Open problems at the *N*=*Z* line

P. Van Isacker, GANIL, France

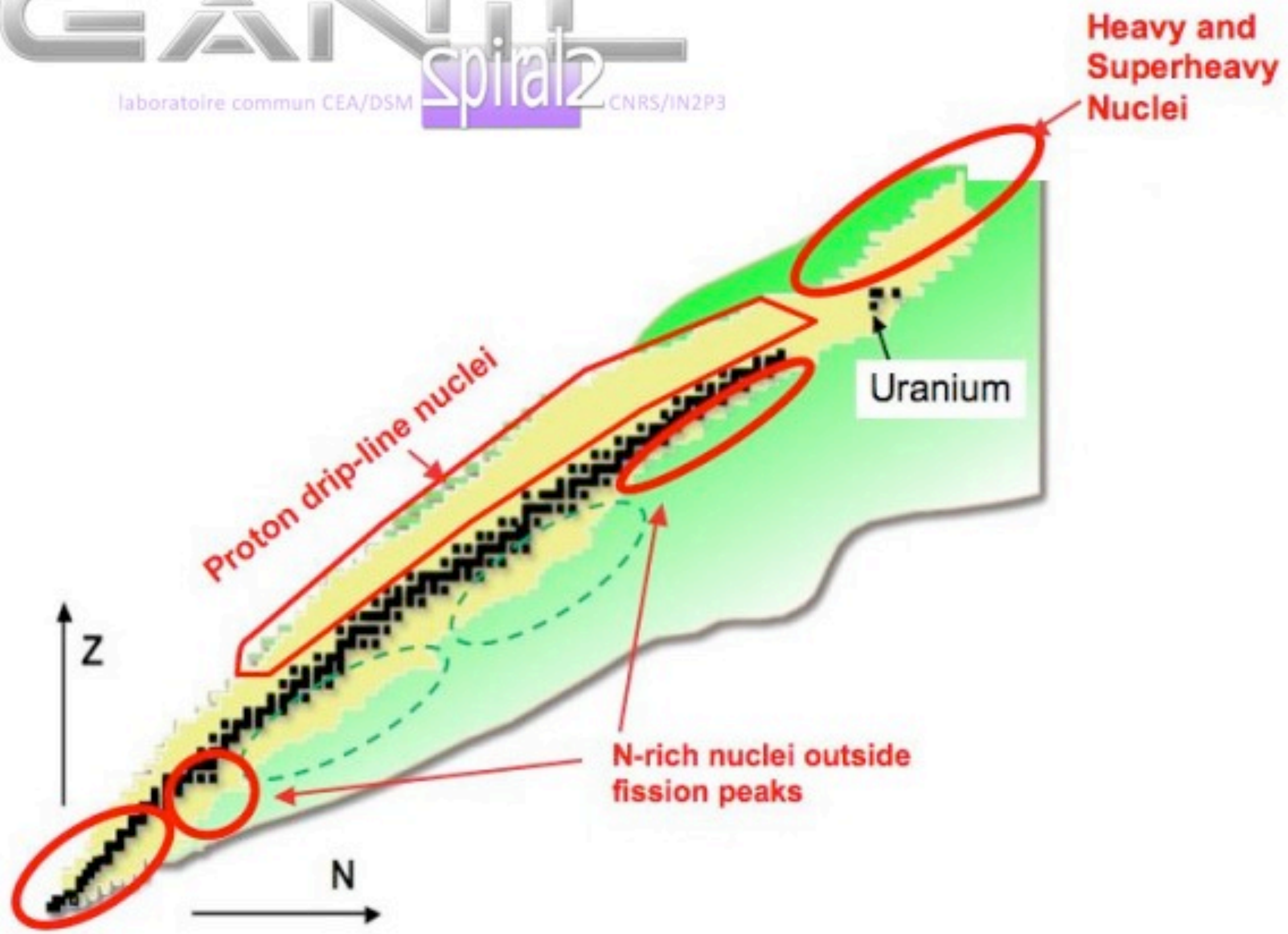
S^3 opportunity for *N*=*Z*

What's so interesting about *N*=*Z*?

Some selected topics

S^3 workshop, ESNT, Saclay, March 2017

Nuclear regions covered by S^3



What's so interesting about *N*=*Z*?

Superallowed $0^+ \rightarrow 0^+$ β decay and precision tests of the standard model (unitarity CKM matrix).

Charge symmetry and charge independence of the nuclear interaction (isospin symmetry).

Extra binding energy due to enhanced correlation effects (e.g., Wigner energy).

***T*=0 pairing and aligned neutron-proton pairs.**

D.D. Warner, M.A. Bentley & PVI, Nature Physics **2** (2006) 311

Pairing

Pairing refers to the interaction between particles in 'time-reversed orbits'.

In nuclei: nucleons with orbital angular momenta coupled to $L=0$.

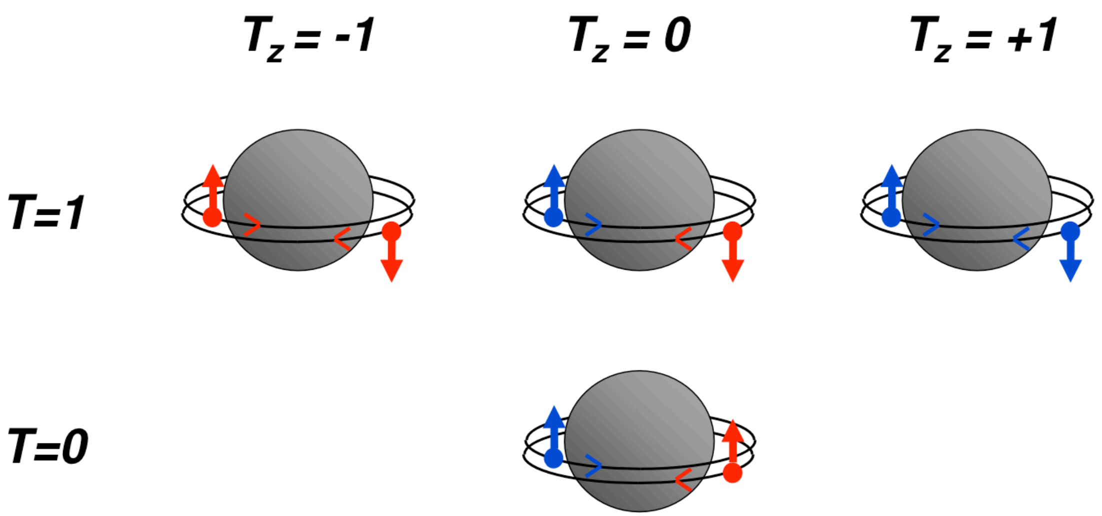
Pairing is essential to understand the properties of nuclei. Analogous to the superconducting metallic state (BCS theory).

