

Signatures for proton-neutron pairs in $N \approx Z$ nuclei



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Review

Overview of neutron–proton pairing

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Resume

ECT*

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IN NUCLEAR PHYSICS AND RELATED AREAS

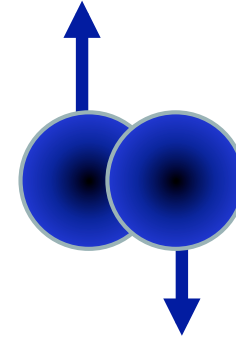
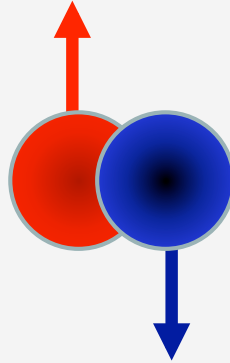
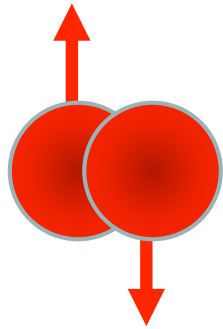
ABOUT US WORKSHOPS TRAINING PROJECTS NUPEX SEMINARS & COLLOQUIA PUBLICATIONS PEOPLE ASSOCIATES

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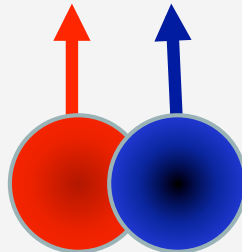
Proton-neutron pairing and alpha-like quartet correlations in nuclei

From Monday, 19 September, 2016 - 09:00 to Friday, 23 September, 2016 - 13:00

Registration closed 05/09/2016.



$T=1, S=0$

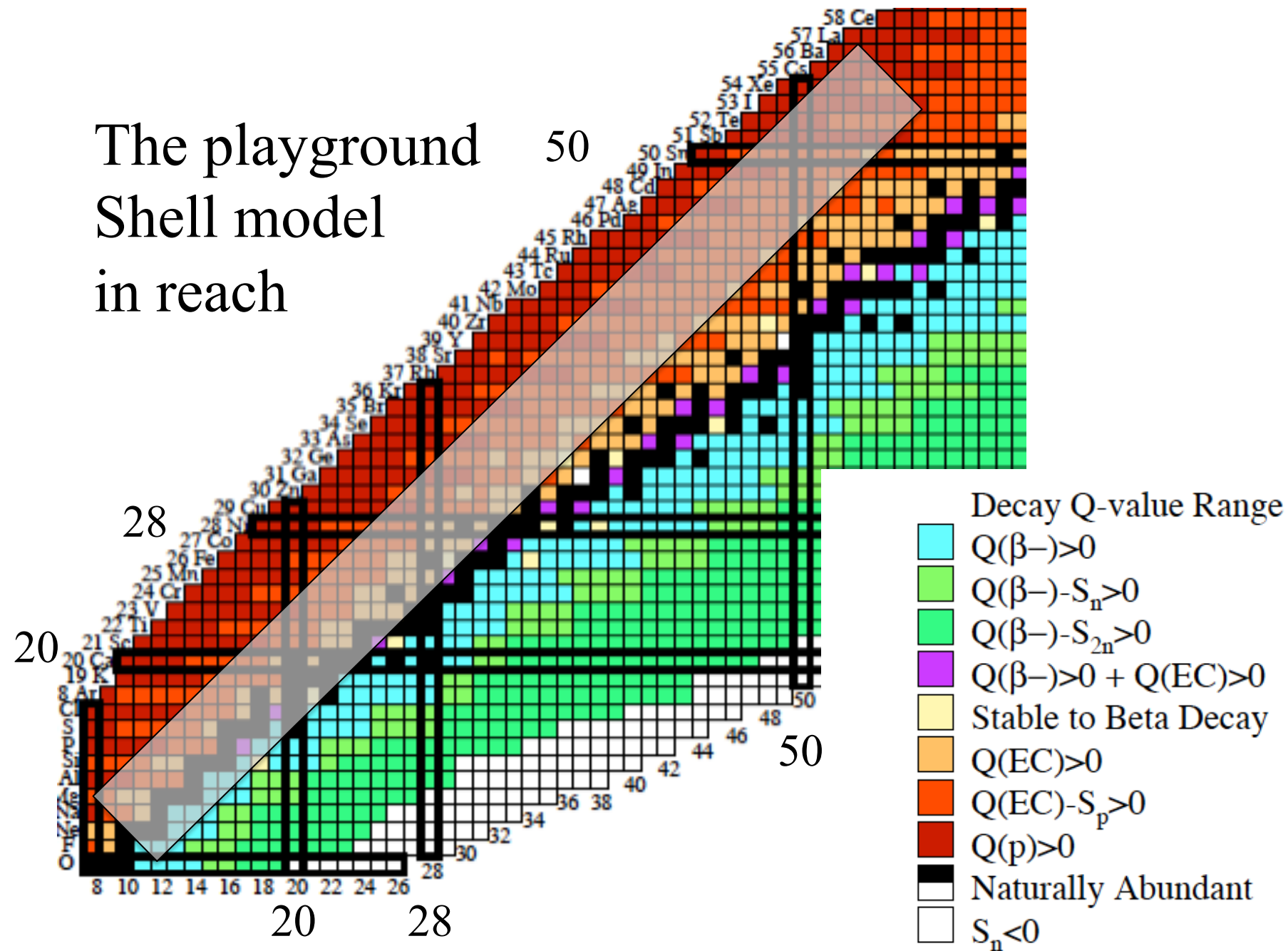


$T=0, S=1$

$T_z=0$

The interaction in both channels is about $v_{01}=1.5v_{10}$.
 Proton-neutron pairing for $N \approx Z$.
 Which channel? ${}^2\text{H}$ has 3S_1 ground state

The playground
Shell model
in reach



Lay out of the talk

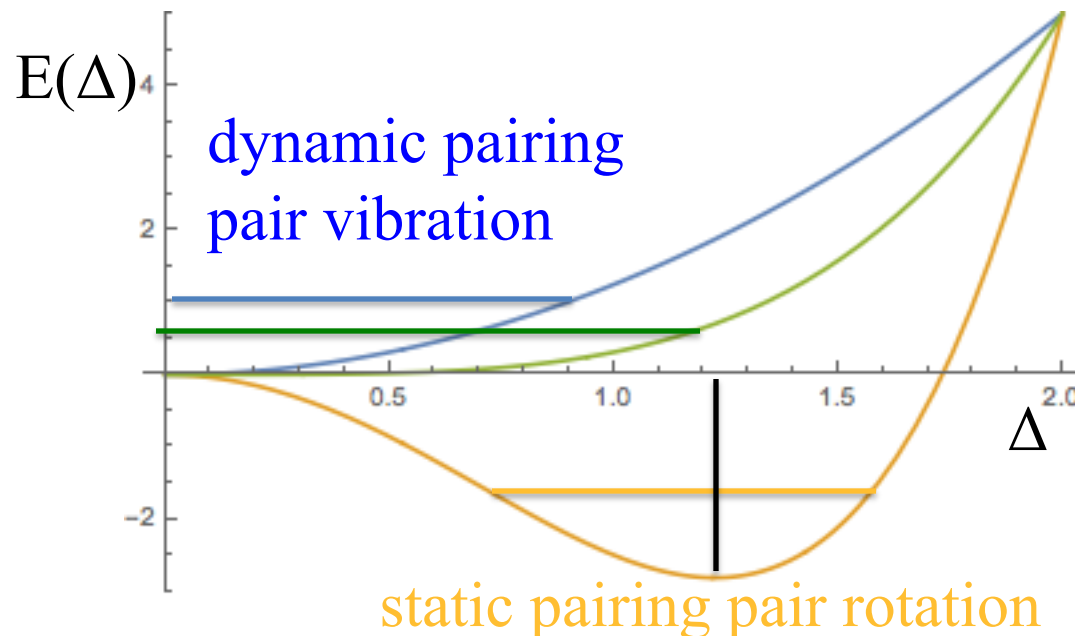
- Smooth crossover vs. phase transition
- Spin orbit vs. short range attraction
- Mean field signals:
symmetry breaking and pair- and iso-rotational bands
- Experimental binding energies and odd-odd spectra
- Shell model calculations: mean field signatures, pair correlation measures
- Isoscalar vs. isovector pair transfer
- Quarteting vs. pairing

“Pairing” : presence of many correlated pairs
of the same type

$N \rightarrow \infty$: pair condensate appears as a phase transition

$N < 300$: strong fluctuations of the condensate
parameter Δ .

instead of phase transition
smooth cross-over



HFB- \rightarrow static equilibrium
QRPA- \rightarrow harmonic oscillations
Problem: critical regime
Shell model describes
the crossover, ruler for
correlation strength needed

mean field value “condensate”+pair vibrations

Analogy with spherical-deformed shape crossover

Collectively enhanced	E2 radiation	Two particle transfer
Regular collective spectra	Quadrupole Vibrations rotational bands	Pair vibrations pair and isovector rotational bands
Modification of intrinsic spectra	Nilsson quasiparticle excitations	Even-odd, even–odd-odd mass differences.

$j=11/2$ spherical shell, pure monopole $T=1, J=0$ pairing

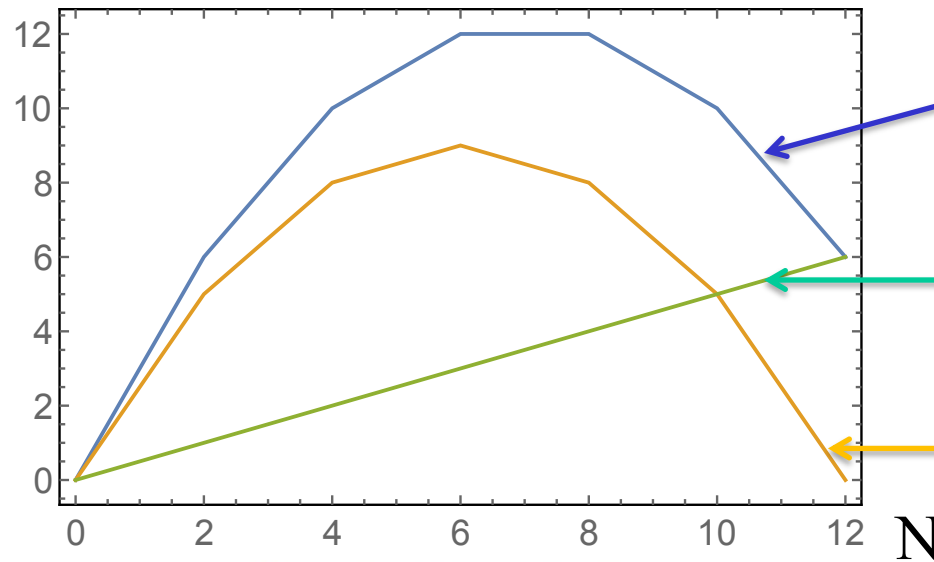
$$H = -GP_1^\dagger P_1$$

Pairing energy/ $(-12G)$

$$\langle N | P_1^\dagger P_1 | N \rangle$$

Transfer probability*12

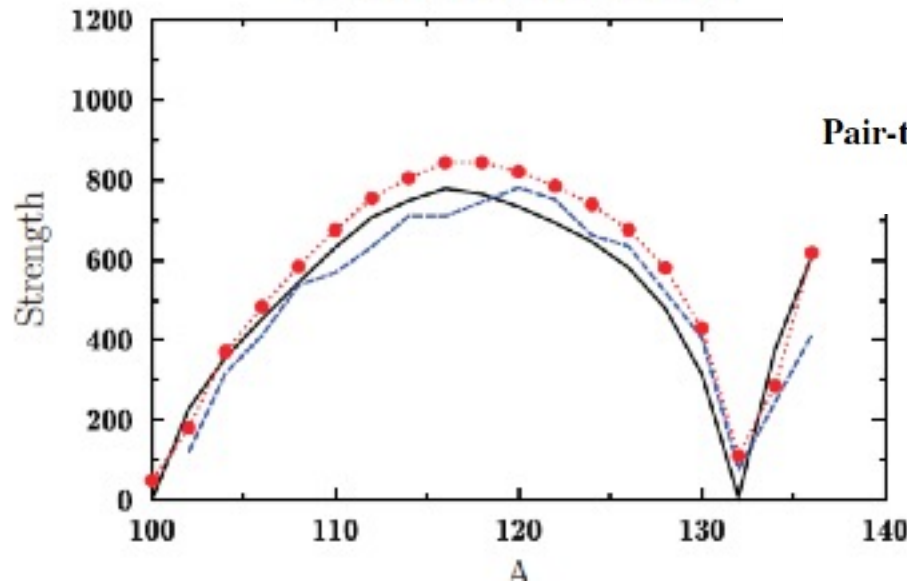
$$\langle N | P_1 | N - 2 \rangle^2$$



Uncorrelated part

Correlation part

Surface interaction



PHYSICAL REVIEW C 85, 034317 (2012)

Pair-transfer probability in open- and closed-shell Sn isotopes

M. Grasso,¹ D. Lacroix,² and A. Vitturi^{3,4}

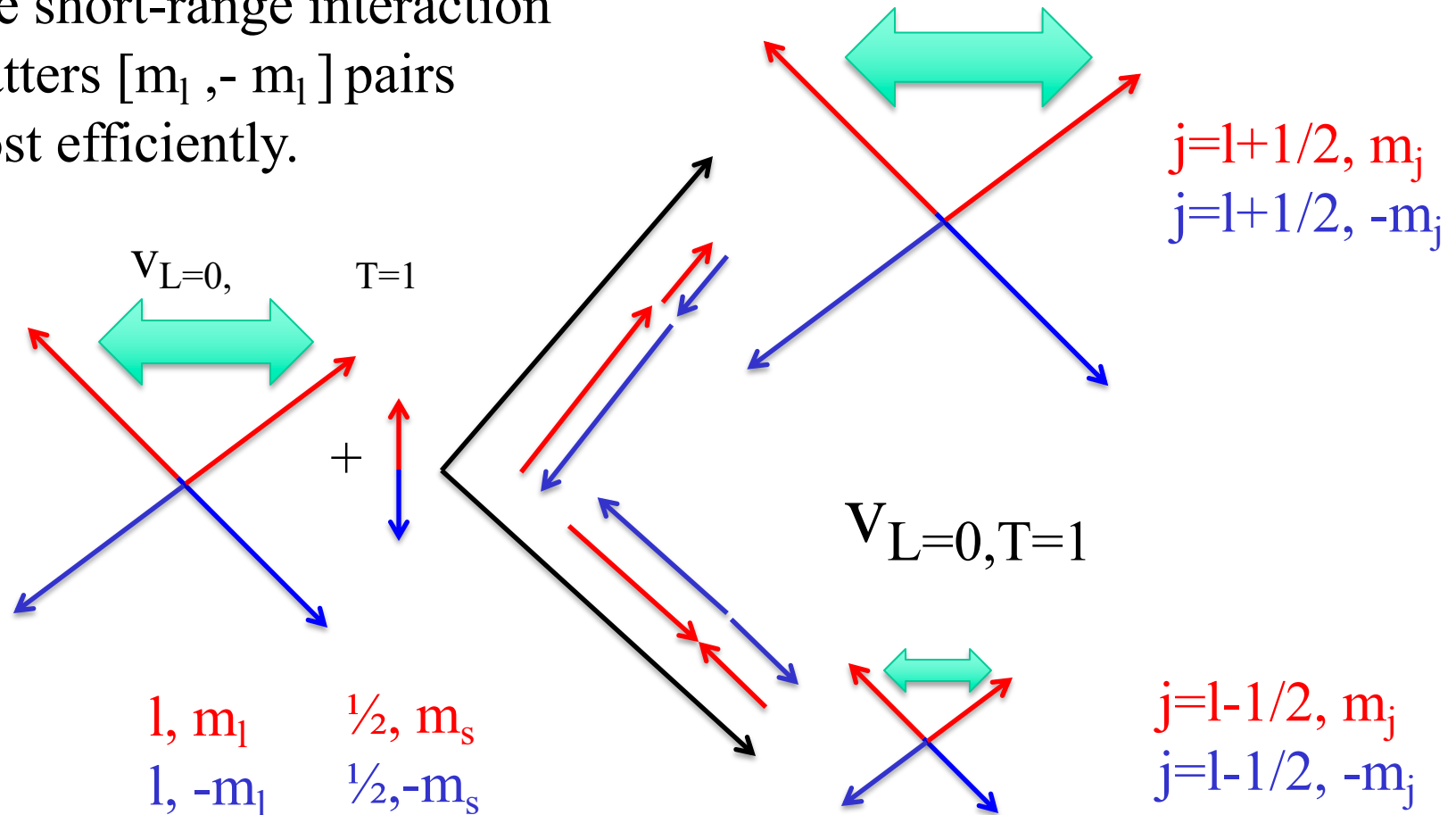
p-n pairing in j-j coupling

The pair correlation strength is determined by how many time scatterings between time reversed pairs are allowed by the Pauli principle.

