Aligned neutron-proton pairs in $N=Z$ nuclei

P. Van Isacker, GANIL, France

Motivation

Shell-model analysis

A model with high-spin bosons

Experimental tests

ESNT workshop, Saclay, November 2015

Spin-aligned T=0 np pairs

Motivation: A simple description of the $N=Z$ nuclei ^{98}In, ^{96}Cd, ^{94}Ag, ^{92}Pd, ^{90}Rh.

Starting point: Shell-model interpretation in terms of spin-aligned T=0 np pairs.

Experiments have been proposed and carried out at GANIL (Cederwall, de France, Wadsworth…).

Several calculations: Qi, Wu *et al* (Stockholm), Coraggio *et al* (Naples), Zhao *et al* (Shanghai), Zuker *et al*, Sambataro & Sandulescu,…

Conflicting conclusions.

S. Zerguine & P. Van Isacker, Phys. Rev. C **83** (2011) 064314
P. Van Isacker, Phys. Scr. **T150** (2012) 014042
P. Van Isacker, Int. J. Mod. Phys. E **22** (2013) 1330028

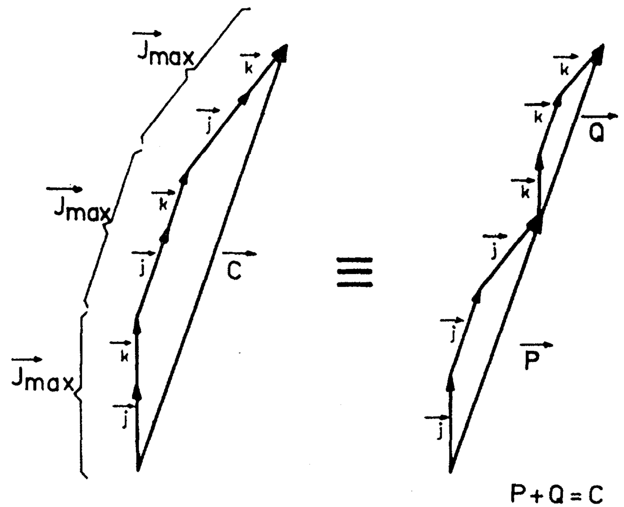
Plus ça change (1)

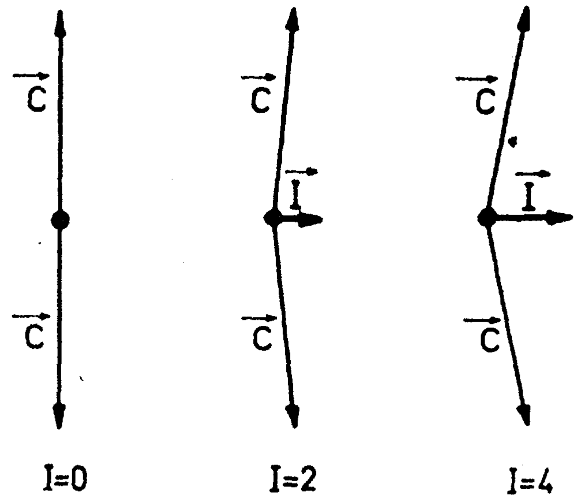
PHYSICAL REVIEW VOLUME 161, NUMBER 4 20 SEPTEMBER 1967

Stretch Scheme, a Shell-Model Description of Deformed Nuclei

MICHAEL DANOS AND VINCENT GILLET
Service de Physique Théorique, Centre d'Etudes Nucléaires de Saclay, Gif-sur-Yvett, Seine et Oise, France
and
National Bureau of Standards, Washington, D. C.
(Received 23 March 1967)

A good angular-momentum wave function containing the maximum possible intrinsic angular momenta leads to a microscopic description of the nuclear rotational spectra in terms of spherical shell-model states. The rotational excitation energies arise from the residual two-body force. In the actual model calculations, the only approximation was a partial violation of the exclusion principle. The computed departures from the $I(I+1)$ law are consistent with experiment. Reasons are given for the preference of positive over negative intrinsic deformations.





Plus ça change (2)