Pairing with neutrons and protons

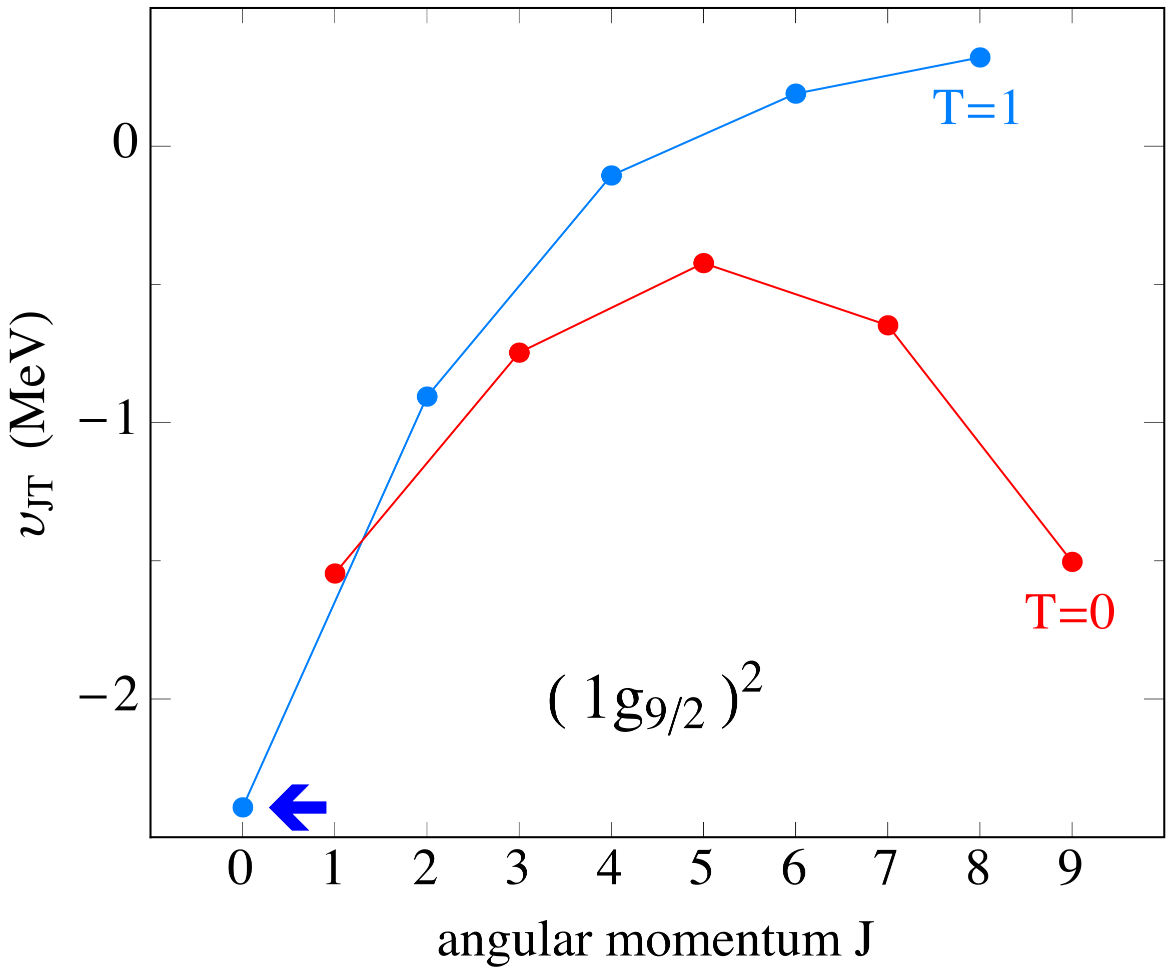
For neutrons and protons *two* pairs and hence *two* pairing interactions are possible:

$^1S_0$ *isovector or spin singlet (S=0,T=1)*

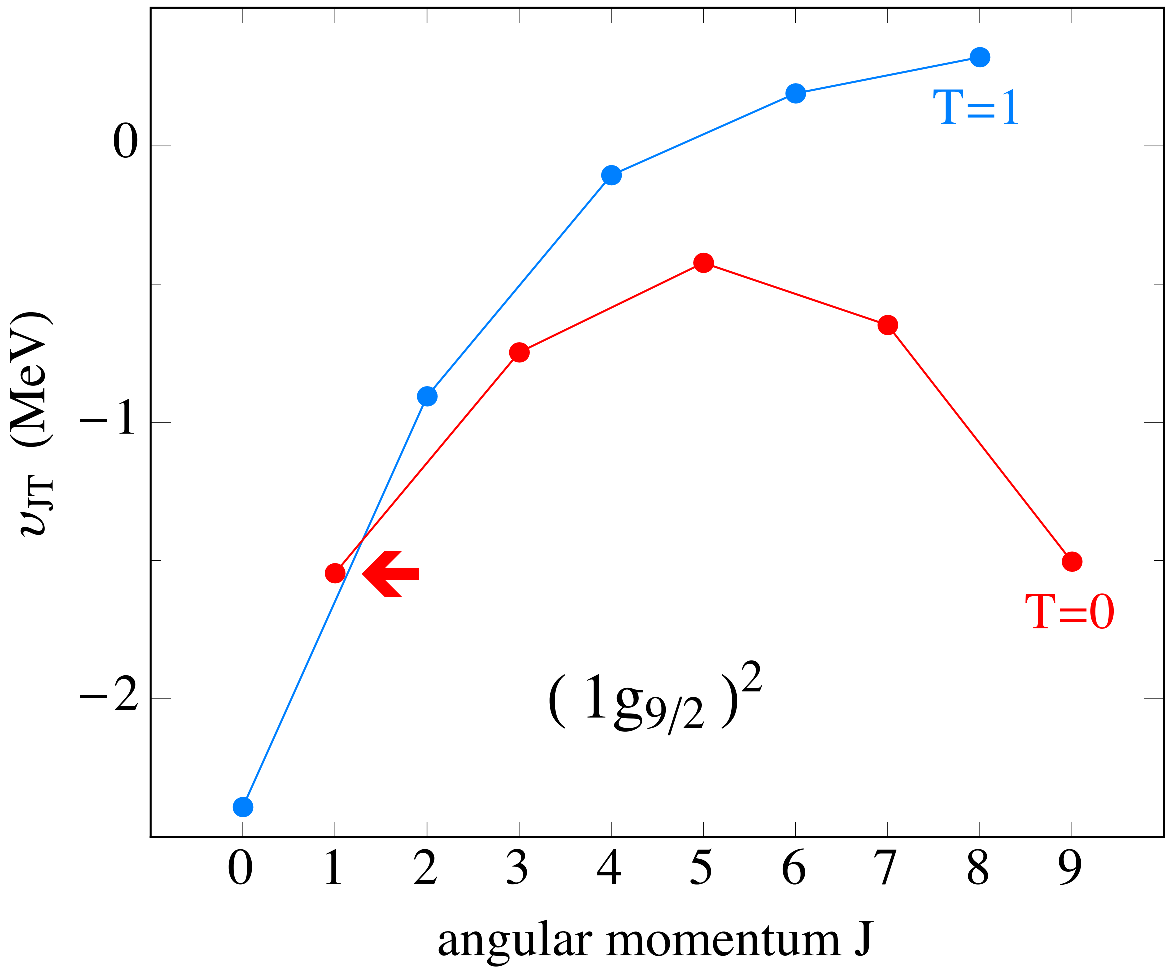
$^3S_1$ *isoscalar or spin triplet (S=1,T=0)*



