Física Nuclear
Nuclear Physics

Instituto de Estructura de la Materia – Consejo Superior de Investigaciones Científicas

Single particle versus collectivity, shapes of exotic nuclei

Andrea Jungclaus

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Rewriting Nuclear Physics textbooks
30 years with Radioactive Ion Beam Physics
Pisa (Italy), July 20th – 24th, 2015

Photo copyright Robert Charity 2014

Single particle versus collectivity, shapes of exotic nuclei

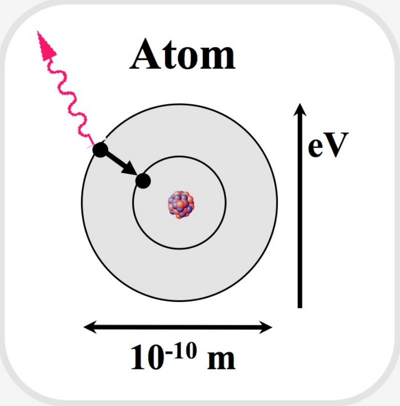
- What a title ! A bit of everything …
- Start with some reminders of "classical" nuclear physics
- What's new over the last 30 years ?
  From the perspective of an observer of the field since 1989 …
  (pure experimentalist, γ-ray spectroscopist interested in A>70 nuclei)

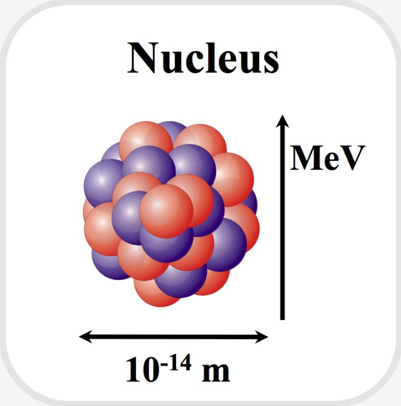
Rewriting Nuclear Physics textbooks
30 years with Radioactive Ion Beam Physics

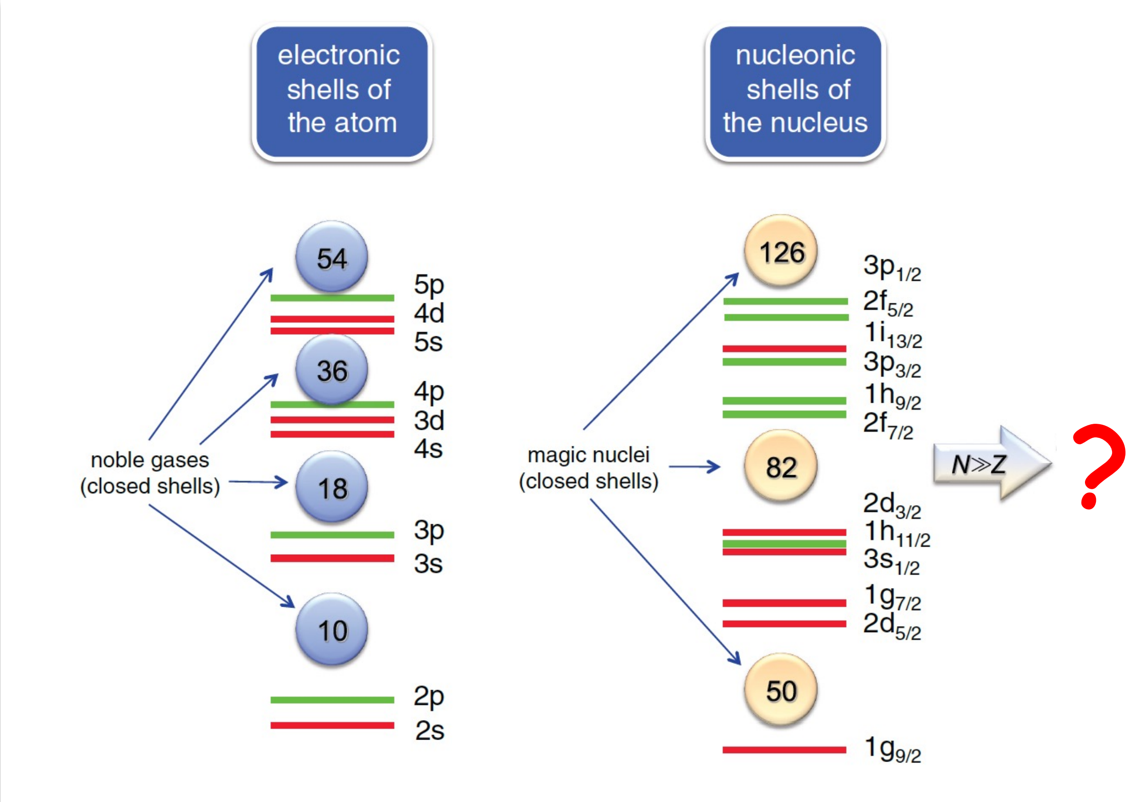
- Radioactive ion beams are an important part, but not the whole story !
- Small selection of examples – only limited time …
- I will simplify (hopefully without getting things wrong), omit, not always show latest etc.
- Try to avoid topics which others may already have shown

Andrea Jungclaus, Eur. Phys. J. Plus 131, 59 (2016)

The shell structure of atomic nuclei



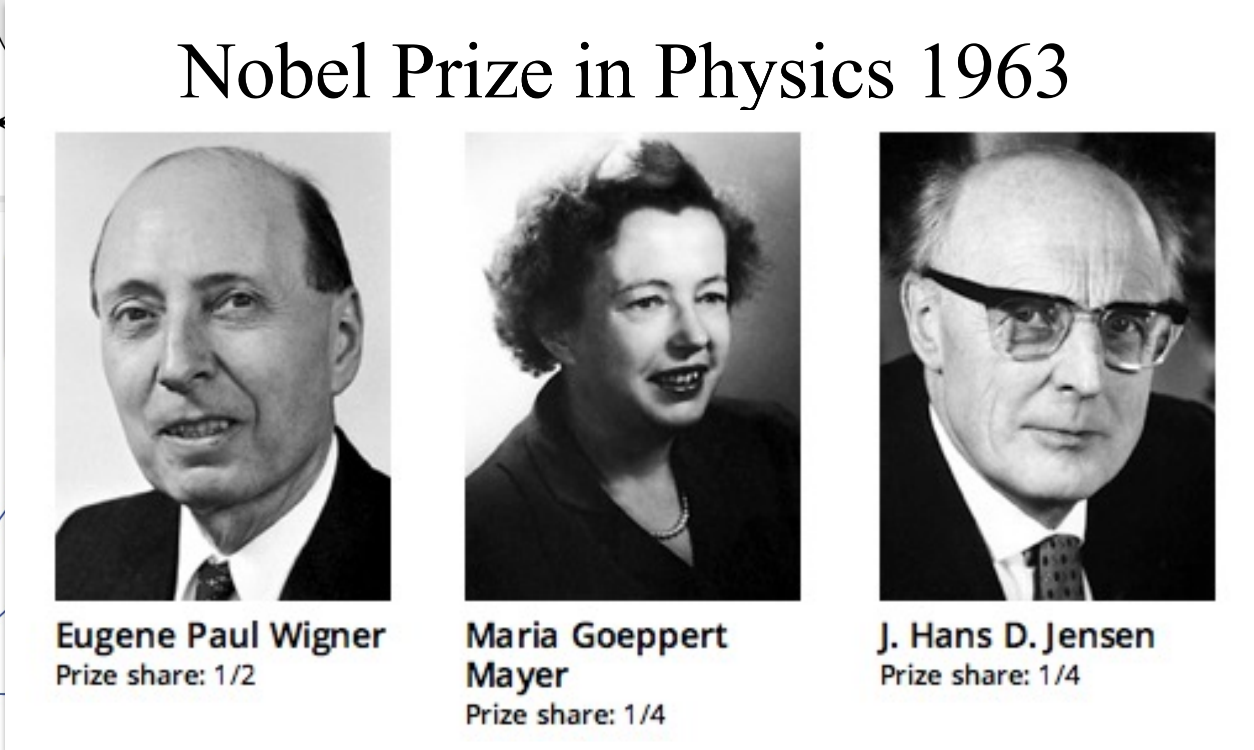




Remember:
Two independent parameters in atomic nuclei, Z and N !

"Shell evolution":
Next part of my talk …

The shell structure of atomic nuclei



Nobel Prize in Physics 1963

Eugene Paul Wigner
Prize share: 1/2

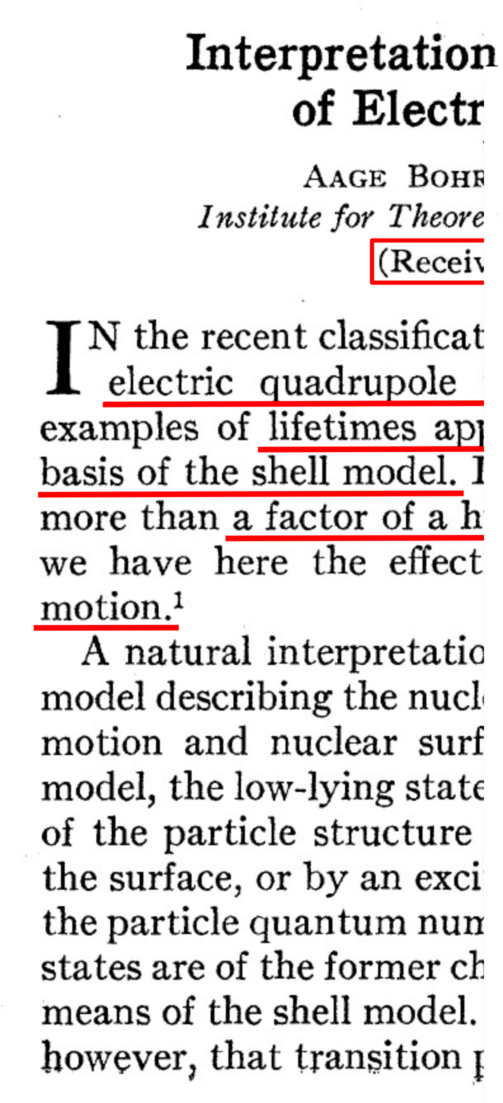
Maria Goeppert Mayer
Prize share: 1/4

J. Hans D. Jensen
Prize share: 1/4

nt parameters
i, Z and N !

"Shell evolution":
Next part of my talk …

The birth of the collective models in 1952



Interpretation of Isomeric Transitions of Electr

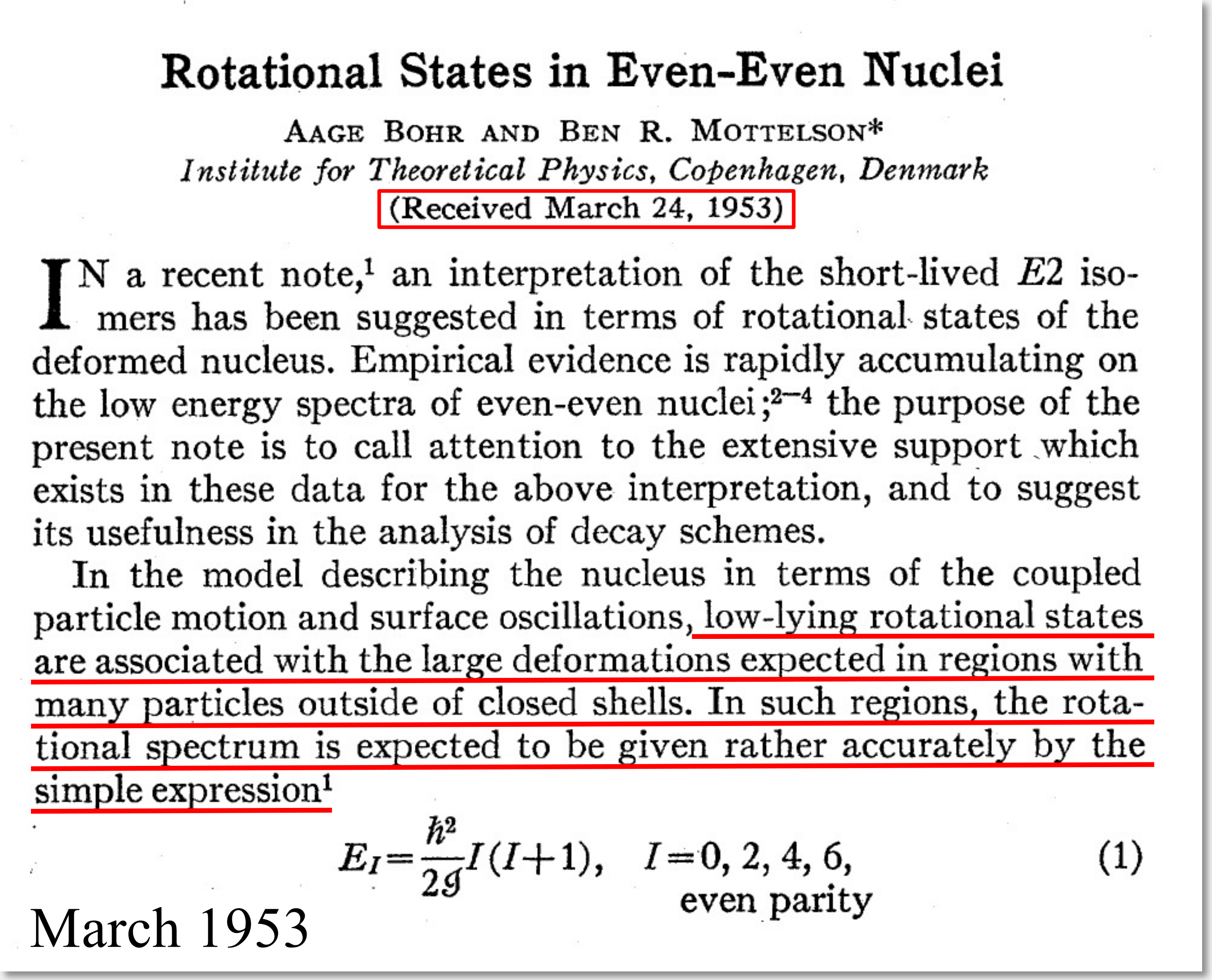
Aage Bohr
Institute for Theore

(Receiv

IN the recent classificat
electric quadrupole
examples of lifetimes ap
basis of the shell model. I
more than a factor of a h
we have here the effect
motion.[1]

A natural interpretatio
model describing the nucl
motion and nuclear surf
model, the low-lying state
of the particle structure
the surface, or by an exci
the particle quantum num
states are of the former ch
means of the shell model.
however, that transition p

Nov. 1952



Rotational States in Even-Even Nuclei

Aage Bohr and Ben R. Mottelson*
Institute for Theoretical Physics, Copenhagen, Denmark

(Received March 24, 1953)

IN a recent note,[1] an interpretation of the short-lived $E2$ isomers has been suggested in terms of rotational states of the deformed nucleus. Empirical evidence is rapidly accumulating on the low energy spectra of even-even nuclei;[2–4] the purpose of the present note is to call attention to the extensive support which exists in these data for the above interpretation, and to suggest its usefulness in the analysis of decay schemes.

In the model describing the nucleus in terms of the coupled particle motion and surface oscillations, low-lying rotational states are associated with the large deformations expected in regions with many particles outside of closed shells. In such regions, the rotational spectrum is expected to be given rather accurately by the simple expression[1]

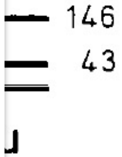
$$E_I=\frac{\hbar^2}{2\mathcal{J}}I(I+1), \quad I=0,2,4,6, \text{ even parity} \qquad (1)$$

March 1953

First observation of rotational bands

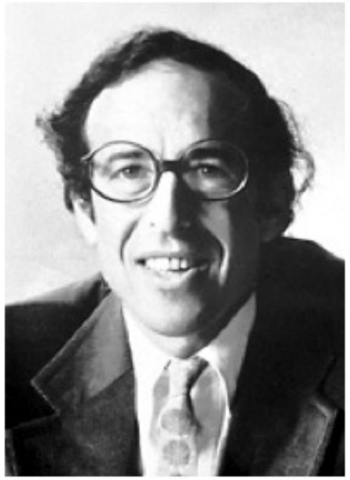
Three examples from 1953:

Fine structure in α decay



Nobel Prize in Physics 1975

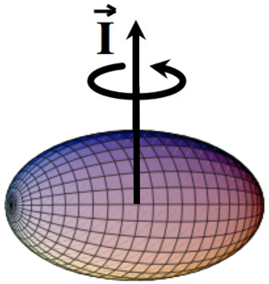
Aage Niels Bohr



Ben Roy Mottelson

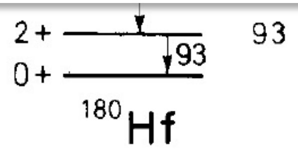
Leo James Rainwater

rotations –

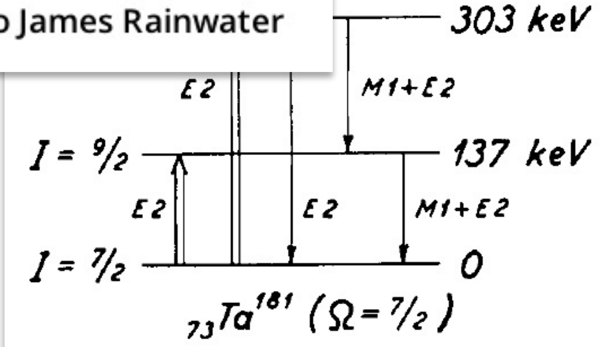


even-even nucleus

$E(4^+)/E(2^+) \sim 3.3$

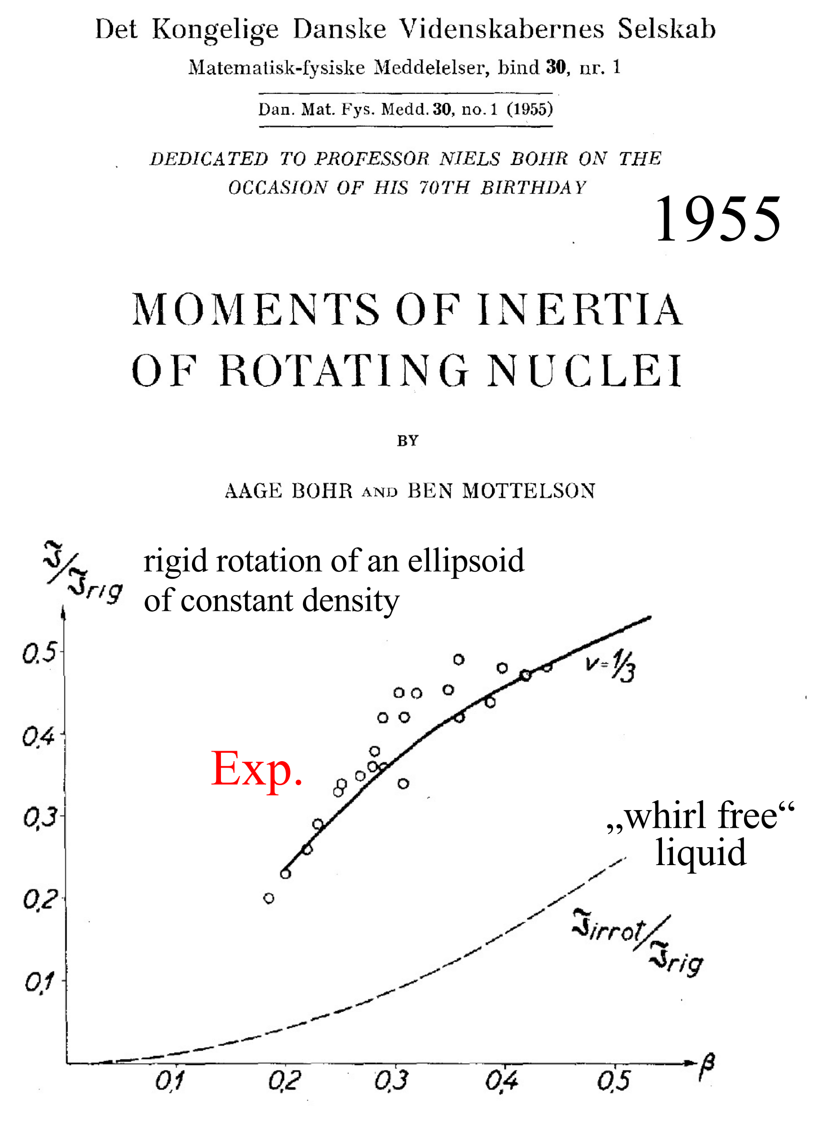


experiment



Bohr Nobel Lecture

The problem of the "wrong" moment of inertia



Det Kongelige Danske Videnskabernes Selskab
Matematisk-fysiske Meddelelser, bind **30**, nr. 1