For a spherical j- shell there are $j+1/2$ such pairs.

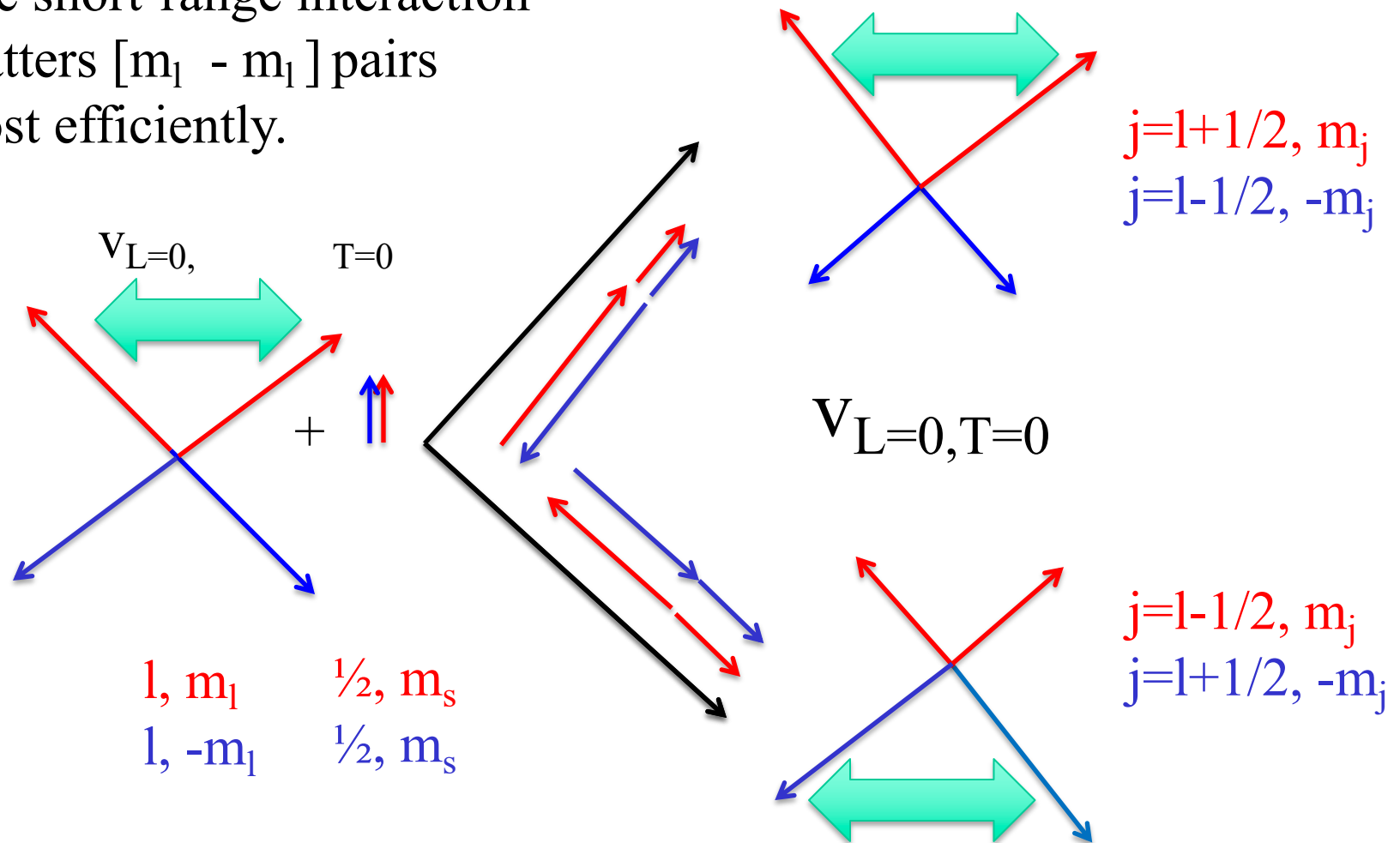
The correlation strength is maximal for the half-filled shell.
Seniority model.

The short-range interaction
scatters $[m_1, -m_1]$ pairs
most efficiently.



The spin-orbit splitting not is important for the $T=1$ pairing.

The short-range interaction
scatters $[m_l - m_l]$ pairs
most efficiently.



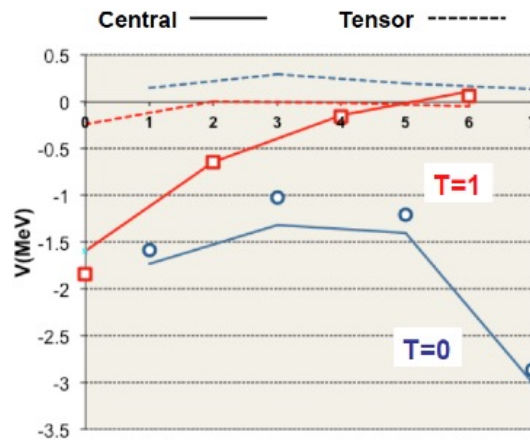
Strong scattering between spin-orbit partners.

Alignment-antialignment of spin and orbital a.m. not perfect.

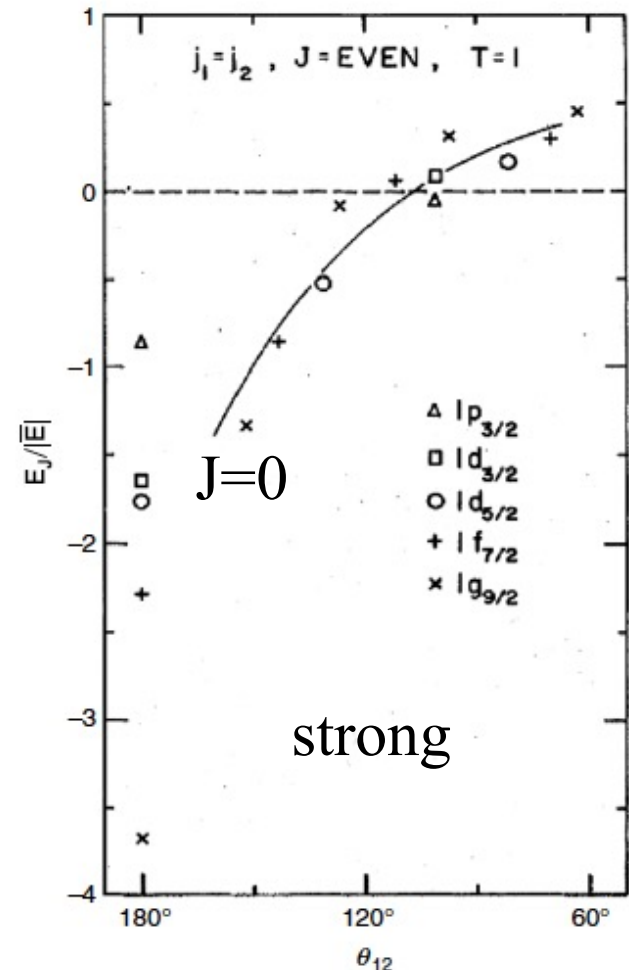
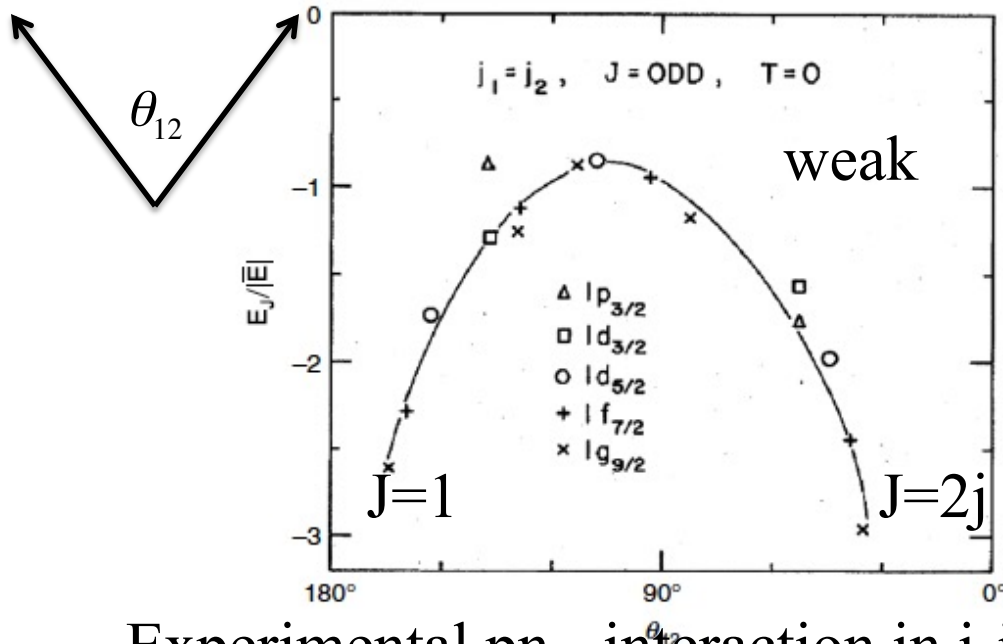
Weak scattering between j, m_j and $j, -m_j$.

The spin-orbit splitting attenuates the $T=0$ pairing.

Schiffer-True interaction



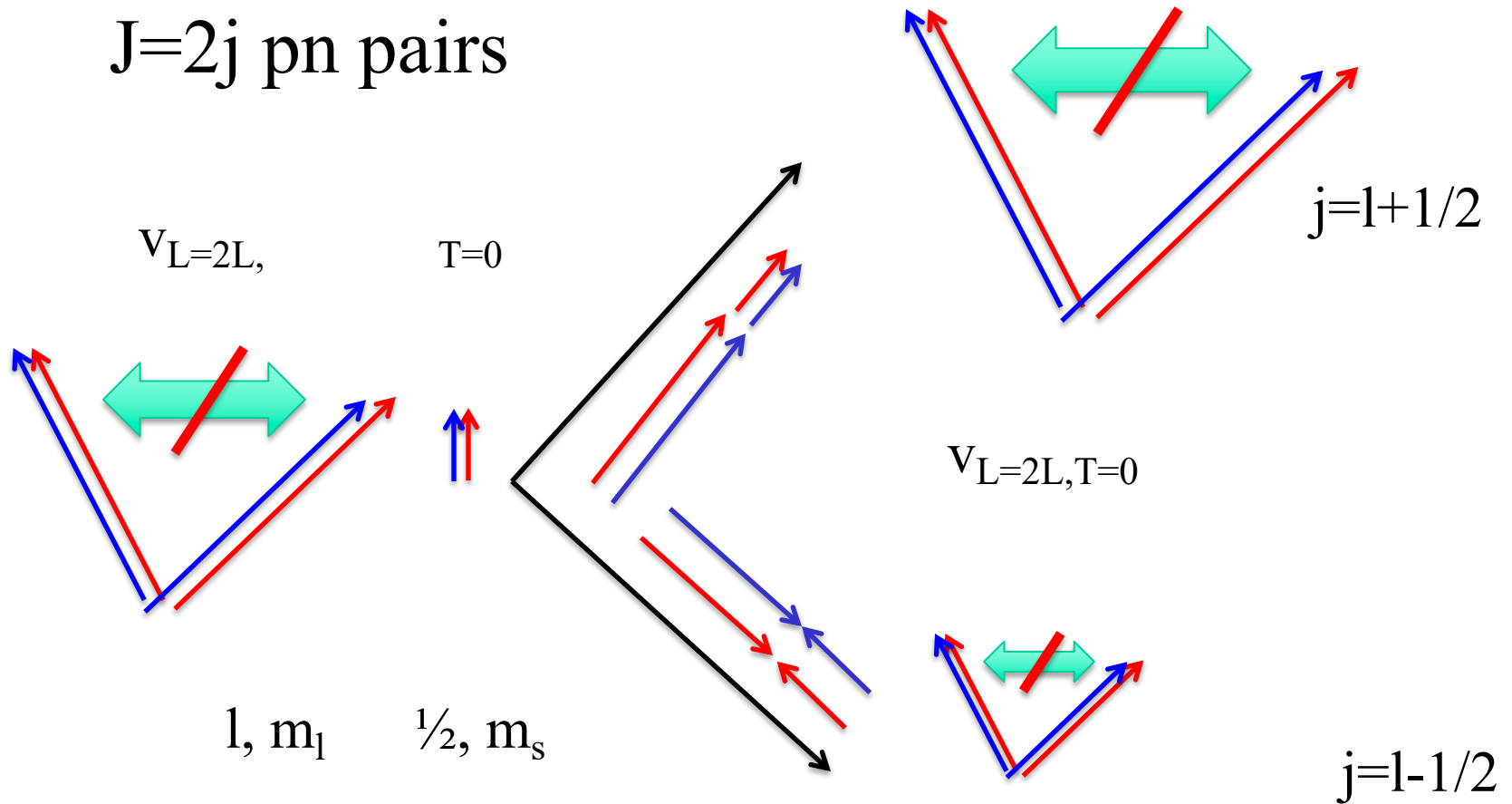
$f_{7/2}$ absolute



Experimental pn - interaction in j-j coupling as function of the angle between the j-orbitals

A normalization is applied such the points fall on one curve.¹²

$J=2j$ pn pairs



No pair scattering: angular momentum projection is conserved.
They do not generate a condensate.