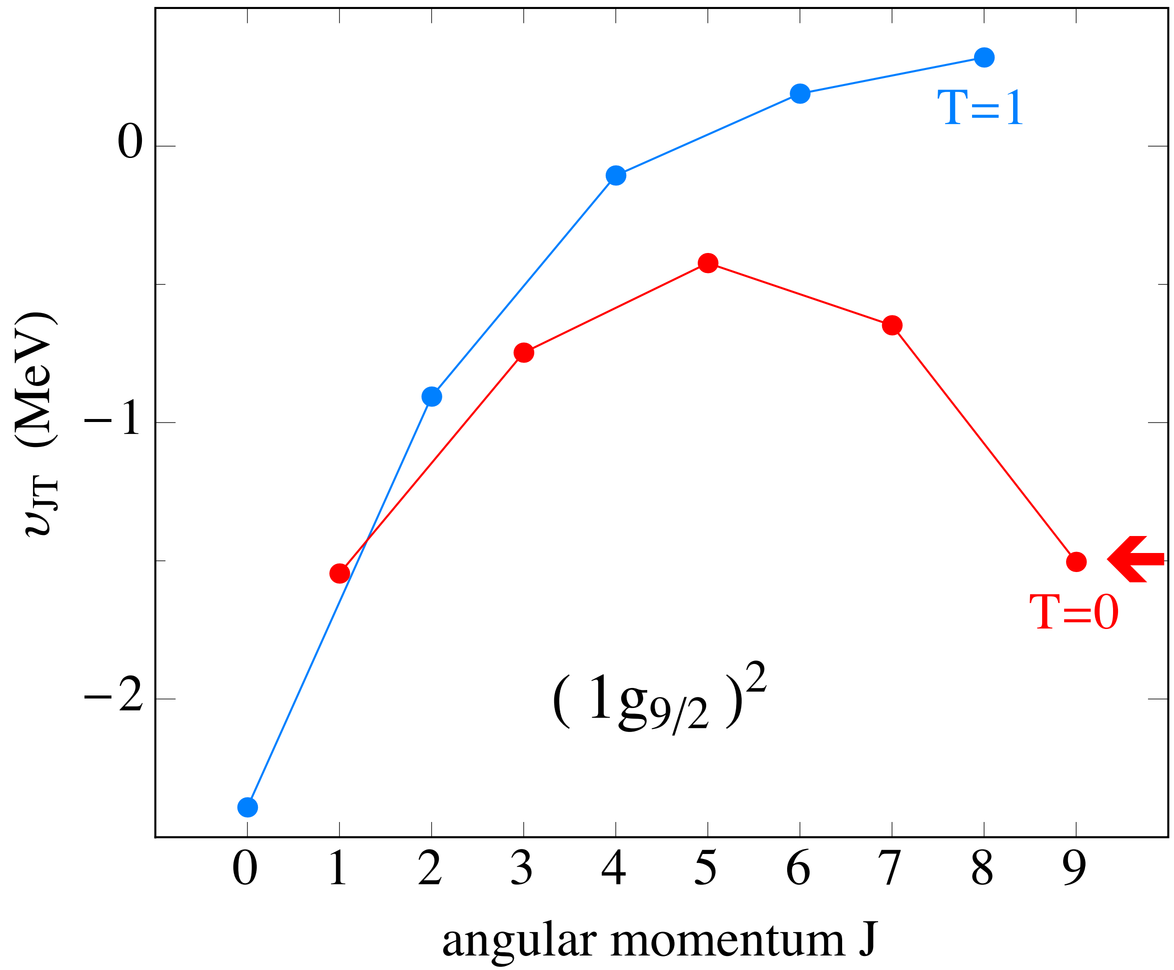
Nucleon-nucleon interaction



Nucleon-nucleon interaction



Nucleon-nucleon interaction



Neutron-proton correlations

The question is **not** whether T=0 interactions between nucleons exist or whether they are important. They do and they are.

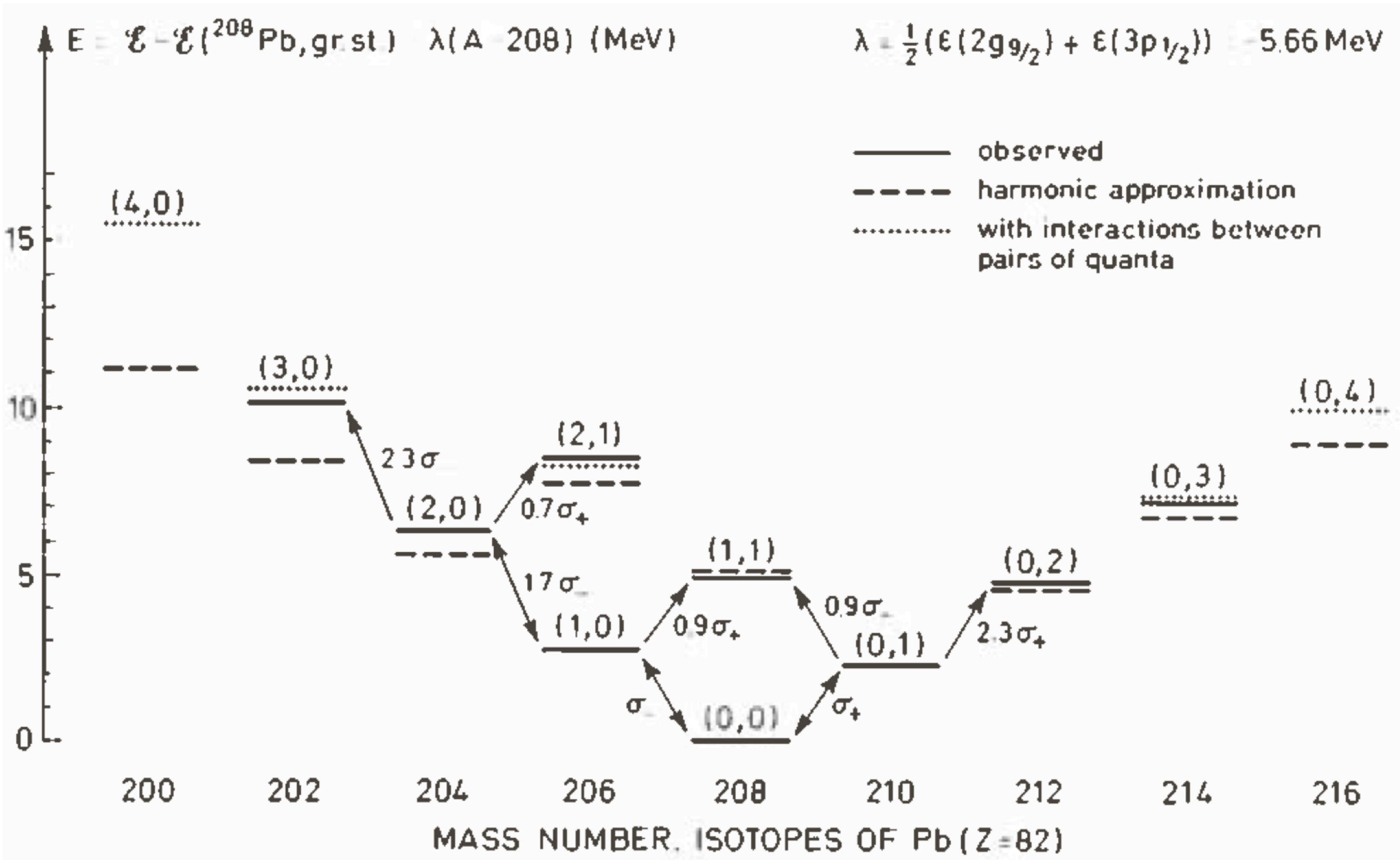
The question is whether T=0 correlations exist, similar to BCS-type ones for T=1.

Test from two-nucleon transfer reactions.

Related (but different) question: Are aligned T=0 neutron-proton pairs dominantly important?