Dan. Mat. Fys. Medd. **30**, no. 1 (1955)

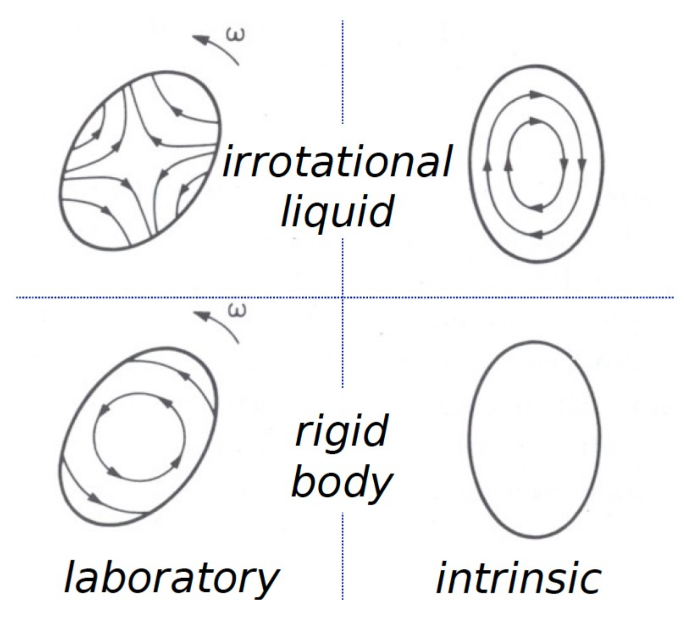
DEDICATED TO PROFESSOR NIELS BOHR ON THE OCCASION OF HIS 70TH BIRTHDAY

1955

MOMENTS OF INERTIA OF ROTATING NUCLEI

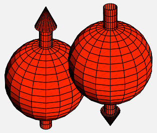
BY

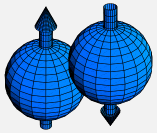
AAGE BOHR AND BEN MOTTELSON



„Nuclei are like egg shells which are filled with a mixture of a normal and a super-conducting liquid !“

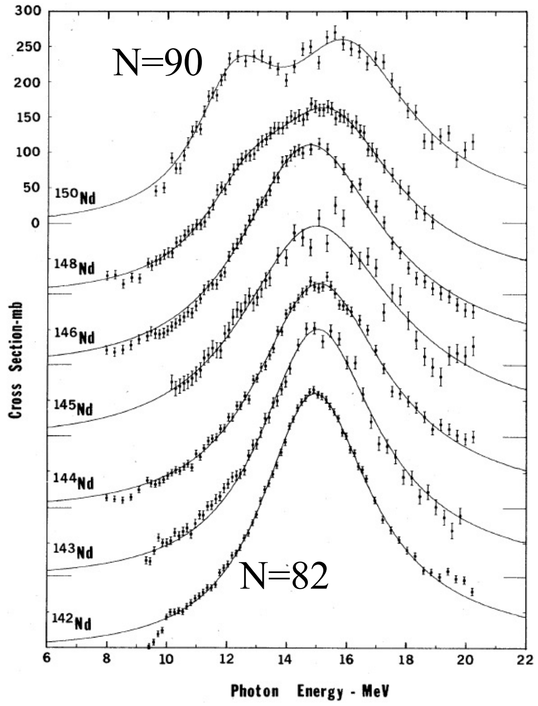
Super conductivity due to **pairing forces** in analogy to the Cooper pairs (electrons) in superconductors.



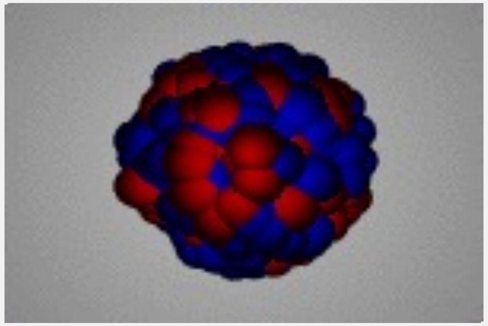


The vibrational degree of freedom

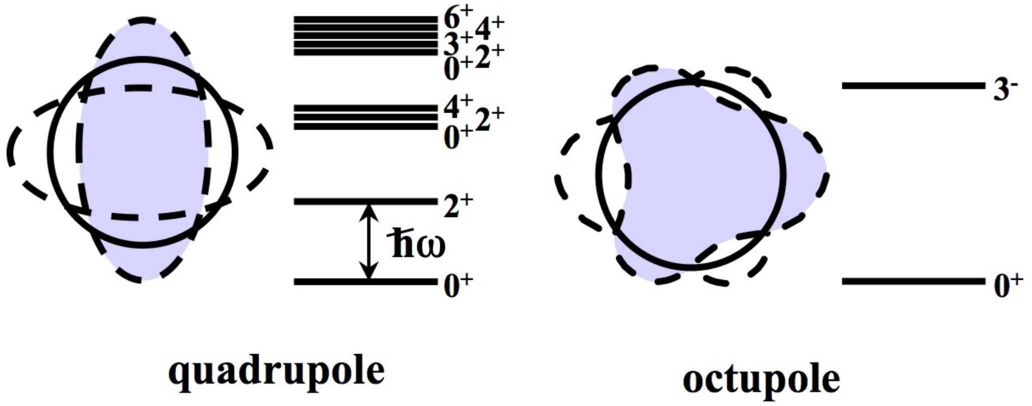
(γ,n) cross section – Nd (Z=60)

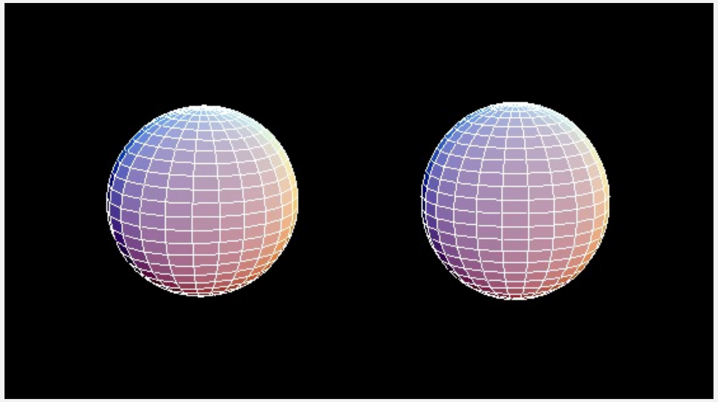


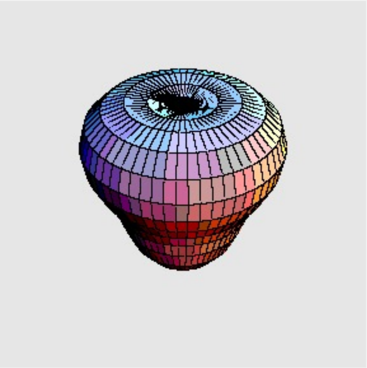
Giant Dipole Resonance



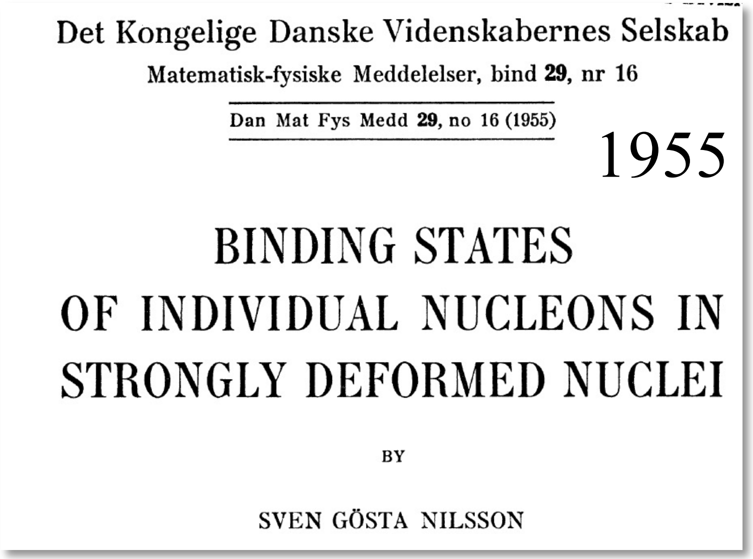
vibrations – 1950s







Deformed nuclei in the Nilsson model



Det Kongelige Danske Videnskabernes Selskab
Matematisk-fysiske Meddelelser, bind **29**, nr 16

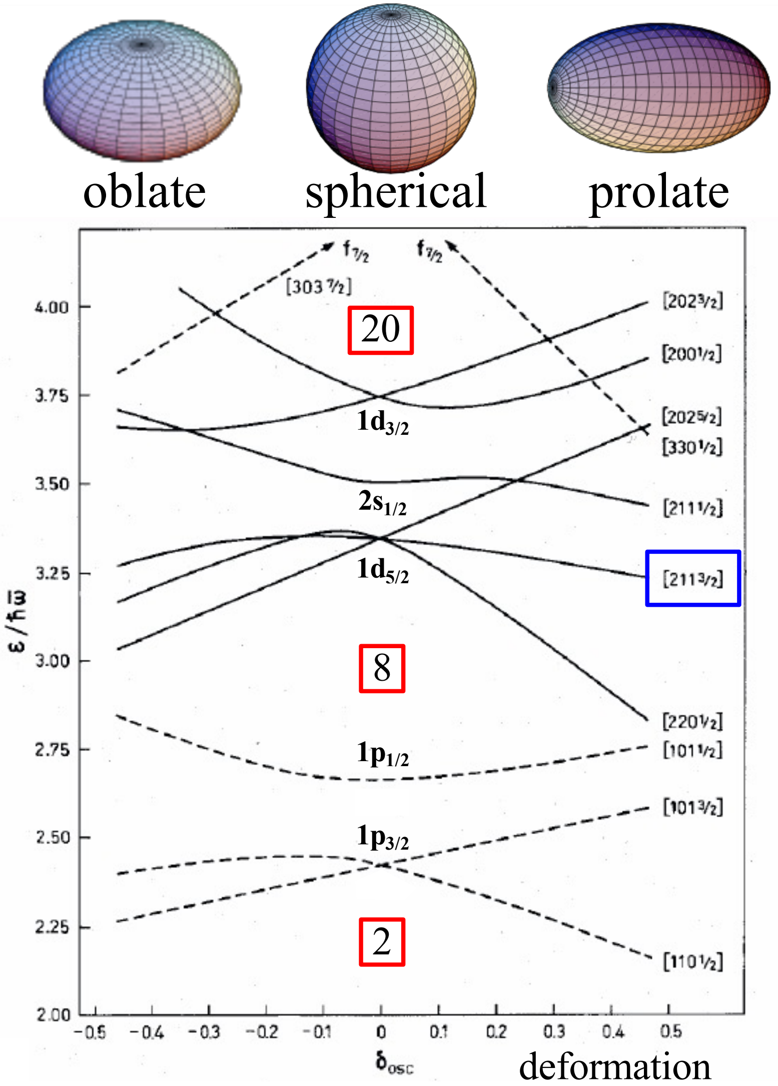
Dan Mat Fys Medd **29**, no 16 (1955)

1955

BINDING STATES
OF INDIVIDUAL NUCLEONS IN
STRONGLY DEFORMED NUCLEI

BY

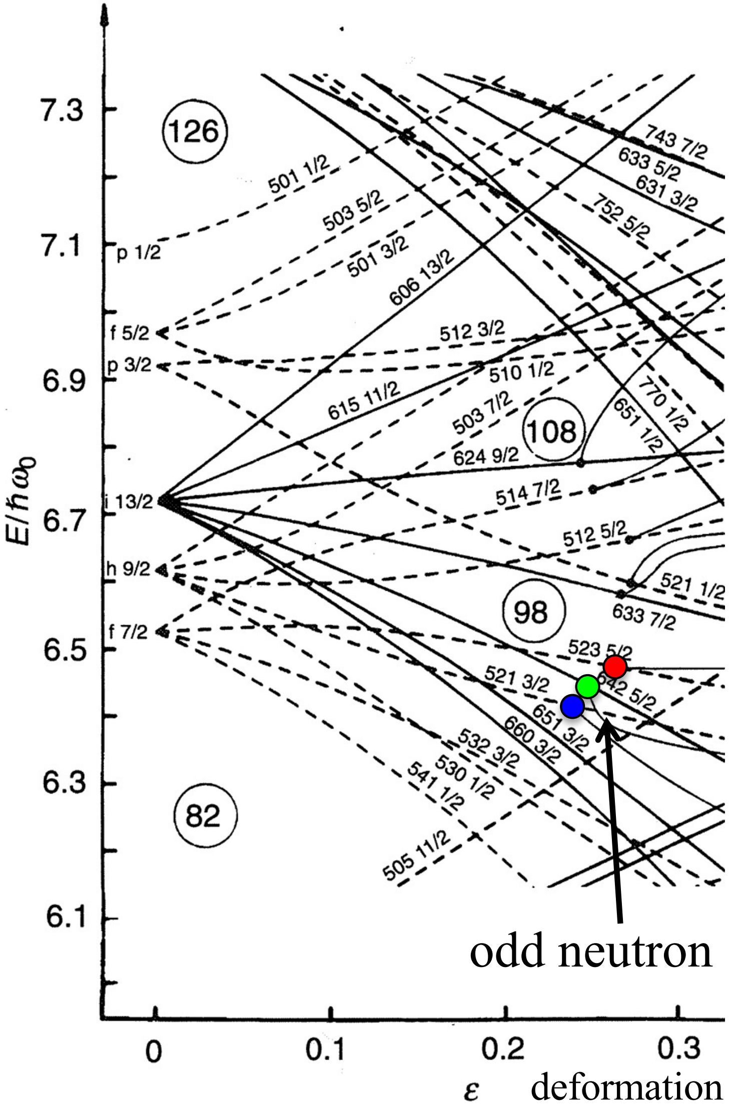
SVEN GÖSTA NILSSON

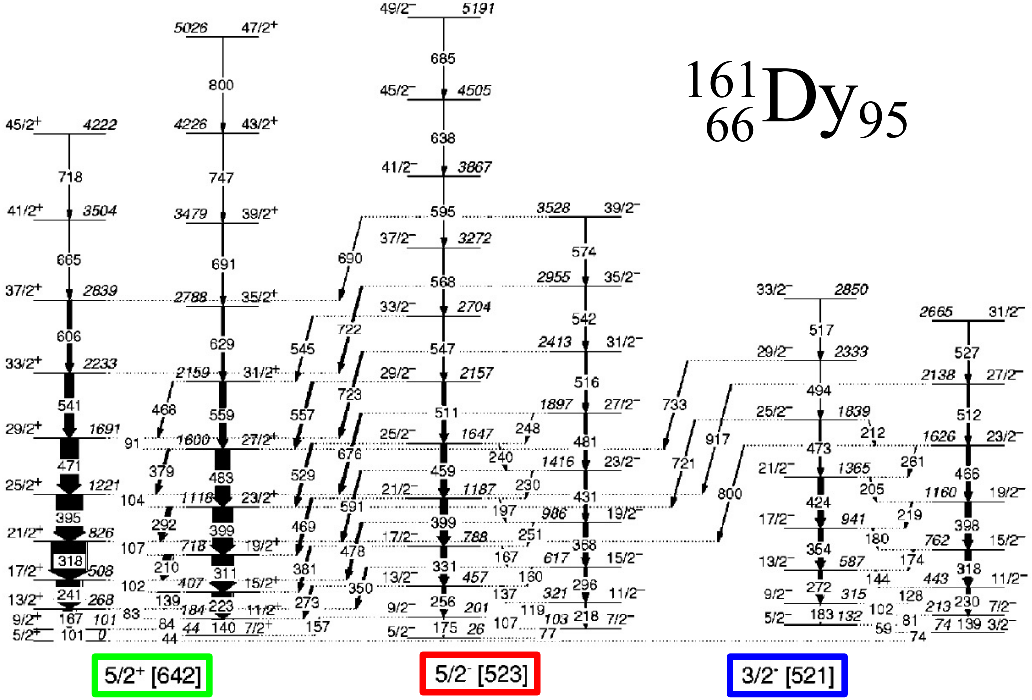


new asymptotic
quantum numbers

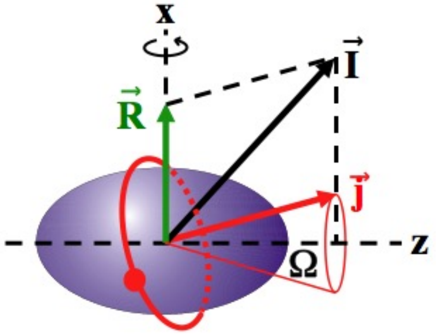
2j+1-fold degeneration is removed,
states with +m and –m still degenerate !

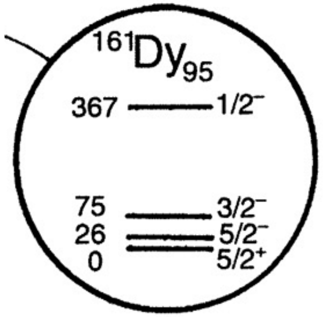
Single-particle motion in a deformed field





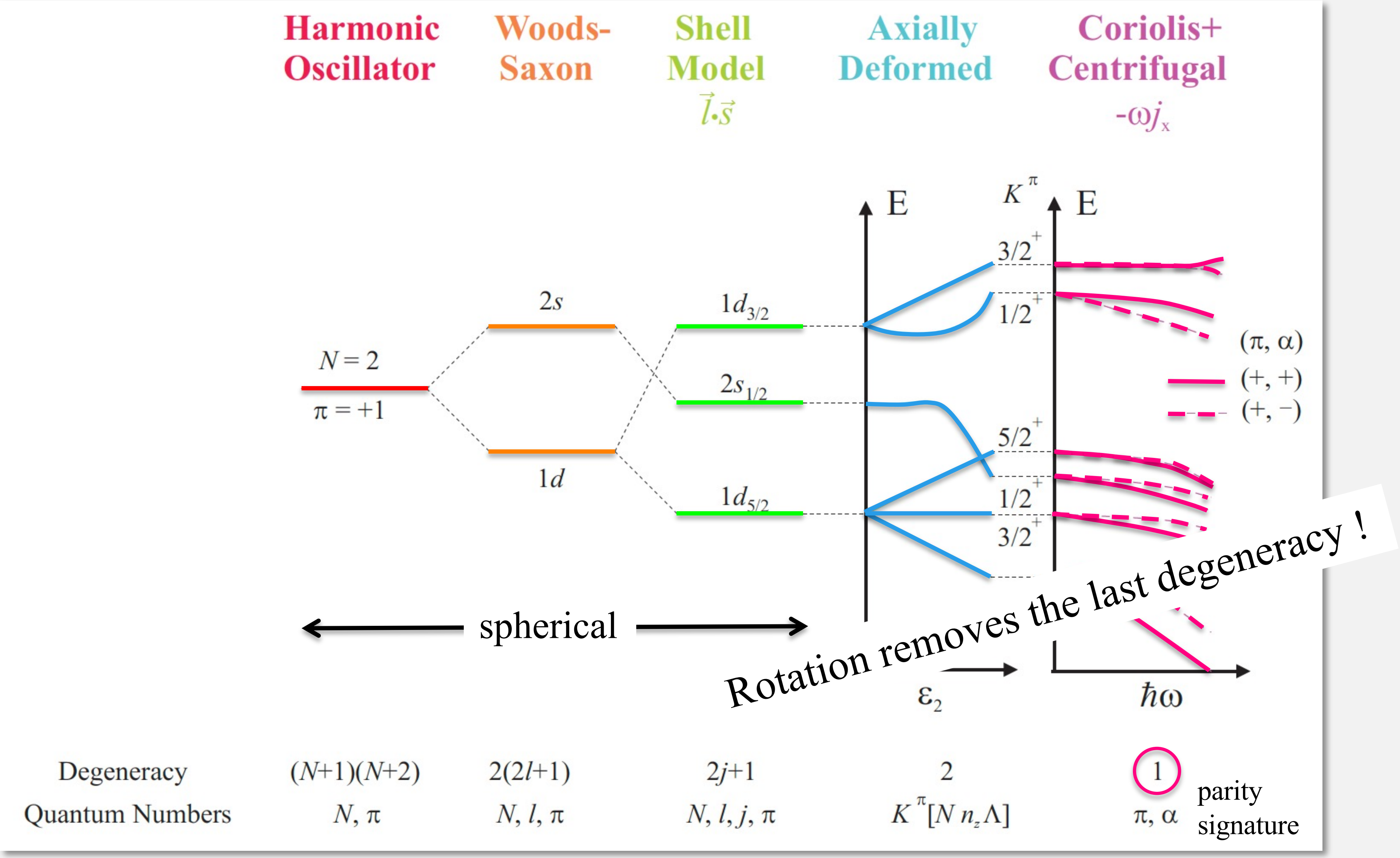
A. Jungclaus et al., Phys. Rev. C67, 034302 (2003)





Three rotational band heads within 75 keV !

