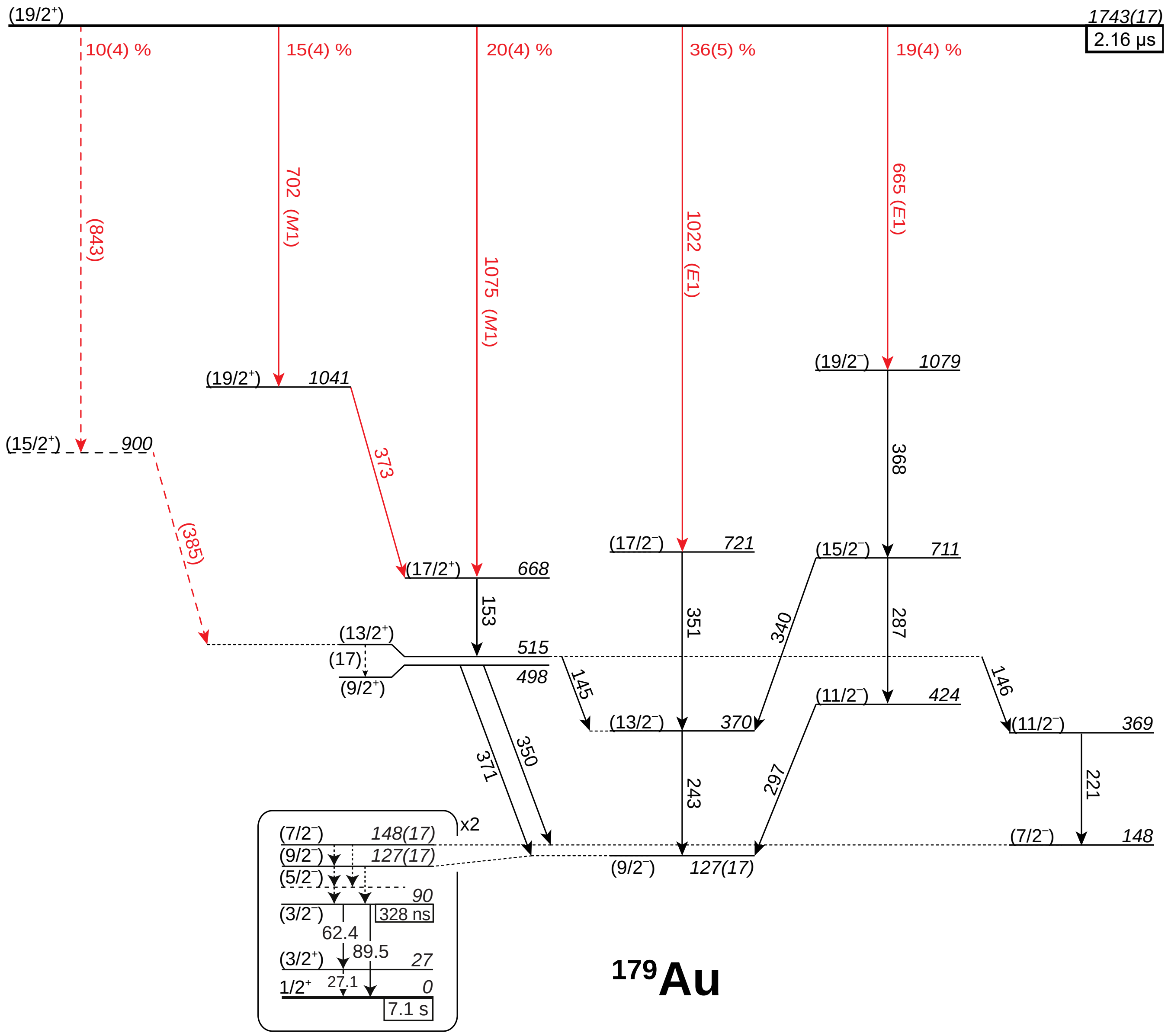
New isomeric state in ^{179}Au: A completely new type of structure?



- Unprecedented in atomic nuclei in general
- Only resembles isomers in Os region, that are also not understood, but they are in even-even nuclei
- Analysis by Matúš Balogh and **Erika Jajčišinová**

M. Balogh *et al.*, Phys. Rev. C **106**, 064324 (2022).

New isomeric state in ^{179}Au: A completely new type of structure?



- Unprecedented in atomic nuclei in general
- New experiment performed at JYFL
- Statistics increased by factor of 40
- Detector development led by **Ján Kliman**
- Data is being analysed by **Magdaléna Šolcová**

M. Balogh *et al.*, Phys. Rev. C **106**, 064324 (2022).

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SAV

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Nadácia ESET

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MINISTERSTVO ŠKOLSTVA, VÝSKUMU, VÝVOJA A MLÁDEŽE SLOVENSKEJ REPUBLIKY

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”Chance favors the prepared mind!”

Louis Pasteur (1822 – 1895)

Ďakujem!
Thank you!
Kiitos!
Dankjewel!
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