Mean field calculations

The HFB equations

$$\beta^+ = Uc^+ + V\bar{c}, \text{ pairs: } \left[c^+ \bar{c}^+ \right]_{TM_T JM}$$

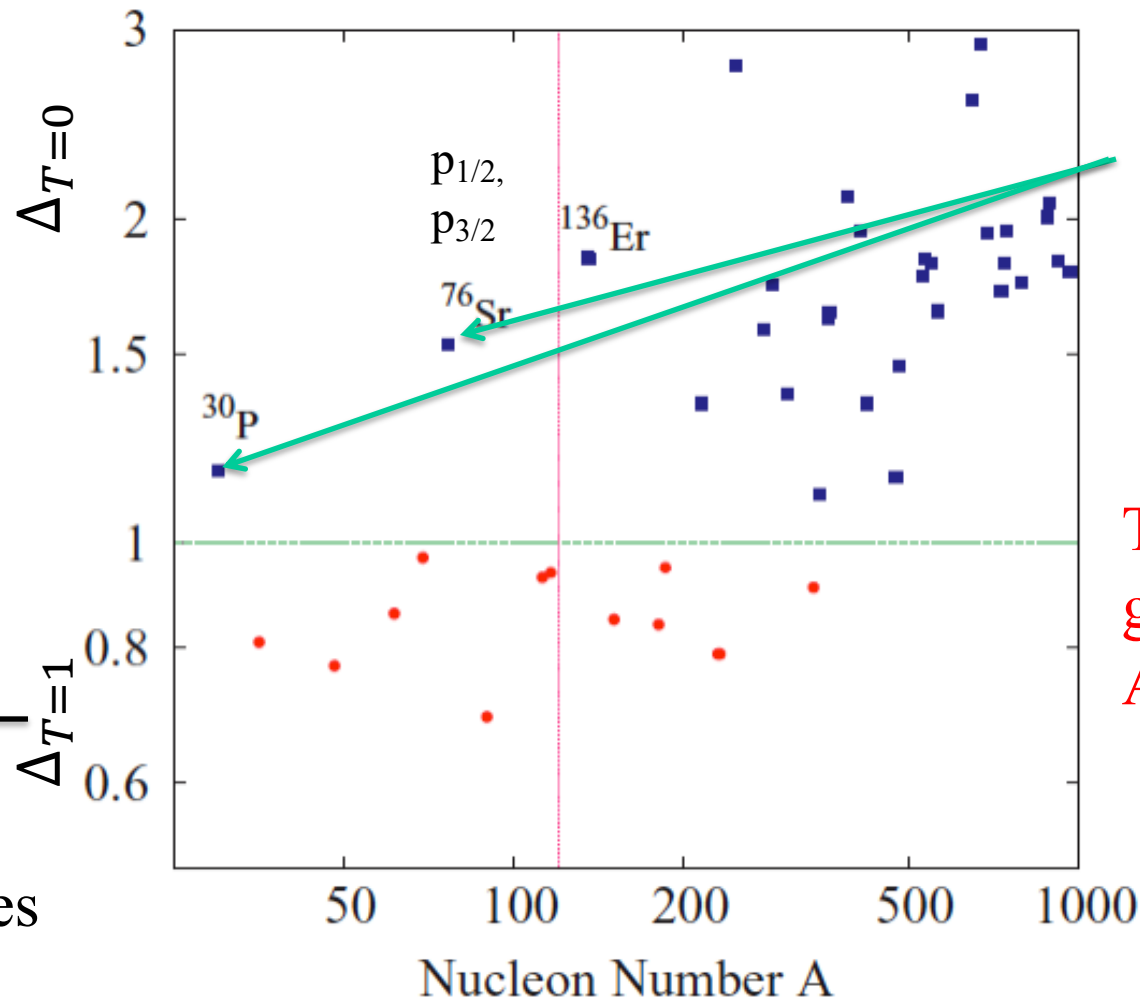
$$\begin{bmatrix} \varepsilon - \lambda + \Gamma & \Delta \\ \bar{\Delta} & -(\varepsilon - \lambda + \bar{\Gamma}) \end{bmatrix} \begin{bmatrix} U \\ V \end{bmatrix} = E \begin{bmatrix} U \\ V \end{bmatrix}$$

$$\Gamma_1 = Tr_2(v_{12}\rho_2), \quad \Delta_1 = Tr_2(\tilde{v}_{12}\kappa_2)$$

The T=0 and T=1 pairfields usually appear as separate solutions.

To describe the coexistence of T=0,1 one needs complex pair fields.

Spin-orbit potential is located in surface \rightarrow ratio $\frac{\# \text{ interior states}}{\# \text{ surface states}}$ increases with A .



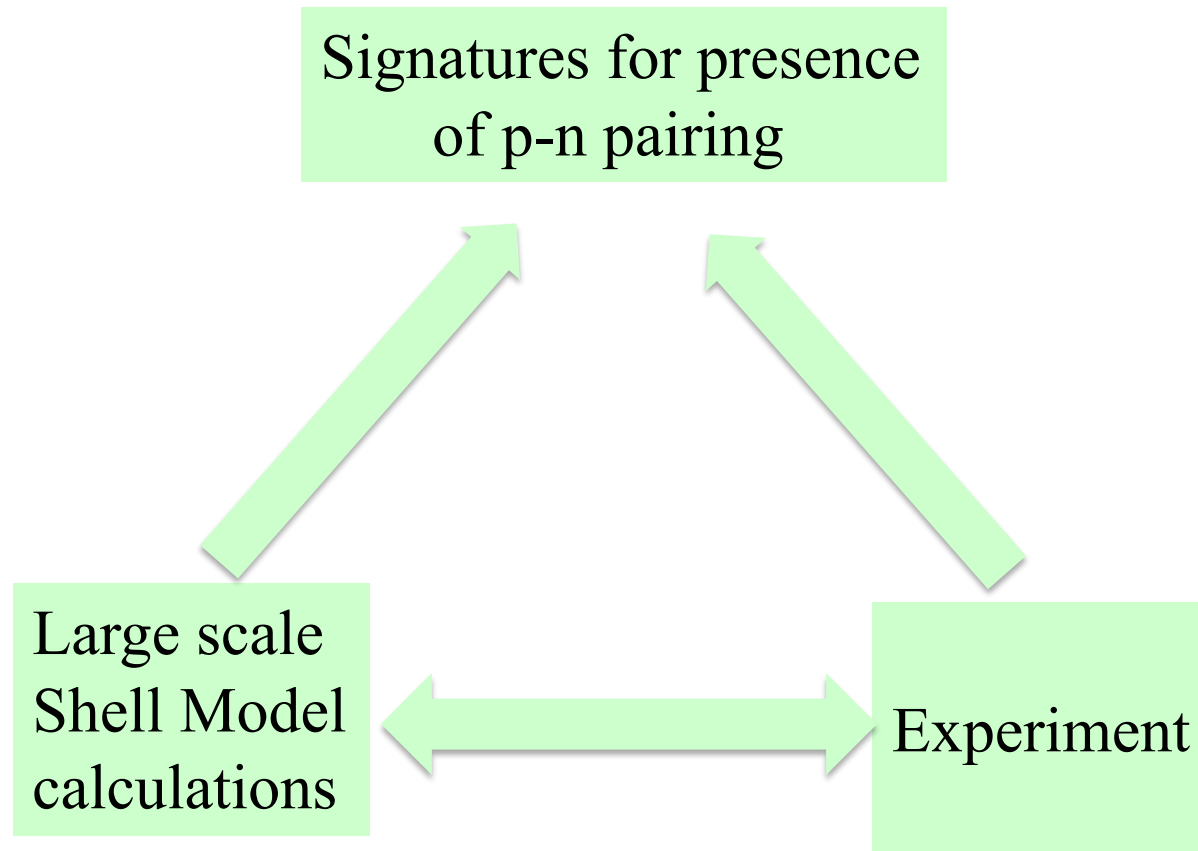
Deformation may change the $T=0$ Preference.

$T=1$
ground states
 $A < 100$

ε spherical Woods Saxon, half filled j-shells

ν monopole term of δ interaction, $\nu_0 = 1.5\nu_1$

G.F. Bertsch, Y. Luo, Phys. Rev. C 81 (2010) 064320¹⁵



Which are suitable indicators of the correlations?

Evidence for the presence of the pair fields in energies

$T=1, J=0$ and $T=0, J=1$ Cooper pairs

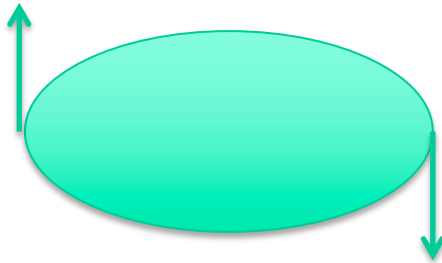
Strong interaction has good isospin and good spin

Spontaneous symmetry breaking \rightarrow pair rotational bands

Subtract Coulomb energy $\langle v_C \rangle$.

Shell model offers more precise ways. Coulomb interaction can be switched off.

Deformed nucleus



Isovector pair field



rotation in ordinary space

rotational energy:

$$E(I) = \langle H \rangle + \frac{I(I+1)}{2\theta}$$

rotation in abstract isospace

isorotational energy:

$$E(I) = \langle H \rangle + \frac{T(T+1)}{2\theta_{iso}}$$

Limit of strong symmetry breaking: Wigner $X=1$
("large deformation" in isovector space)

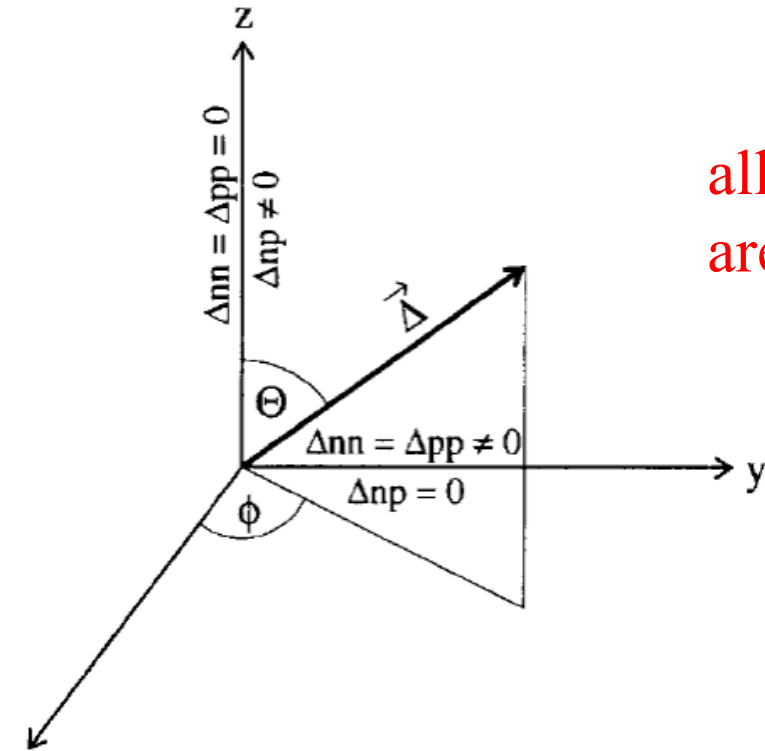
The experimental X often close to 1, but not as close as for ordinary rotation.

Weak deformation.

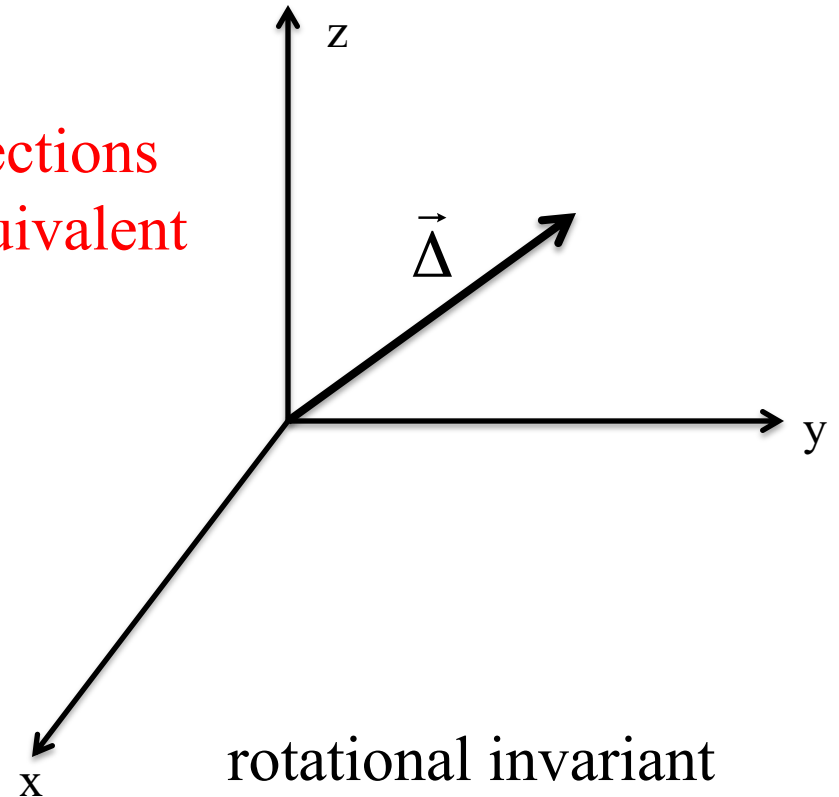
$T=1, J=0$ pair field
vector in isospace

$T=0, J=1$ pair field
vector in ordinary space

Both are invariant under a rotation by π in gauge space



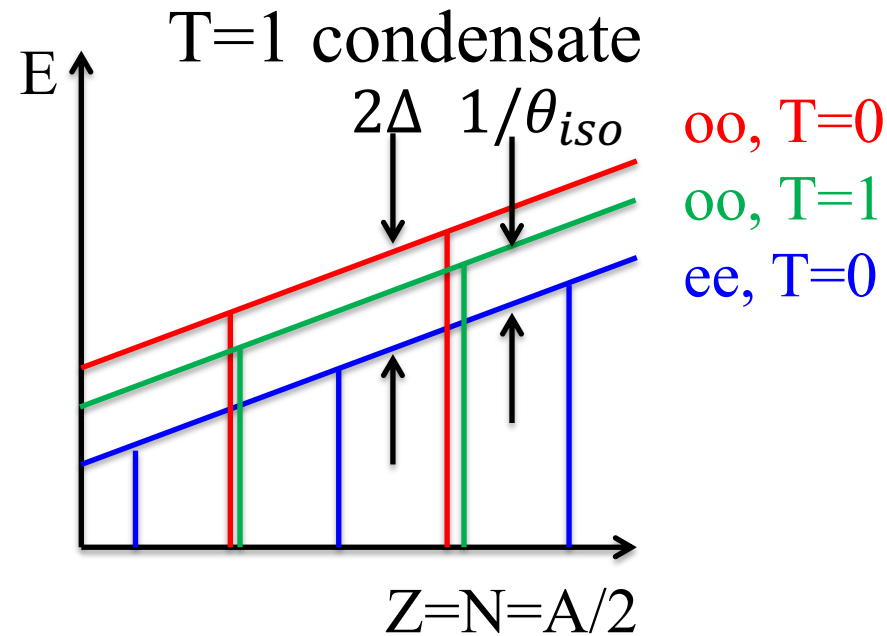
all directions
are equivalent



isospin invariant
Hamiltonian \rightarrow
iso-rotational excitations (SU2)
 $\Delta A=2$ pair band

rotational invariant
Hamiltonian \rightarrow
rotational excitations (SU2)
 $\Delta A=2$ pair band

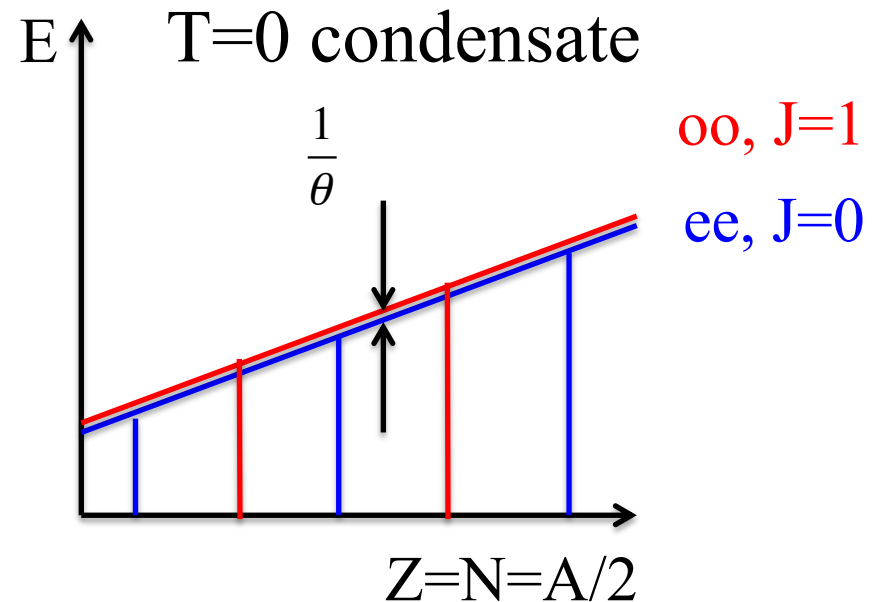
p-n condensates generate pair-rotational bands:
 Regular sequence of ground states include the odd-odd nuclei



$$\frac{T(T+1)}{2\theta_{iso}} = \frac{75\text{MeV}}{A} T(T+1)$$

symmetry energy

Isorotation generates a quartet sequence.