Single-particle motion in a rotating deformed field



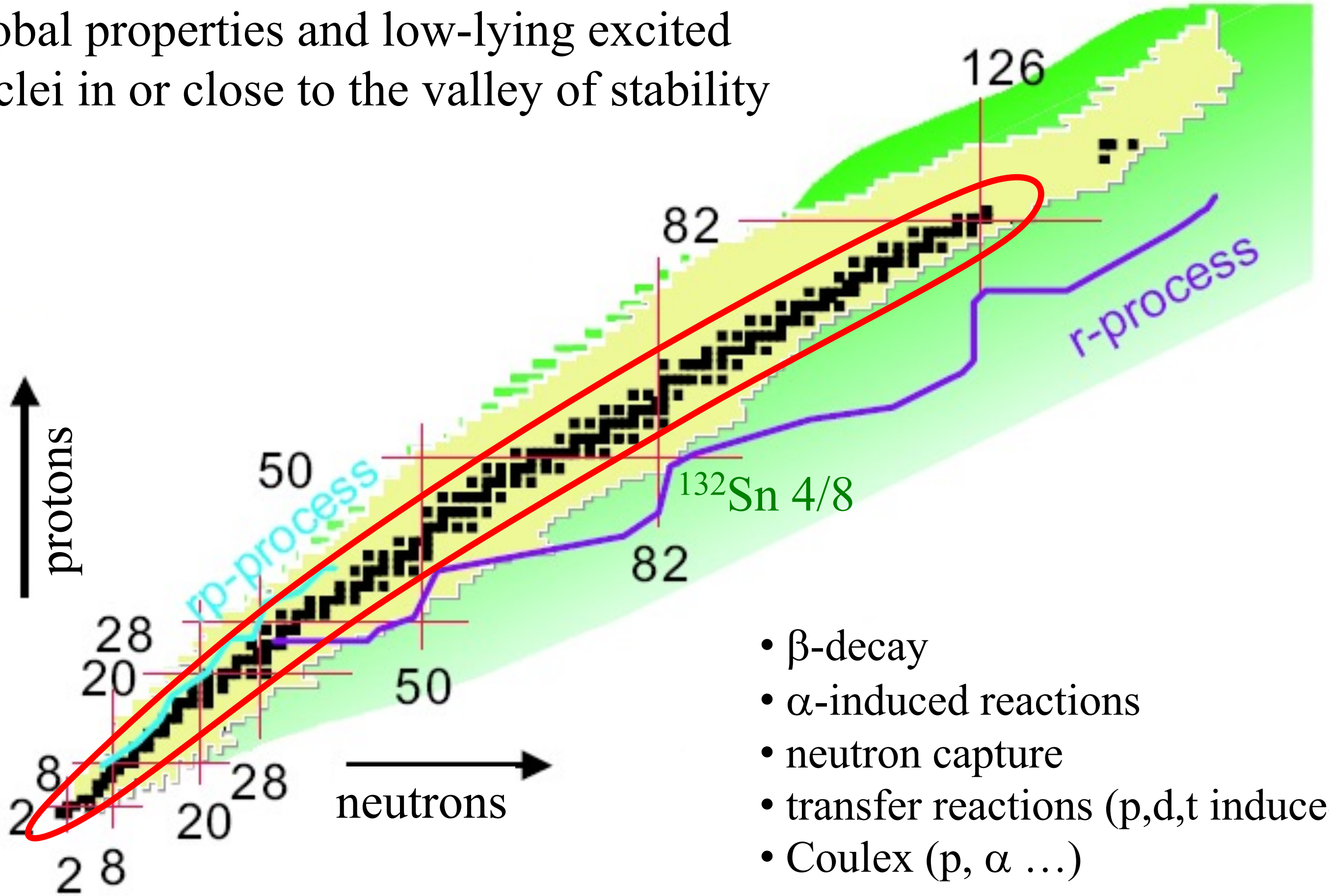
Rotation removes the last degeneracy !

	Harmonic Oscillator	Woods-Saxon	Shell Model	Axially Deformed	Coriolis+ Centrifugal
Degeneracy	$(N+1)(N+2)$	$2(2l+1)$	$2j+1$	2	①
Quantum Numbers	N, π	N, l, π	N, l, j, π	$K^\pi[N n_z \Lambda]$	π, α parity signature

Single-particle energies depend on deformation and rotational frequency !

Over the next twenty years ...

Study of global properties and low-lying excited states of nuclei in or close to the valley of stability



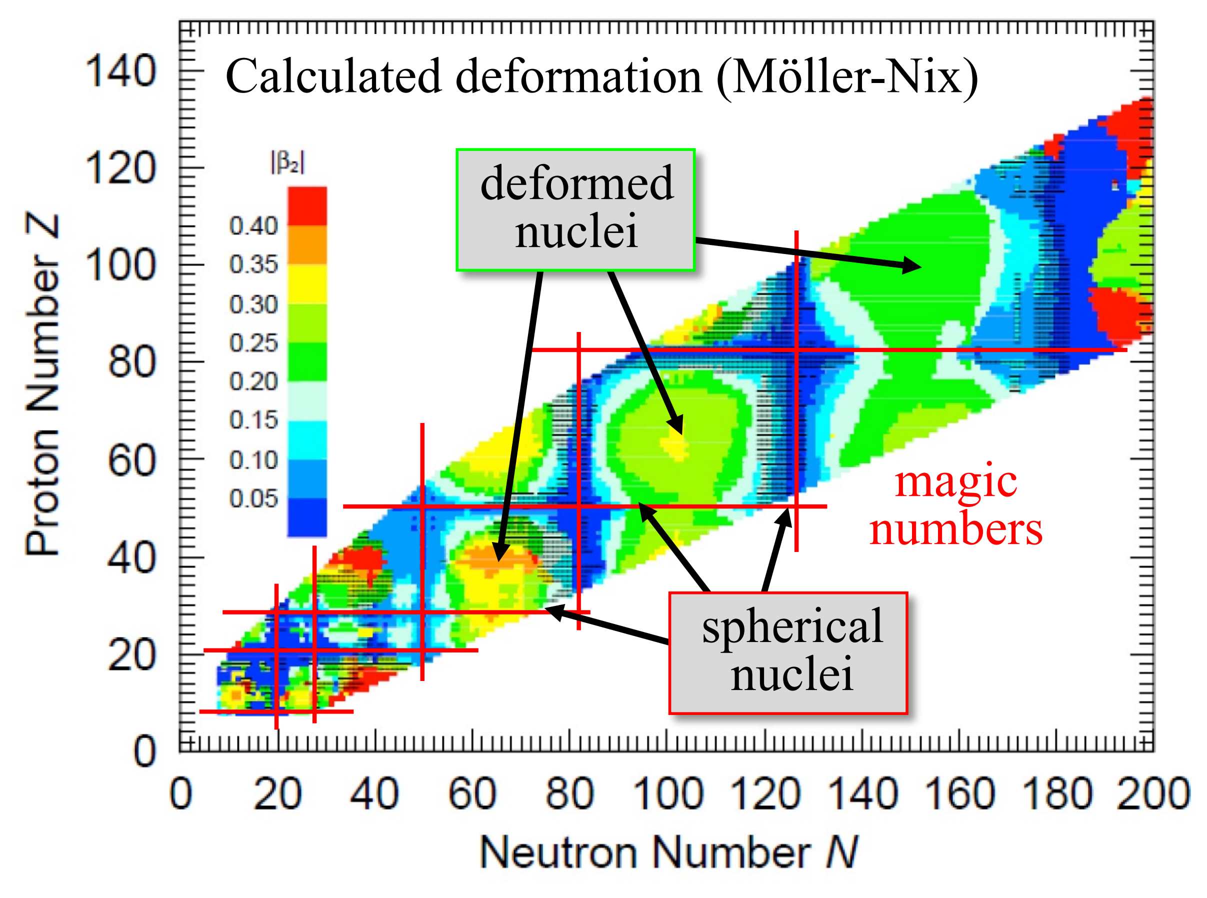
^{132}Sn 4/8

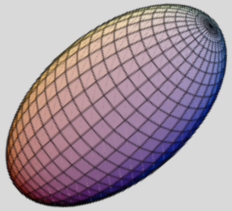
- β-decay
- α-induced reactions
- neutron capture
- transfer reactions (p,d,t induced)
- Coulex (p, α …)
- γ-induced neutron emission

- <u>scattering experiments (e, p …)</u>

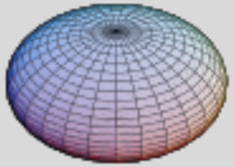
Radii and density distributions !

„Classical“ nuclear physics



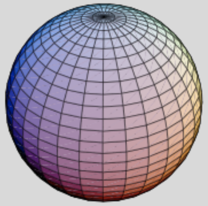


prolate nucleus



oblate nucleus

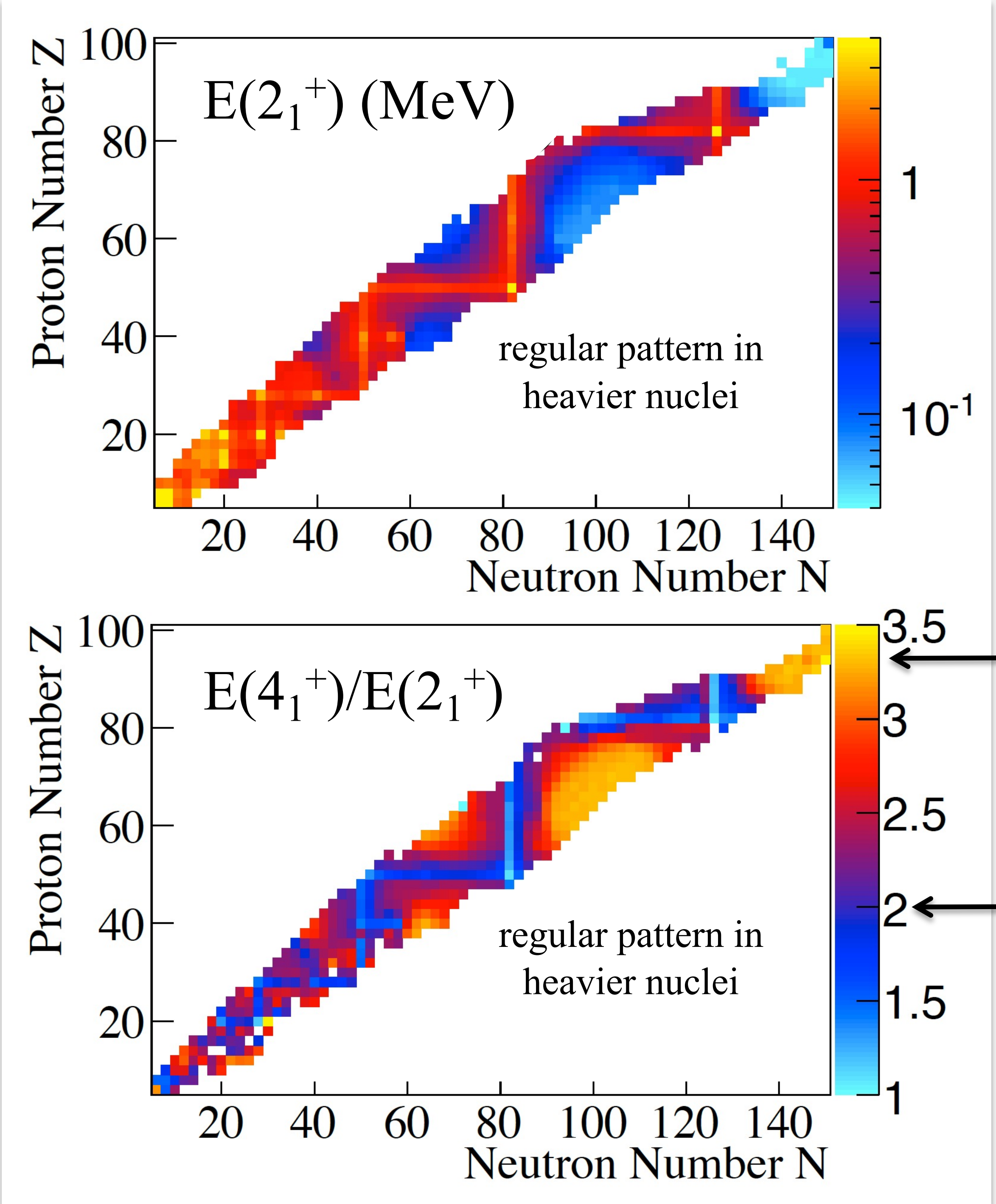
rotations and vibrations
→ collective models

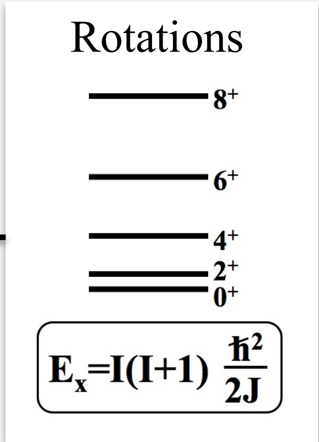


spherical nucleus

Single-particle excitations
→ nuclear shell model
vibrations → collective models

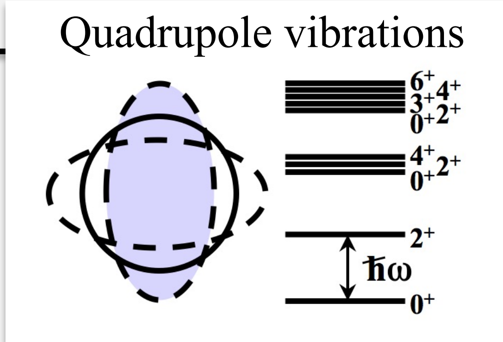
$E(2^+)$ and $E(4^+)/E(2^+)$ as global indicators in even-even nuclei





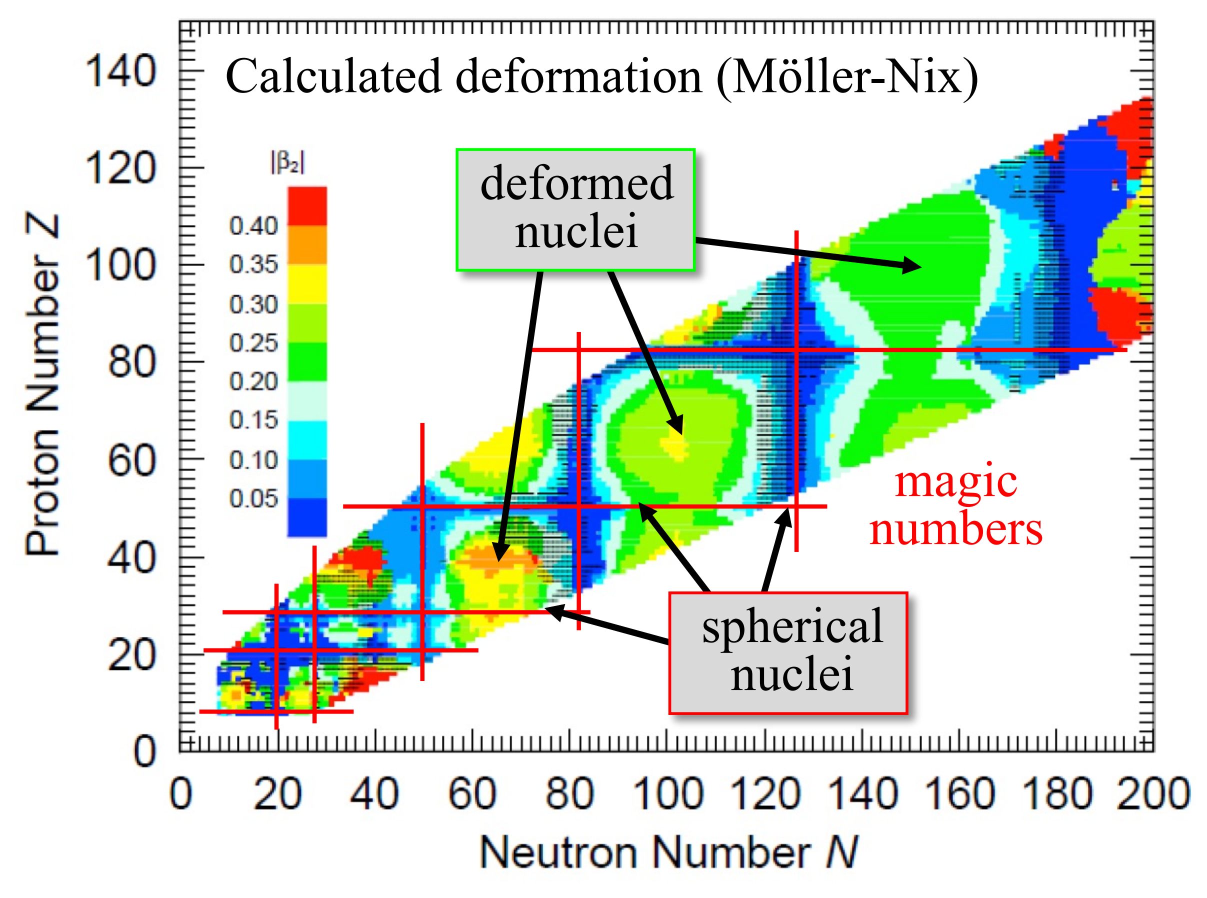
$$E_x = I(I+1)\,\frac{\hbar^2}{2J}$$

$E(4_1^+)/E(2_1^+)$
$=(4*5)/(2*3)$
$=20/6=\mathbf{3.3}$



$E(4_1^+)/E(2_1^+)$
$=2h\omega/h\omega=\mathbf{2}$

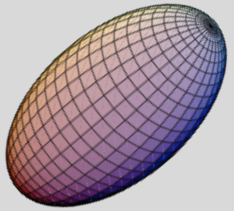
„Classical" nuclear physics



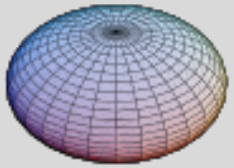
deformed nuclei

magic numbers

spherical nuclei

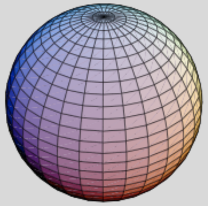


prolate nucleus



oblate nucleus

rotations and vibrations
→ collective models



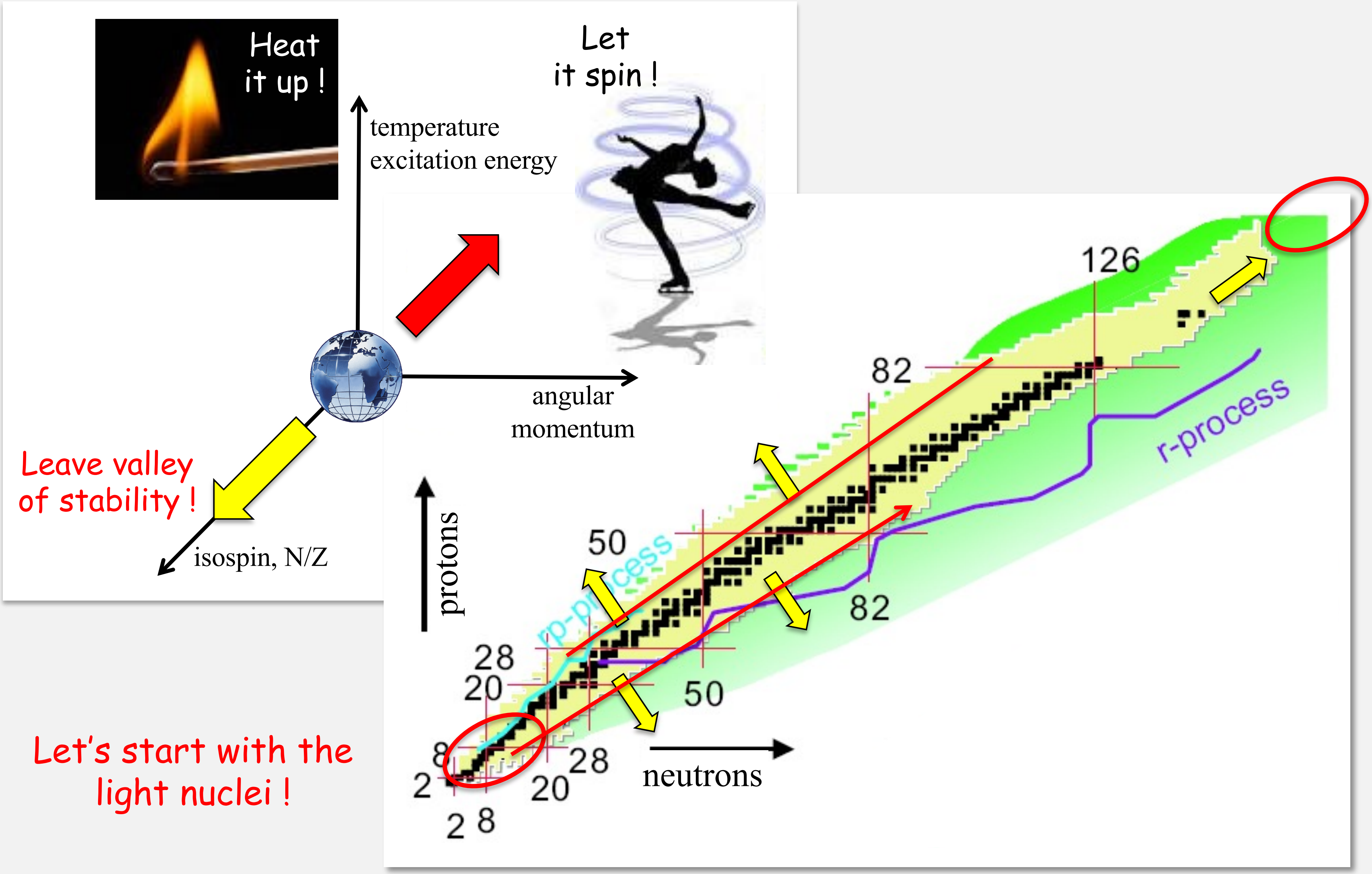
spherical nucleus

Single-particle excitations
→ nuclear shell model
vibrations → collective models

Is that already the full story ?

