Opportunities at FRIB from spectroscopy and lifetime measurements

Hiro IWASAKI
(FRIB/MSU)

Work presented supported by DE-SC0020451/DE-SC0000661

Nuclear regions of (personal) interest at NSCL

Transition strengths for low-lying excited states

Shape coexistence in A = 70-80 nuclei

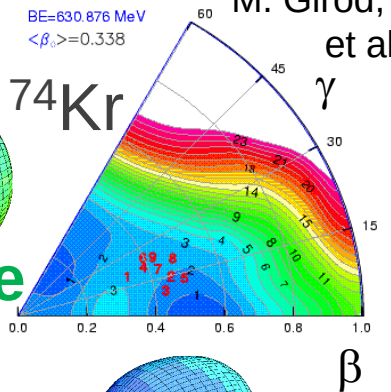
Shell evolution : normal vs intruder configuration

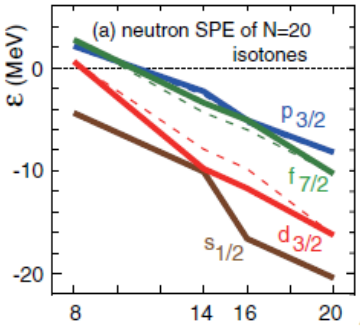
N=Z

oblate

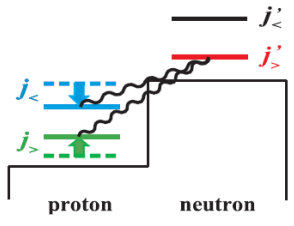
prolate

M. Girod, et al.





T.Otsuka, et al.



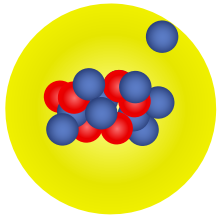
Z

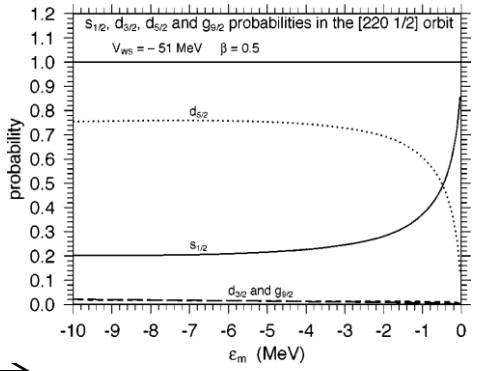
20

8

8 20 28 N

Halo vs deformation?





I.Hamamoto, et al.

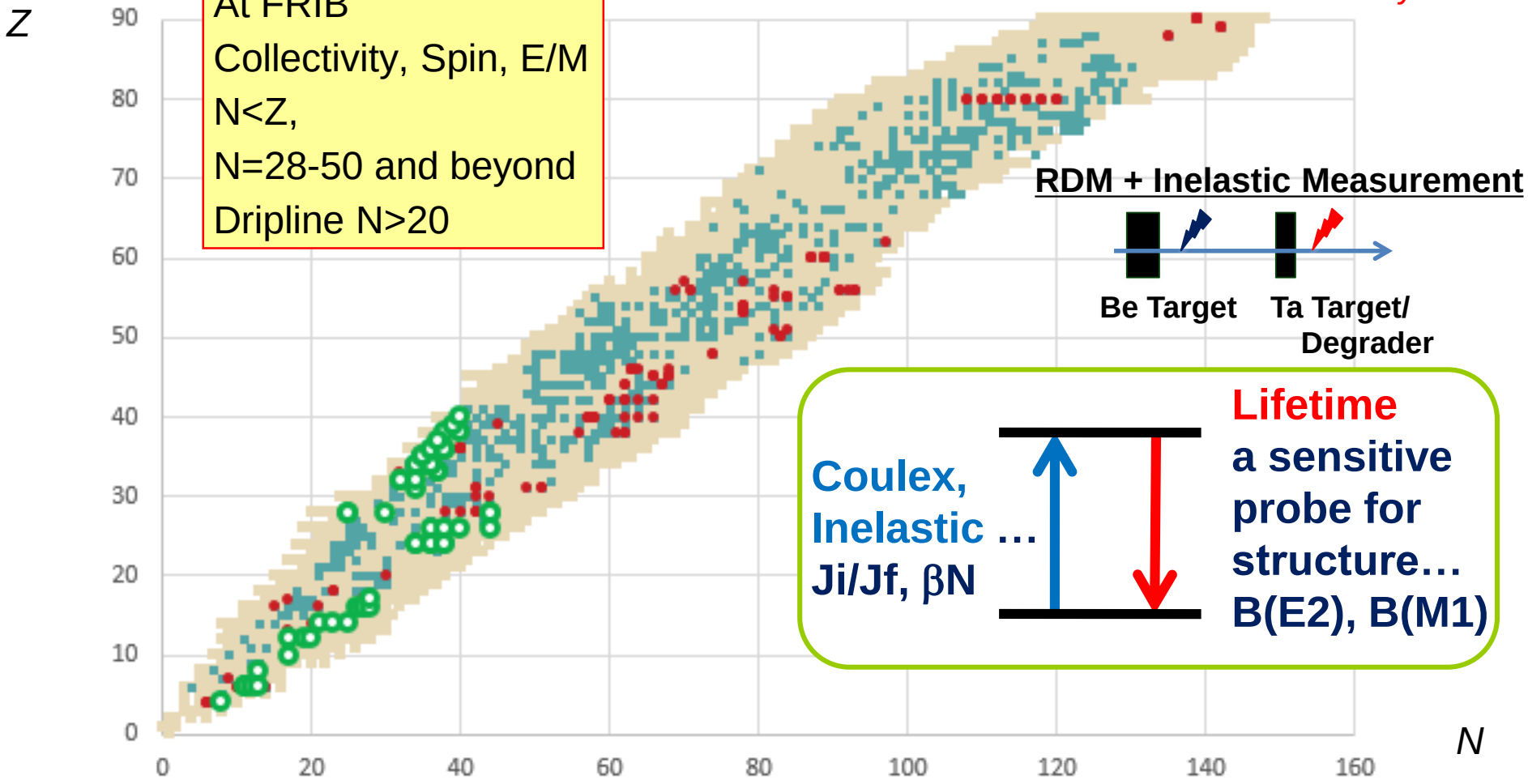
Chart of Lifetime Measurements

…Known isotopes (~3000 nuclides)

…Lifetime studied in the last 20 years (~5000 levels for ~700 nuclides)

…Lifetime studied with rare isotope beams (~250 levels for ~120 nuclides)