DL/NUC/P265T

preprint Daresbury Laboratory

DL/NUC/P265T

HIGH MULTIPOLE PROTON-NEUTRON PAIRING IN NUCLEI

by

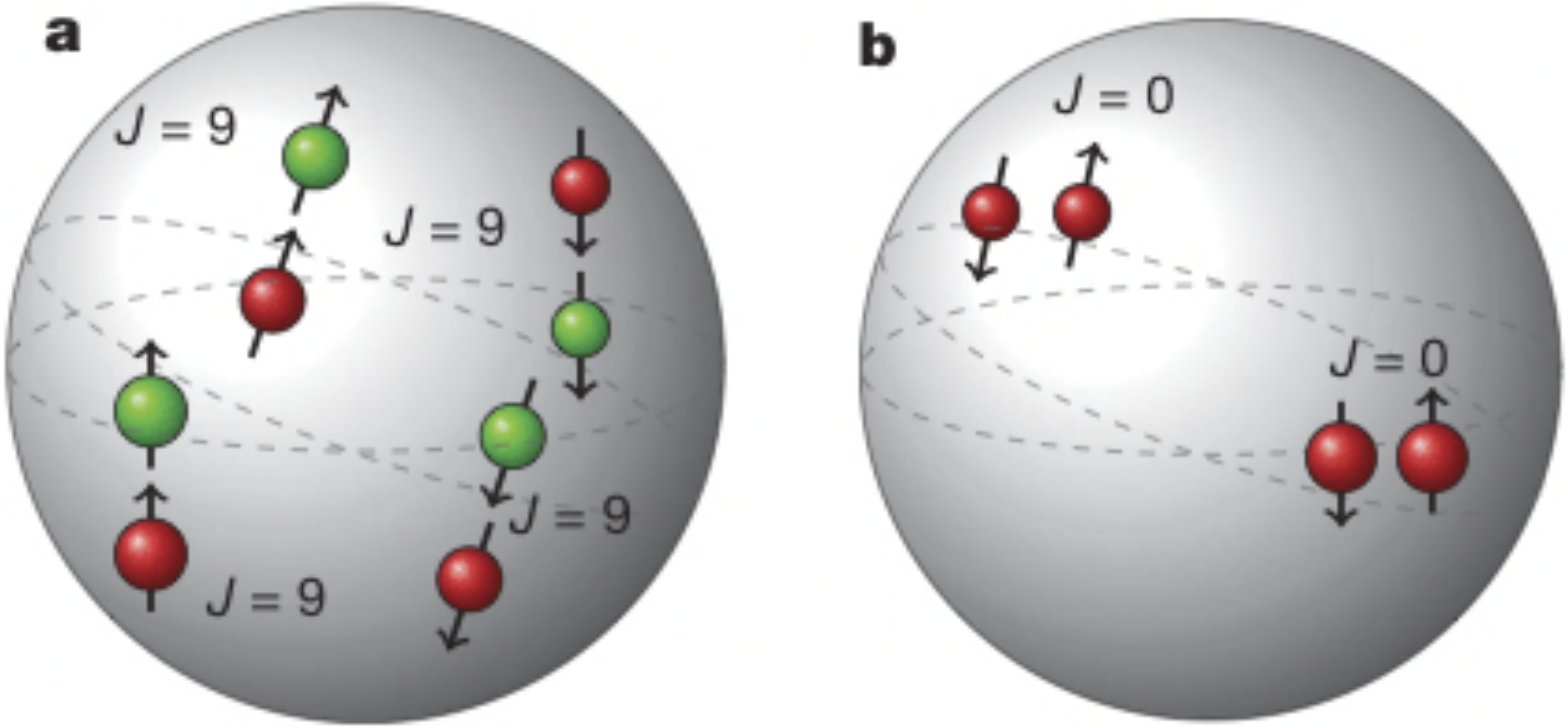
H.J. DALEY, SERC Daresbury Laboratory

To be submitted to Nucl. Phys. A

NOVEMBER, 1987

Science and Engineering Research Council
DARESBURY LABORATORY
Daresbury, Warrington WA4 4AD

Nuclear belly dancer



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

An open mind

J.P. Elliott:

It might be argued [...] that the model [IBM] will fail in these light nuclei. We began this investigation with an open mind, being as much interested in demonstrating the failure of the model in this region as in showing its success.