No !!!!!!!!!!!!!!!!

Let's play with all degrees of freedom

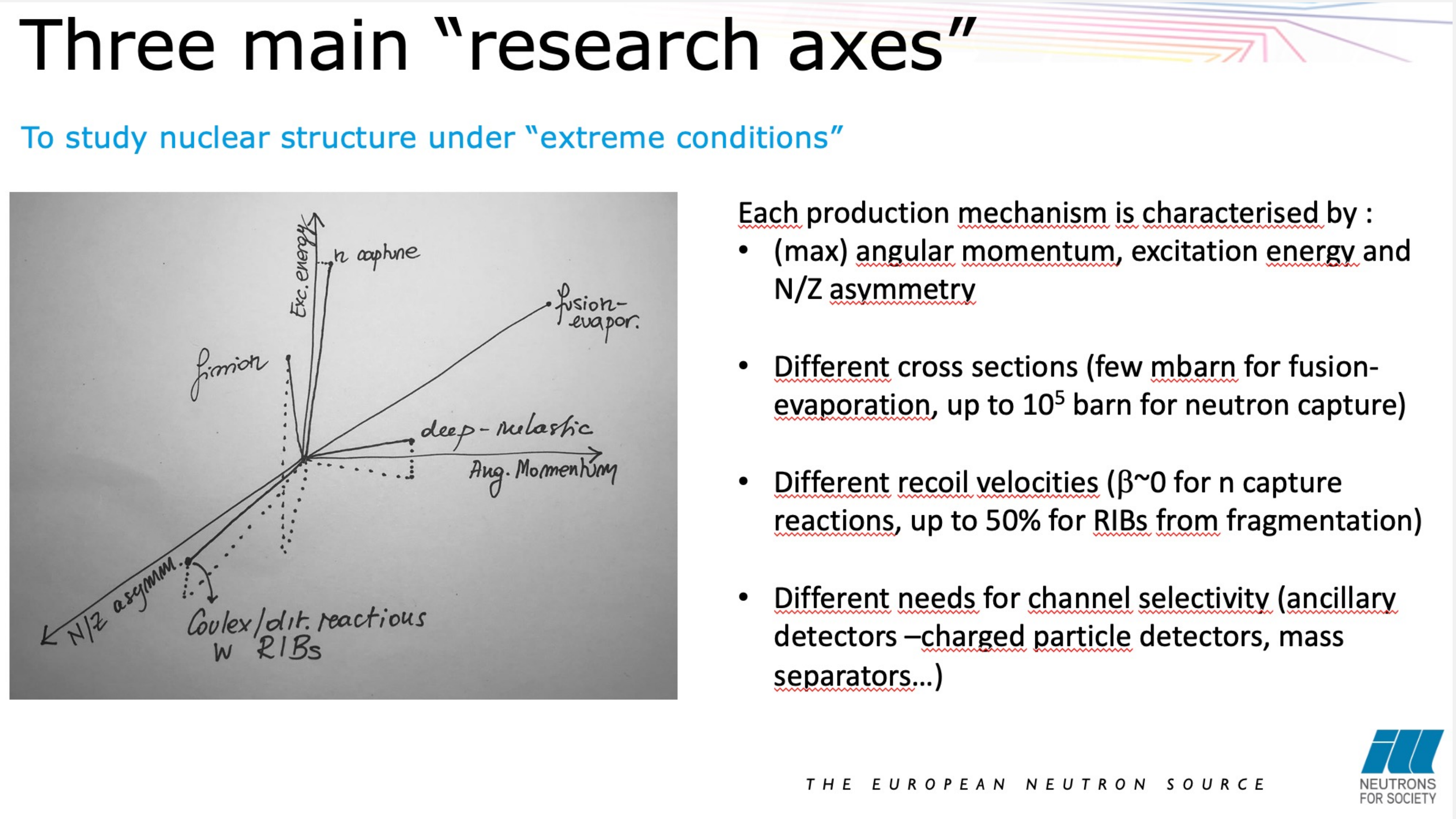


Heat it up !

Let it spin !

Leave valley of stability !

Let's start with the light nuclei !



Three main “research axes”

To study nuclear structure under “extreme conditions”

Each production mechanism is characterised by :

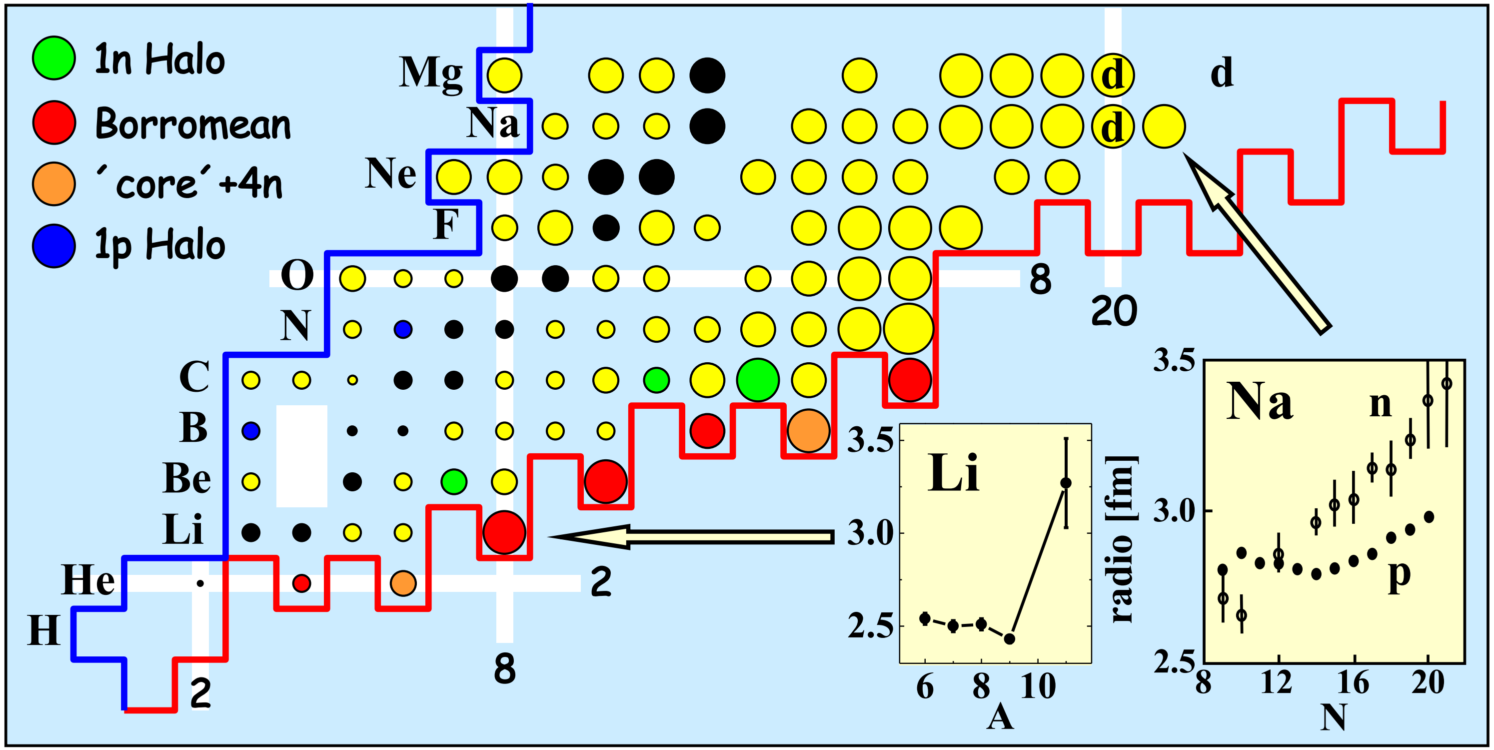
- (max) angular momentum, excitation energy and N/Z asymmetry
- Different cross sections (few mbarn for fusion-evaporation, up to 10^5 barn for neutron capture)
- Different recoil velocities (β~0 for n capture reactions, up to 50% for RIBs from fragmentation)
- Different needs for channel selectivity (ancillary detectors –charged particle detectors, mass separators…)

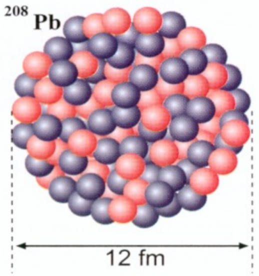
THE EUROPEAN NEUTRON SOURCE

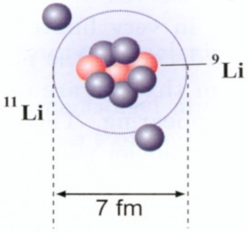
NEUTRONS FOR SOCIETY

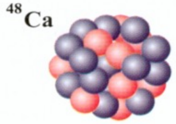
Caterina Michelagnoli, 1. Lecture

Nuclear radii - halos and neutron skins



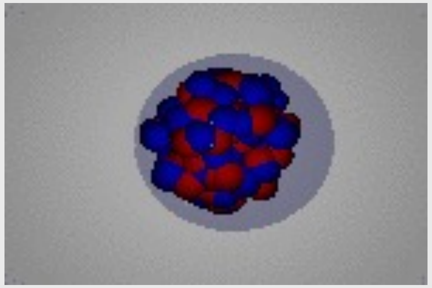




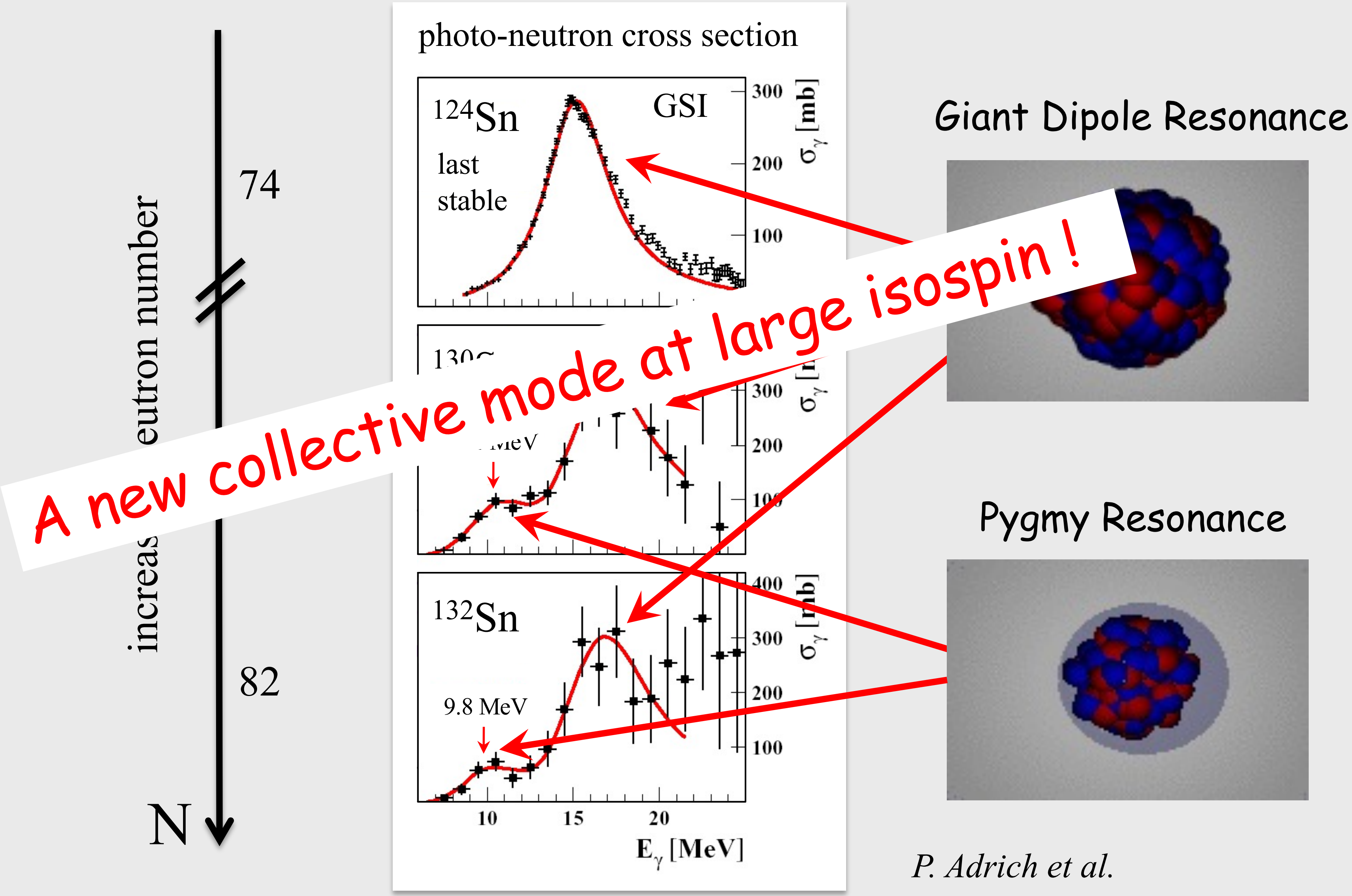


Remember:

- ○ $R = r_0 \cdot A^{1/3}$ $r_0 = 1.1\text{-}1.2$ fm
- ○ The thickness t of the nuclear surface is constant.
- ○ Protons and neutrons are uniformly mixed.



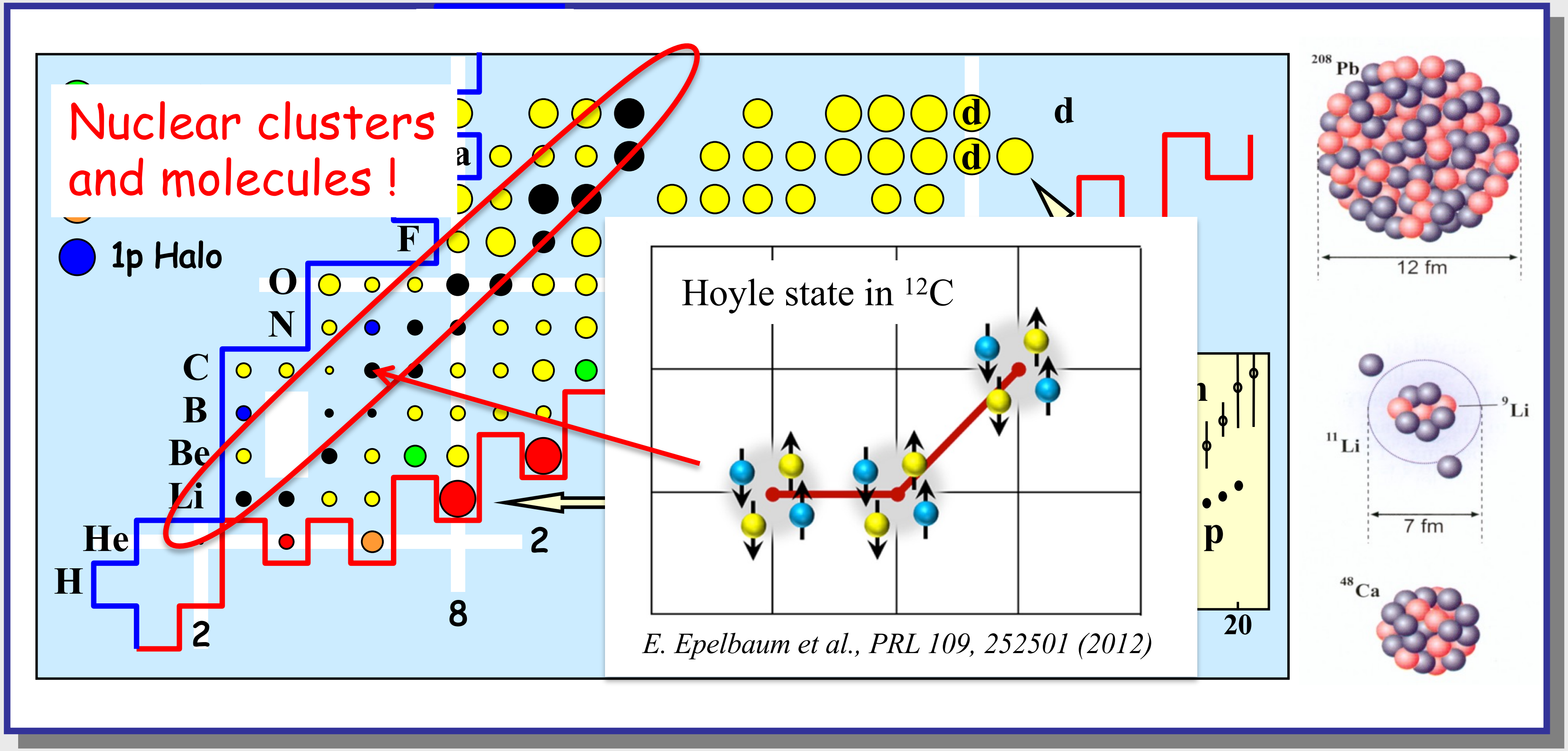
The Pygmy resonance in neutron-rich Sn isotopes



A new collective mode at large isospin !