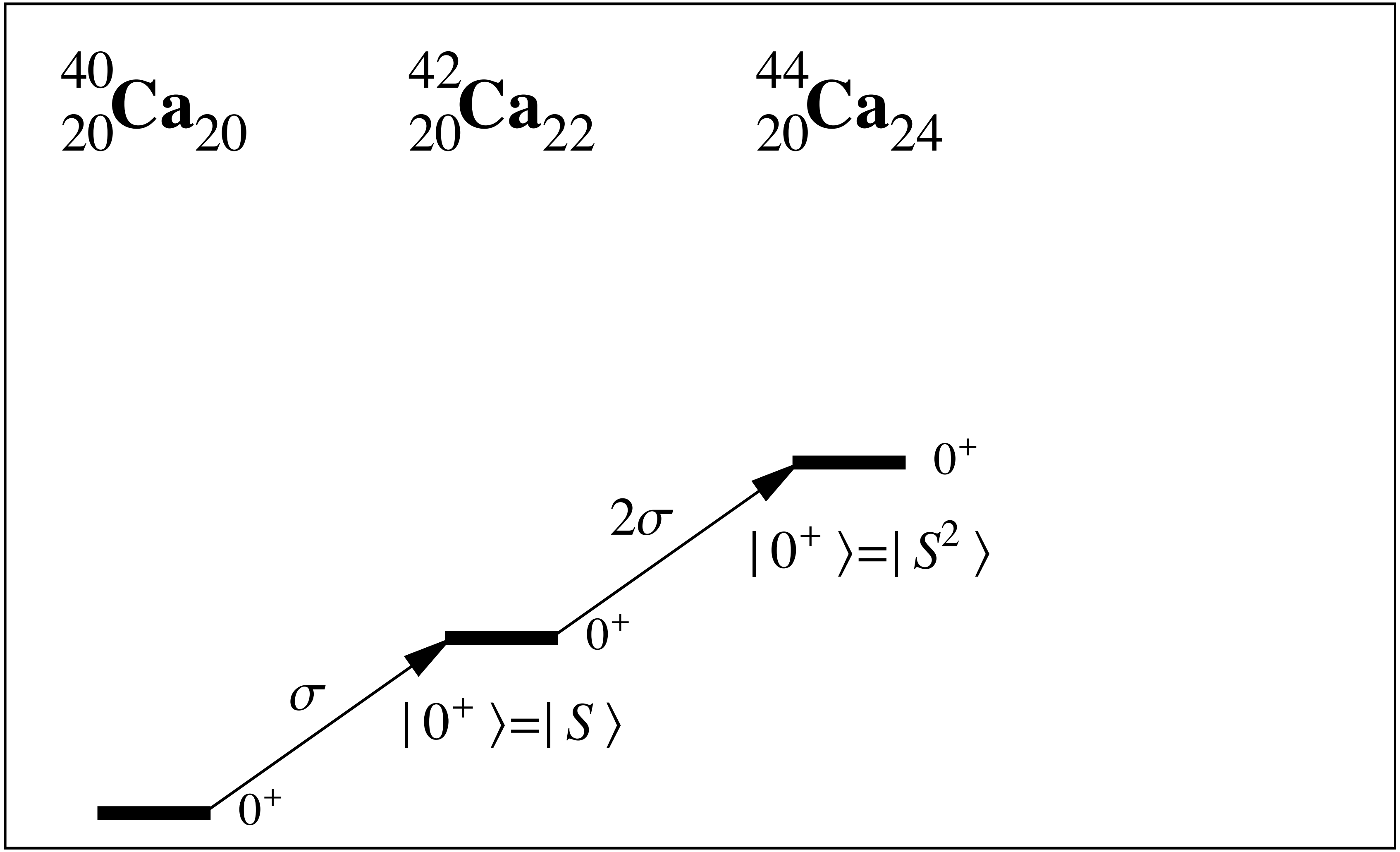
Test from magnetic & electric moments of N=Z nuclei.