>50% data came in the last 5 years

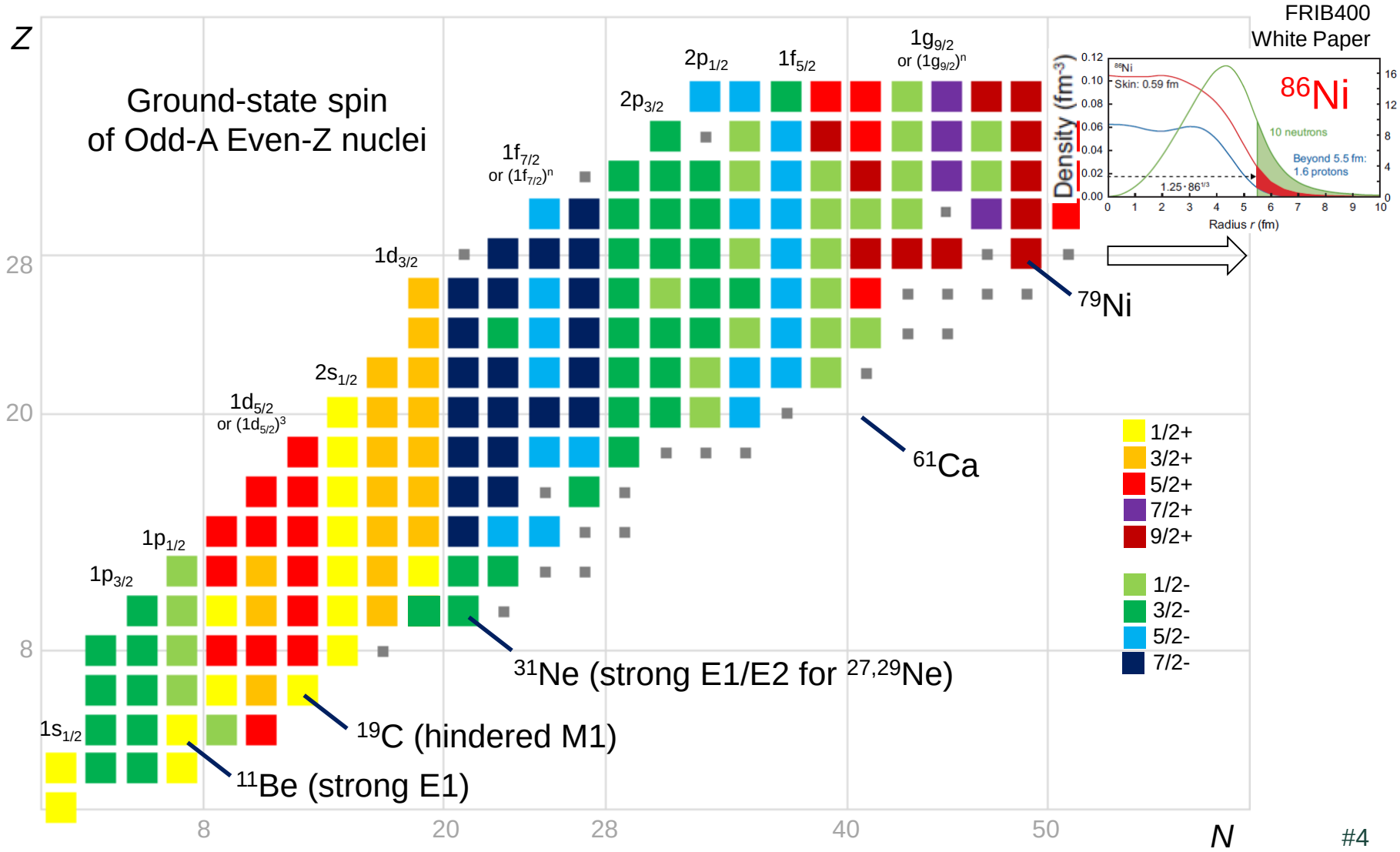


from XUNDL ($T_{1/2}$<100ns), Jun Chen (MSU/USNDP)

Unified understanding of nuclear structure and its evolution

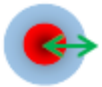
Integrated picture of structural evolution of exotic nuclei

- Coordinated efforts with nuclear data and theory (sensitivity studies)
- New experiments toward dripline (FRIB400), toward higher spins (ReA/ISLA), etc



Electromagnetic responses of halo

transition operators r^1Y^1 $s+\ell$ r^2Y^2

Type of halo	Configuration of valence neutron	B(E1) established	B(M1) - to be	B(E2) established-
Spherical 	Pure $s_{1/2}$ + core (0^+)	◎	×	△
Deformed 	Mixed (sd) or (pf) + core	◎	○	○

◎ Enhanced
○ Favored (unhindered)
× Hindered
△ Depend on core deformation

Large B(E1) – evidence for halo

^{11}Be ($1/2^+ \rightarrow 1/2^-$) : 0.1 e^2fm^2, 0.36 W.u.

^{27}Ne ($1/2^+ \rightarrow 3/2^-$) : >0.030 e^2fm^2, >0.052 W.u.

Hindered B(M1) – *s*-wave dominance for halo

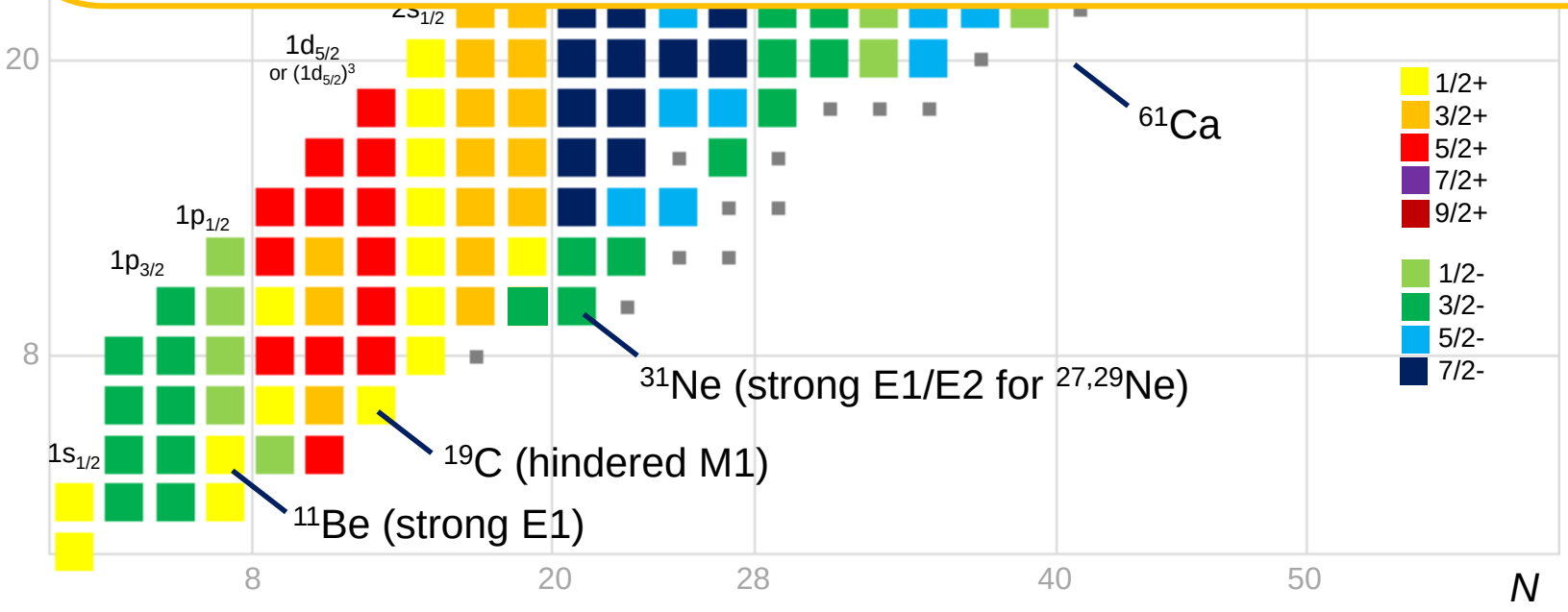
^{19}C ($3/2^+ \rightarrow 1/2^+$) : $3.21(25) \times 10^{-3}\ \mu_N^2$, 1.8×10^{-3} W.u.