P. Adrich et al.
Phys. Rev. Lett. 95 (2005) 132501

Nuclear radii – halos and neutron skins



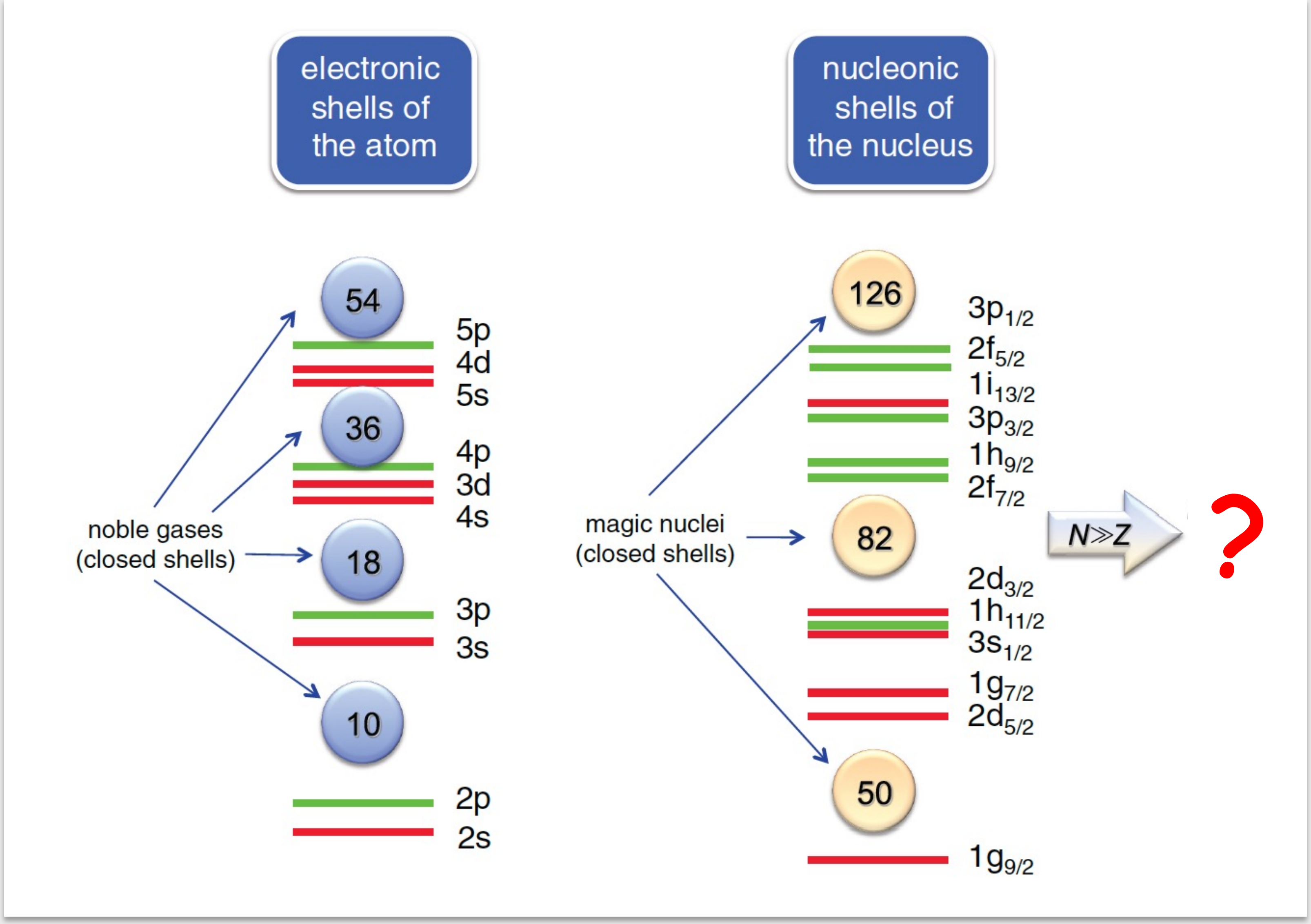
Nuclear clusters and molecules !

Hoyle state in ^{12}C

E. Epelbaum et al., PRL 109, 252501 (2012)

Light nuclei are indeed a rich playground !

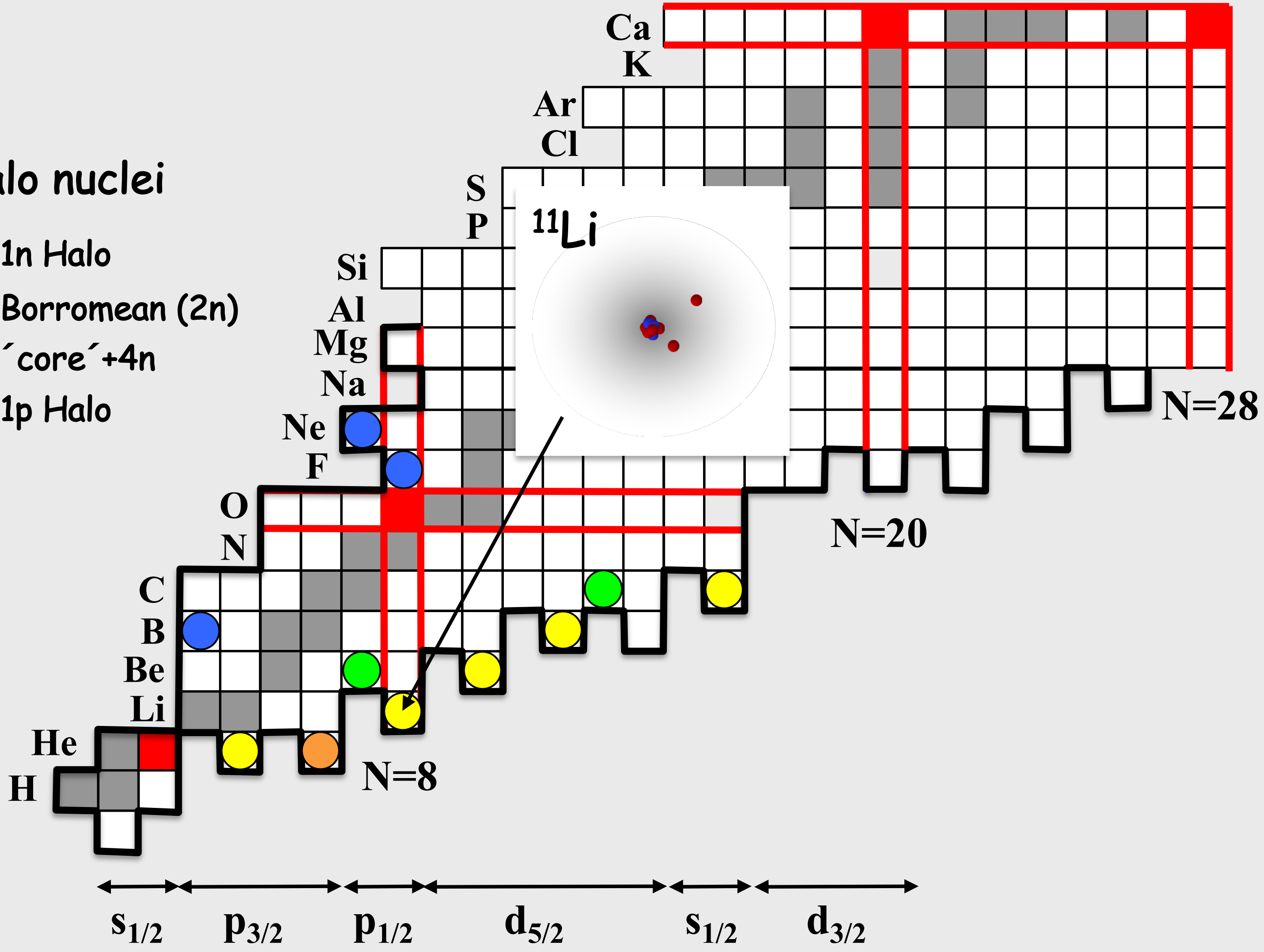
“Shell evolution” on the neutron-rich side



Neutron halos and the N=8 shell closure

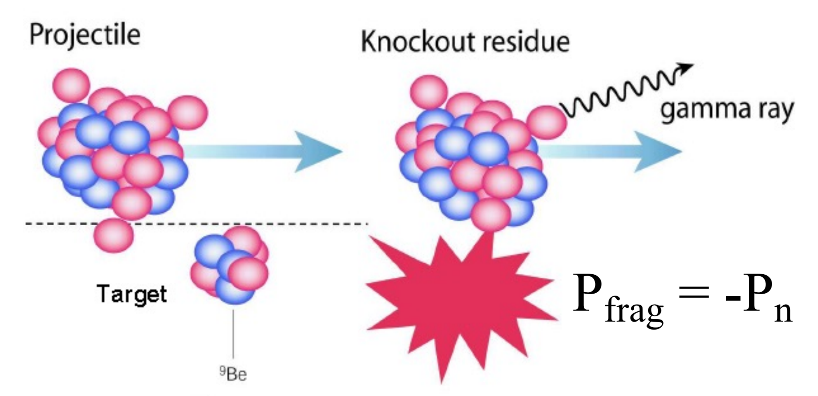
Halo nuclei

- 🟢 1n Halo
- 🟡 Borromean (2n)
- 🟠 ´core´+4n
- 🔵 1p Halo



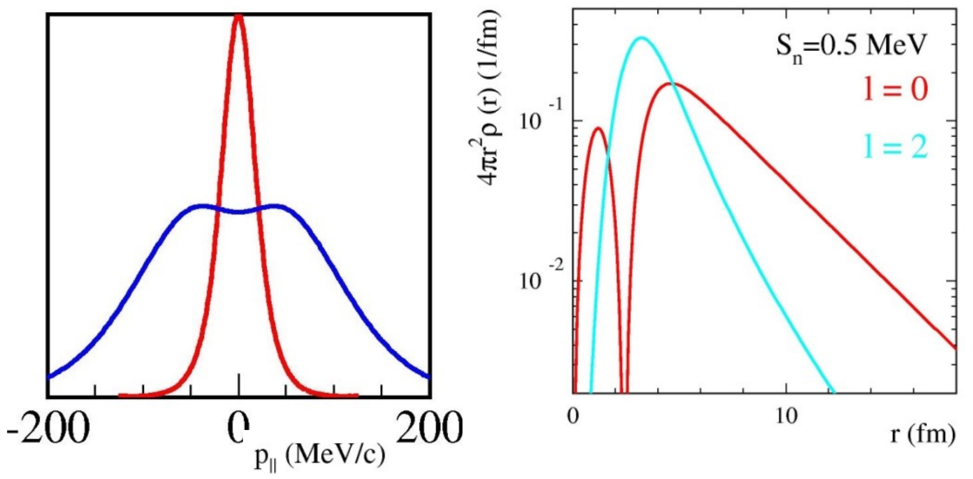
Knockout reactions at relativistic energies

knockout reaction



$P_{frag} = -P_n$

Heisenberg's uncertainty principle



momentum distribution | density distribution

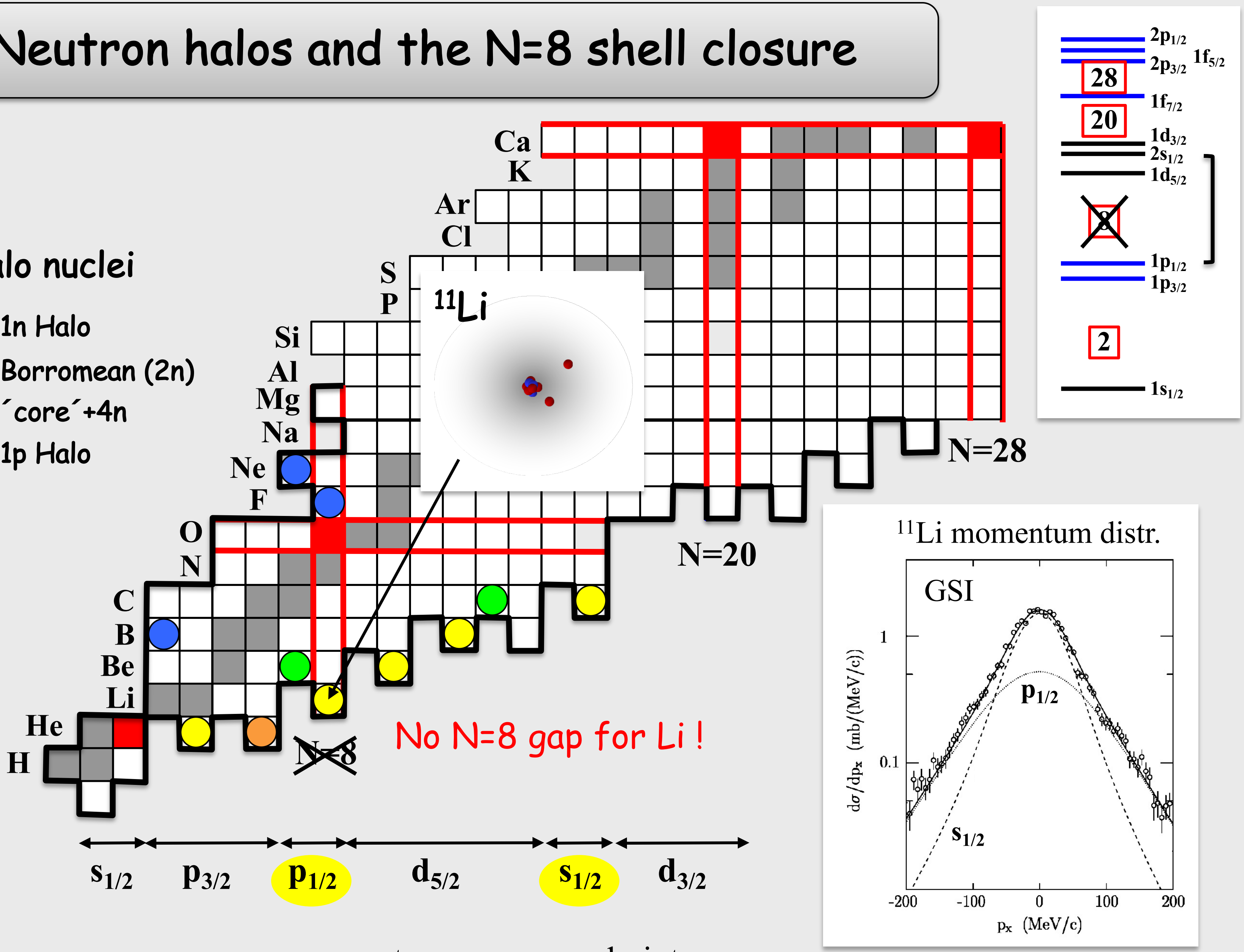
narrow momentum distribution | **extended** wavefunction

→ angular momentum ℓ of the removed nucleon

Neutron halos and the N=8 shell closure

Halo nuclei

- 🟩 1n Halo
- 🟨 Borromean (2n)
- 🟧 ´core´+4n
- 🟦 1p Halo

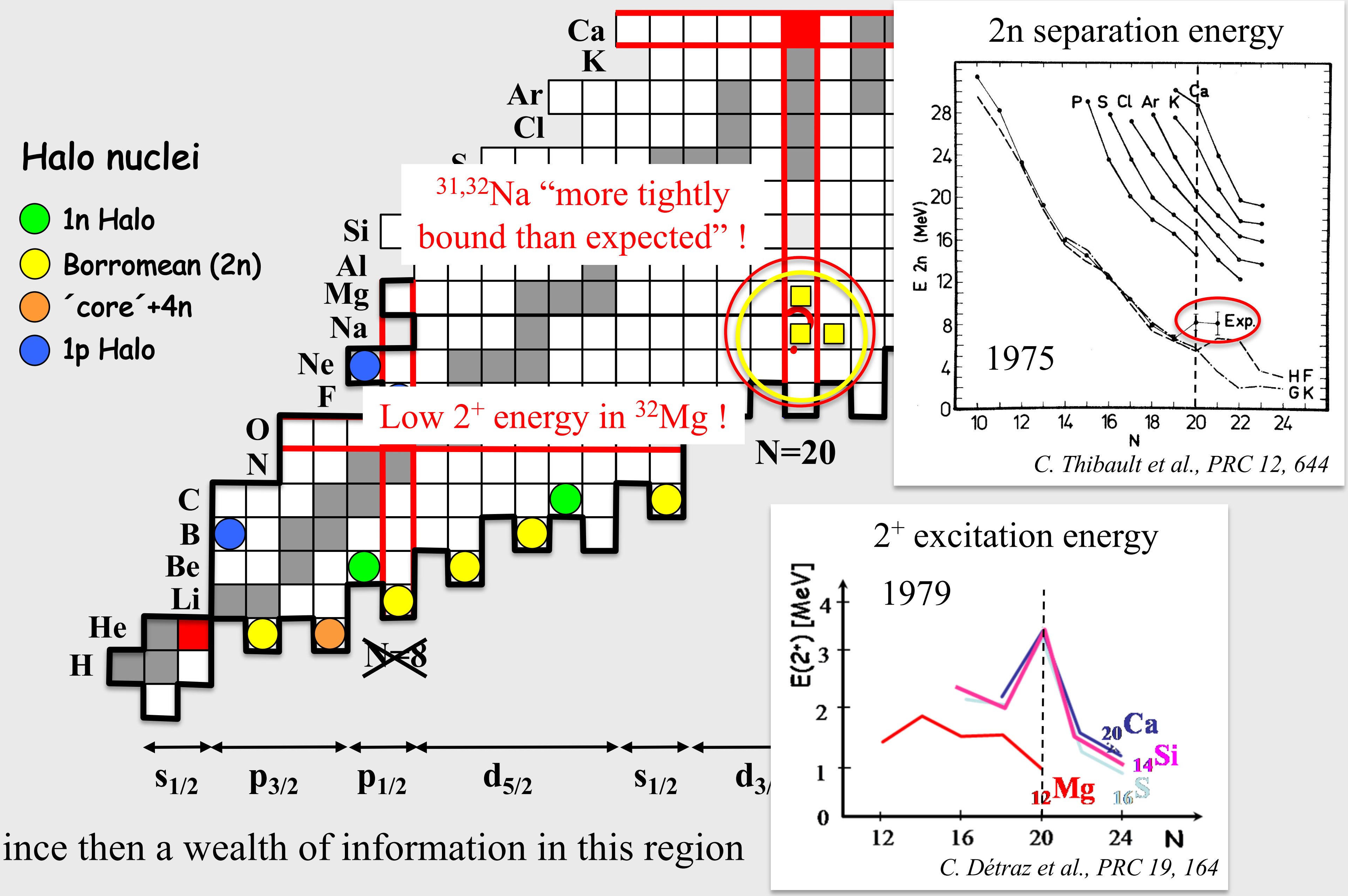


No N=8 gap for Li !

strong s-wave admixture

H. Simon et al., Phys. Rev. Lett. 83, 496 (1999)

What about the N=20 shell closure ?



^{31,32}Na “more tightly bound than expected” !

Low 2^+ energy in ^{32}Mg !