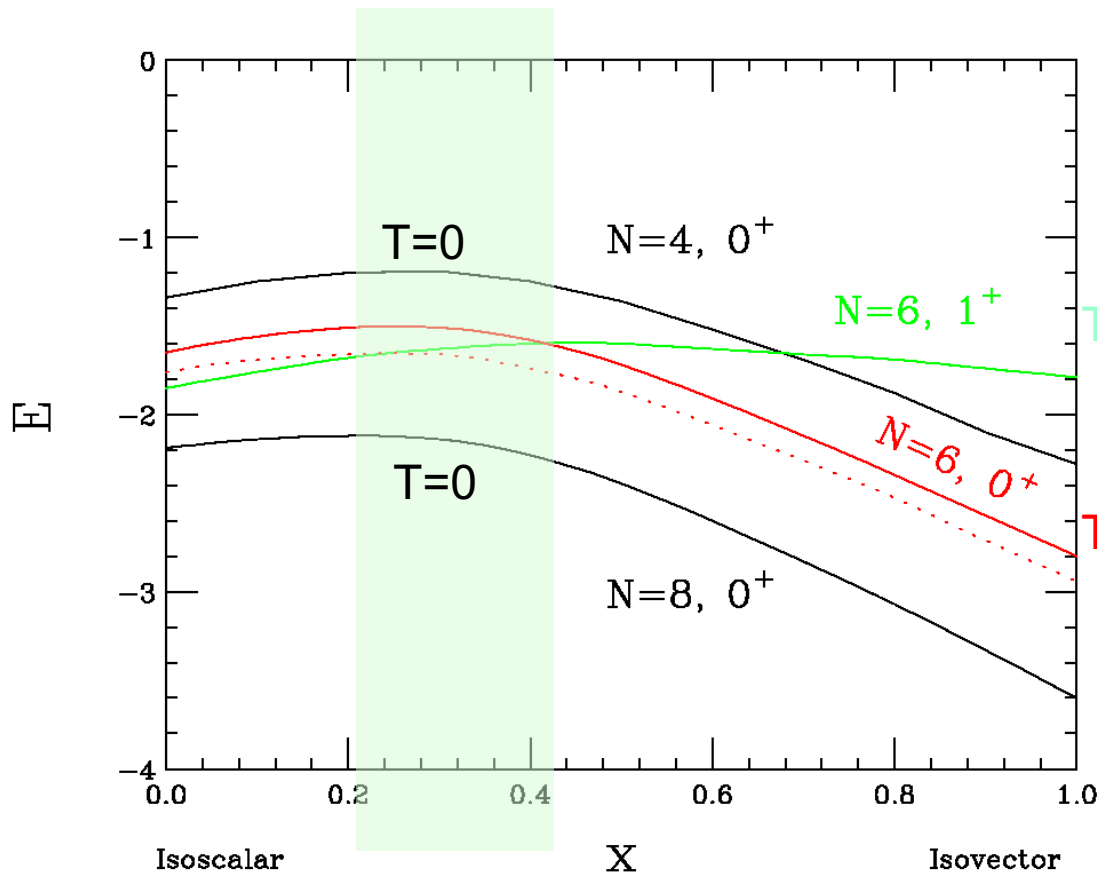
$$\frac{J(J+1)}{2\theta} \quad \theta \text{ large,}$$

cranking, Shell Model

The states form a pair-rotational band. No gap in the spectrum₂₀

Competition of T=1 and T=0 pairing in a spherical $h_{11/2}$ shell

$$H/G = -xP_1^\dagger P_1 - (1-x)P_0^\dagger P_0$$



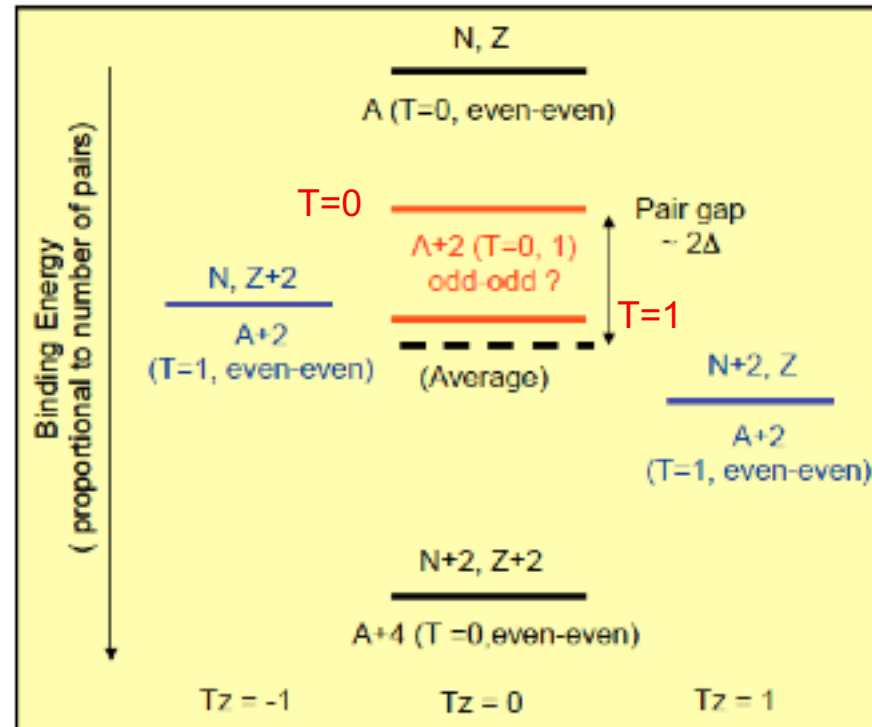
A. Machiavelli

In real nuclei

$$\theta_{iso} \ll \theta$$

average of N=4 and 6

Experimental evidence



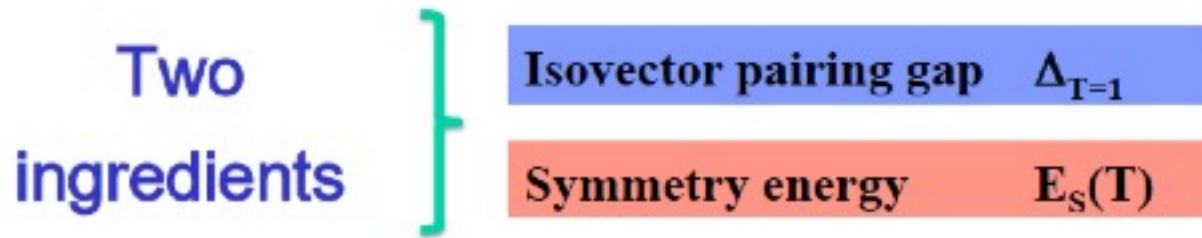
Averaging eliminates the Coulomb energy approximately

Must compare states with the same isospin :

$T = 0$ states: Use the even-even $N=Z$ neighbors as a reference

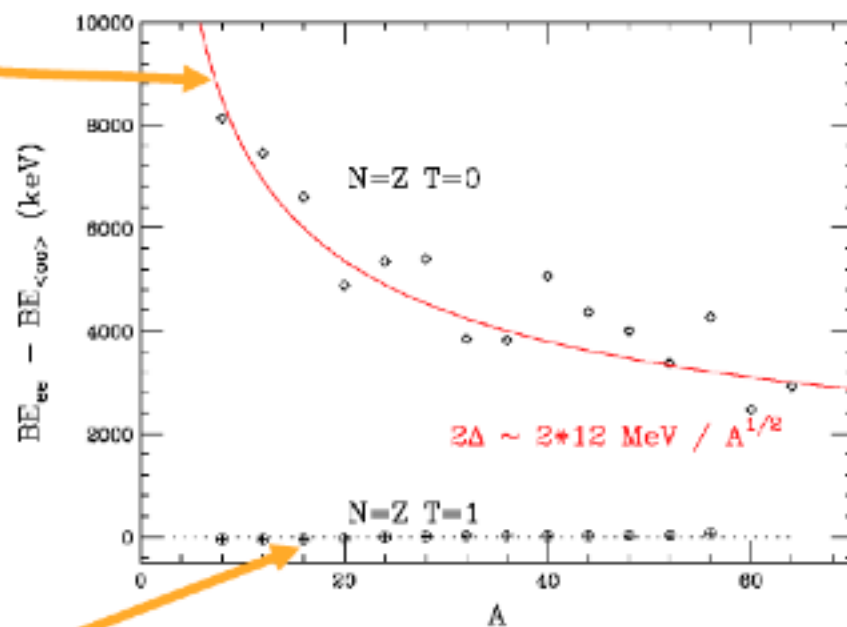
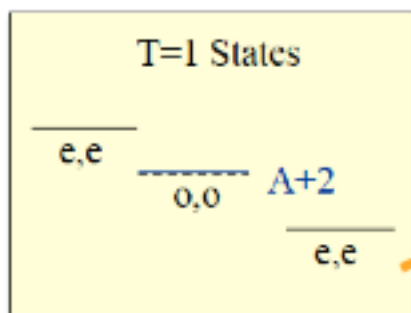
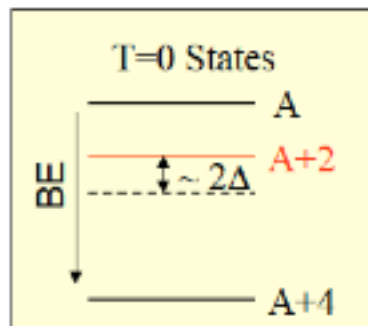
$T = 1$ states: Use the even-even isobaric analogs as a reference

Energies near $N=Z$



Even-even	$T=0$	E_0
<hr/>		
Odd-odd	$T=0$	$E_0 + 2\Delta_{T=1} + E_S(0)$
	$T=1$	$E_0 + 0 + E_S(1)$
<hr/>		
Even-even	$T=1$	$E_0 + 2\Delta_{T=1} + E_S(1)$
<hr/>		
Odd-even	$T=1/2$	$E_0 + \Delta_{T=1} + E_S(1/2)$