B(E2) – characterize deformation w/ enhanced? collectivity

no available data for weakly-bound systems, $r^2 \uparrow$ *vs* $e_n \downarrow$

Open questions

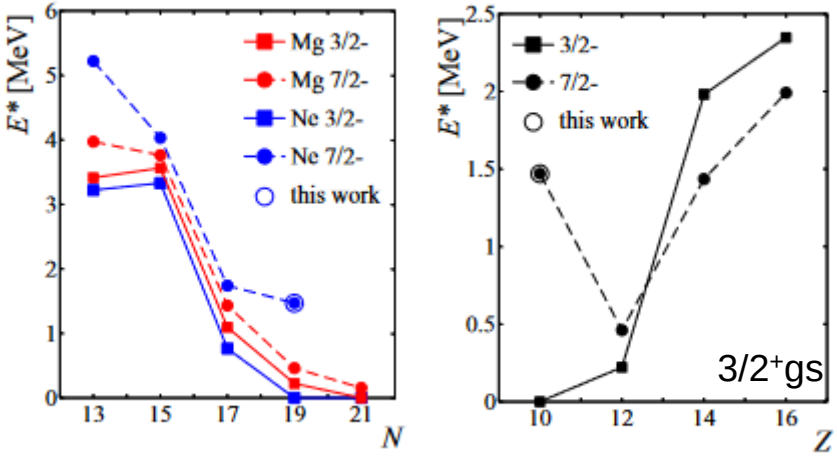
- **How can we track and understand the structural evolution toward drip lines? (N=19, 27 etc)**
- **Where does the shell model picture break down? (^{29}F etc)**
- **Is there any universality in heavier neutron-rich regions? (3s$_{1/2}$ etc)**
- **Can we identify unique phenomena characteristic of weakly-bound multi-neutrons? (^{40}Mg, p-wave, etc)**
- **What is the interplay between weak-binding (or neutron excess) and angular momentum? (high spin/isospin)**



Evolution within and beyond shell model picture

Now – 20kW for N~20

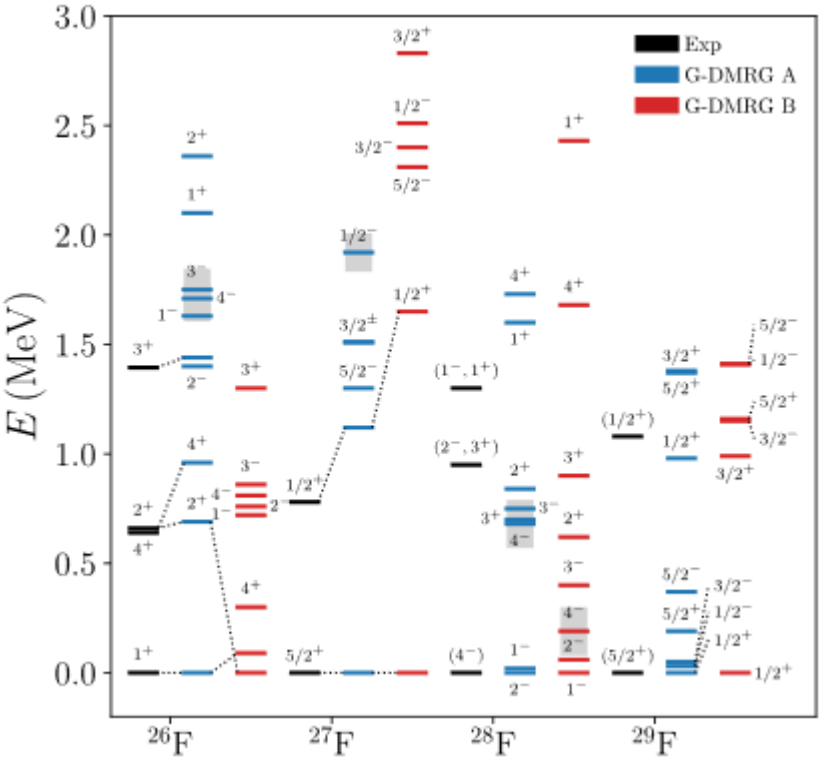
Evolution of the lowest-energy $7/2^-$ and $3/2^-$ states in Mg/Ne isotopic chains (left) and among **N=19 isotones (right)**



Transition from 1p1h to 3p3h states?
Effects due to continuum?

M.Holl et al., PRC 105, 034301 (2022)

Spectra for neutron-rich F isotopes



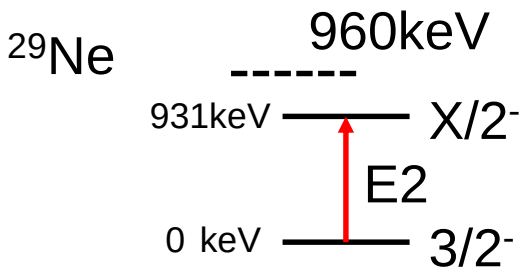
Spectra for neutron-rich F isotopes
Unique spin ($1/2^+$) for the ^{29,31}F gs

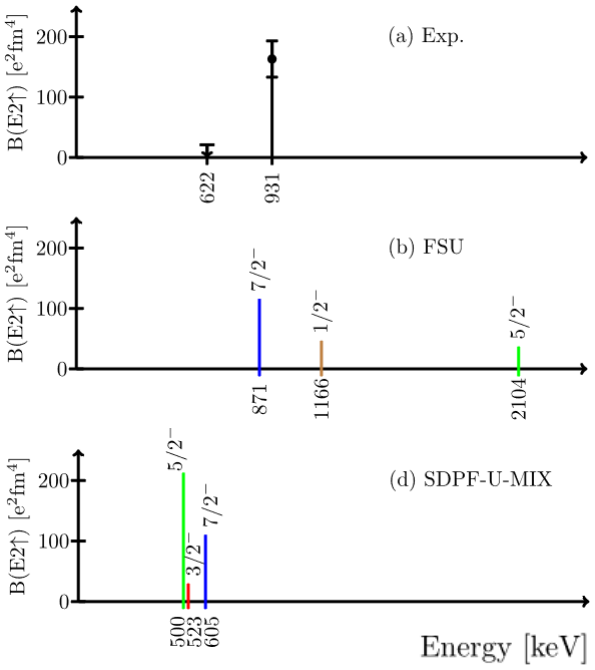
K.Fossez and J.Roureau,
PRC 106, 034312 (2022)

Collectivity of weakly-bound neutrons

20 – 400kW

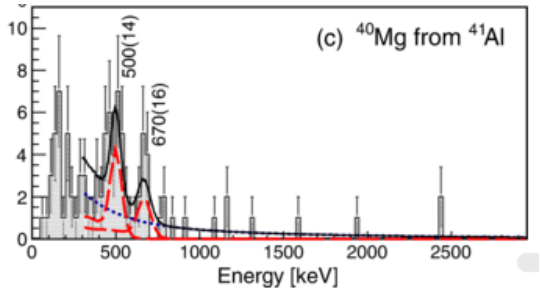
Enhanced E2 collectivity ??
- effects due to spatial extension
- decoupling (reduced neutron effective charges)
- impact of angular momentum

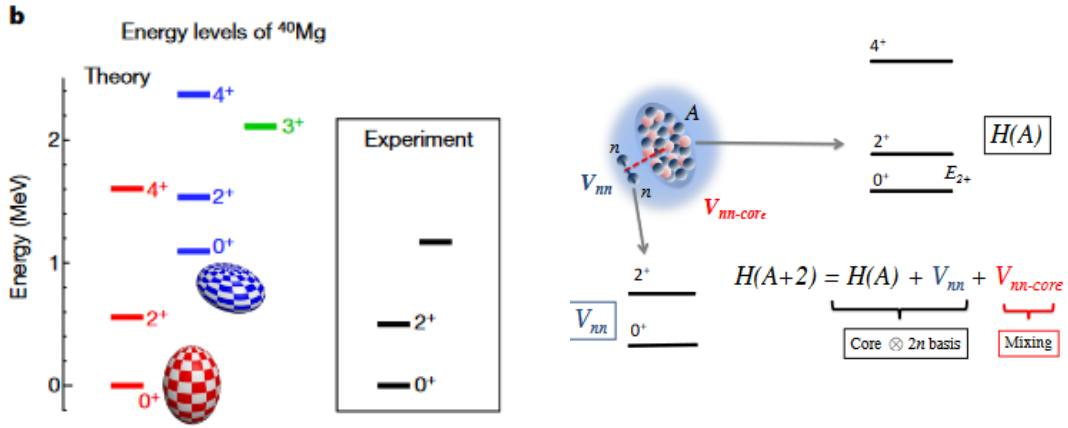




A.Revel et al., PLB 838, 137704 (2023)