P. Halse *et al.*, Nucl. Phys. **417** (1984) 301

Approximations

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

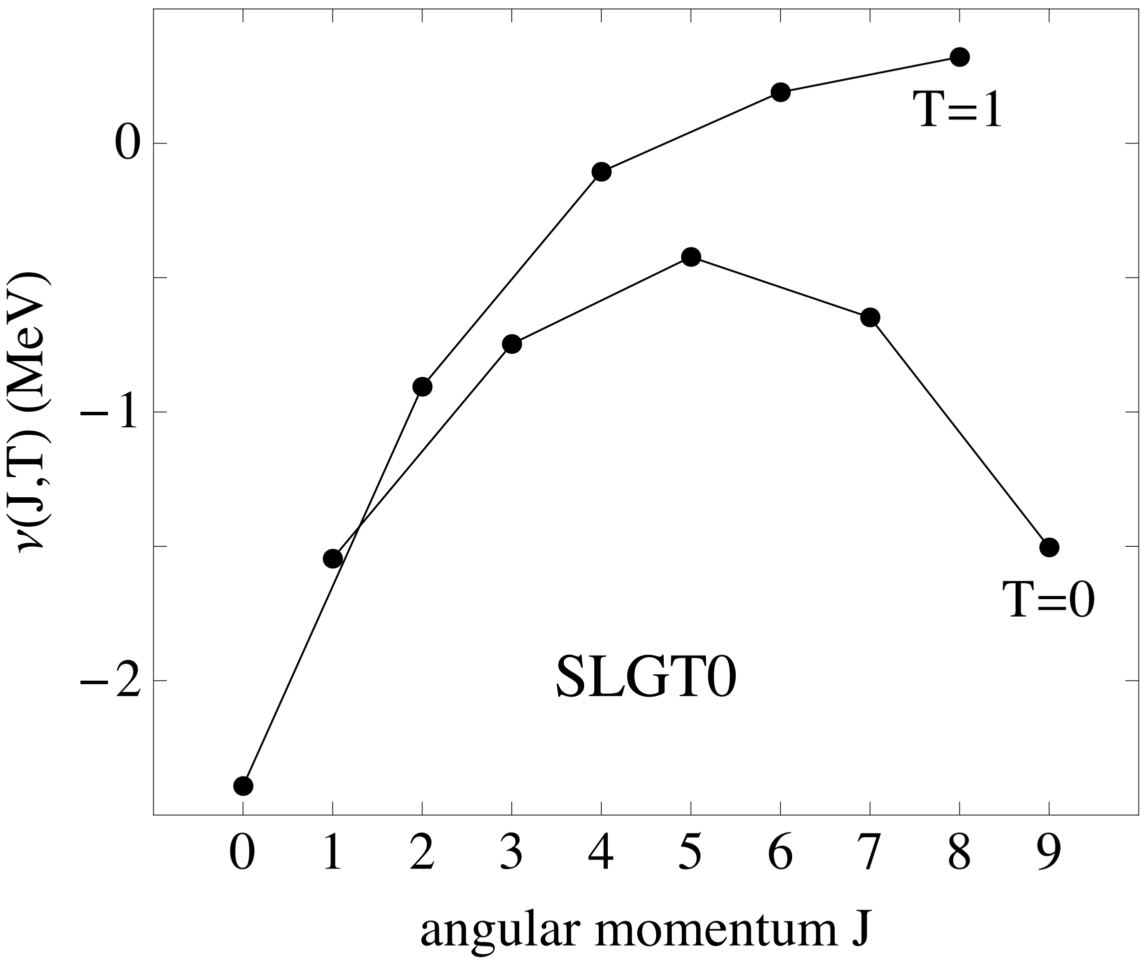
Approximations:

(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.

Shell-model interaction: $1g_{9/2}$



E.J.D. Serduke *et al.*, Nucl. Phys. A **256** (1976) 45
H. Herndl and B.A. Brown, Nucl. Phys. A **627** (1997) 35

Pair analysis in the shell model

Define different types of nucleon pairs:

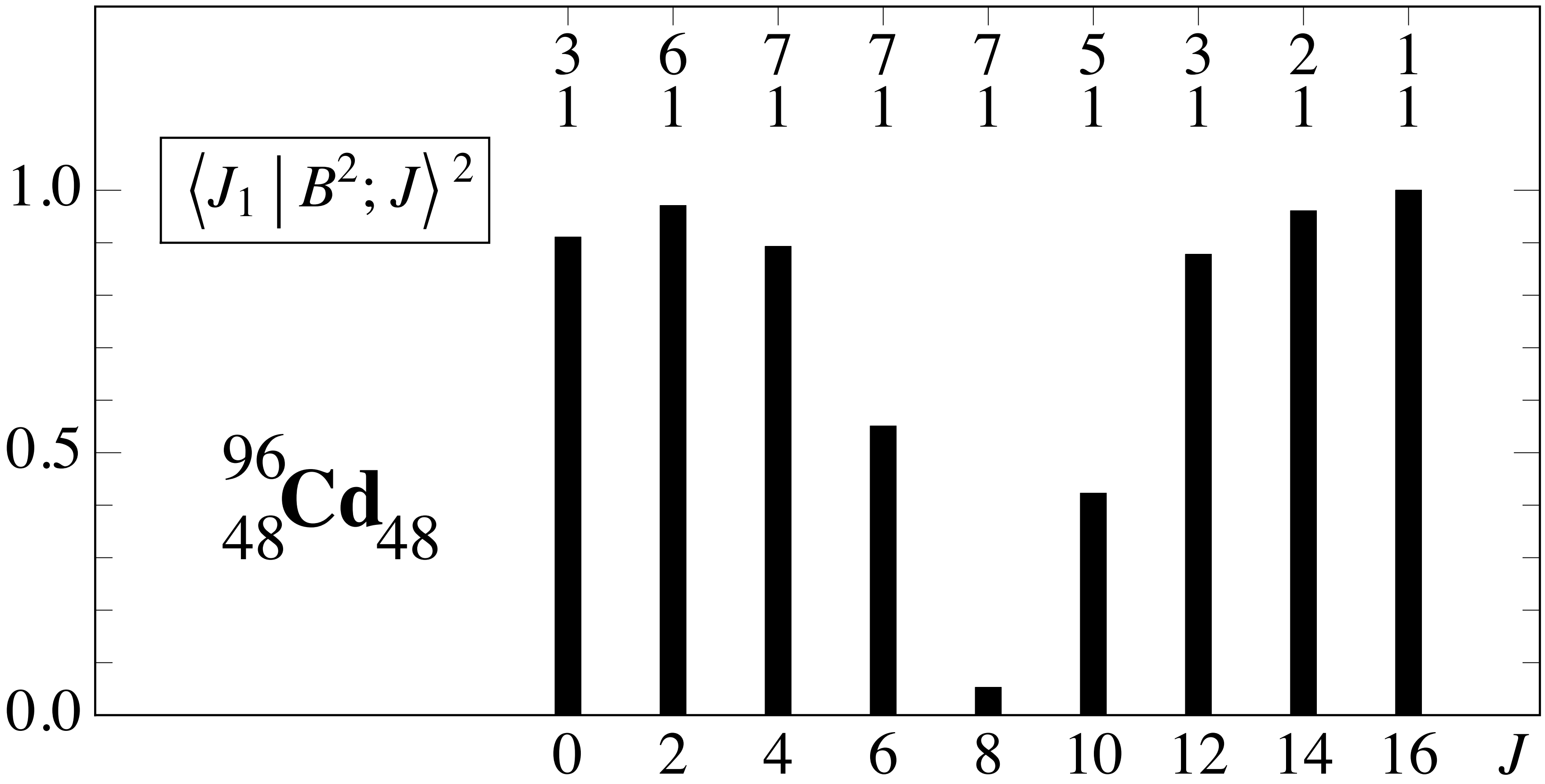
$$B^{+}_{JT} = \left(a^{+}_{j1/2} \times a^{+}_{j1/2}\right)^{(JT)}$$