T=0 states give a pair gap

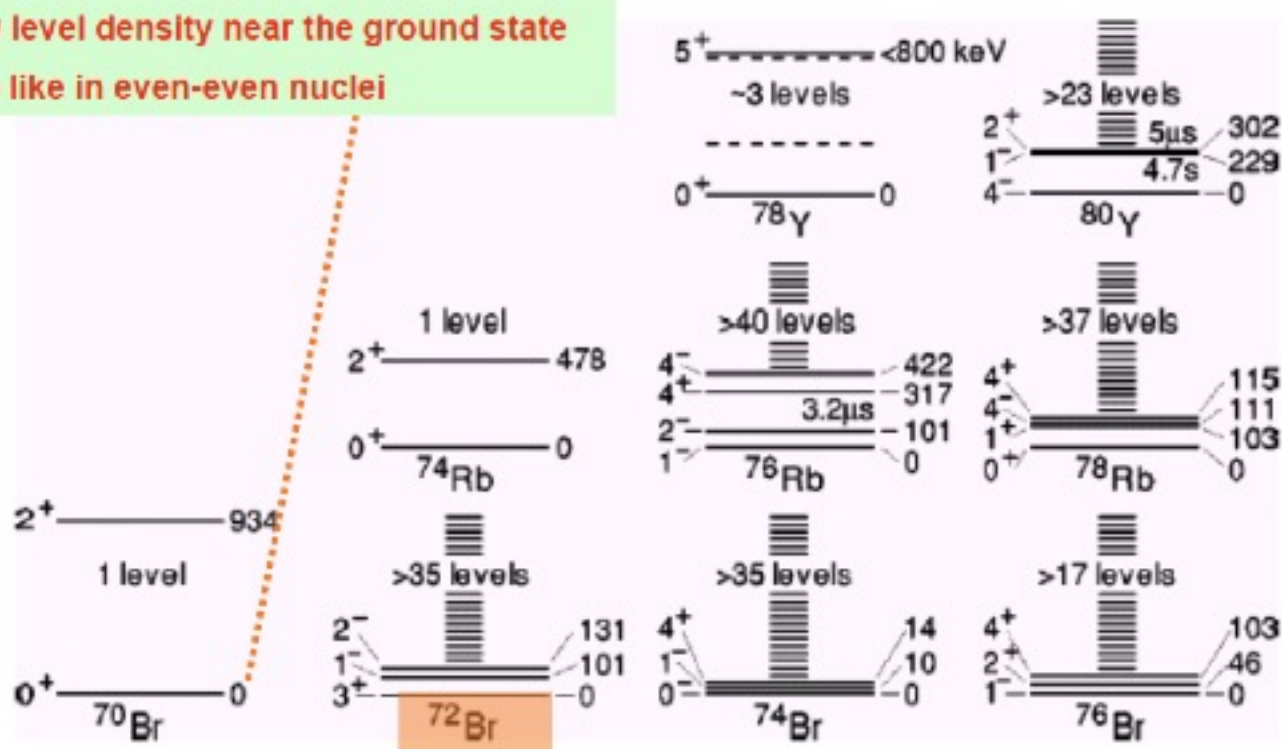


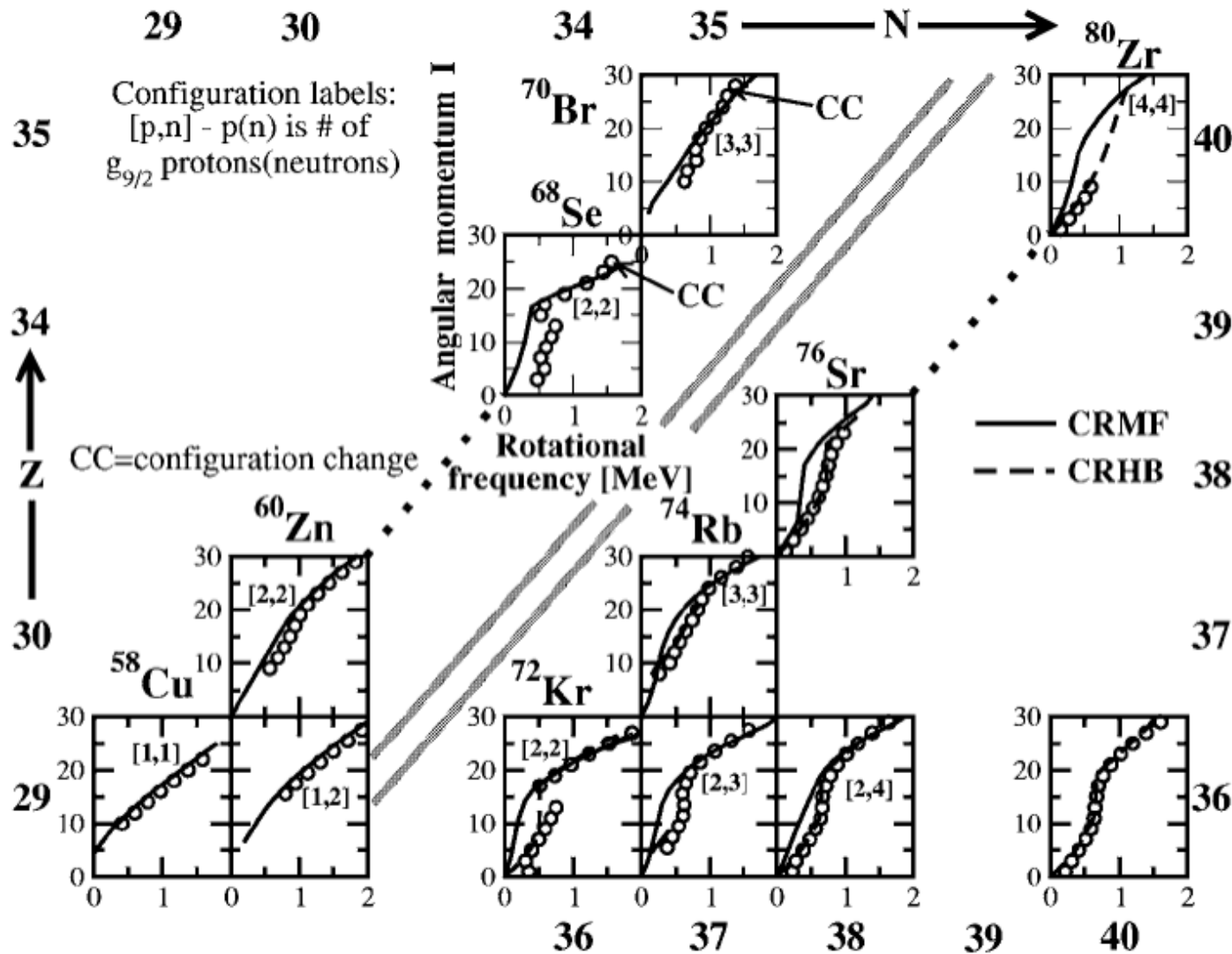
T = 1 states give no pair gap

$T=0$ and $T=1$ states in the odd-odd $N=Z$ nucleus, $^{70}_{35}\text{Br}_{35}$

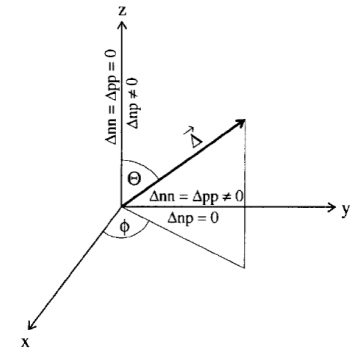
D. G. Jenkins,^{1,2,*} N. S. Kelsall,³ C. J. Lister,² D. P. Balamuth,¹ M. P. Carpenter,² T. A. Sienko,²
S. M. Fischer,⁴ R. M. Clark,⁵ P. Fallen,⁵ A. Görgen,⁵ A. O. Macchiavelli,⁵ C. E. Svensson,⁵ R. Wadsworth,³
W. Reviol,⁶ D. G. Sarantis,⁶ G. C. Ball,⁷ J. Rikovsky Stone,^{8,9} O. Juillet,¹⁰ P. Van Isacker,¹⁰
A. V. Afanasjev,^{2,11,12} and S. Frauendorf^{11,13}

Low level density near the ground state
Gap like in even-even nuclei



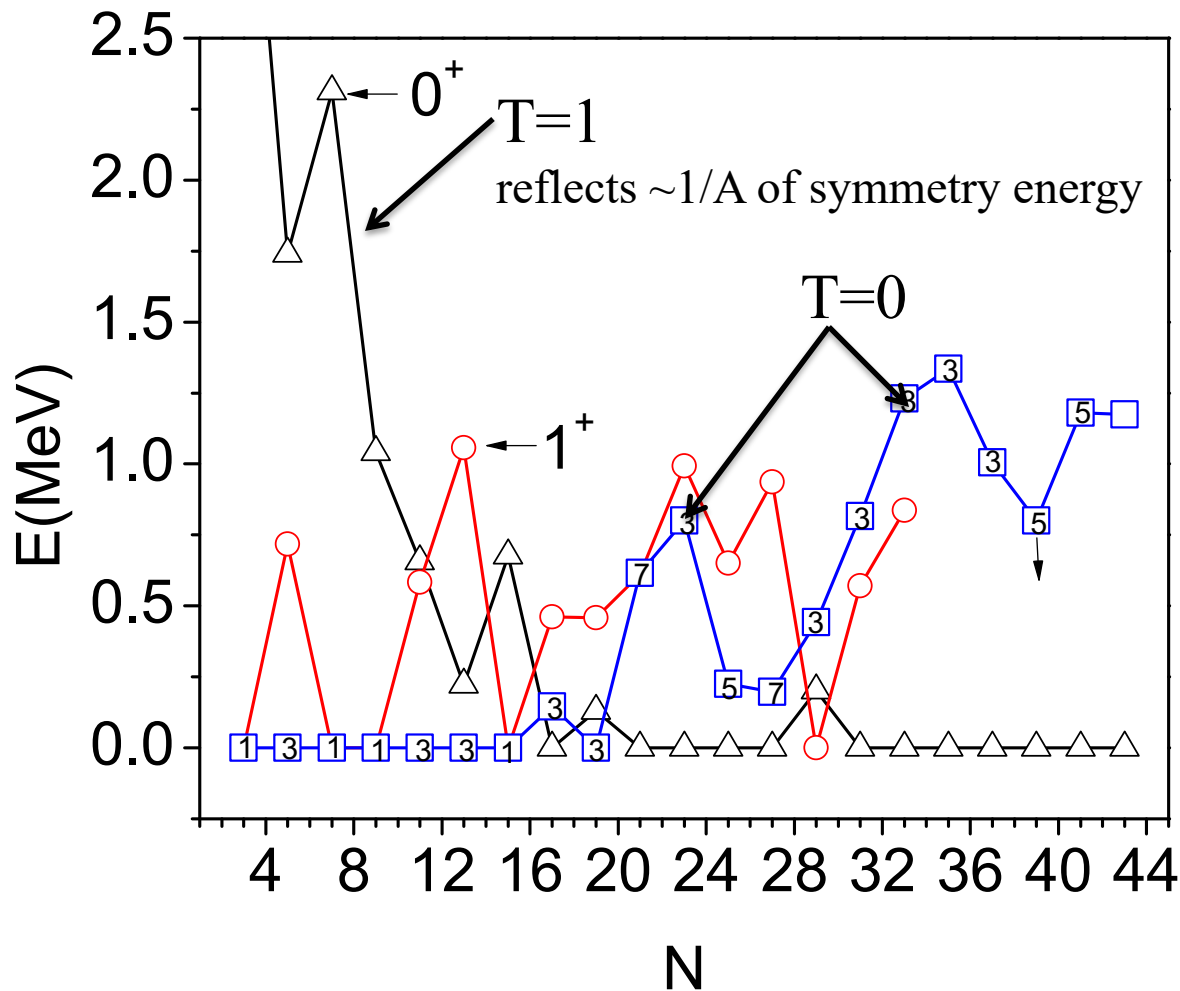


A. V. Afanasjev,
Int. J. Mod. Phys.
E 16, 275 (2007)

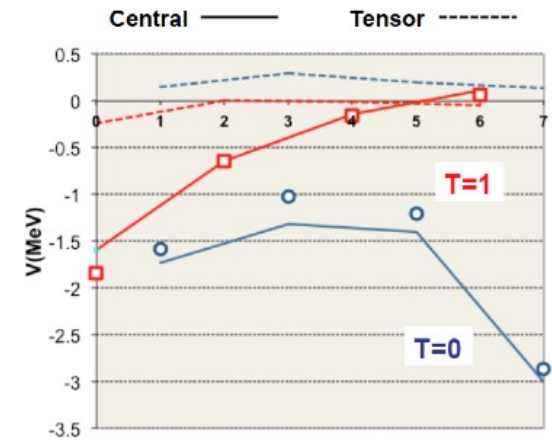


T=1 rotational states have the same structure for all directions of the IV pair field .

To calculate the rotational spectra one can use the y- direction of the condensate, which has no pn-component.



Low-lying states in odd-odd $N=Z$ nuclei



$J=2j$ the j of p and n are parallel
 “spin-alignment”
 $J=1$ the j of p and n are almost antiparallel (except $j=1/2$)

Gapless
quasiparticle
states are not
observed

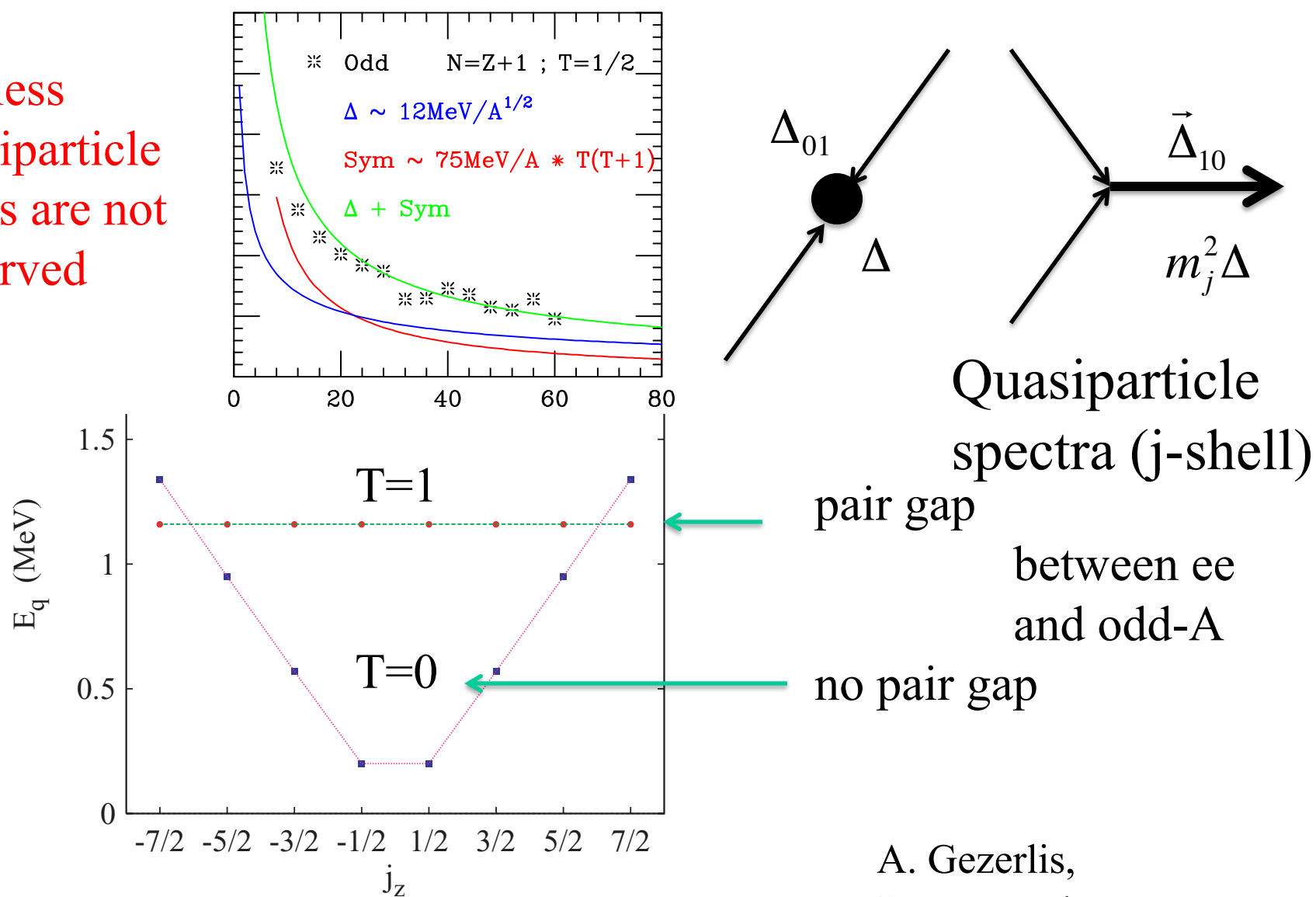


FIG. 1. (Color online) Quasiparticle energies in ^{48}Cr for the f -shell space. Red circles, spin-singlet; blue squares, spin-triplet with condensate in the $S_z = 0$ channel. Lines are drawn to guide the eye.