^{40}Mg

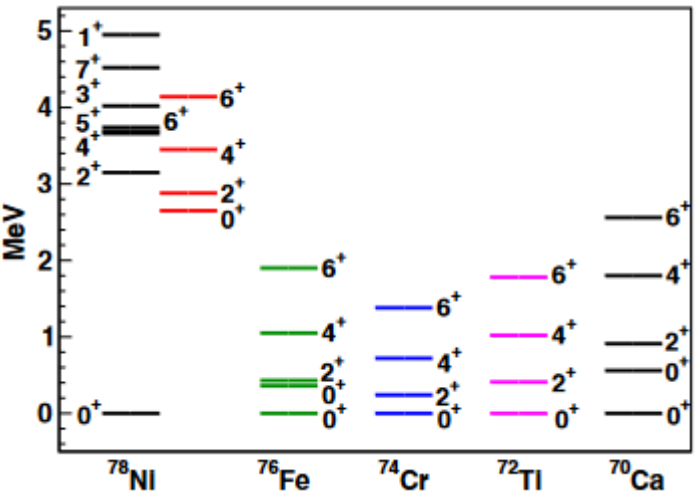


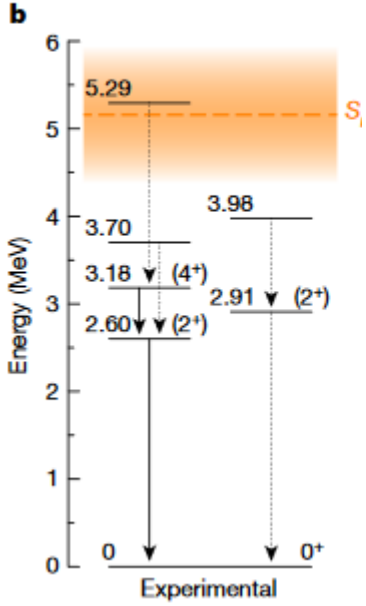


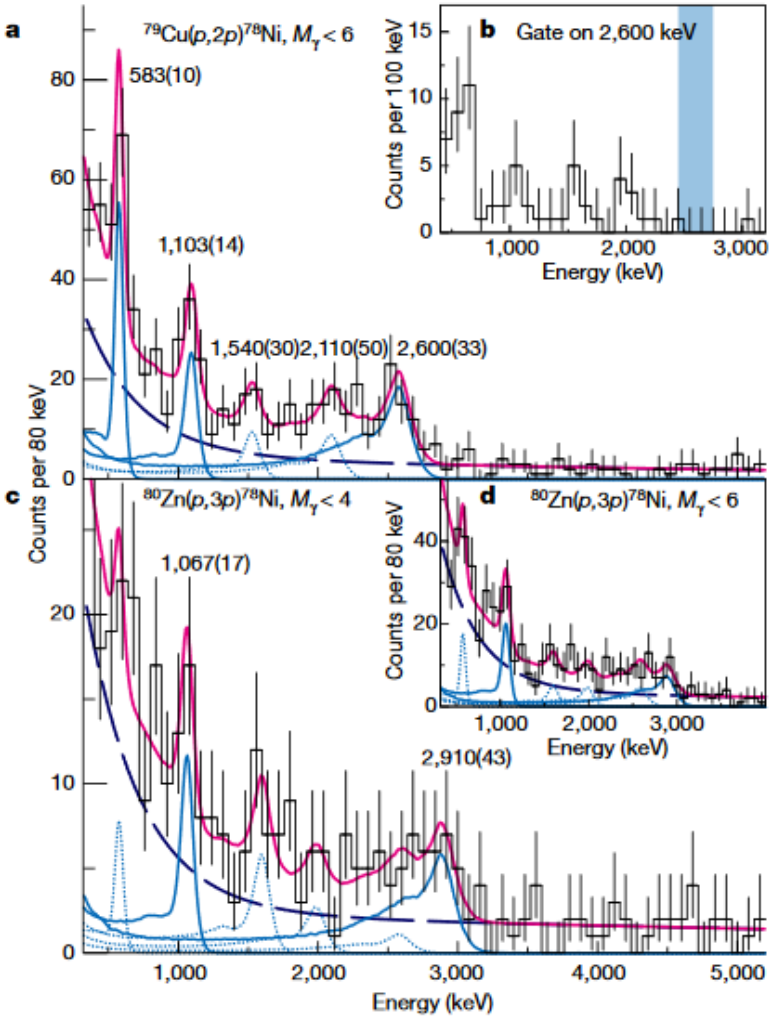
H.L.Crawford et al., PRL 122, 052501 (2019)
N.Tsunoda et al., Nature 587, 66 (2020)
A.O.Macchiavelli et al., Eur. Phys. J. A 58, 66 (2022)

Ni isotopes at N=50 and beyond

100 – 400kW







Effective single neutron energies at N=50 1g9/2 vs 2d5/2, 3s1/2

E2 collectivity from $2_{1,2}^{+}$, 4_{1}^{+} in ^{78}Ni

Identification of excited states in ^{76}Fe, ^{74}Cr, etc.

R.Taniuchi et al., Nature 569, 53 (2019)

F.Nowachi et al., PRL117, 272501 (2016)

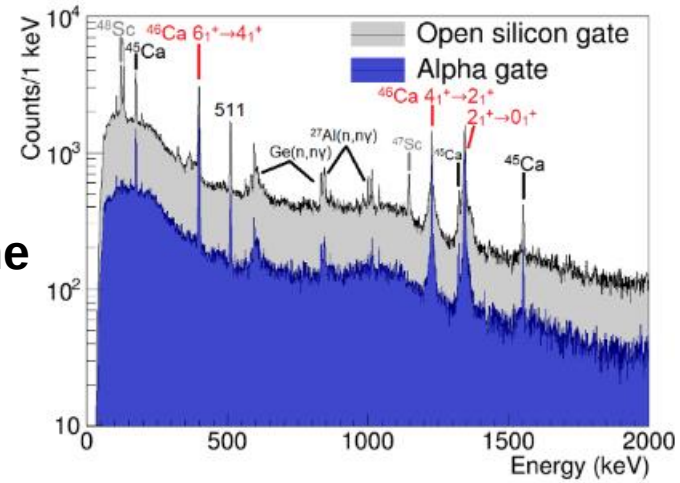
Fusion at ReA

100 – 400kW for ^{50,52}Ca

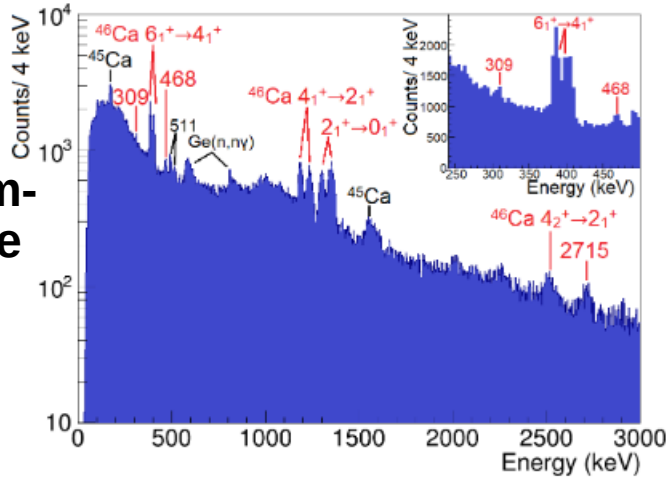
Gamma-ray spectroscopy with fusion reactions using a reaccelerated RI beam of ^{45}K with intensity of 9.8×10^4 pps was performed, suggesting independent band structures in ^{46}Ca formed from different particle-hole configurations.