2n separation energy

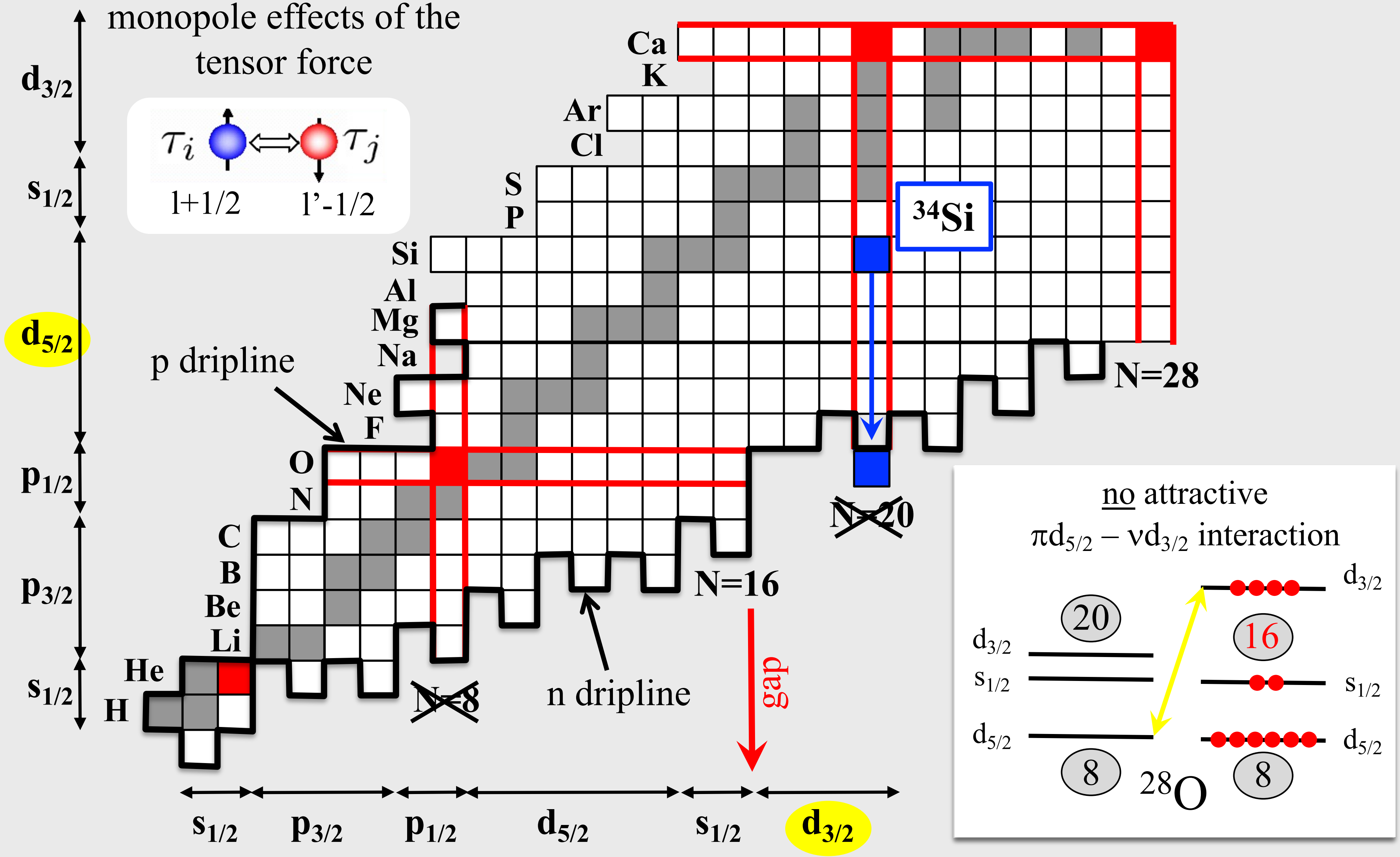
C. Thibault et al., PRC 12, 644

2^+ excitation energy

C. Détraz et al., PRC 19, 164

Since then a wealth of information in this region

Explanation within the shell model picture



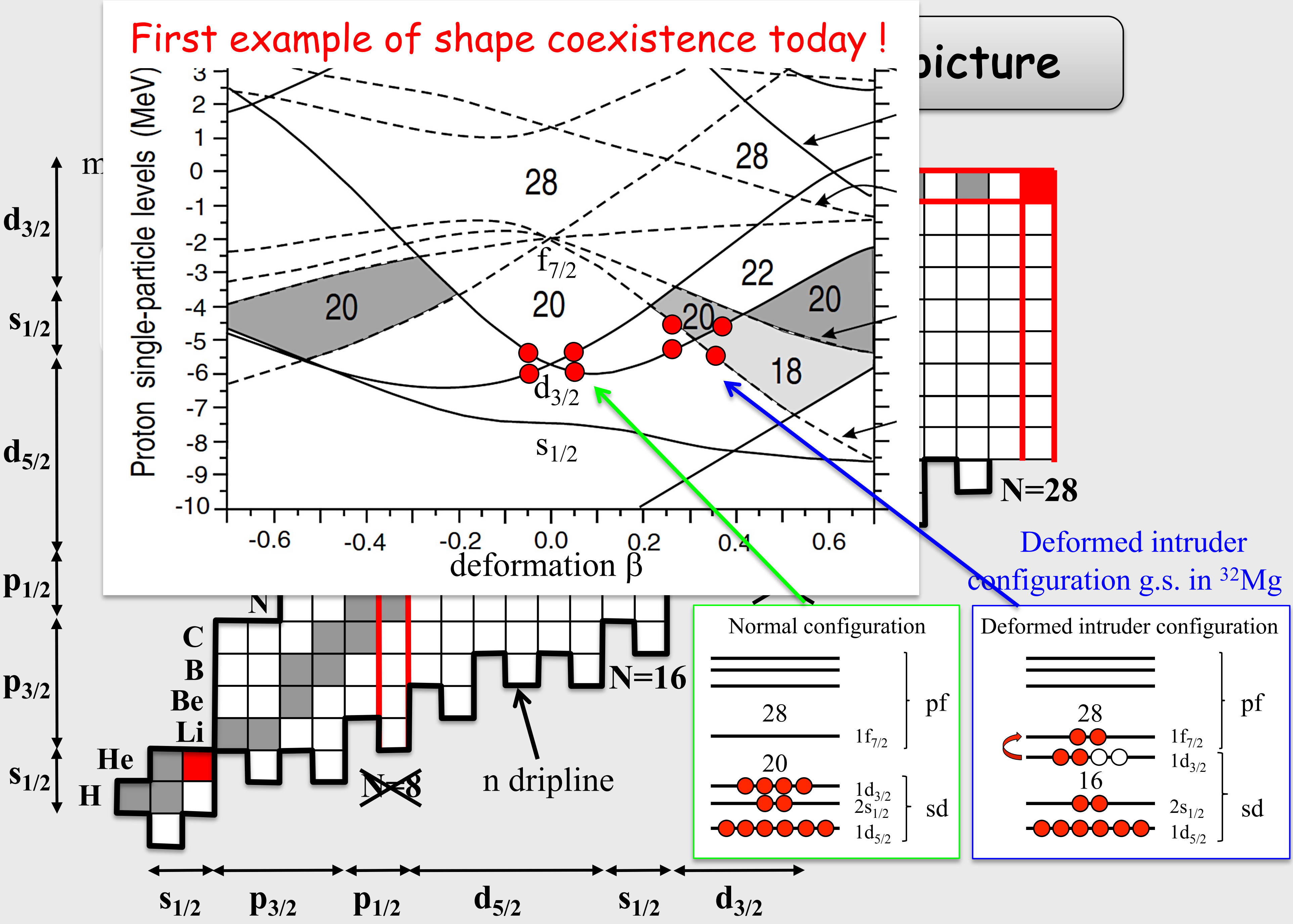
monopole effects of the tensor force

no attractive $\pi d_{5/2} - \nu d_{3/2}$ interaction

T. Otsuka et al., Phys. Rev. Lett. 87, 082502 (2001); Phys. Rev. Lett. 95, 232502 (2005)

picture

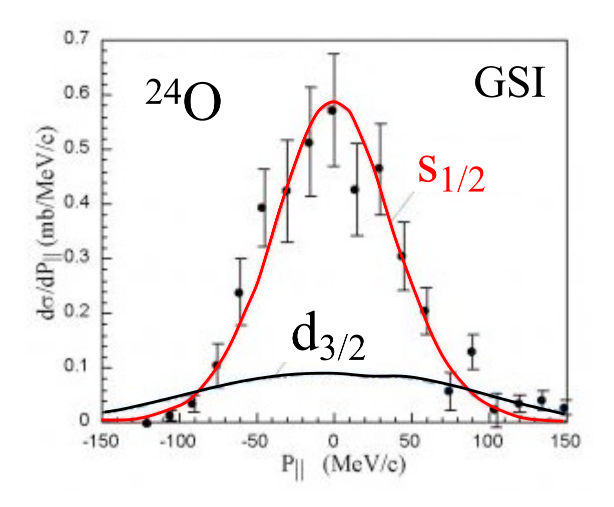
First example of shape coexistence today !



Deformed intruder configuration g.s. in ^{32}Mg !

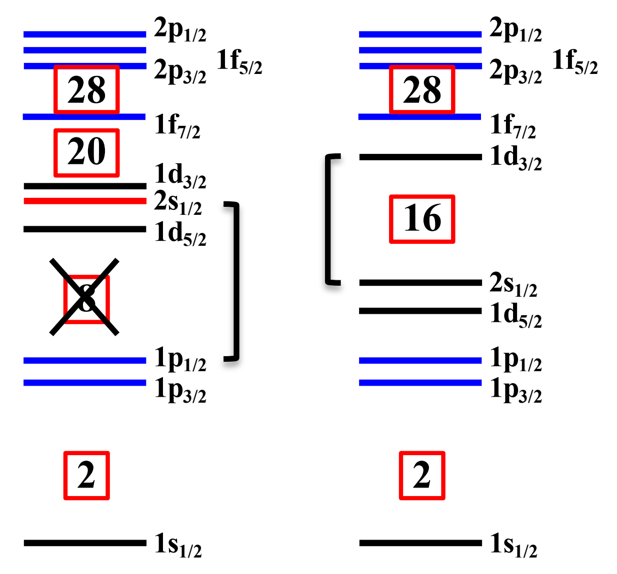
T. Otsuka et al., Phys. Rev. Lett. 87, 082502 (2001); Phys. Rev. Lett. 95, 232502 (2005)

Momentum distributions in ^{23,24}O

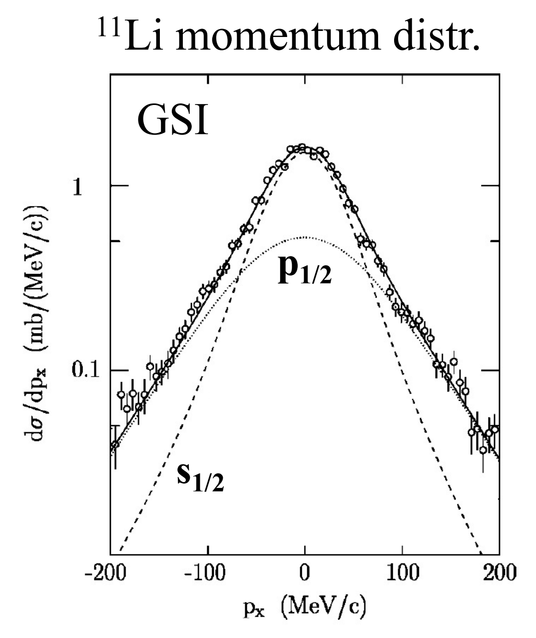


R. Kanungo et al., PRL 102, 152501 (2009)

Last neutron occupies **$s_{1/2}$** orbital, no **$d_{3/2}$** component !

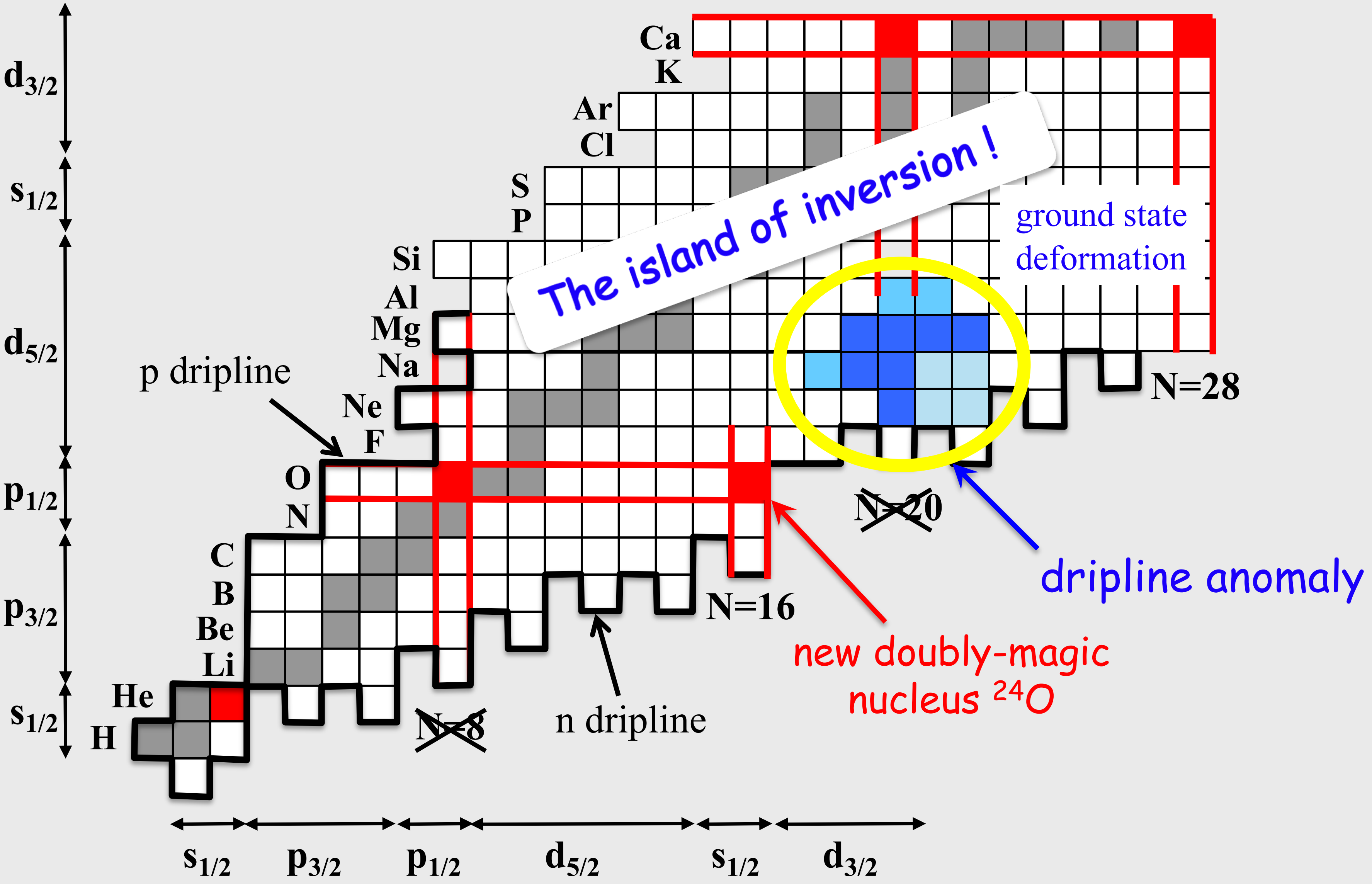


$s_{1/2}$ and **$d_{3/2}$** close in energy,
mixing to be expected
No mixing → N=16 gap !

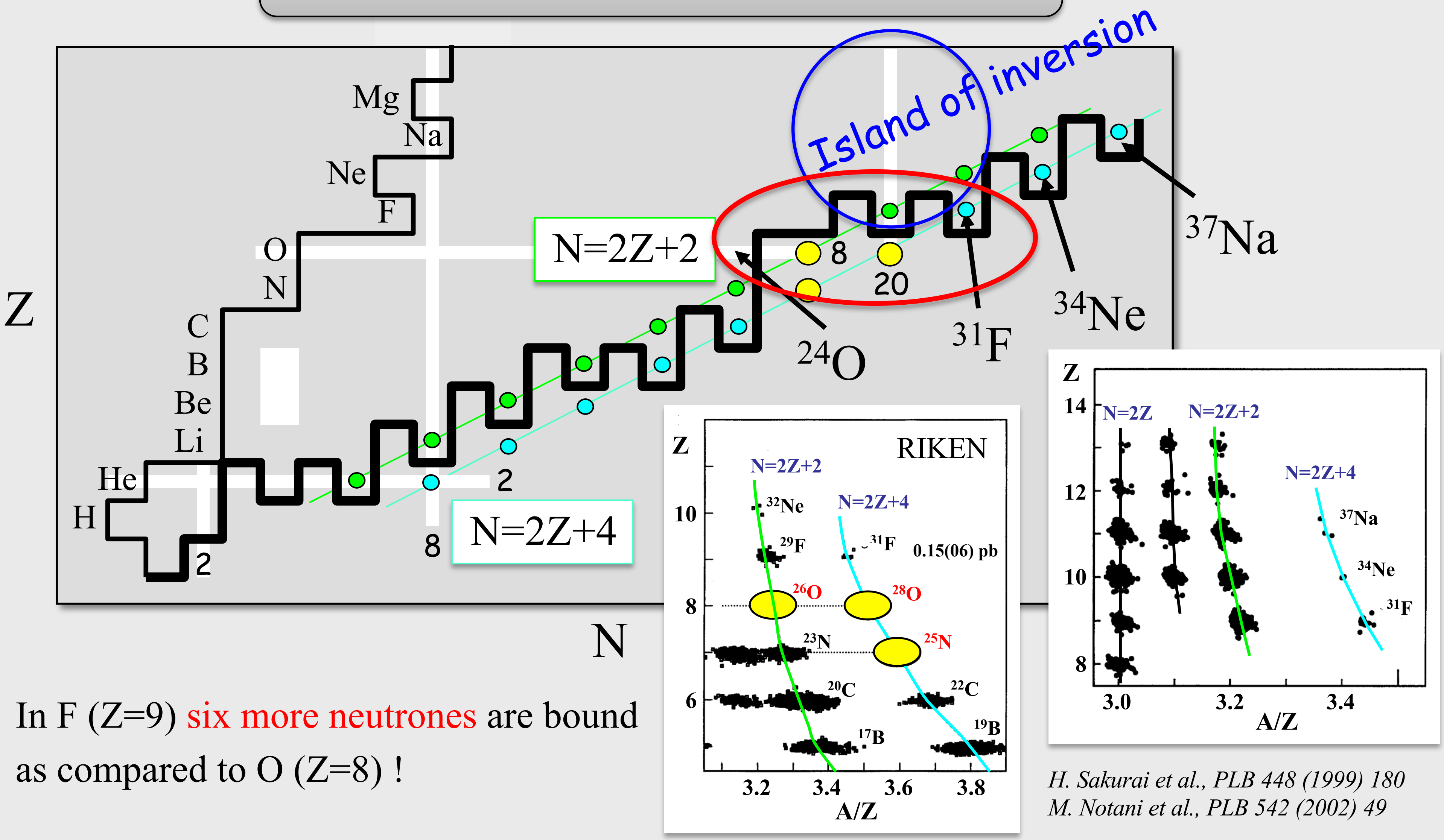


Spherical magic number at N=16,
^{24}O doubly magic !

New magic number and the island of inversion



The neutron dripline up to Na



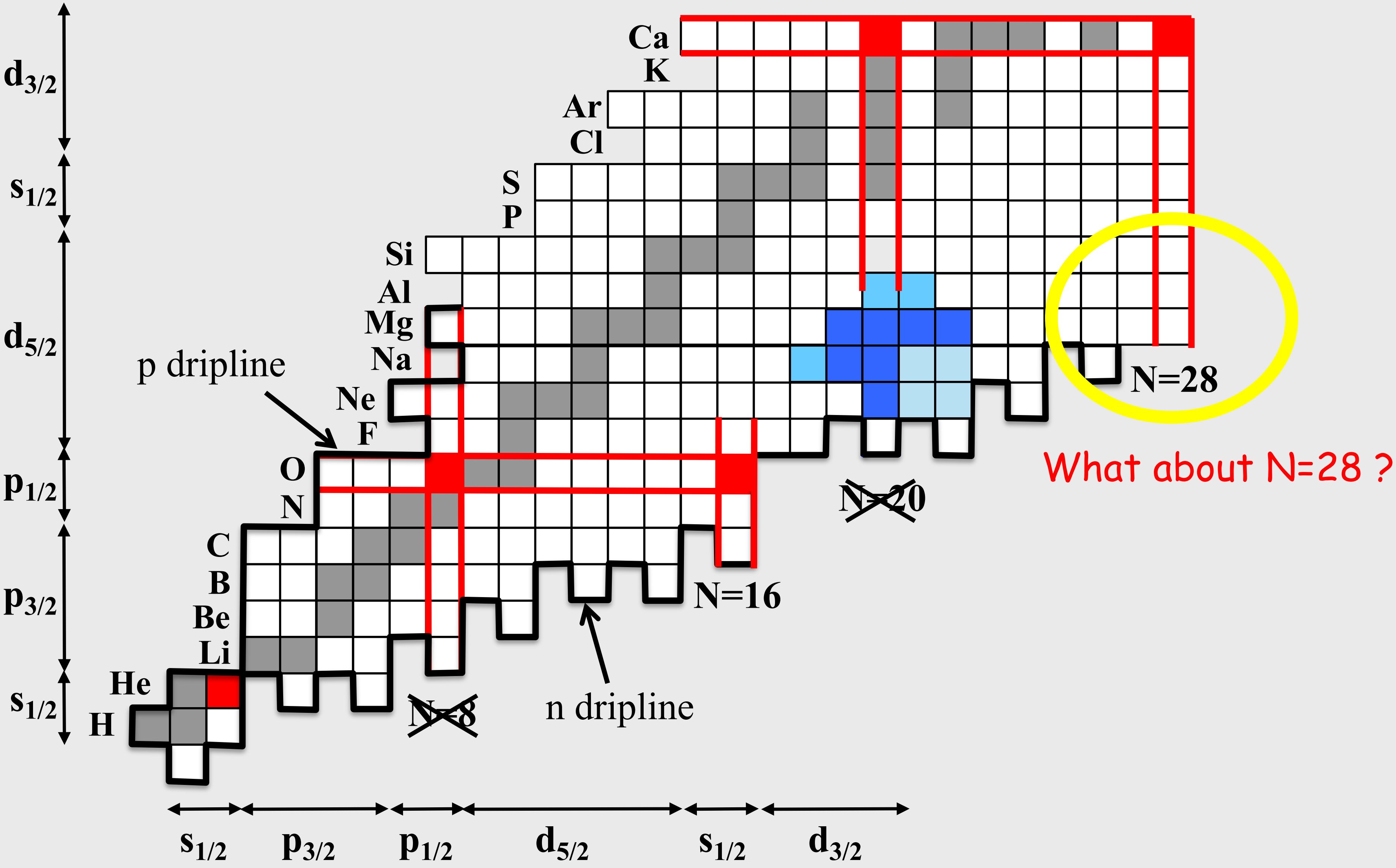
H. Sakurai et al., PLB 448 (1999) 180
M. Notani et al., PLB 542 (2002) 49

In F (Z=9) six more neutrones are bound as compared to O (Z=8) !