T=1 pair vibrations in Pb

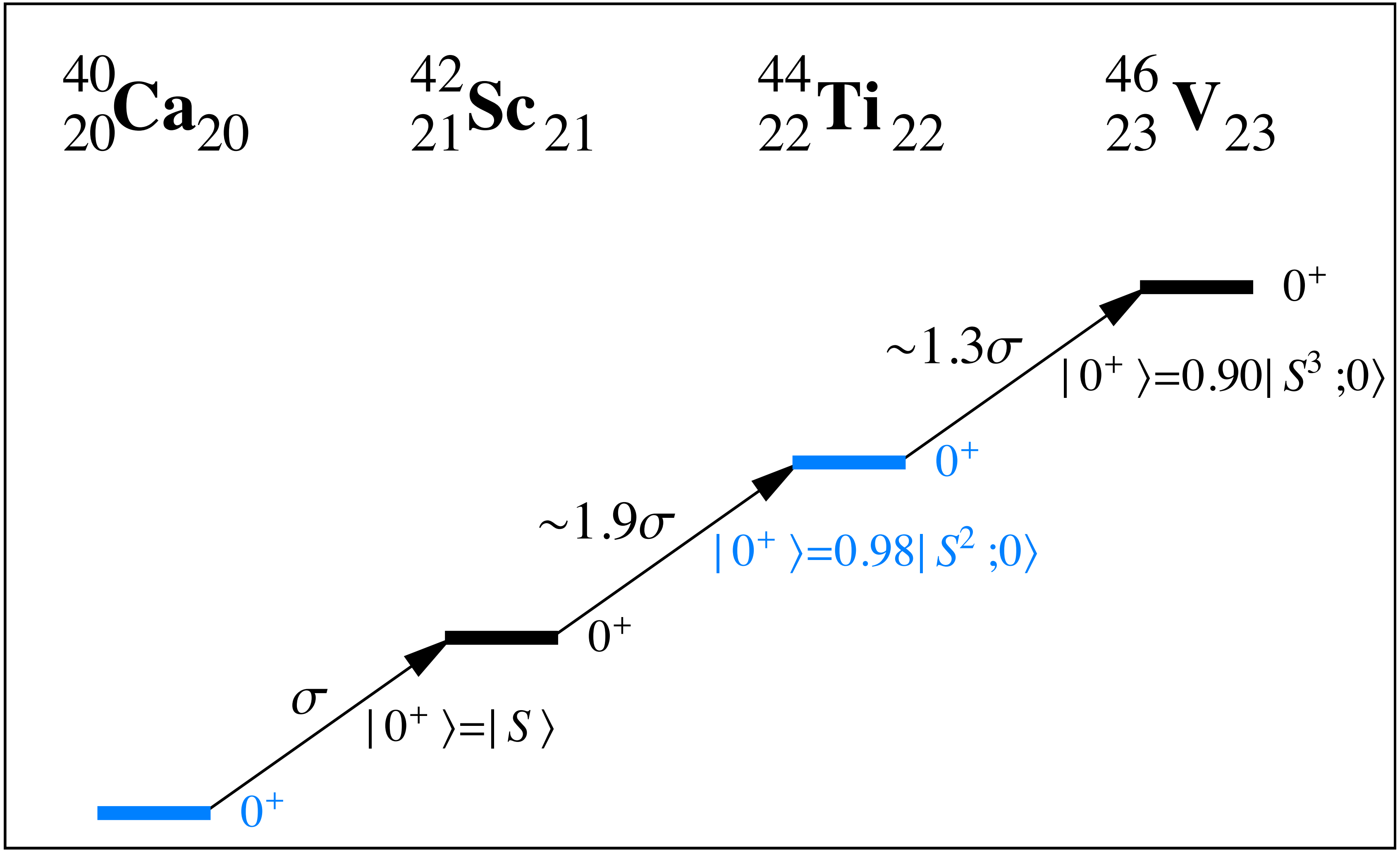


A. Bohr & B.R. Mottelson, Volume 2, page 646

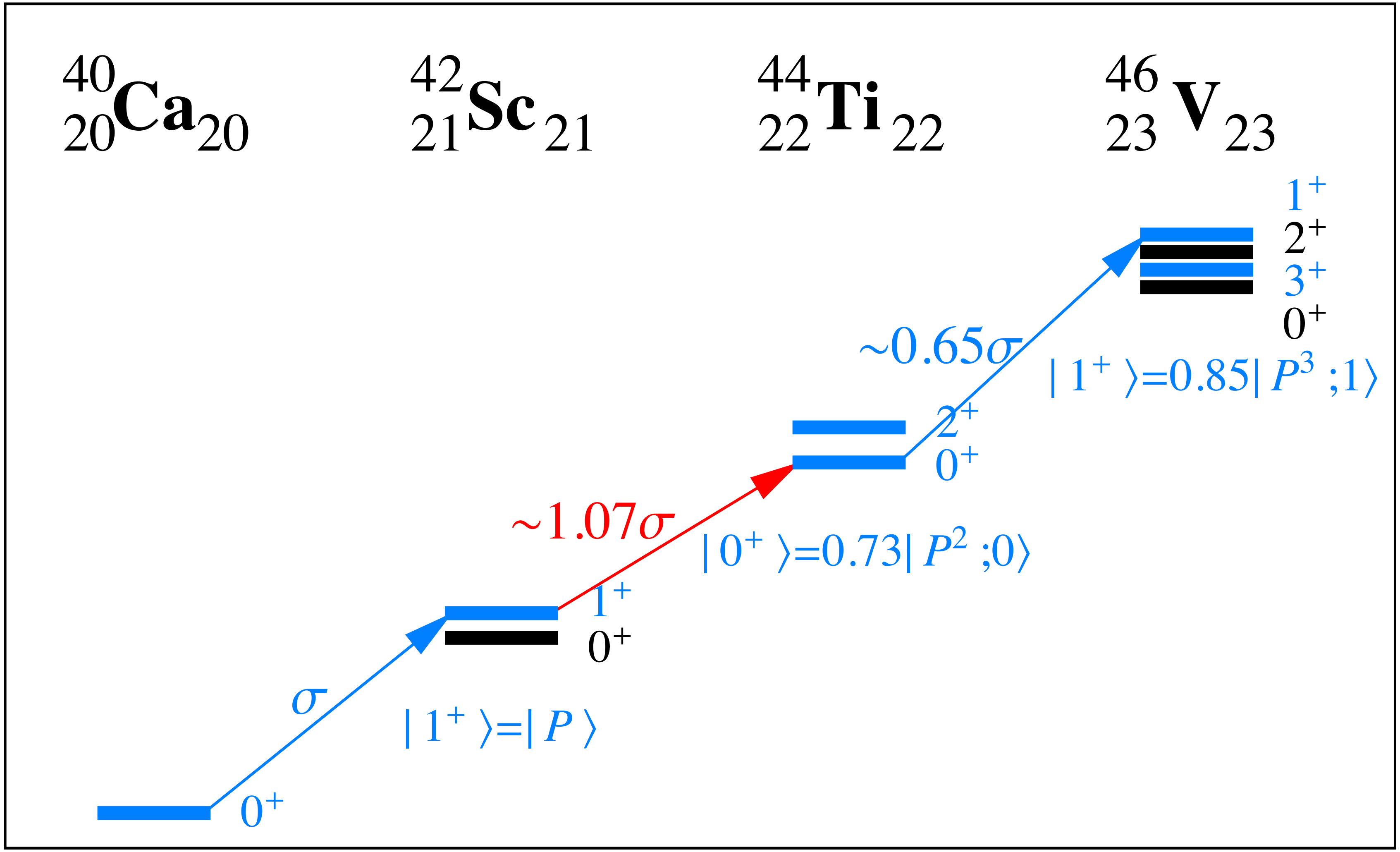
T=1 pair vibrations in Ca



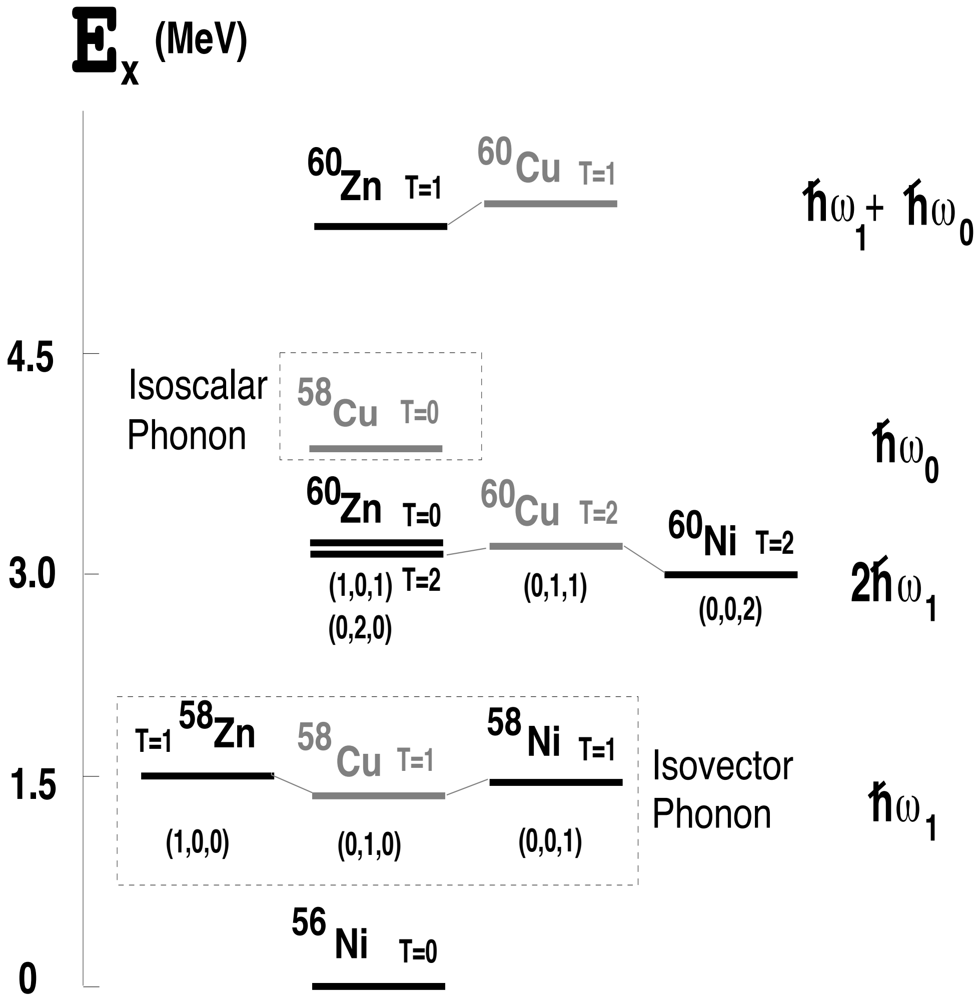
T=1 pair vibrations in Ca-Sc-Ti-V?



T=0 pair vibrations in Ca-Sc-Ti-V?



Pair vibrations on ^{56}Ni



A.O. Macchiavelli et al., arXiv:nucl-th/9912041

Pair vibrations & rotations

Pairing hamiltonian for several shells. For two shells and identical nucleons:

$$\hat{H}(\Delta\varepsilon, g) = \Delta\varepsilon(\hat{n}_+ - \hat{n}_-) - g\hat{V}_{J=0,T=1}$$

Phase transition occurs as a function of $g/\Delta\varepsilon$:

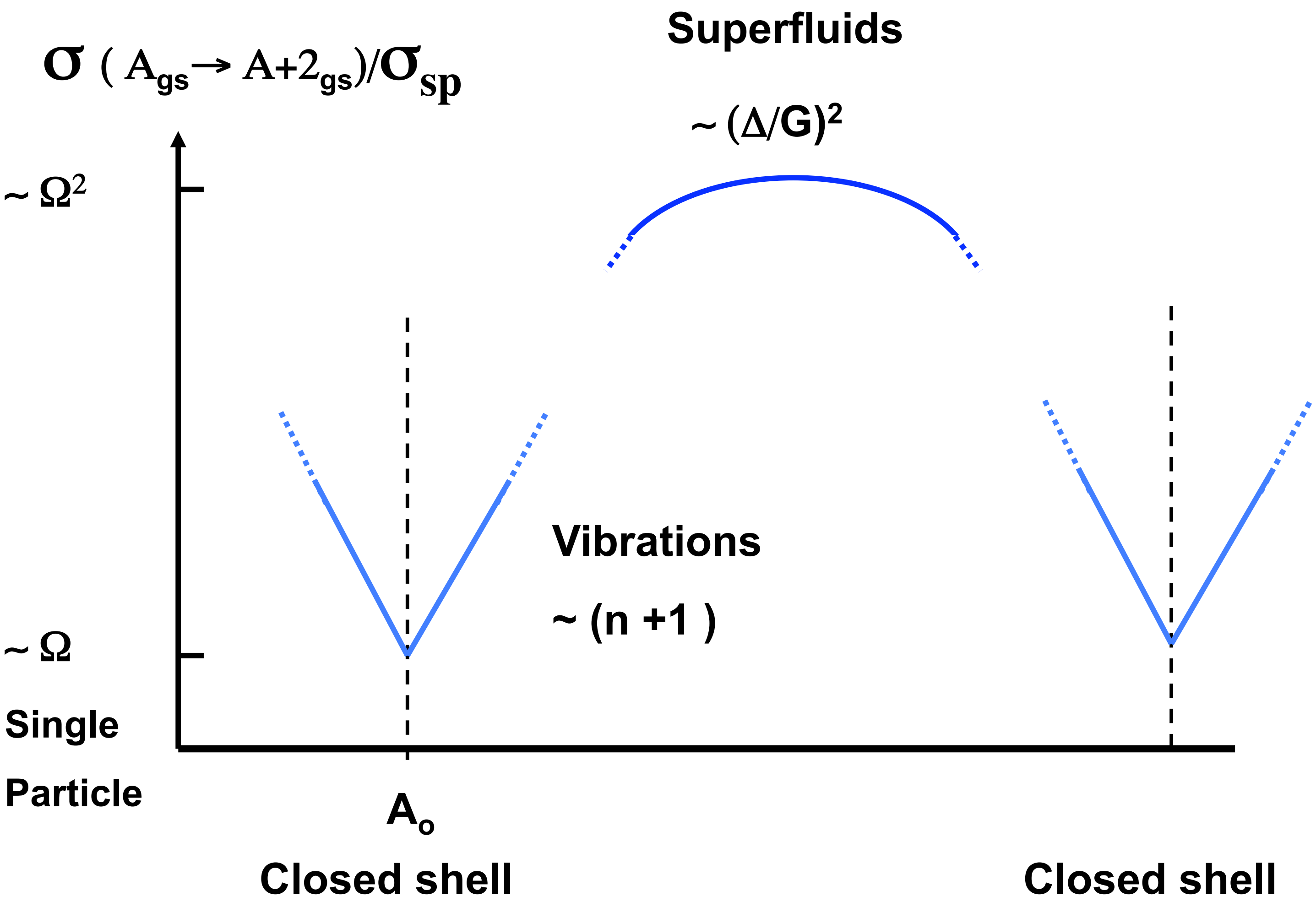
For $g<g_{crit}$: pair vibrations (ex: Pb isotopes)

For $g>g_{crit}$: pair rotations (ex: Sn isotopes)

Two different coupling schemes:

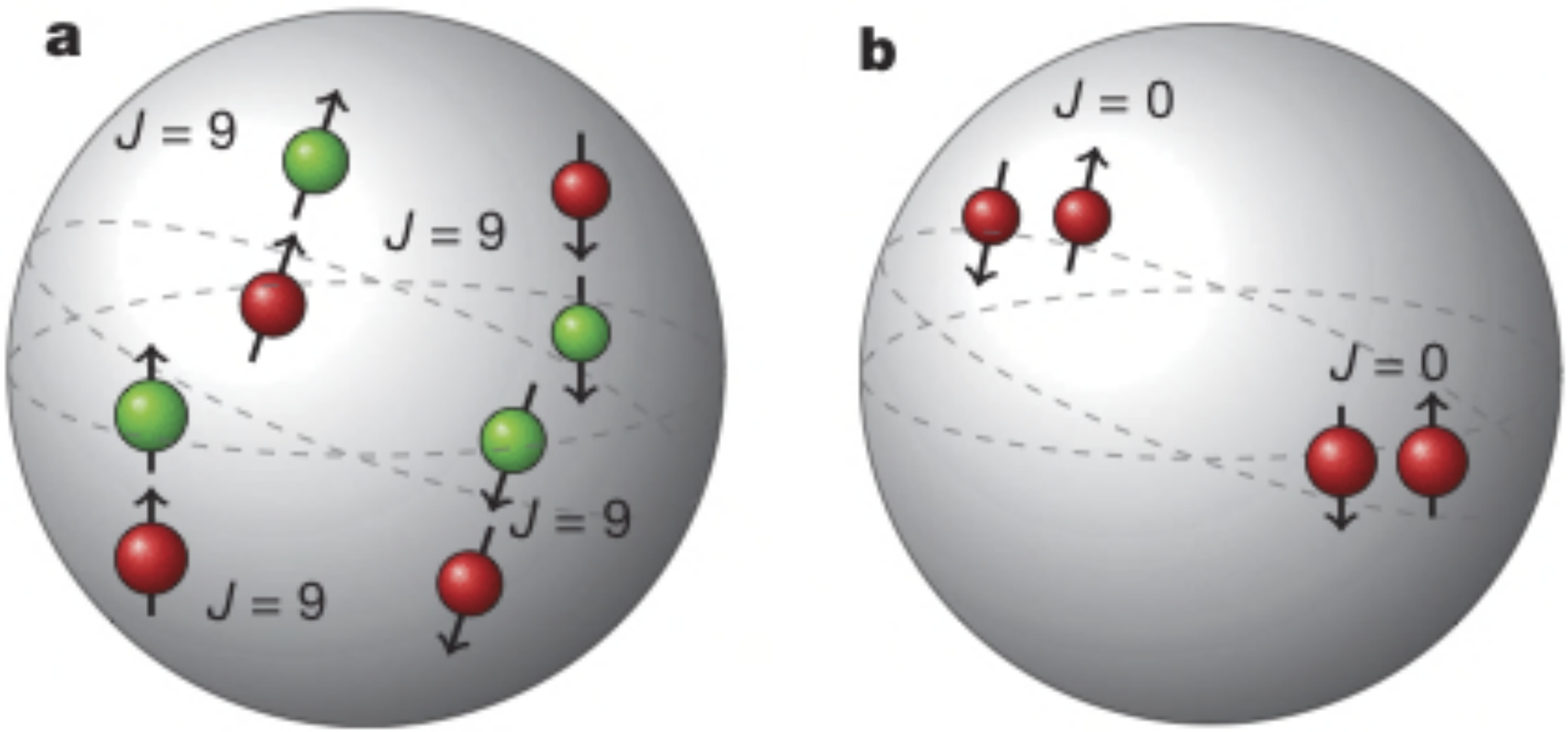
$$\mathrm{SU}_+(2)\times\mathrm{SU}_-(2)\supset\begin{pmatrix}\mathrm{U}_+(1)\times\mathrm{U}_-(1)\\ \mathrm{SU}(2)\end{pmatrix}\supset\mathrm{U}(1)$$

Pair vibrations and rotations



A.O. Macchiavelli

Spin-aligned coupling scheme



B. Cederwall *et al.*, Nature **469** (2011) 68

A new coupling scheme?

Our results reveal evidence for a spin-aligned, isoscalar neutron–proton coupling scheme.

[T]his coupling scheme replaces normal superfluidity (characterized by seniority coupling) in the ground and low-lying excited states of the heaviest *N*=*Z* nuclei.

B. Cederwall *et al.*, Nature **469** (2011) 68

Approximations

Hypothesis: N=Z nuclei can be described in the (spherical) shell model, in an appropriate model space and with an appropriate interaction.

Approximations:

(A) Truncate shell model to a single high-j shell.

(B) Truncate single-j shell space to one written in terms of aligned-spin B (J=9) pairs.

(C) Replace aligned-spin B pairs by b bosons.