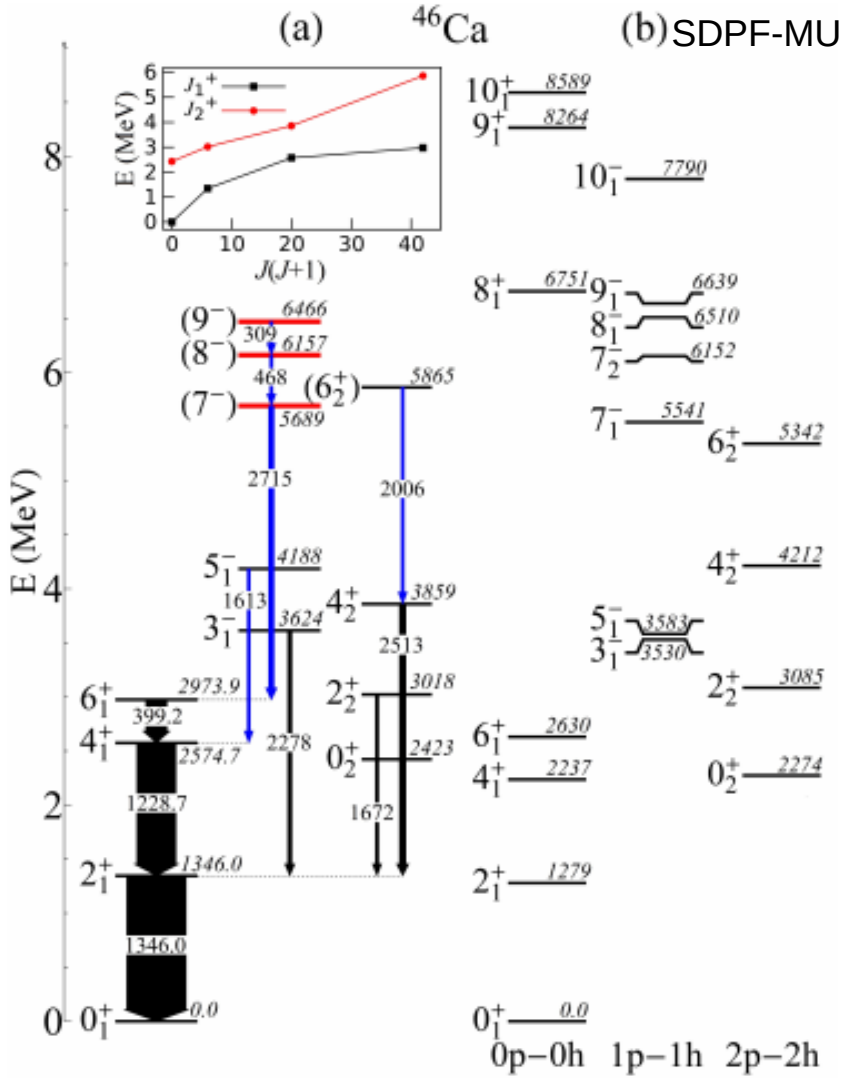
^{7}Li(^{45}K,α2n)^{46}Ca

Lab-frame



Beam-frame

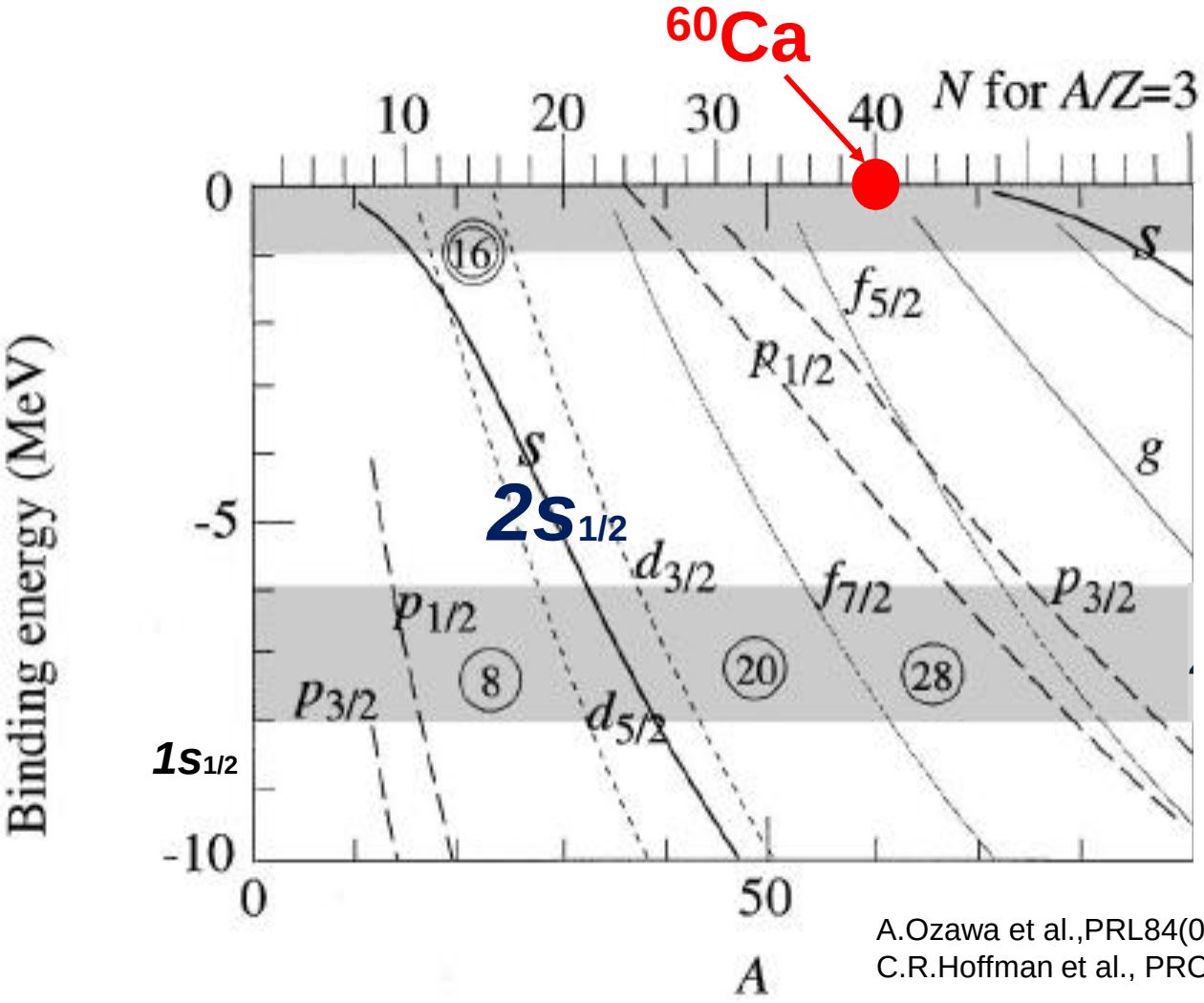




J. Ash et al. PRC L051302 (2021)

Evolution from stable Sn to exotic Ca

Lowering of the *3S1/2* state near the dripline?