Additional binding due to deformation !!!

The mere existence of a nucleus already tells us something …

New magic number and the island of inversion



What about N=28 ?

nature Vol 449|25 October 2007|doi:10.1038/nature06213

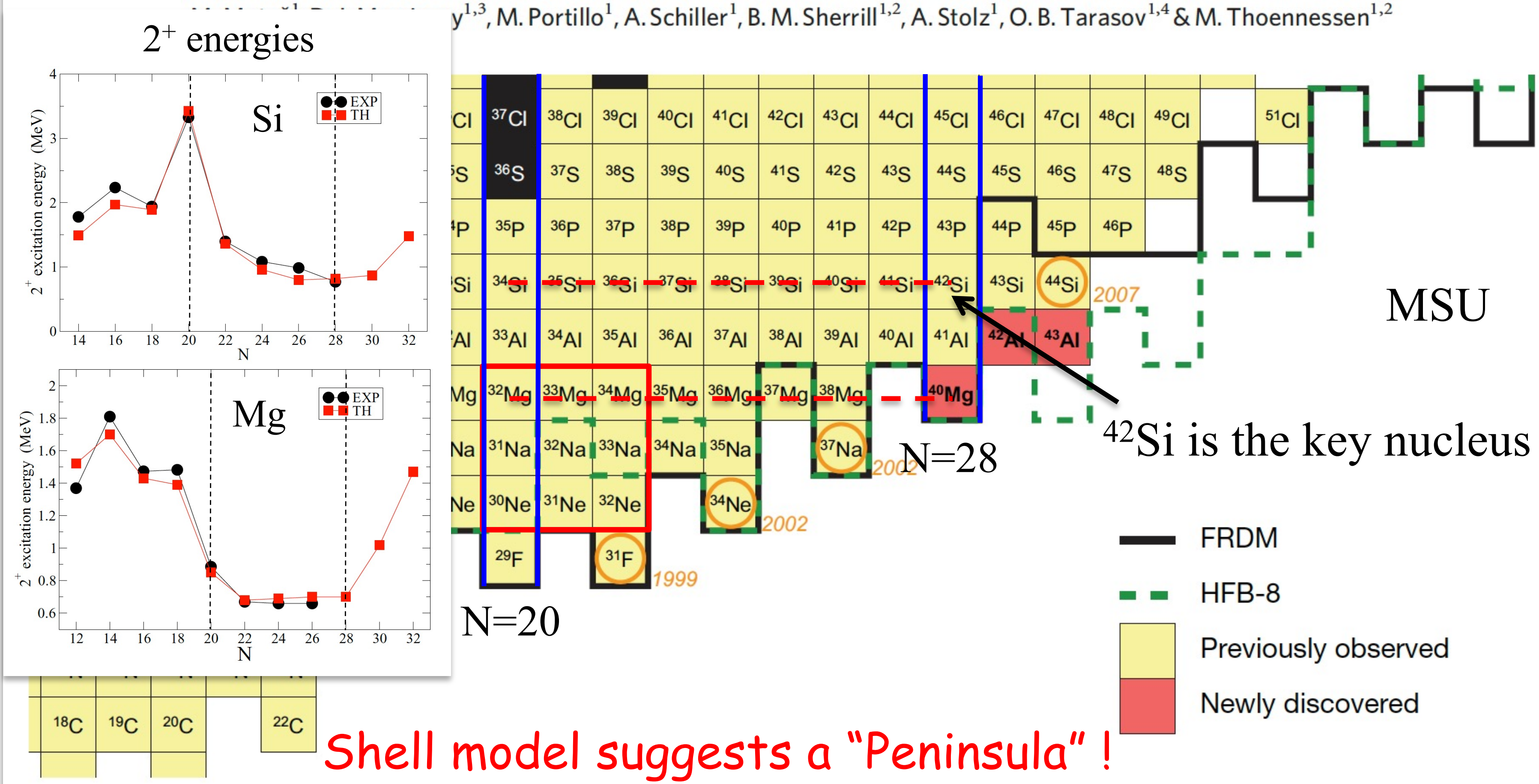
LETTERS

A second "island of inversion" at N=28 ?

Discovery of ^{40}Mg and ^{42}Al suggests neutron drip-line slant towards heavier isotopes

2007

T. Baumann[1], A. M. Amthor[1,2], D. Bazin[1], B. A. Brown[1,2], C. M. Folden III[1], A. Gade[1,2], T. N. Ginter[1], M. Hausmann[1],
y[1,3], M. Portillo[1], A. Schiller[1], B. M. Sherrill[1,2], A. Stolz[1], O. B. Tarasov[1,4] & M. Thoennessen[1,2]



MSU

N=28

^{42}Si is the key nucleus

N=20

Shell model suggests a "Peninsula" !

What about the N=28 shell closure ?

More complete experimental
information needed !

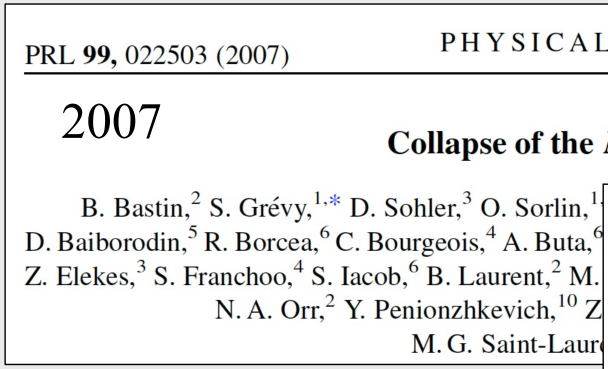
nature — Vol 435|16 June 2005|doi:10.1038/nature03619

LETTERS

2005

'Magic' nucleus ^{42}Si

J. Fridmann[1], I. Wiedenhöver[1], A. Gade[2], L. T. Baby[1], D. Bazin[2], B. A. Brown[2], C. M. Campbell[2], J. M. Cook[2], P. D. Cottle[1], E. Diffenderfer[1], D.-C. Dinca[2], T. Glasmacher[2], P. G. Hansen[2], K. W. Kemper[1], J. L. Lecouey[2], W. F. Mueller[2], H. Olliver[2], E. Rodriguez-Vieitez[3], J. R. Terry[2], J. A. Tostevin[4] & K. Yoneda[2]

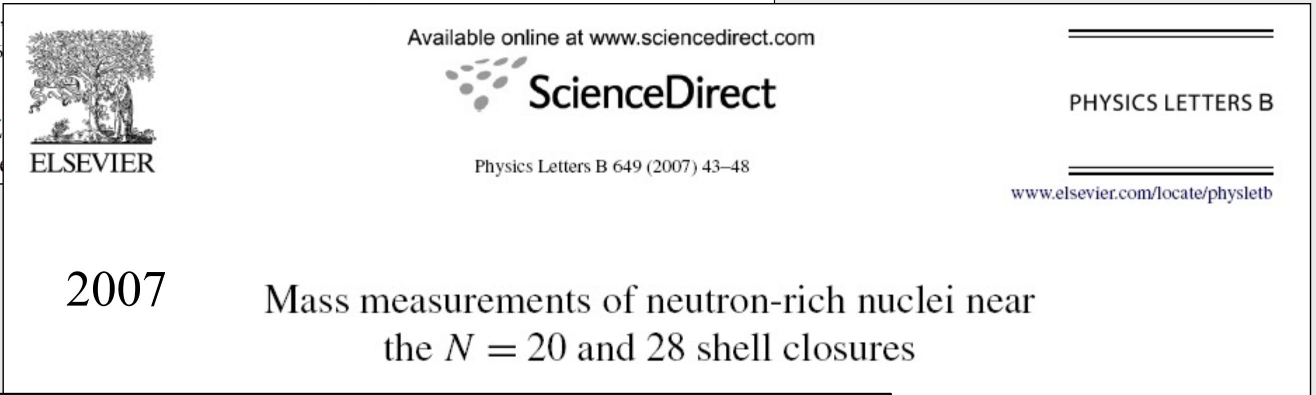


PRL **99,** 022503 (2007) — PHYSICAL REVIEW LETTERS — week ending 13 JULY 2007

2007

Collapse of the $N = 28$ Shell Closure in ^{42}Si

B. Bastin,[2] S. Grévy,[1,*] D. Sohler,[3] O. Sorlin,
D. Baiborodin,[5] R. Borcea,[6] C. Bourgeois,[4] A. Buta,
Z. Elekes,[3] S. Franchoo,[4] S. Iacob,[6] B. Laurent,[2] M.
N. A. Orr,[2] Y. Penionzhkevich,[10] Z
M. G. Saint-Laur



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PHYSICS LETTERS B

ELSEVIER

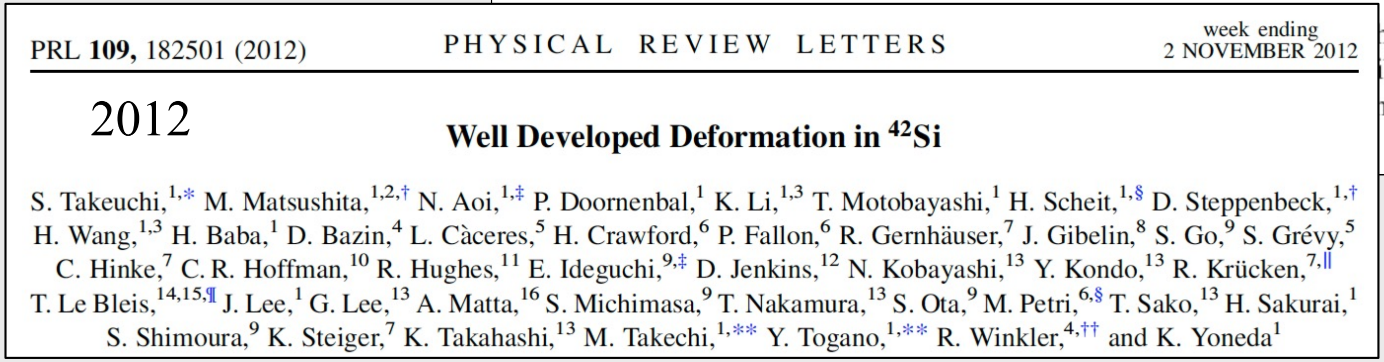
Physics Letters B 649 (2007) 43–48

www.elsevier.com/locate/physletb

2007

Mass measurements of neutron-rich nuclei near the $N = 20$ and 28 shell closures

homaz[a], D. Baiborodin[c],
ibert[f], L. Giot[a], A. Khouaja[a],
h[h], S. Pita[a], M. Rousseau[a],



PRL **109,** 182501 (2012) — PHYSICAL REVIEW LETTERS — week ending 2 NOVEMBER 2012

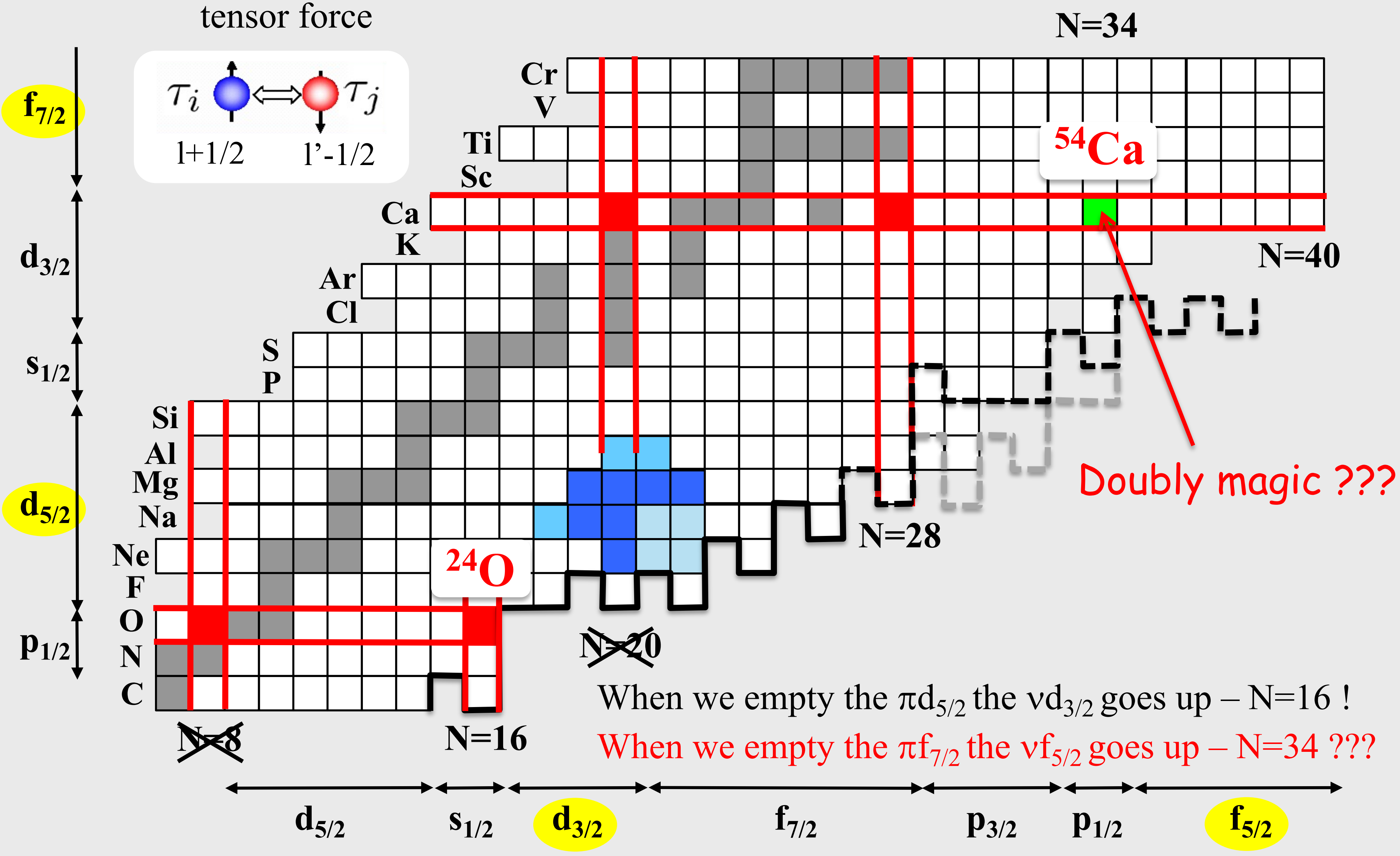
2012

Well Developed Deformation in ^{42}Si

S. Takeuchi,[1,*] M. Matsushita,[1,2,†] N. Aoi,[1,‡] P. Doornenbal,[1] K. Li,[1,3] T. Motobayashi,[1] H. Scheit,[1,§] D. Steppenbeck,[1,†] H. Wang,[1,3] H. Baba,[1] D. Bazin,[4] L. Càceres,[5] H. Crawford,[6] P. Fallon,[6] R. Gernhäuser,[7] J. Gibelin,[8] S. Go,[9] S. Grévy,[5] C. Hinke,[7] C. R. Hoffman,[10] R. Hughes,[11] E. Ideguchi,[9,‡] D. Jenkins,[12] N. Kobayashi,[13] Y. Kondo,[13] R. Krücken,[7,||] T. Le Bleis,[14,15,¶] J. Lee,[1] G. Lee,[13] A. Matta,[16] S. Michimasa,[9] T. Nakamura,[13] S. Ota,[9] M. Petri,[6,§] T. Sako,[13] H. Sakurai,[1] S. Shimoura,[9] K. Steiger,[7] K. Takahashi,[13] M. Takechi,[1,**] Y. Togano,[1,**] R. Winkler,[4,††] and K. Yoneda[1]

Is N=34 a new magic number far-off stability ?

monopole effects of the
tensor force



When we empty the $\pi d_{5/2}$ the $\nu d_{3/2}$ goes up – N=16 !

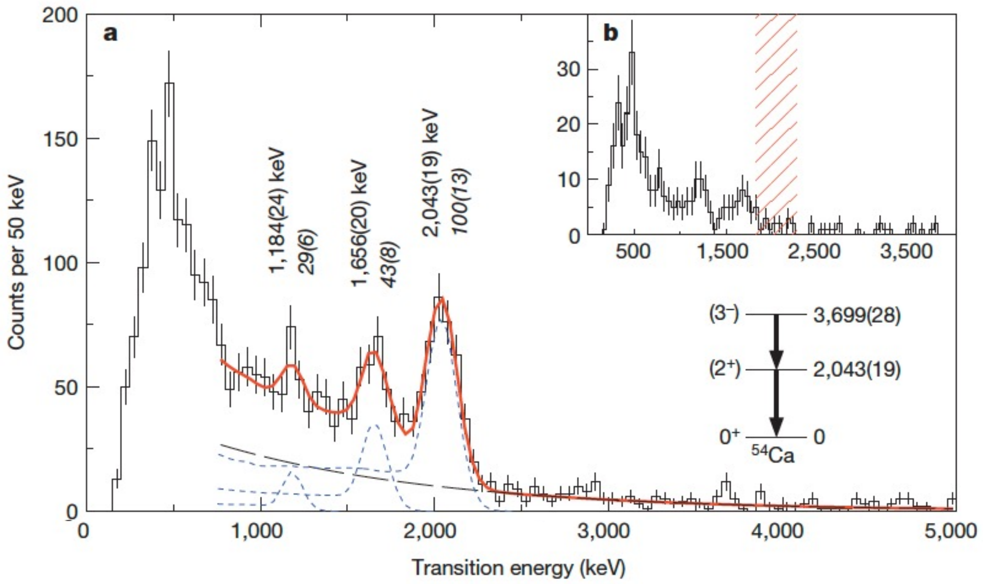
When we empty the $\pi f_{7/2}$ the $\nu f_{5/2}$ goes up – N=34 ???

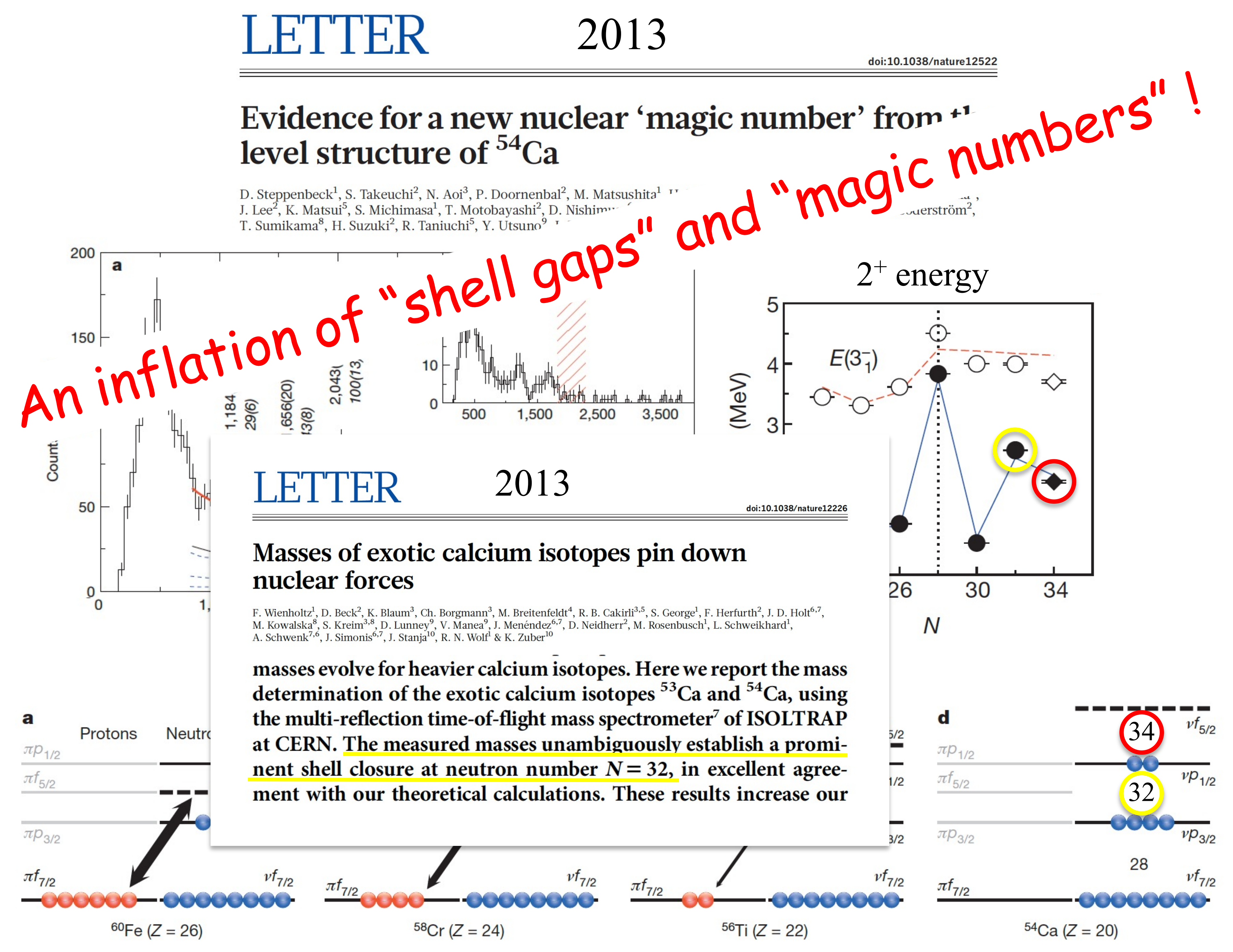
LETTER 2013

doi:10.1038/nature12522

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

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





An inflation of "shell gaps" and "magic numbers" !