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

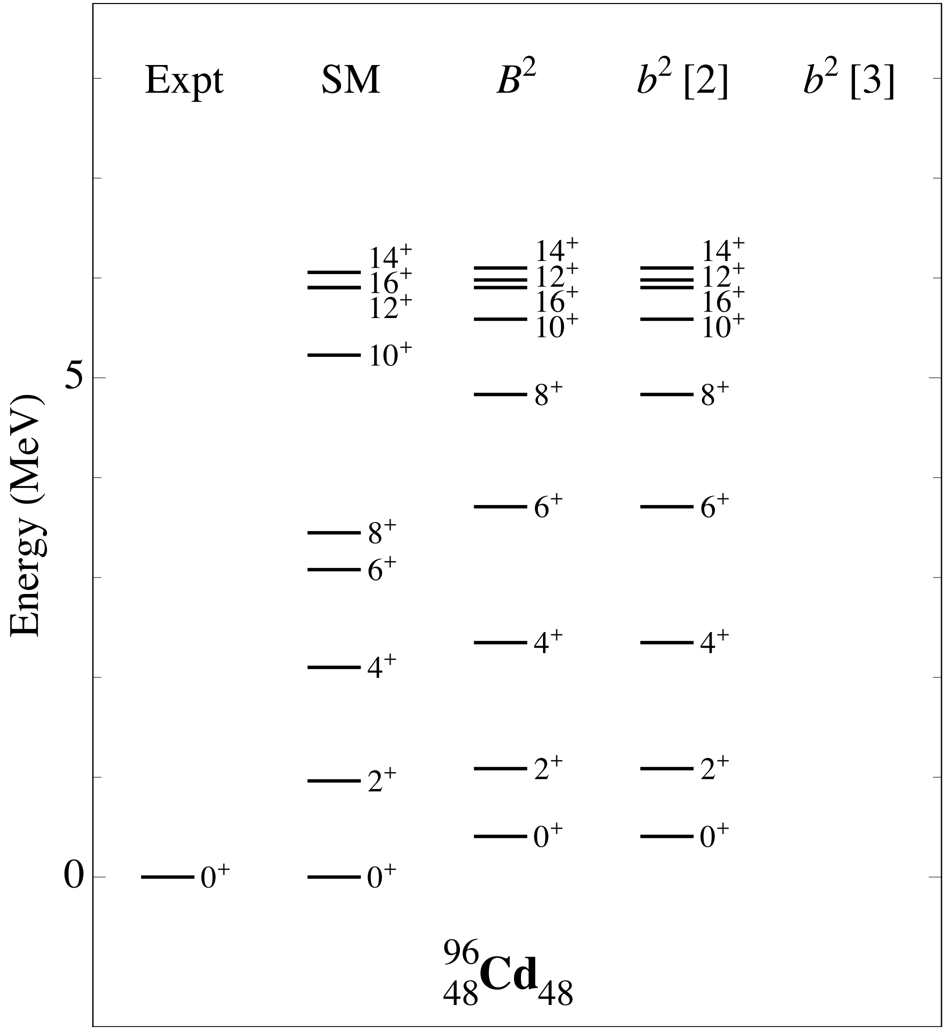
Calculate overlap with shell-model wave functions with the nucleon-pair shell model in an isospin-invariant formulation.