S. Zerguine and P. Van Isacker, Phys. Rev. C **83** (2011) 064314
P. Van Isacker, Int. J. Mod Phys. E 22 (2013) 1330028

Pair analysis in the shell model

Define different types of nucleon pairs:

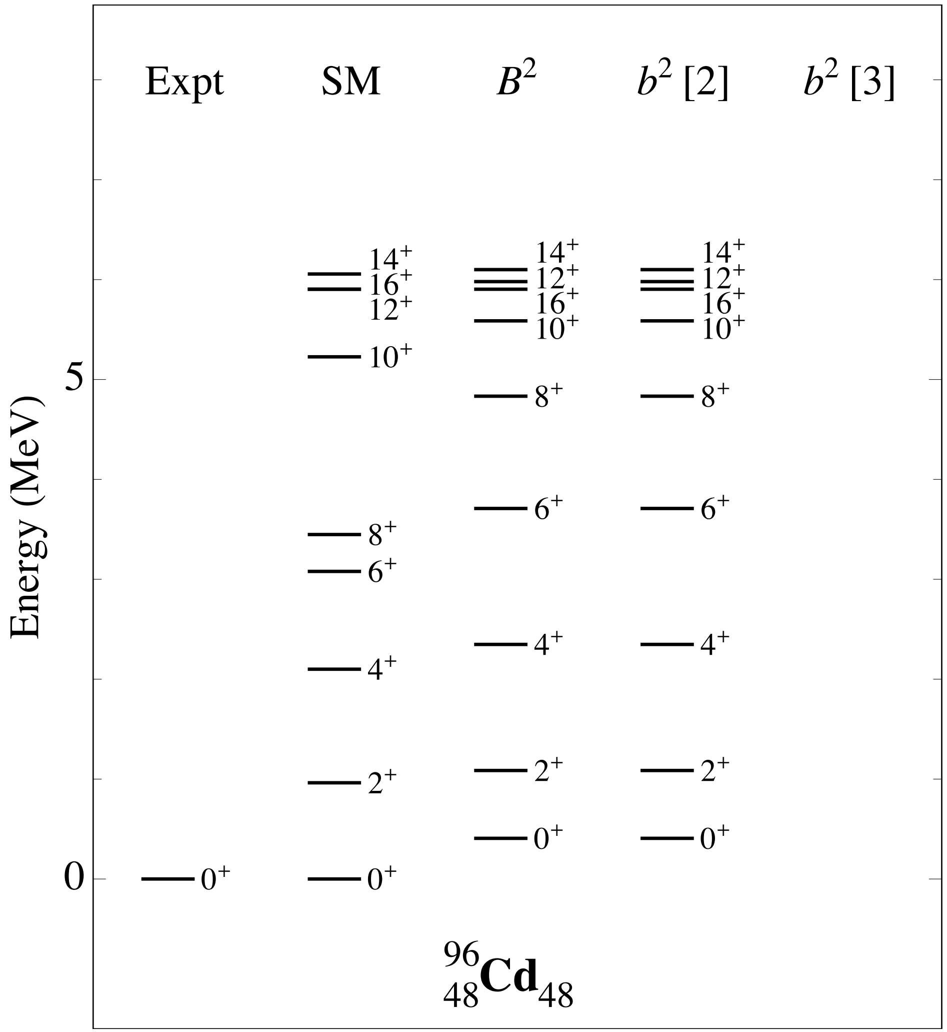
$$B^+_{JT} = \left(a^+_{j1/2} \times a^+_{j1/2}\right)^{(JT)}$$

$$S^+ : J = 0, T = 1; \quad D^+ : J = 2, T = 1; \quad B^+ : J = 9, T = 0.$$

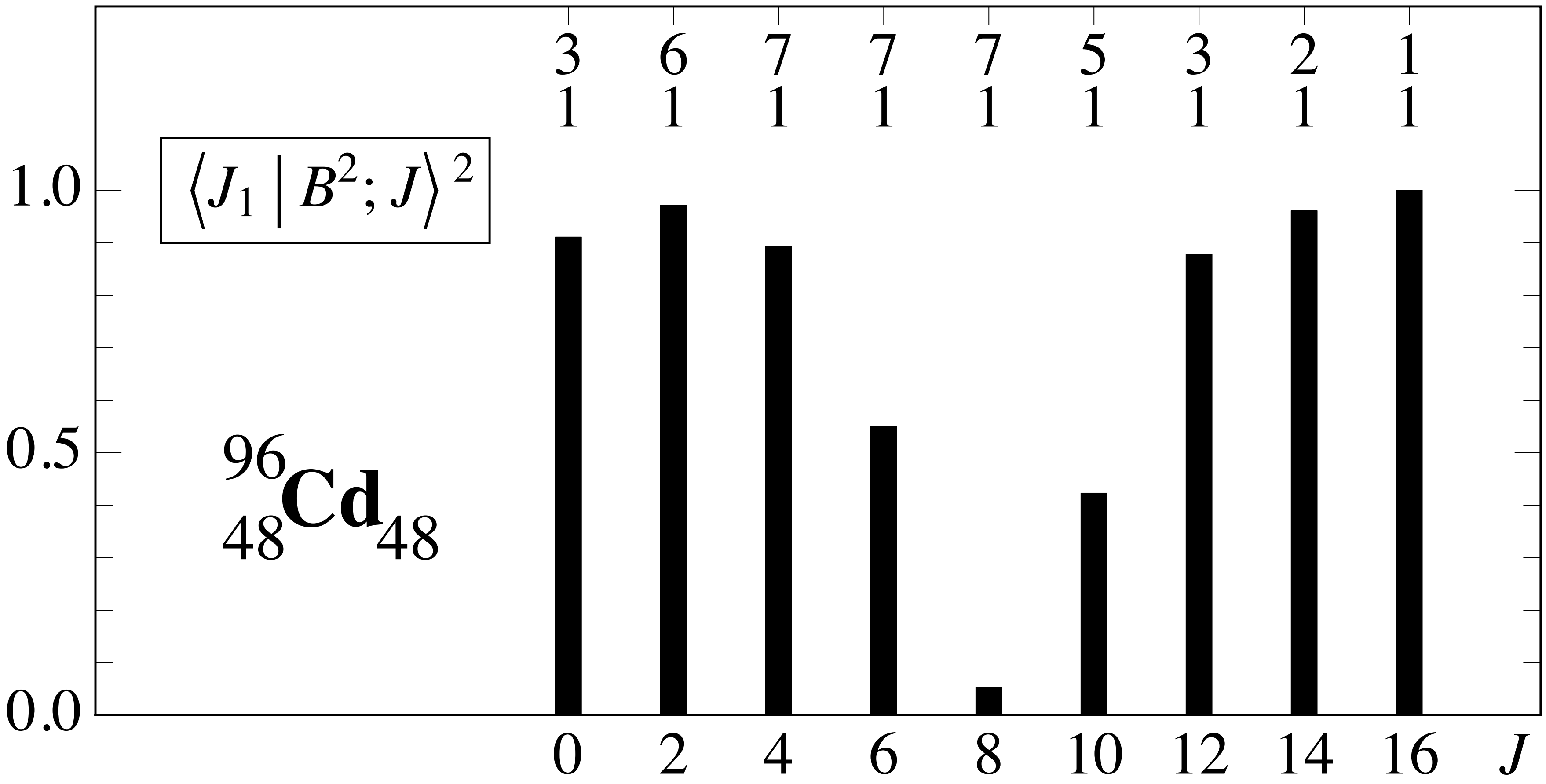
Calculate overlap with shell-model wave functions with the nucleon-pair shell model in an isospin-invariant formulation.