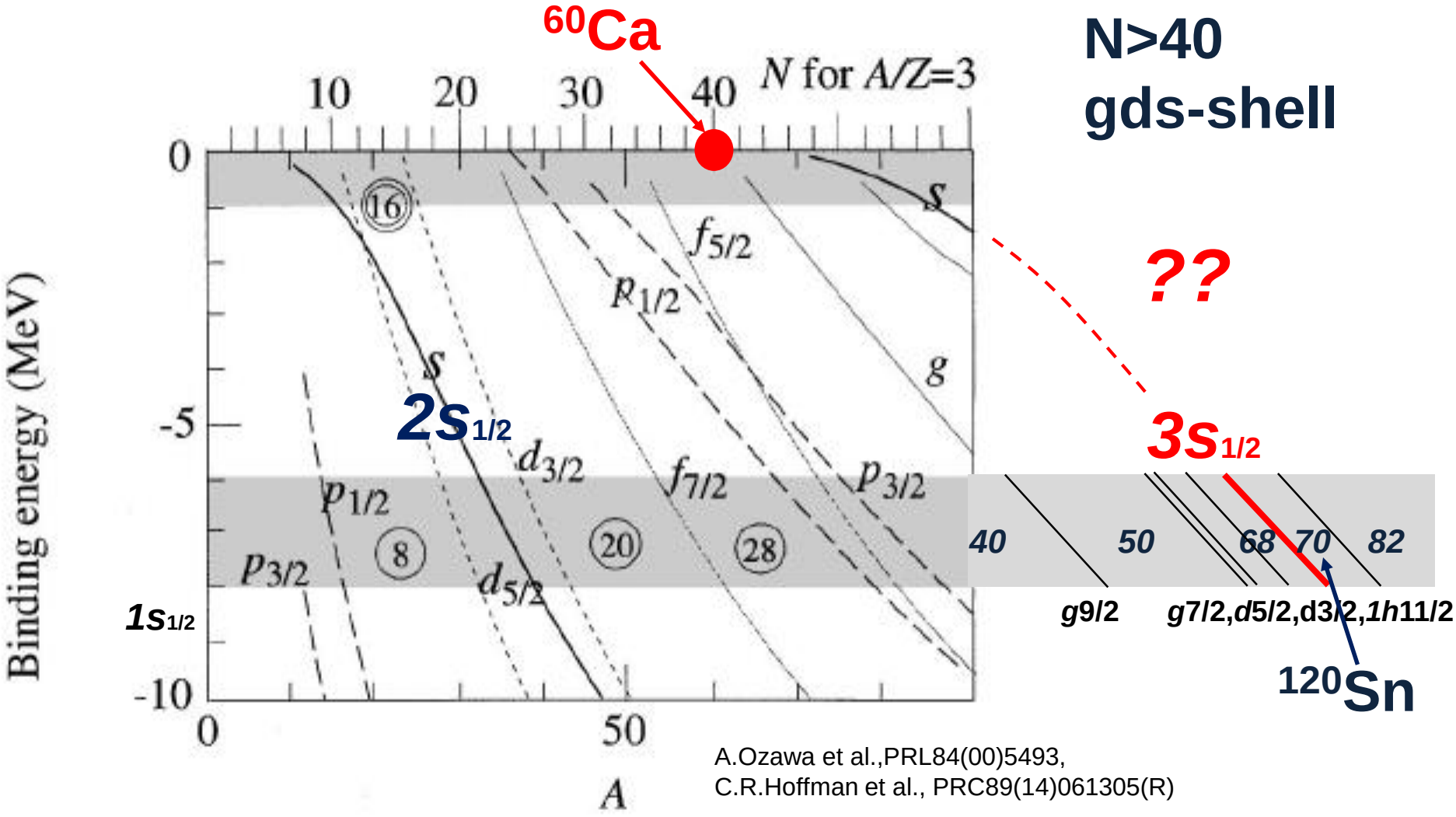


N>40
gds-shell

A.Ozawa et al.,PRL84(00)5493,
C.R.Hoffman et al., PRC89(14)061305(R)

Evolution from stable Sn to exotic Ca

Lowering of the *3S1/2* state near the dripline?



A.Ozawa et al.,PRL84(00)5493,
C.R.Hoffman et al., PRC89(14)061305(R)

Level Schemes in N=69 isotones

^{17}C,^{19}C (Z=6,N=11,13) → ^{117}Sn, ^{119}Sn (Z=50, N=67,69)

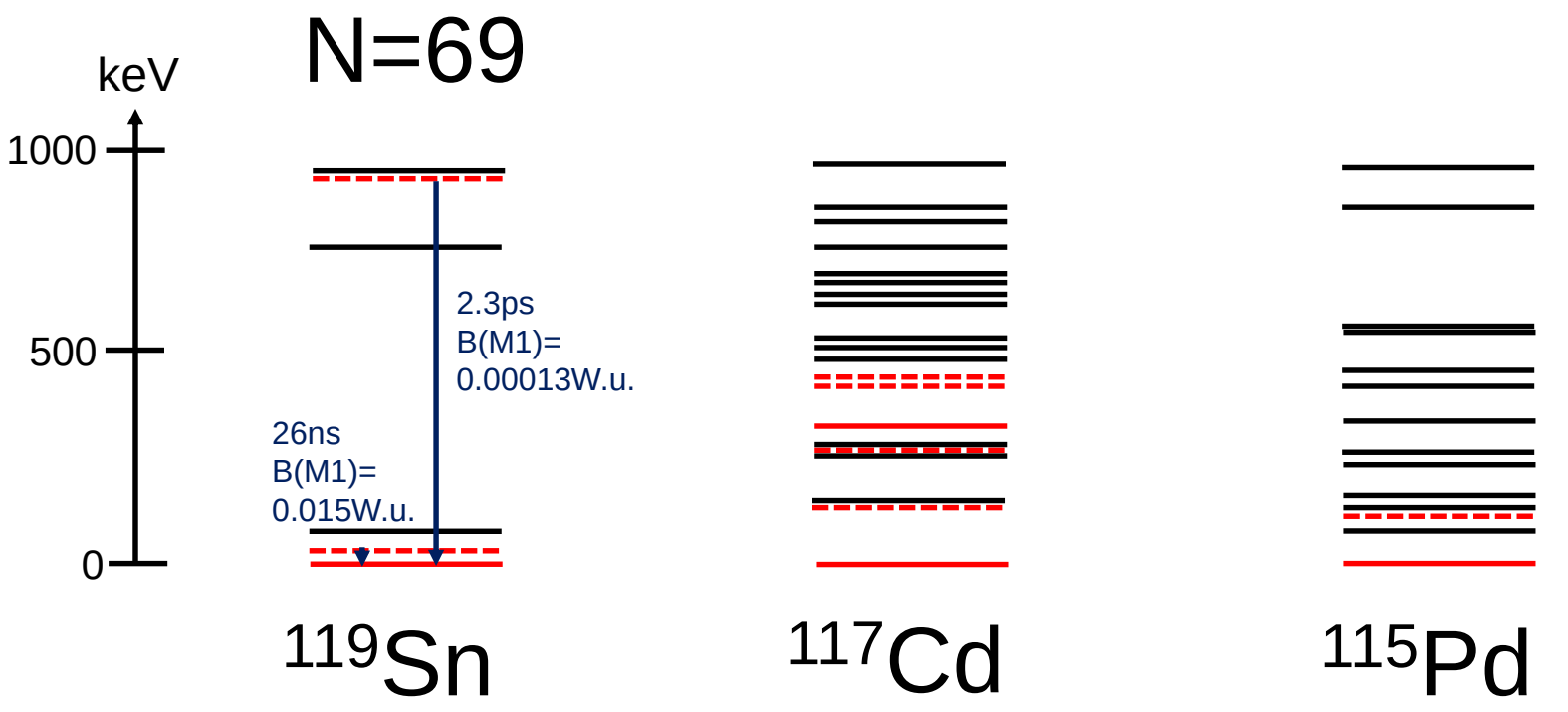
^{115}Cd, ^{117}Cd (Z=48, N=67,69)