A. Gezerlis,
G. F. Bertsch,
and Y. L. Luo,
PRL 106, 252502(2011)

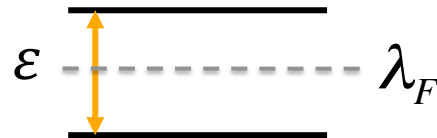
Two-level model

S. Pang, Nucl. Phys. A 128 (1969) 497.

J. Evans et al., A 367 (1981) 77.

G. Dussel et al., Nucl. Phys. A 153 (1970) 469.

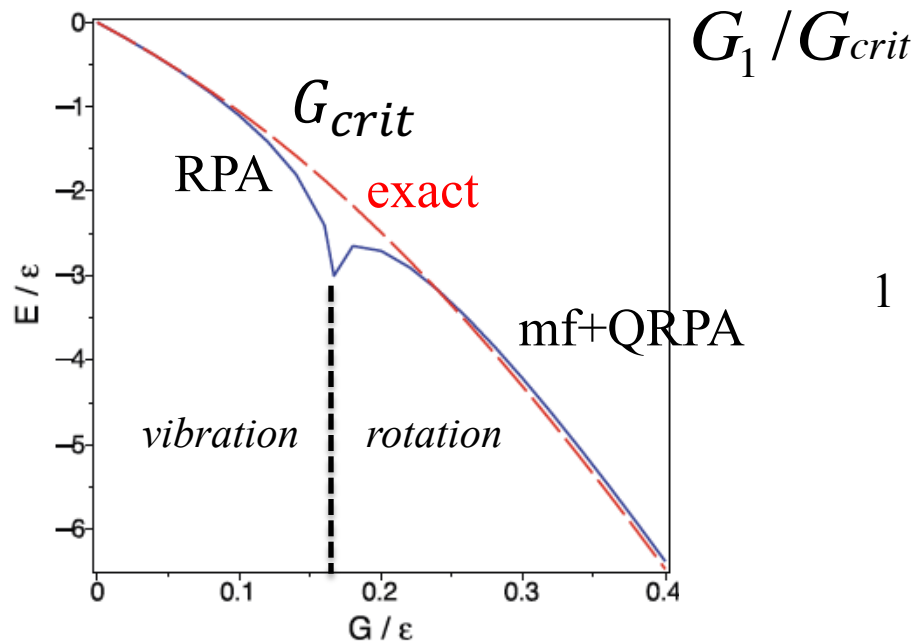
$j \Omega$



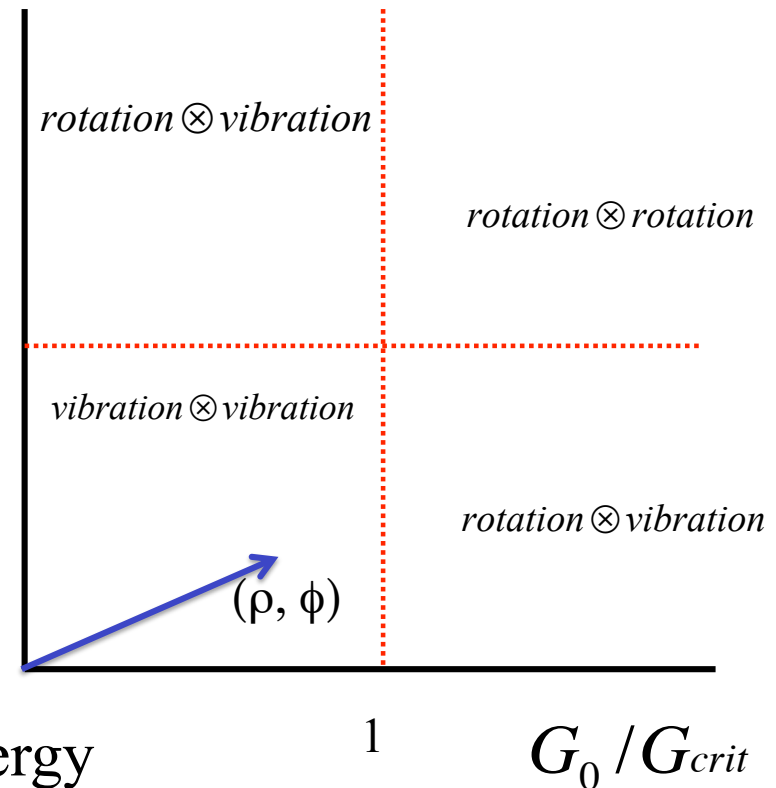
Pair vibrations vs. pair rotations

$$H = \frac{1}{2} \epsilon (N_2 - N_1) - G_0 \sum_{\mu} S_{\mu}^{+} S_{\mu} - G_1 \sum_m P_m^{+} P_m$$

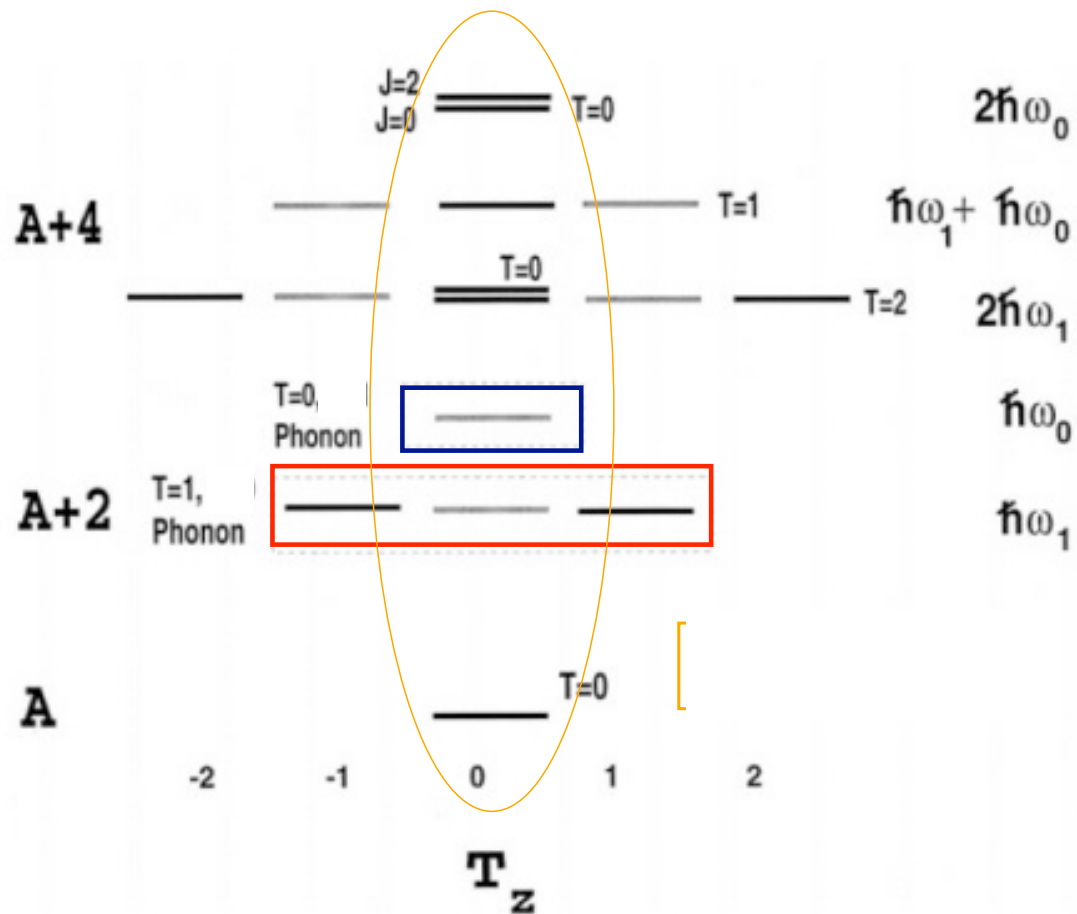
$j = 13/2$ half filled



$\sim \epsilon(1-G/G_{crit})$ RPA vibrational energy

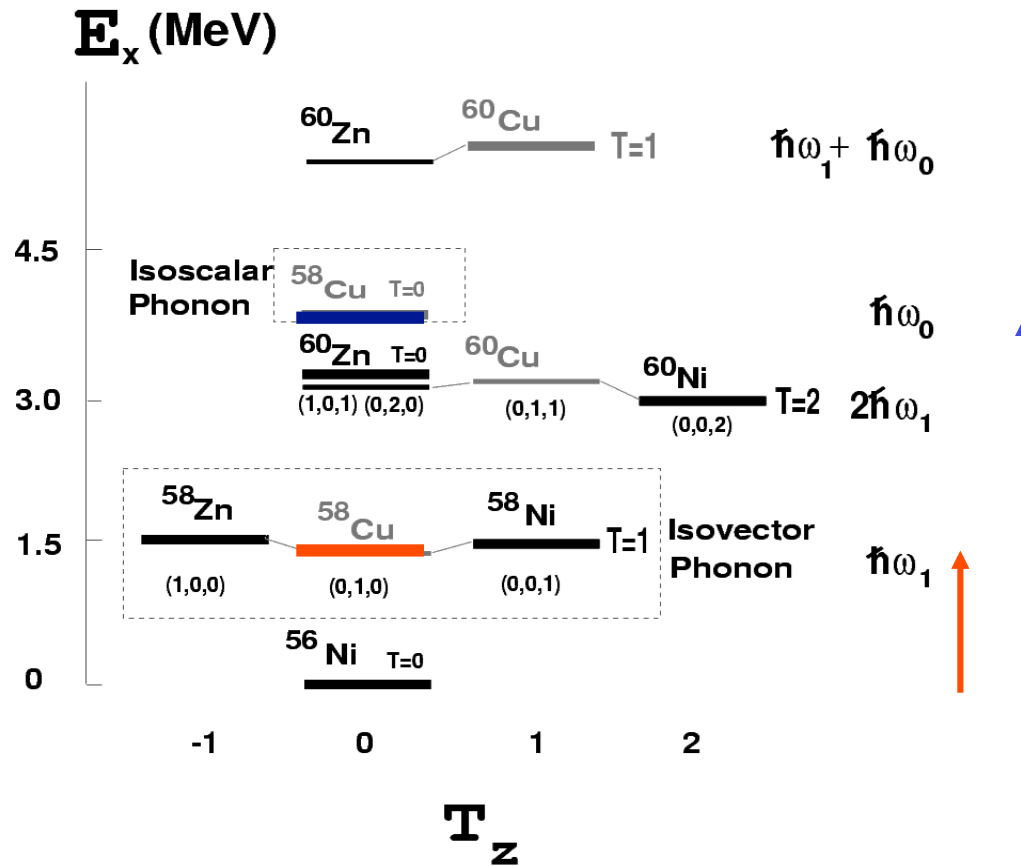


Harmonic pair vibrational spectrum



Experimental pair vibrational spectrum

D.R.Bes, R.A.Brogia, O.Hansen and O.Nathan Phys. Rep. 34(1977)1



isovector pair vibration configurations (n_{-1}, n_0, n_1)

Pairing in an eight-level model sliding with the Fermi level

$$H = h_{\text{nilsson}} - G_v \sum_{M_T} P_{M_T}^+ P_{M_T} - G_S D^+ D + CT(T + 1)$$

$$P_{-1}^+ = \sum_i c_{pi}^+ c_{p\bar{i}}^+ \quad P_0^+ = \frac{1}{\sqrt{2}} \sum_i c_{pi}^+ c_{n\bar{i}}^+ - c_{p\bar{i}}^+ c_{ni}^+ \quad P_1^+ = \sum_i c_{ni}^+ c_{n\bar{i}}^+$$

$$D^+ = \frac{1}{\sqrt{2}} \sum_i c_{pi}^+ c_{n\bar{i}}^+ + c_{p\bar{i}}^+ c_{ni}^+$$

8 levels diagonalization I. Bentley, S. F. PRC 88, 014322 (2013)

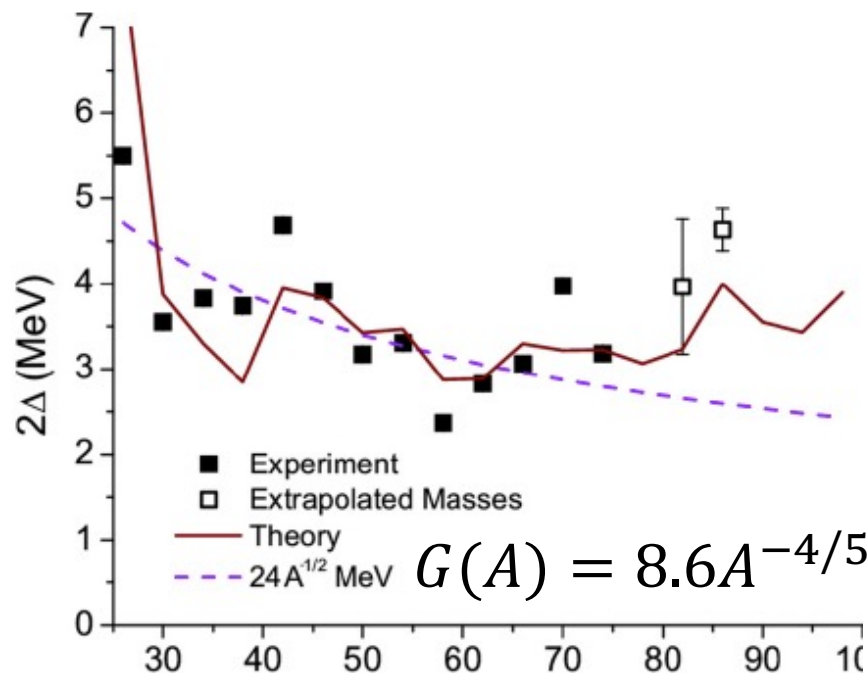
pure isovector scenario $G_S=0$:

Smooth $G_V=G(A)$, adjusted by Δ from e-o mass differences or lowest $T=0$ excitation in o-o nuclei.. Smooth $C(A)$ adjusted to symmetry energy. Results:

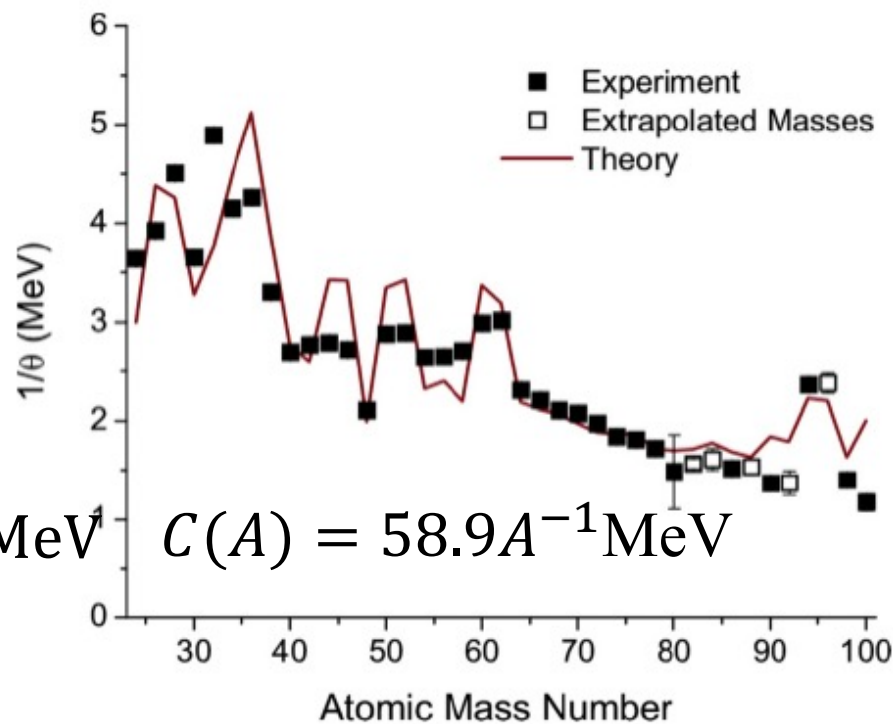
$$E_S(A, T) = \text{constant} + \frac{T(T + X)}{2\theta} \quad 2\Delta = \frac{B(A-2, 0, 0) - 2B(A, 0, 0) + B(A+2, 0, 0)}{2}$$