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

B-pair analysis of ^{96}Cd



Spectrum of ^{96}Cd



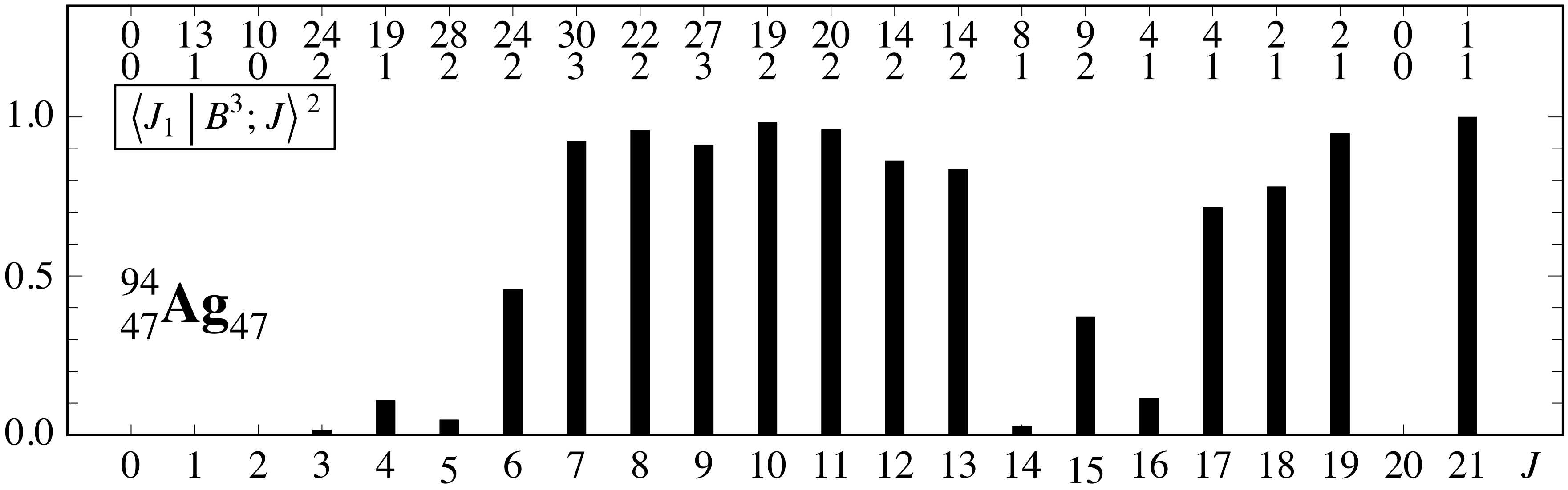
Mapping to bosons

Transform to a much simpler problem in terms of interacting bosons: $B^{+} \rightarrow b^{+}$

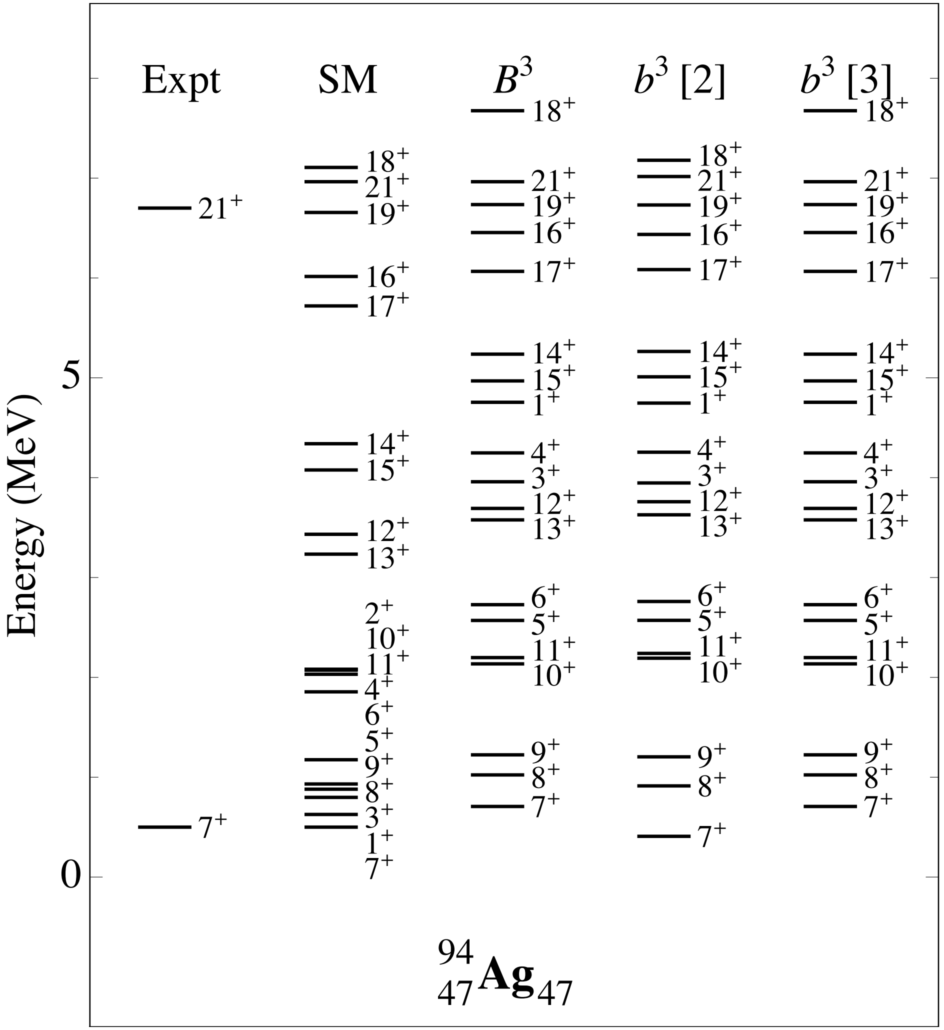
Boson energies and boson-boson interactions are derived from the shell model (i.e., *not* fitted).