⋮ ⋮

^{107}Zr, ^{109}Zr (Z=40, N=67,69)

(3/2⁺)

(1/2⁺)

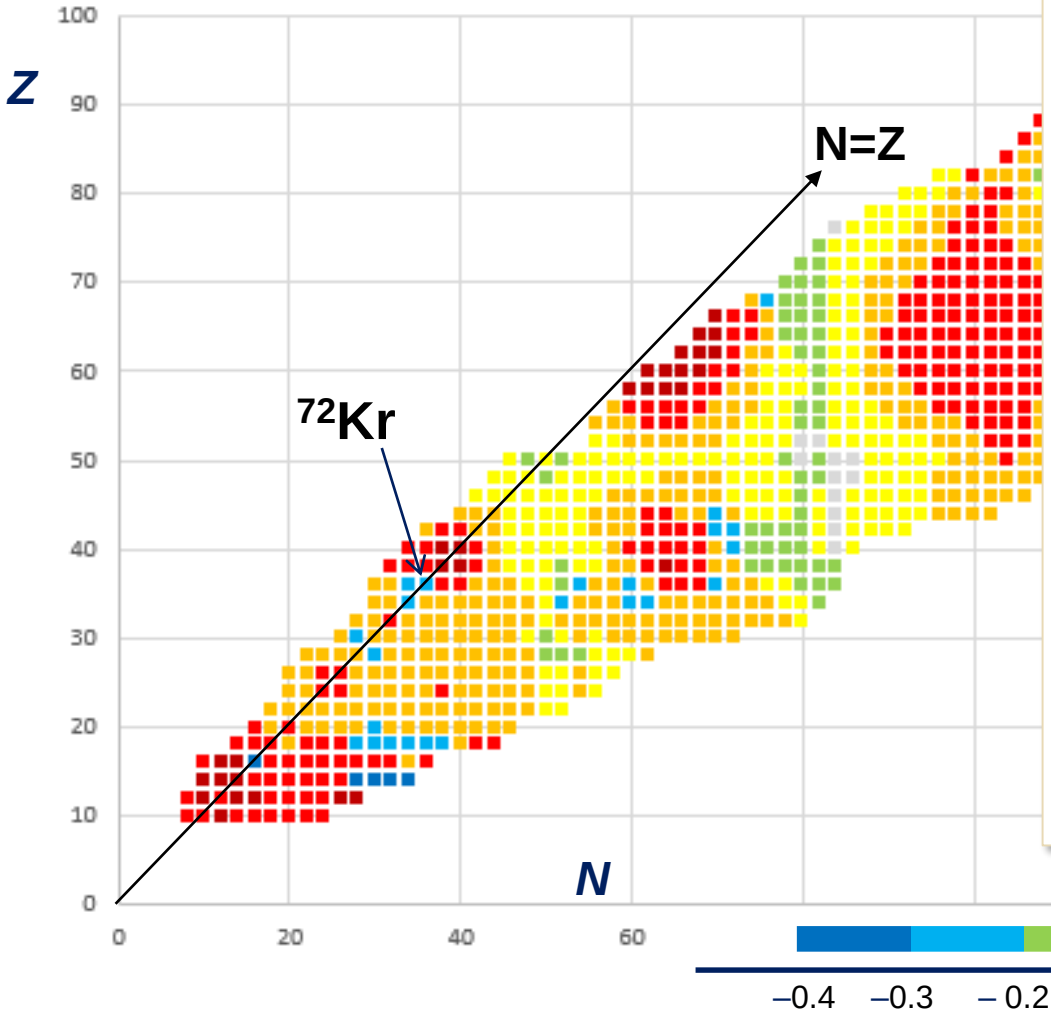


20 – 100kW

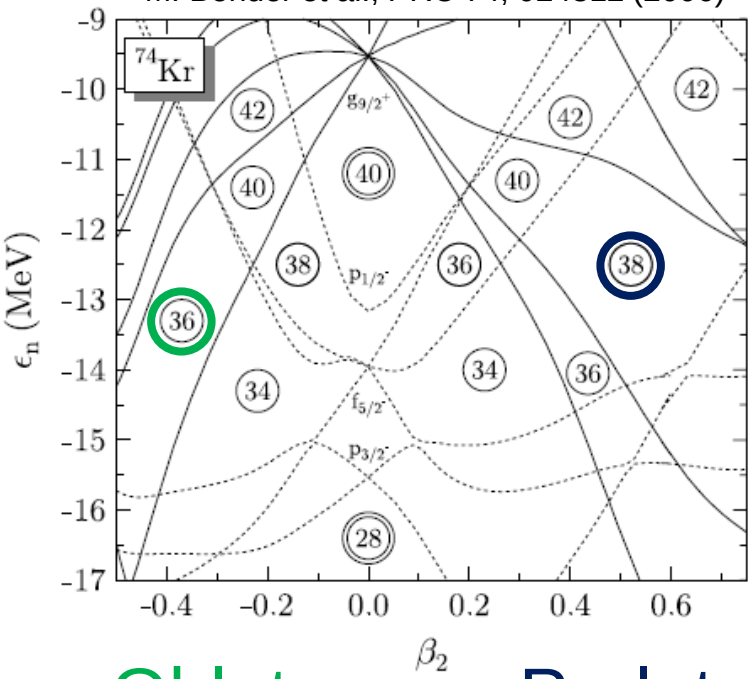
l-forbidden M1 transitions and pseudospin symmetry, P. von Neumann-Cosel, J.N.Ginocchio, PRC62 (00) 014308

Shape evolution along the N=Z line and beyond

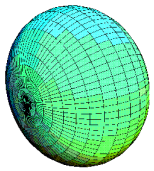
- Shell effects are amplified
- Presence of various shapes
- Possible ground-state oblate deformation



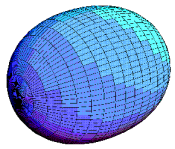
M. Bender et al., PRC 74, 024312 (2006)