$$E(T = 1) - E(T = 0)$$

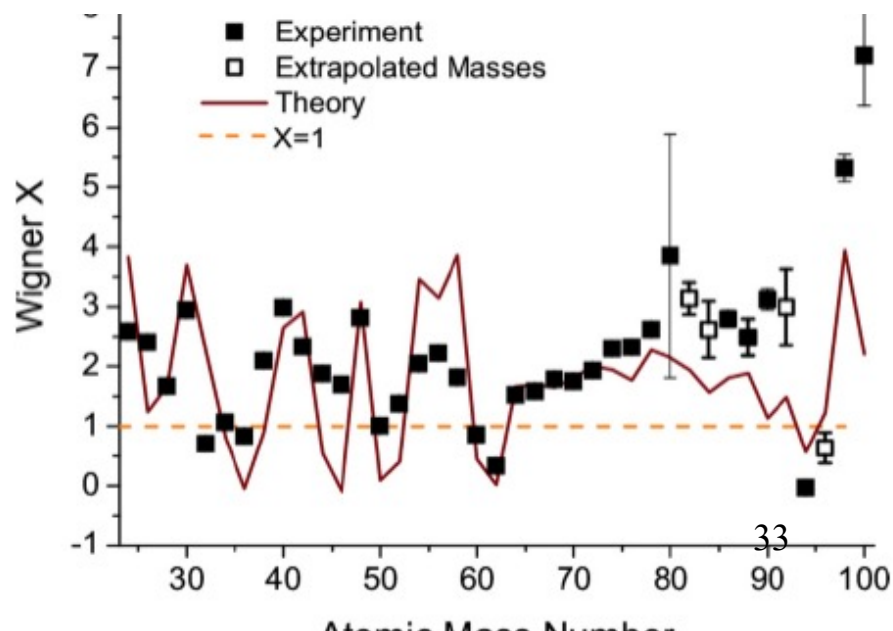
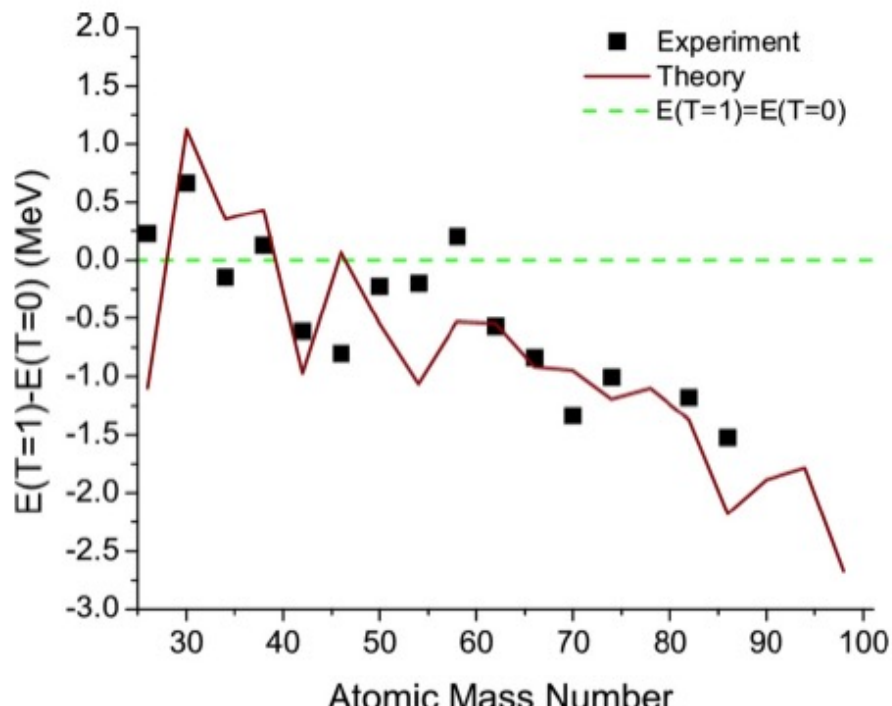
X=0 vibration
X=1 rotation



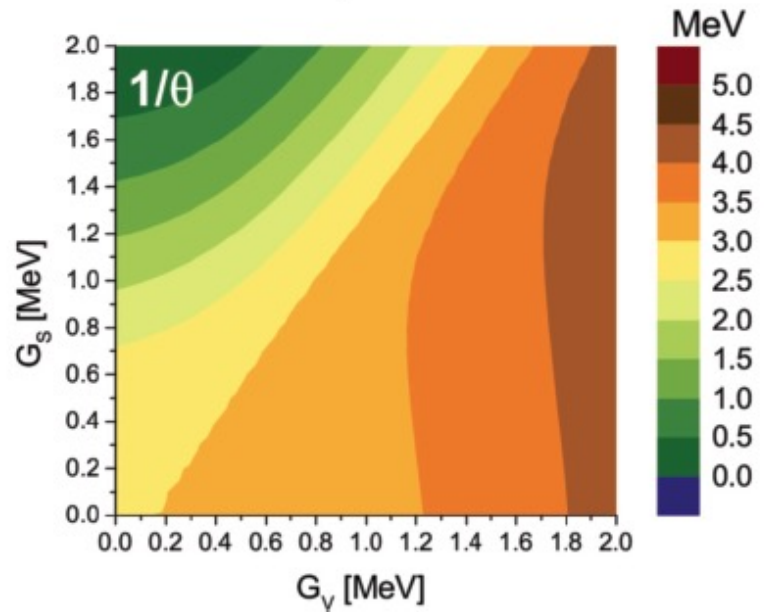
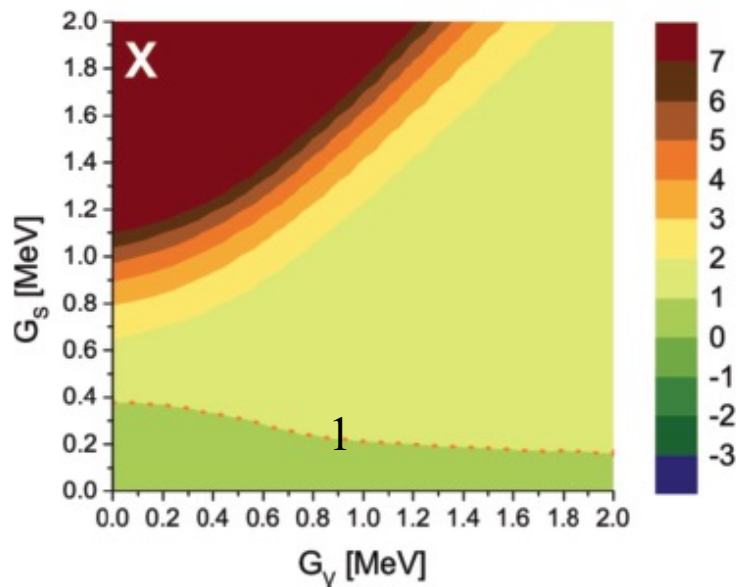
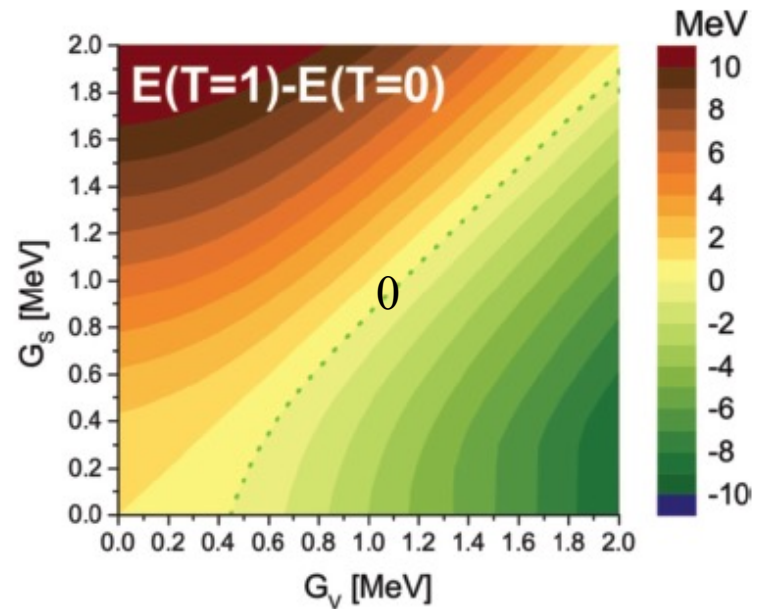
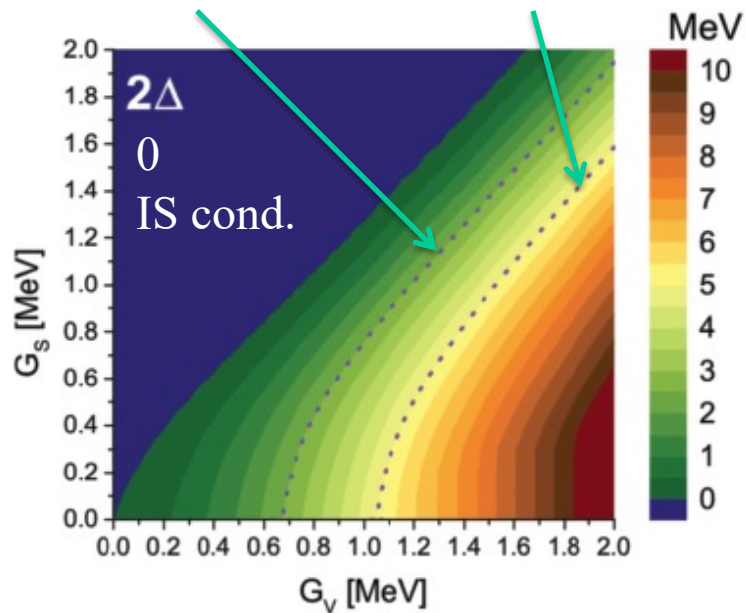
$$G(A) = 8.6A^{-4/5} \text{ MeV}$$



$$C(A) = 58.9A^{-1} \text{ MeV}$$



$$2\Delta = 24\text{MeV}/\sqrt{20} \quad 24\text{MeV}/\sqrt{100}$$



There is room for isoscalar pair vibrations.

Pure isovector pairing approach that exactly conserves isospin describes the binding and excitation energies in detail, including the Wigner X term and local fluctuations.

No new parameters compared to standard $N \gg Z$ approach.
Strength of pn interaction determined by isospin conservation.

Strength of $T=1$ interaction adjusted to ee-oo mass differences or e-o mass differences $G = 8.6A^{-4/5}\text{MeV}$.

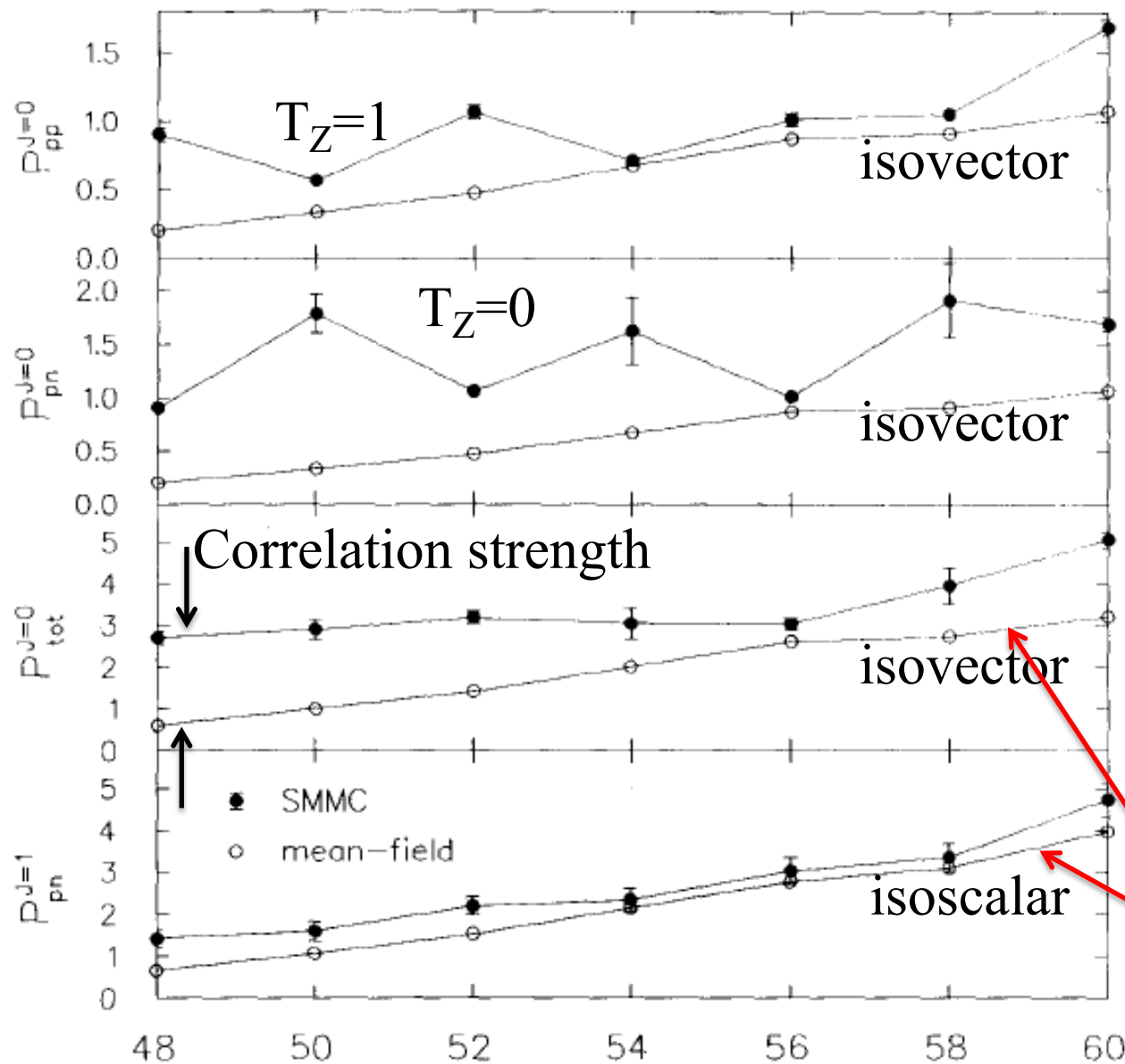
Symmetry energy correction $C = 58.9A^{-1}\text{MeV}$.

The agreement with the data leaves room for isoscalar vibrational correlations.