J.-Q. Chen, Nucl. Phys. A **562** (1993) 218; 626 (1997) 686
G.J. Fu *et al.*, Phys. Rev. C **87** (2013) 044310

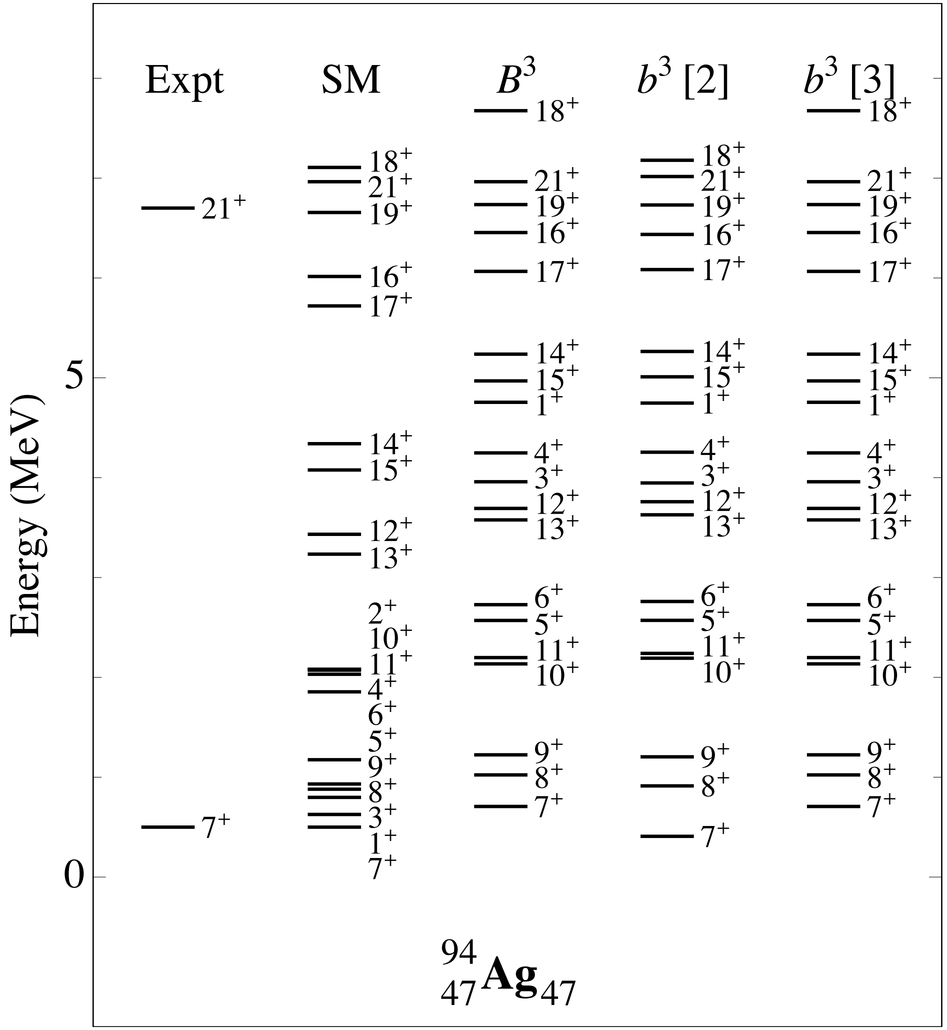
Spectrum of ^{96}Cd



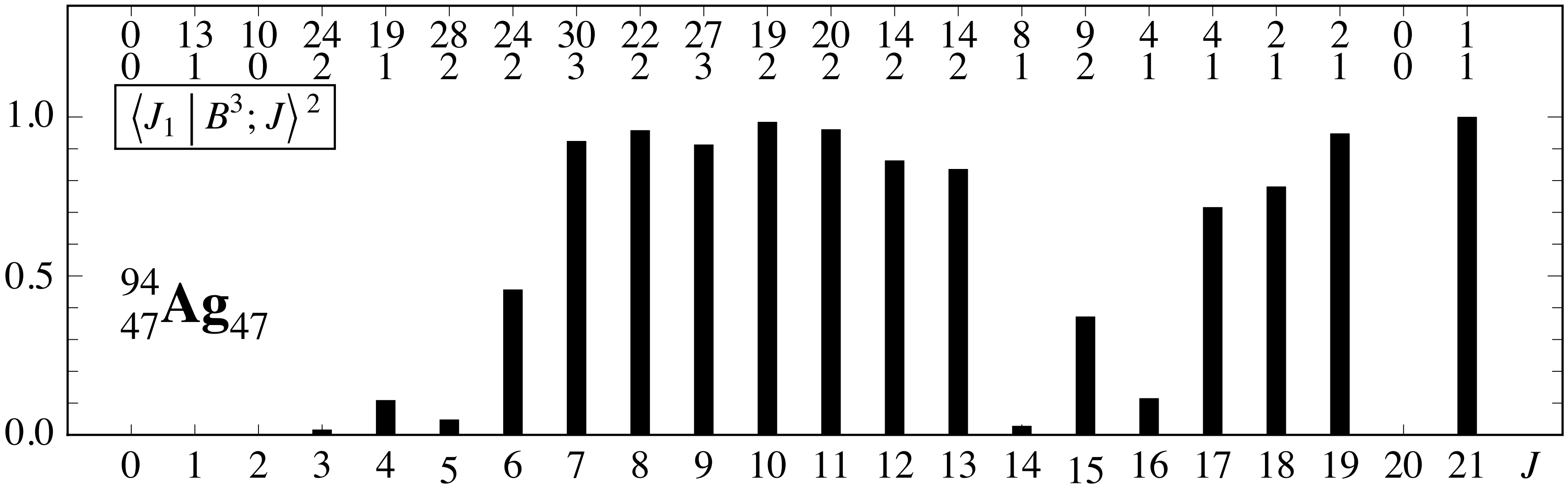
B–pair analysis of ^{96}Cd



Spectrum of ^{94}Ag



B–pair analysis of ^{94}Ag



Magnetic dipole moments

For any state in a single-j shell

$$g(\alpha J) = \frac{1}{2}(g_\nu + g_\pi) \approx \begin{cases} 0.52 \text{ to } 0.55\ \mu_N & (1f_{7/2}) \\ 0.51 \text{ to } 0.54\ \mu_N & (1g_{9/2}) \end{cases}$$

The same result is obtained with *b*-IBM mapped from a single-j shell model.

∴ Magnetic dipole moments test approximation (A) but are insensitive to (B) and (C).

In ^{46}V: $\mu(3_1^+) = 1.64(3)\ \mu_N$

In ^{50}Mn: $\mu(5_1^+) = 2.76(1)\ \mu_N$

F.C. Charlwood *et al.*, Phys. Lett. B **690** (2010) 346

Q moment of 7^+ isomer in ^{94}Ag

Shell model in $pf_{5/2}g_{9/2}$ space (M=7 -> dim=37327):

$$Q\left(7_1^+\right) = 0.62\ \mathrm{b}$$

Shell model in $1g_{9/2}$ (J=7 -> dim=84):

$$Q\left(7_1^+\right) = 6.60\left(e_\nu + e_\pi\right)\left(\ell_{\mathrm{ho}}\right)^2 \approx 0.60\ \mathrm{b}$$

Expression in terms of b bosons:

$$Q\left(b^3[16]7\right) = \sqrt{\frac{3093027730092336 4}{627253477610841}}\left(e_\nu + e_\pi\right)\left(\ell_{\mathrm{ho}}\right)^2 \approx 0.64\ \mathrm{b}$$

∴ Measurement of $Q(7^+)$ tests (A). Calculation confirms (B+C).

A. Poves, private communication LSSM

Conclusions

Superallowed $0^+ \rightarrow 0^+$ β decay: mirror transitions constrain the nuclear-structure corrections.

The J=2 (0?) anomaly remains unresolved and calls for experiments at higher A.

A BCS-like phase for T=0 pairing? Test from deuteron transfer.

Dominance of T=0 aligned pairs? Test from magnetic and quadrupole moments.