LETTER 2013

doi:10.1038/nature12522

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

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1],
J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishim
derström[2],
T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9]

LETTER 2013

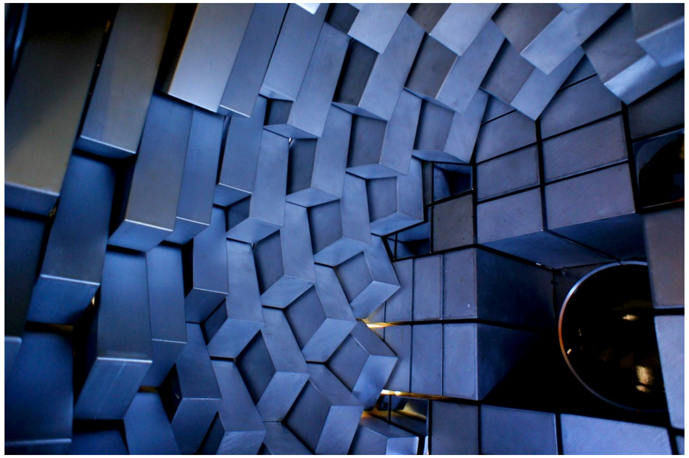
doi:10.1038/nature12226

Masses of exotic calcium isotopes pin down nuclear forces

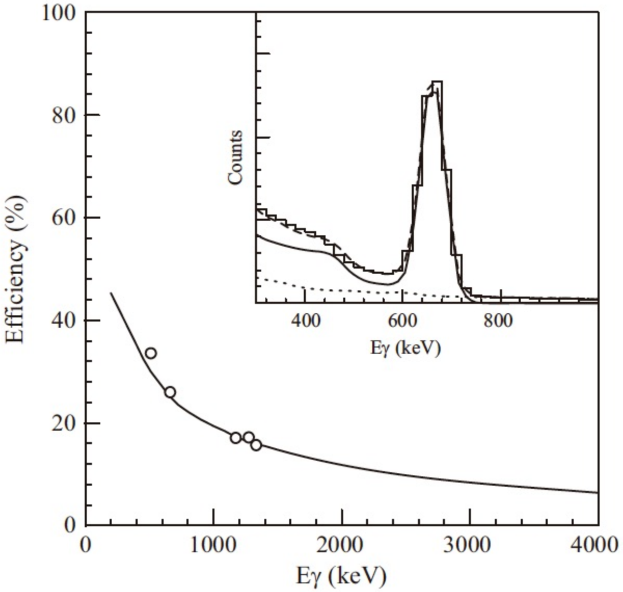
F. Wienholtz[1], D. Beck[2], K. Blaum[3], Ch. Borgmann[3], M. Breitenfeldt[4], R. B. Cakirli[3,5], S. George[1], F. Herfurth[2], J. D. Holt[6,7], M. Kowalska[8], S. Kreim[3,8], D. Lunney[9], V. Manea[9], J. Menéndez[6,7], D. Neidherr[2], M. Rosenbusch[1], L. Schweikhard[1], A. Schwenk[7,6], J. Simonis[6,7], J. Stanja[10], R. N. Wolf[1] & K. Zuber[10]

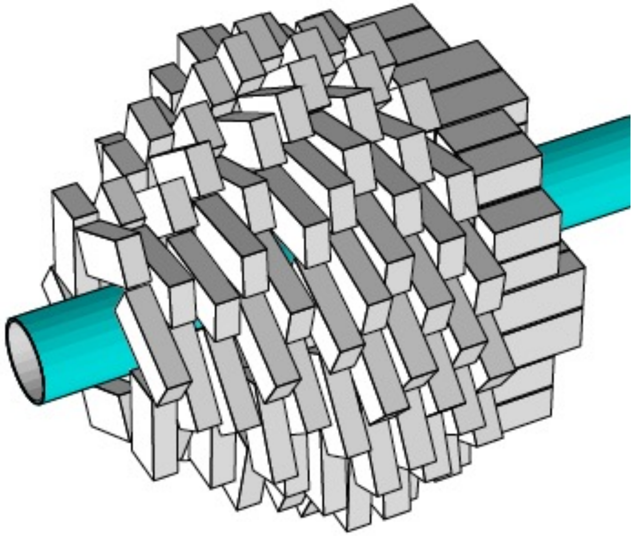
masses evolve for heavier calcium isotopes. Here we report the mass determination of the exotic calcium isotopes ^{53}Ca and ^{54}Ca, using the multi-reflection time-of-flight mass spectrometer[7] of ISOLTRAP at CERN. The measured masses unambiguously establish a prominent shell closure at neutron number $N = 32$, in excellent agreement with our theoretical calculations. These results increase our

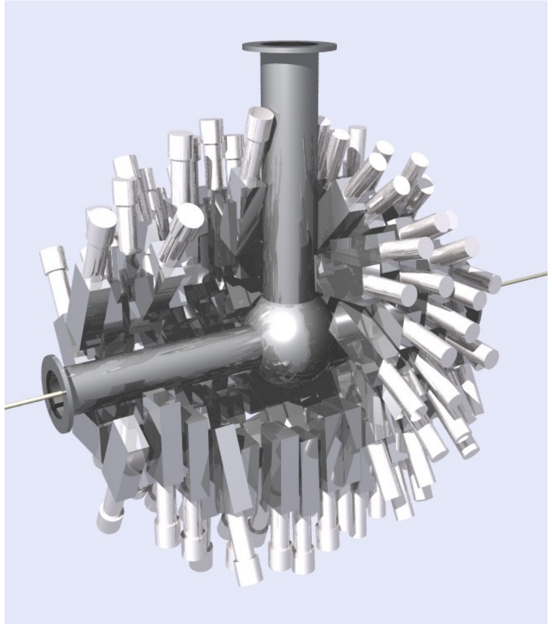
The γ-ray spectrometer DALI2 at RIKEN

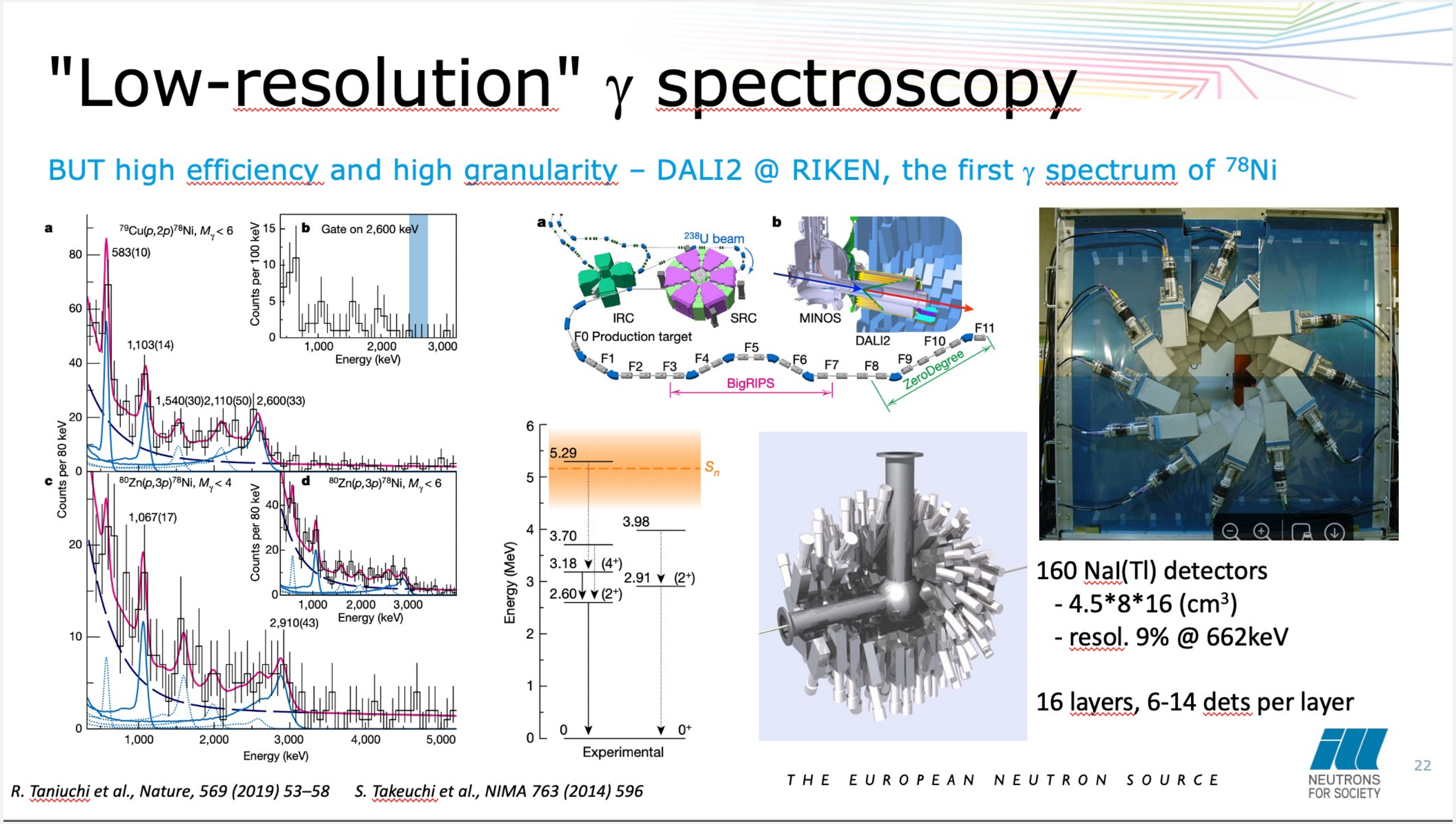


186 NaI (Tl) scintillators









"Low-resolution" γ spectroscopy

BUT high efficiency and high granularity – DALI2 @ RIKEN, the first γ spectrum of ^{78}Ni

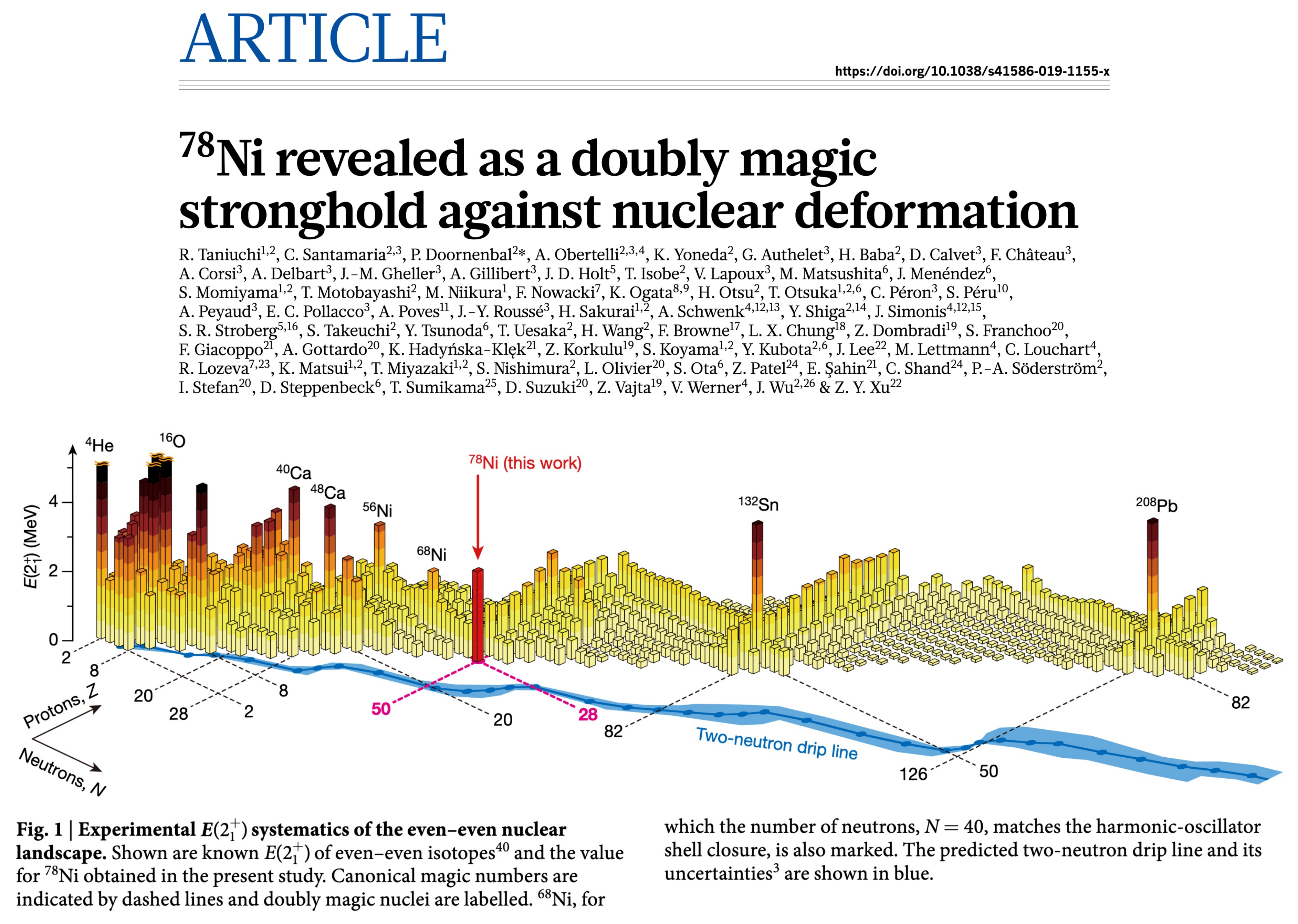
160 NaI(Tl) detectors
- 4.5*8*16 (cm^3)
- resol. 9% @ 662keV

16 layers, 6-14 dets per layer

R. Taniuchi et al., Nature, 569 (2019) 53–58   S. Takeuchi et al., NIMA 763 (2014) 596

THE EUROPEAN NEUTRON SOURCE

NEUTRONS FOR SOCIETY



https://doi.org/10.1038/s41586-019-1155-x

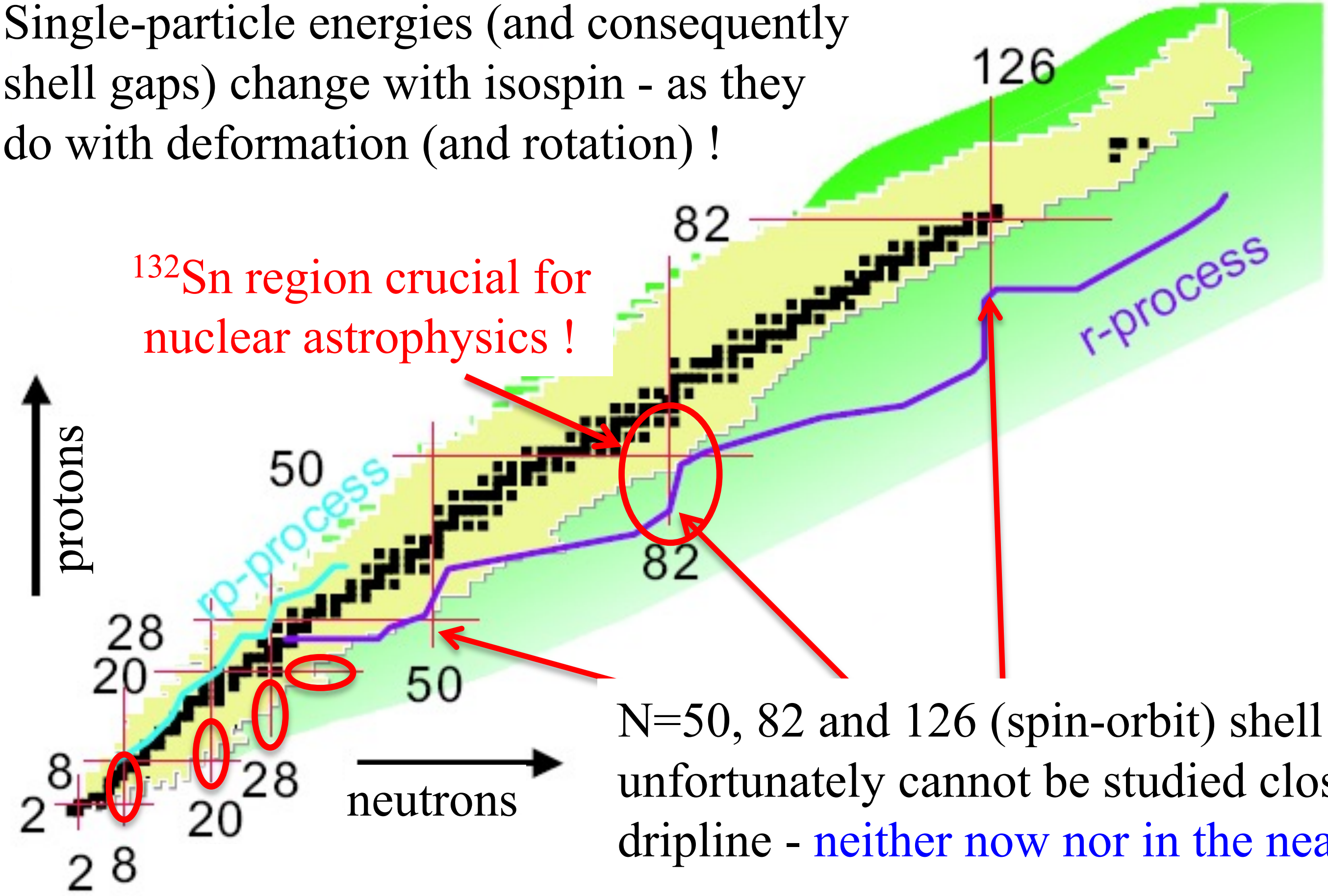
^{78}Ni revealed as a doubly magic stronghold against nuclear deformation

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]

Fig. 1 | Experimental $E(2_1^+)$ systematics of the even–even nuclear landscape. Shown are known $E(2_1^+)$ of even–even isotopes[40] and the value for ^{78}Ni obtained in the present study. Canonical magic numbers are indicated by dashed lines and doubly magic nuclei are labelled. ^{68}Ni, for which the number of neutrons, $N = 40$, matches the harmonic-oscillator shell closure, is also marked. The predicted two-neutron drip line and its uncertainties[3] are shown in blue.

The heavier neutron-rich region

Single-particle energies (and consequently shell gaps) change with isospin - as they do with deformation (and rotation) !



^{132}Sn region crucial for nuclear astrophysics !

N=50, 82 and 126 (spin-orbit) shell closures unfortunately cannot be studied close to the dripline - neither now nor in the near future.