T. Otsuka *et al.*, Nucl. Phys. A **309** (1978) 1
L.D. Skouras *et al.*, Nucl. Phys. A **516** (1990) 255

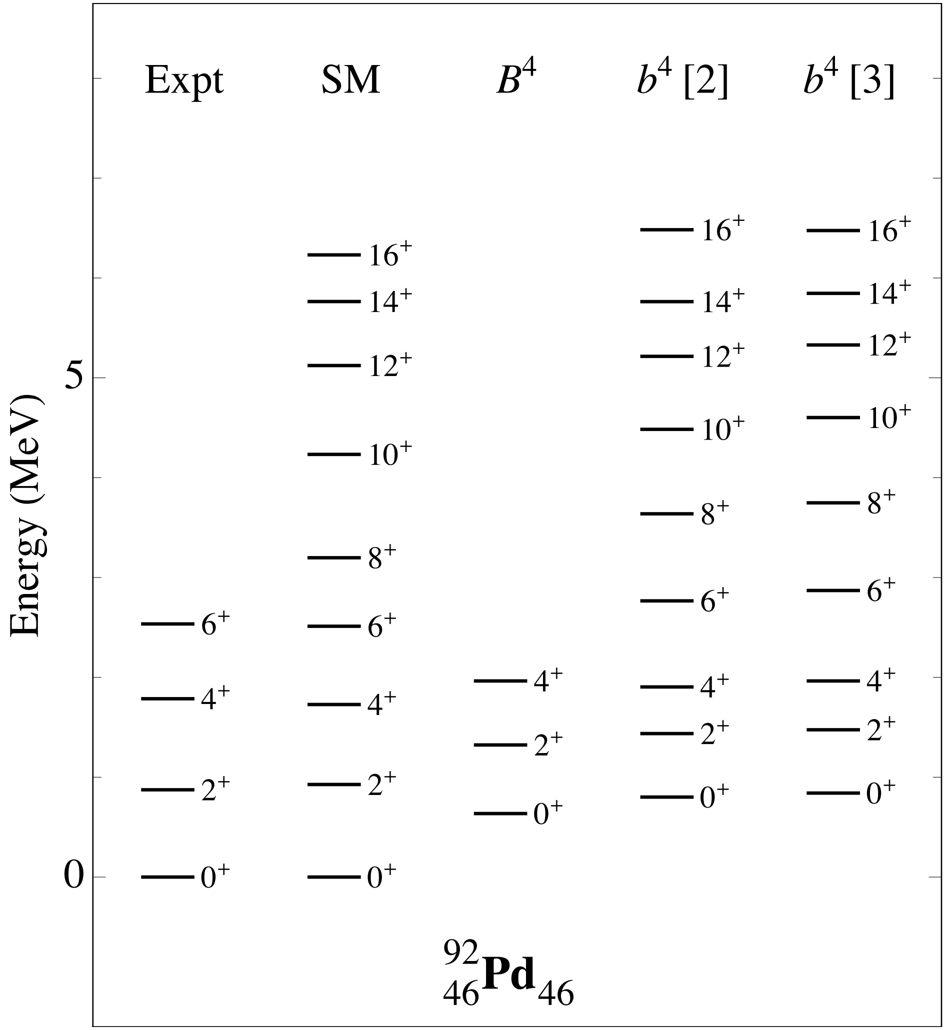
B-pair analysis of ^{94}Ag



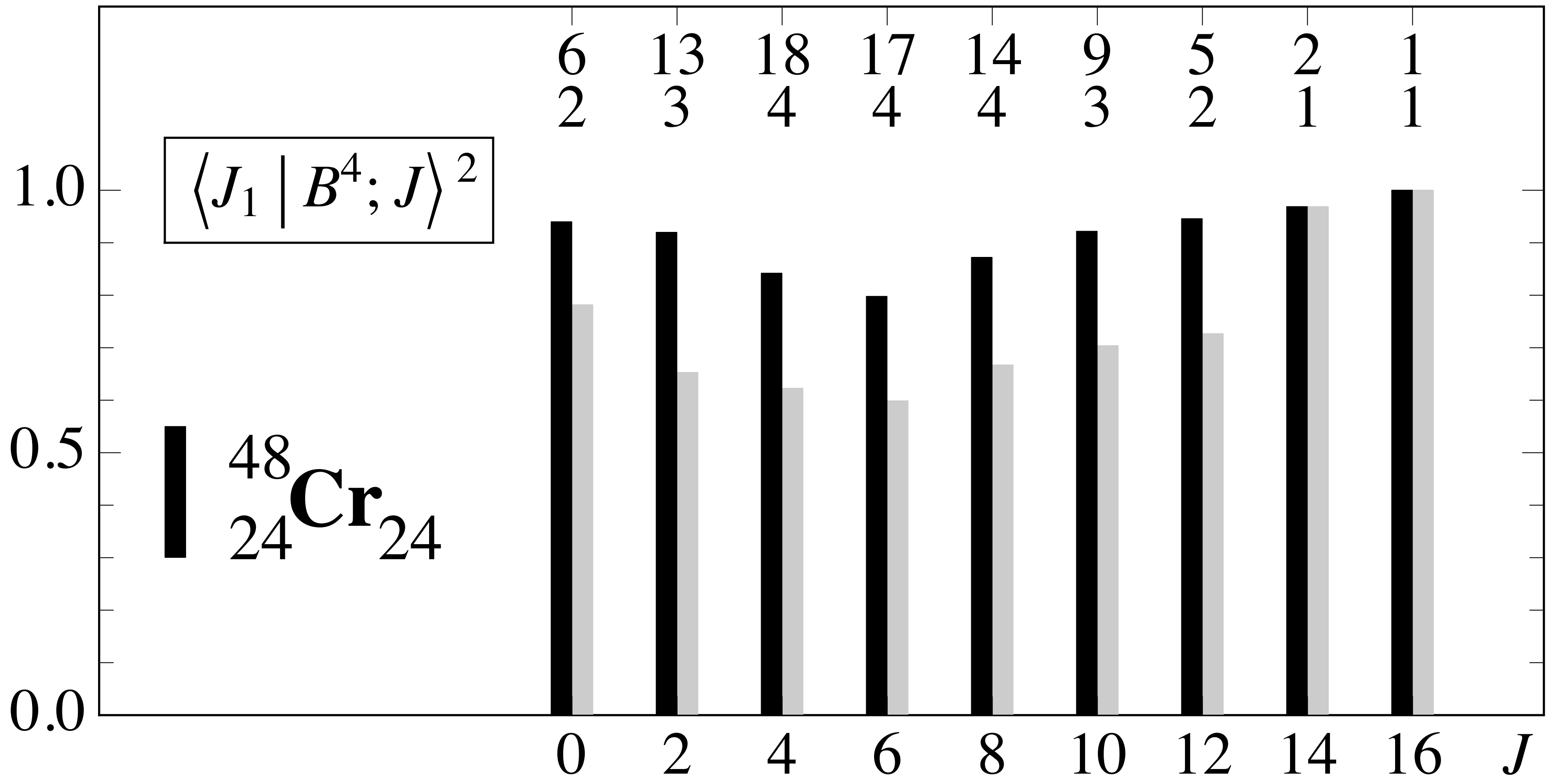
Spectrum of ^{94}Ag



Spectrum of ^{92}Pd



B-pair analysis of ^{48}Cr



Magnetic dipole moments

For any state in a single-j shell

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

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 21⁺ isomer in ^{94}Ag

Shell model in $pf_{5/2}g_{9/2}$ space (M=21 -> dim=2):

$$Q\left(21_1^+\right) = 0.44 \text{ b}$$

Shell model in $1g_{9/2}$ (J=21 -> dim=1):

$$Q\left(21_1^+\right) = \sqrt{\frac{196}{9}}\left(e_\nu + e_\pi\right)\left(\ell_{\text{ho}}\right)^2 \approx 0.42 \text{ b}$$

Expression in terms of b bosons:

$$Q\left(b_\infty^3 21\right) = \sqrt{\frac{81949367824}{3489855625}}\left(e_\nu + e_\pi\right)\left(\ell_{\text{ho}}\right)^2 \approx 0.44 \text{ b}$$

∴ Calculation confirms (A+C).

A. Poves, private communication LSSM

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

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

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

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

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

Expression in terms of b bosons:

$$Q\left(b^3[16]7\right) = \sqrt{\frac{3093027730092364}{627253477610841}}\left(e_\nu + e_\pi\right)\left(\ell_{\text{ho}}\right)^2 \approx 0.64 \text{ b}$$

∴ Calculation confirms (A+B+C).