Oblate



Prolate



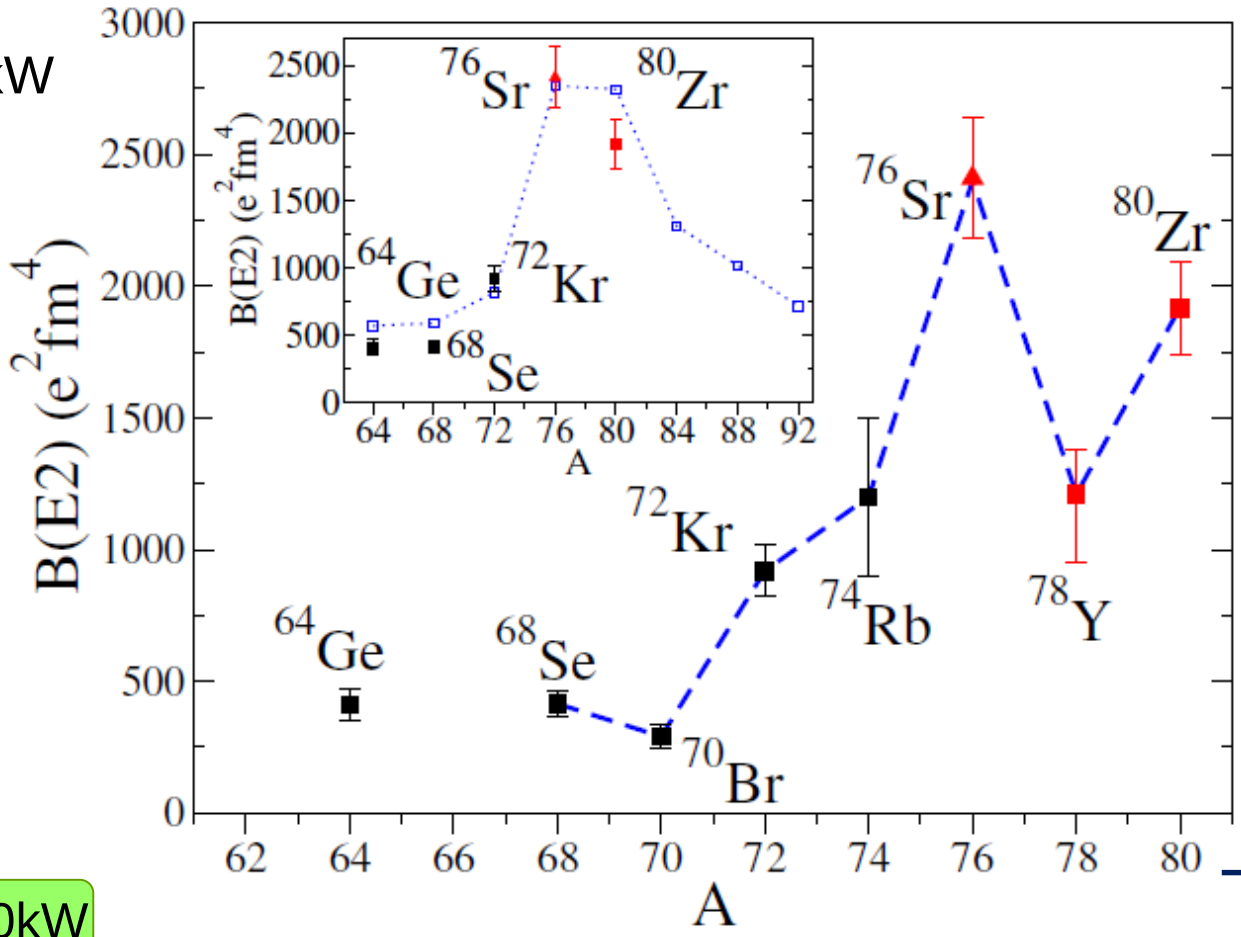
Nilsson orbitals for ^{74}Kr (Z=36, N=38)

β (deformation)

Maximum Collectivity at N=Z and odd-even effects

- The maximum collectivity along the N=Z line is confirmed at ^{76}Sr
- An intriguing even-odd staggering, as yet unexplained, is observed - deuteron (T=0) or alpha-like correlations in N=Z ?

Now – 20kW



?

^{100}Sn

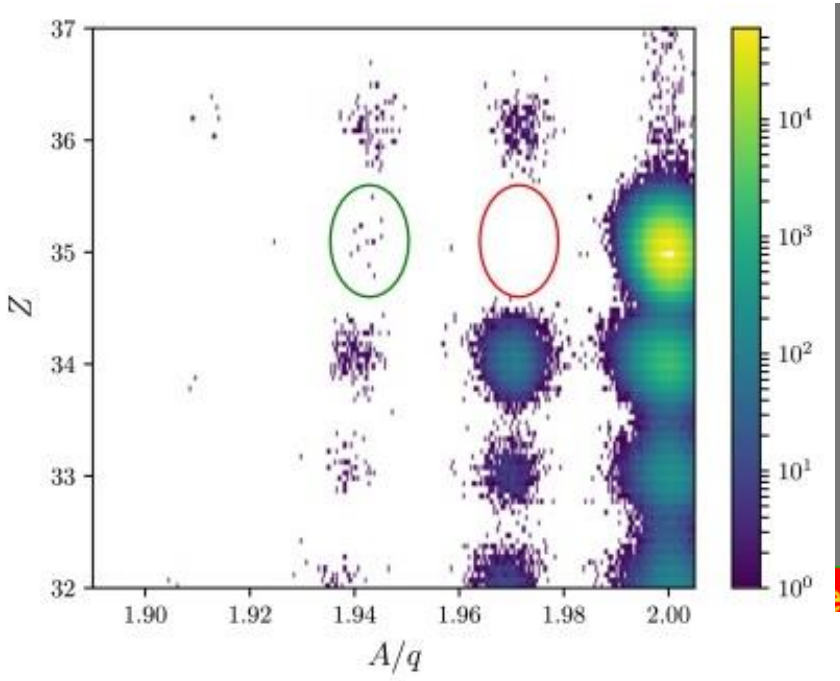
Now – 20kW

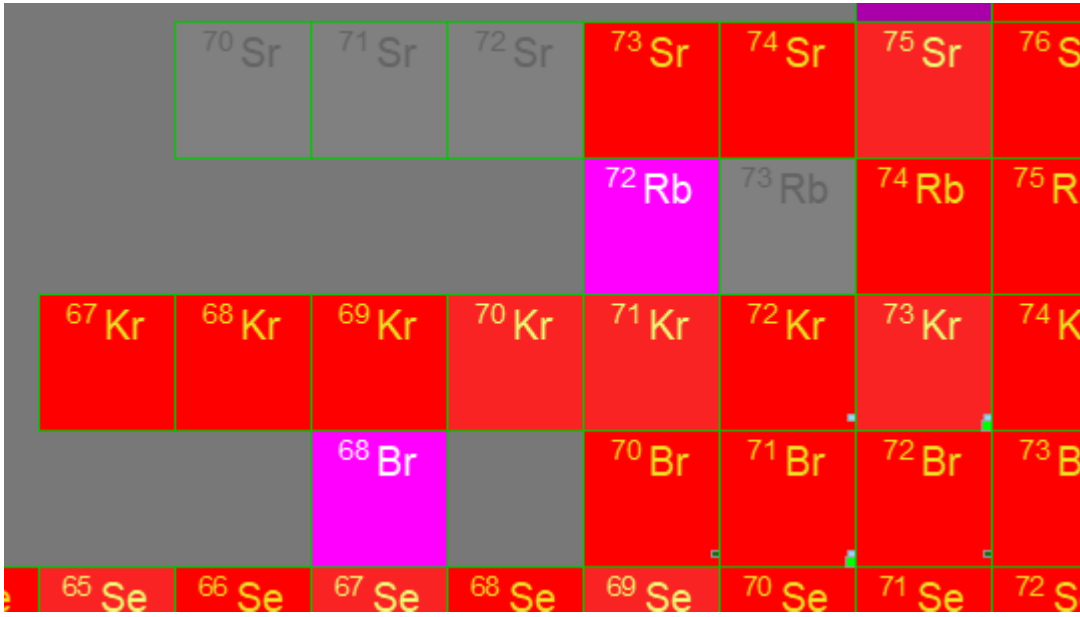
R.D.O.Llewellyn, et al., PRL124, 152501 (2020)

Proton-neutron correlation at drip line

- Possible extent of proton dripline (sandbank) and peculiar proton-neutron correlation at the dripline can be studied by spectroscopy and lifetime measurements … ^{68}Br, ^{72}Rb

20 – 400kW





K.Wimmer, et al., PLB795, 266 (2019)
H.Suzuki, et al., PRL119, 192503 (2017)

Thank you