A. Poves, private communication LSSM

A discussion between physicists

What is the correct coupling scheme for these nuclei? Seniority or aligned pairs?

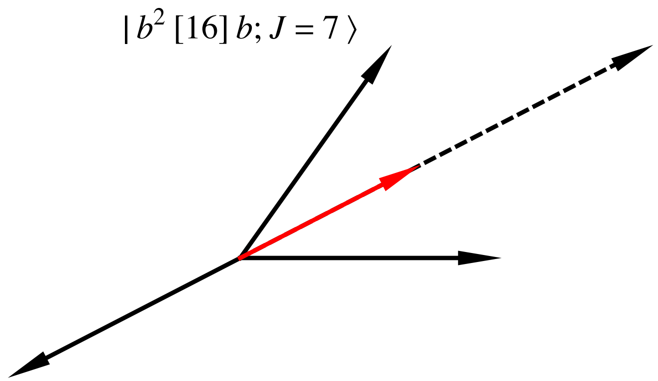
Physicist 1: The 7^+ state in ^{94}Ag can be written as

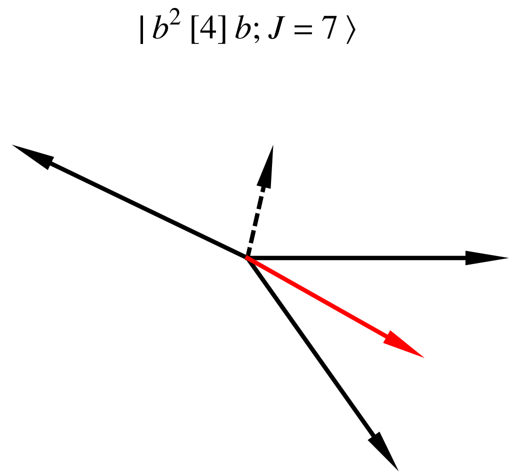
$$\left|7^+\right\rangle = \left|B^2[16]B; J=7\right\rangle$$

Physicist 2: Not at all, this 7^+ state should be written as

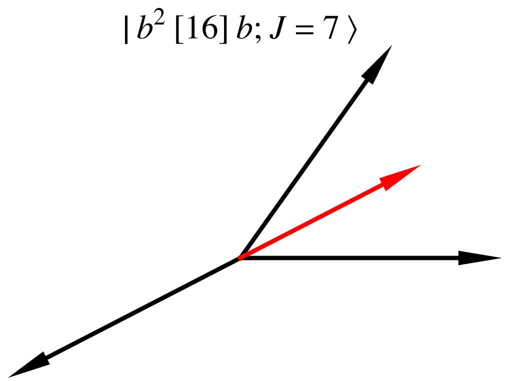
$$\left|7^+\right\rangle = \left|B^2[4]B; J=7\right\rangle$$

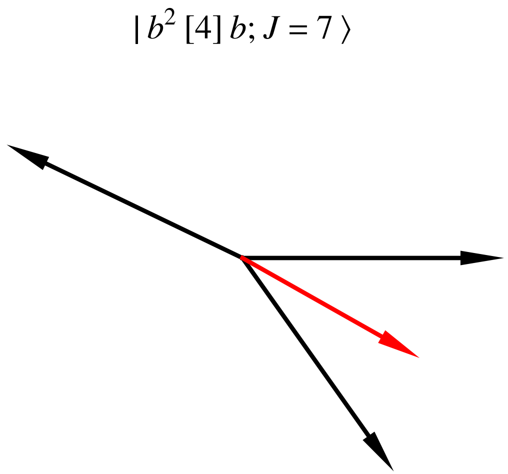
(Anti)-symmetric amnesia





(Anti)-symmetric amnesia





Fermion pairs versus bosons

In the $1g_{9/2}$ nucleon-pair shell model:

$$\left\langle B^2[4]\,B; J=7 \middle| B^2[16]\,B; J=7 \right\rangle = \sqrt{\frac{112919600563049280}{139849953265085321}} \approx 0.899$$

In the *b*-IBM:

$$\left\langle b^2[4]\,b; J=7 \middle| b^2[16]\,b; J=7 \right\rangle = \sqrt{\frac{7012200}{8733503}} \approx 0.896$$

∴ The *B* pair behaves as a boson.

Conclusions

(A) Truncation of the shell model to a single-j shell. (?)

(B) Truncation of the single-j shell space to one written in terms of aligned-spin B (J=7 or 9) pairs. (✓)

(C) Replacement of aligned-spin B pairs by b bosons. (✔)

S. Zerguine & P. Van Isacker, Phys. Rev. C **83** (2011) 064314
P. Van Isacker, Phys. Scr. **T150** (2012) 014042
P. Van Isacker, Int. J. Mod. Phys. E **22** (2013) 1330028