Large scale shell models

- Good agreement of energies with experiment expected, same analysis as for experiment.
- More accurate removal of Coulomb energy possible.
- Pair-correlation strength can be calculated:
pair-counting operators $\langle N | P_{TJ}^\dagger P_{TJ} | N \rangle$,
pair correlation operator $\langle N | P_{TJ}^\dagger P_{TJ} | N \rangle - \langle N0 | P_{TJ}^\dagger P_{TJ} | N0 \rangle$,
pair transfer operator $\langle N | P_{TJ}^\dagger | N - 2 \rangle$

Strong (static) isovector correlations

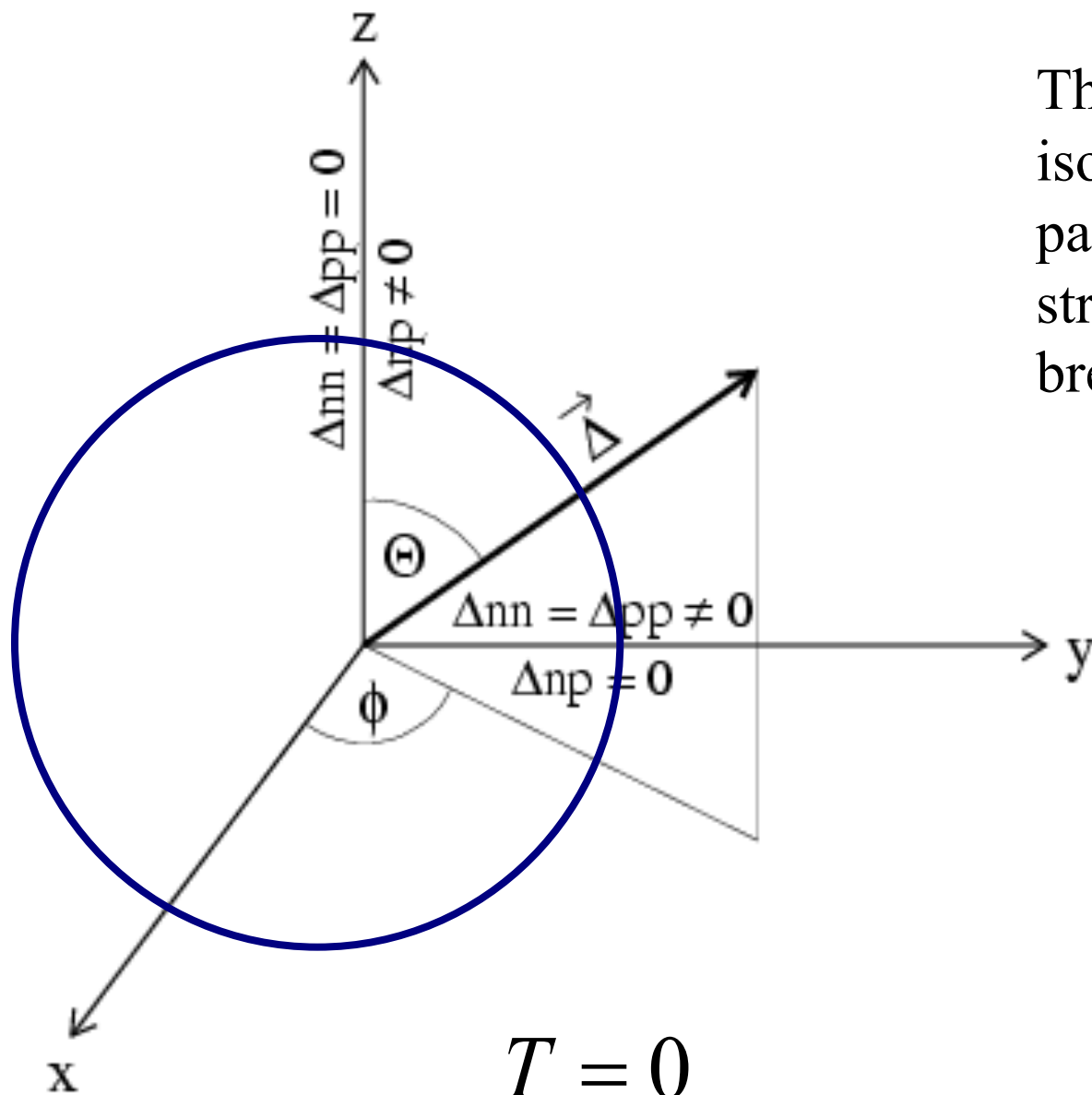


Shell Model
Monte Carlo
K. H. Langanke
et al.
NPA 613(97)253

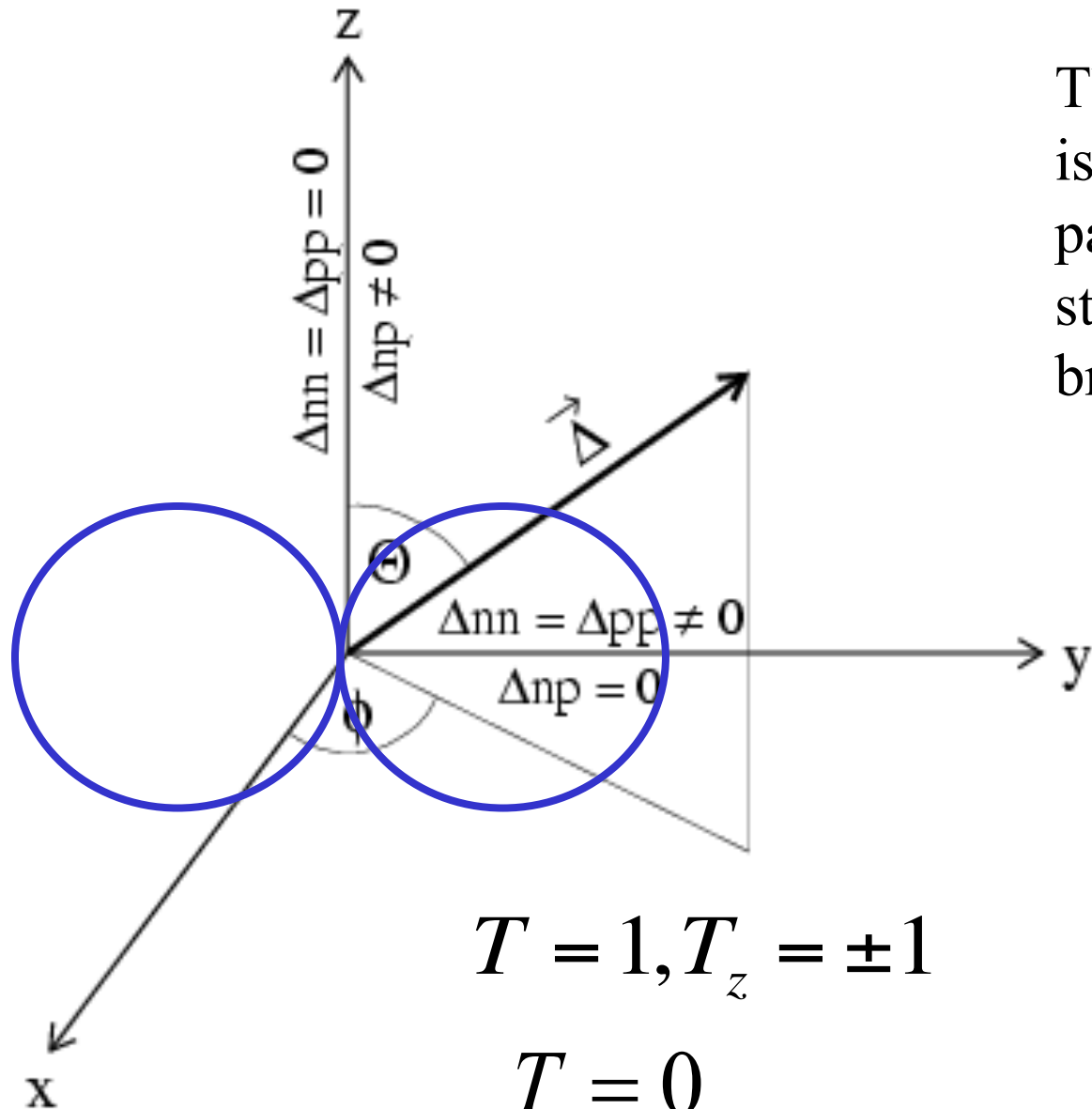
expectation
values of
pair counting
operators

No pair
correlations
HF expectation
value

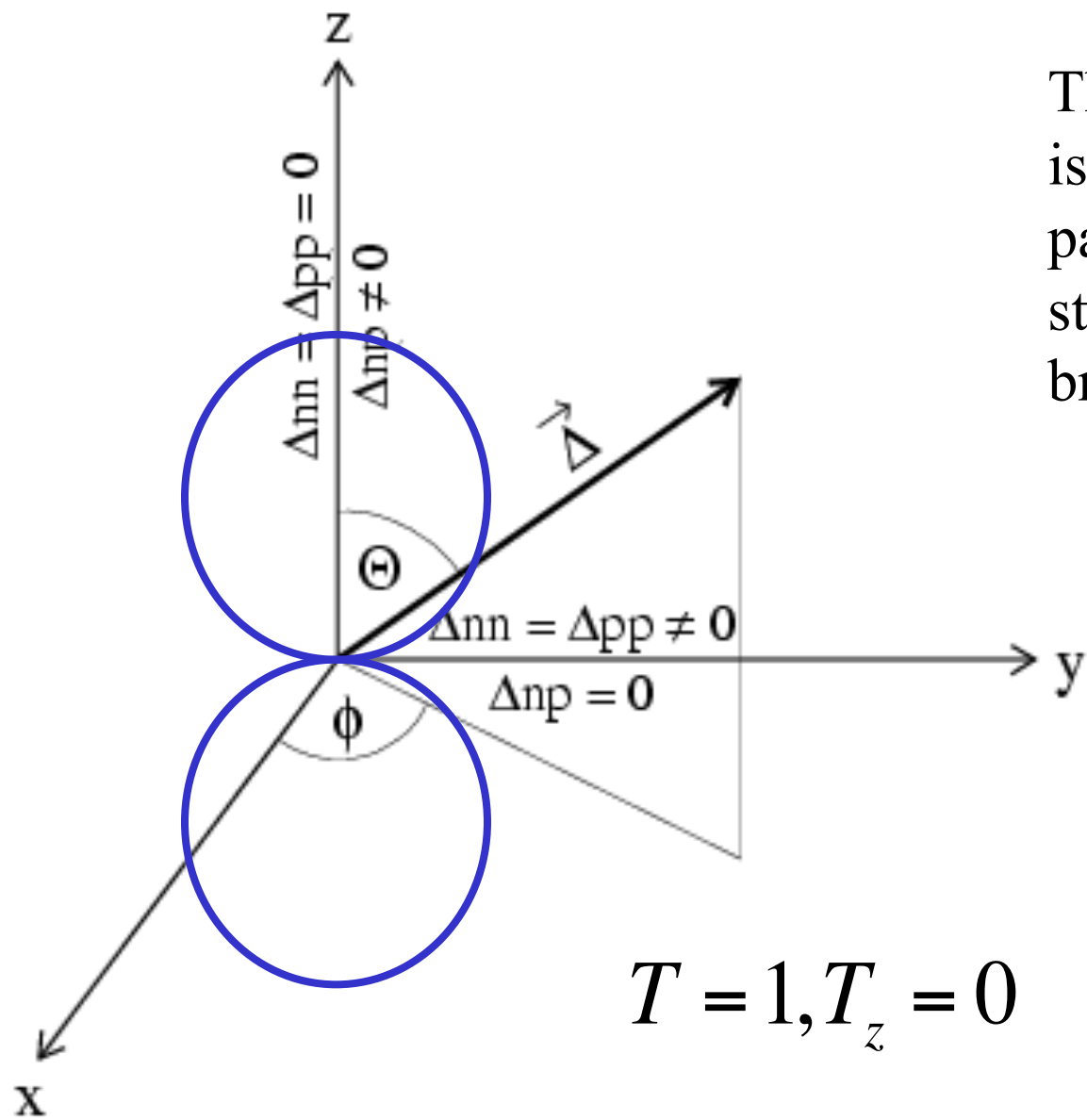
Weak but finite (dynamical) isoscalar correlations



The
iso-rotational
pattern of
strong symmetry
breaking



The
iso-rotational
pattern of
strong symmetry
breaking



The
iso-rotational
pattern of
strong symmetry
breaking

$$T = 1, T_z = 0$$

Pair transfer strength

$j=13/2$ spherical shell, pure monopole $T=1, J=0$ pairing

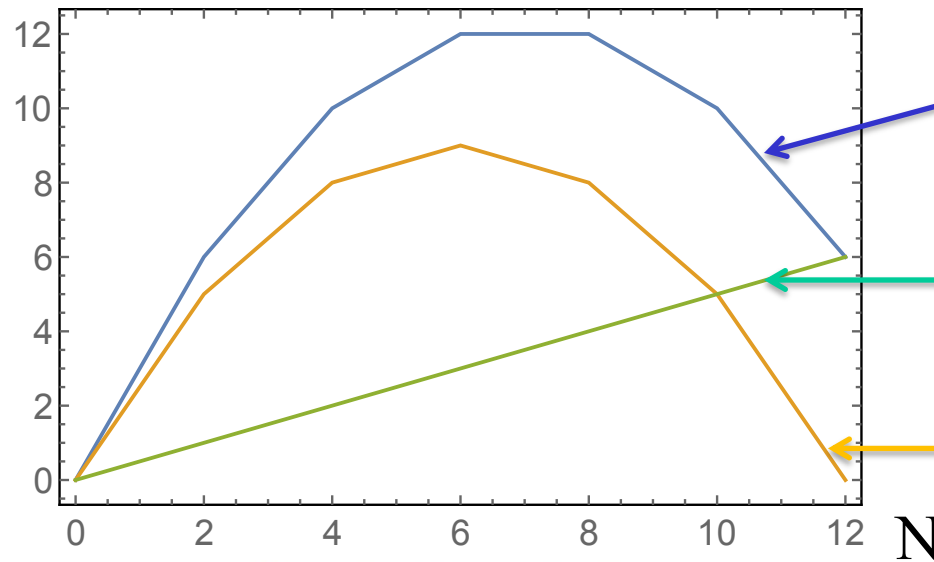
$$H = -GP_1^\dagger P_1$$

Pairing energy/ $(-12G)$

$$\langle N | P_1^\dagger P_1 | N \rangle$$

Transfer probability*12

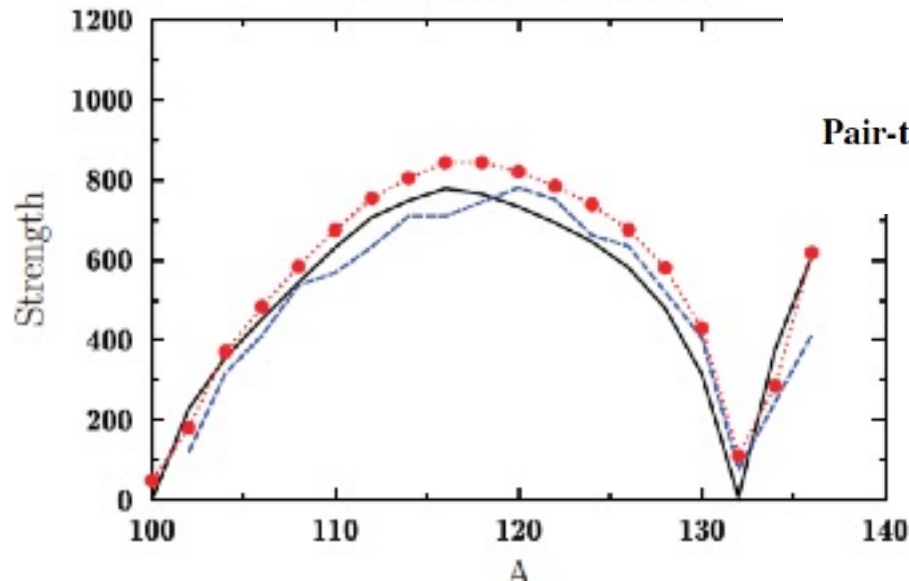
$$\langle N | P_1 | N - 2 \rangle^2$$



Uncorrelated part

Correlation part

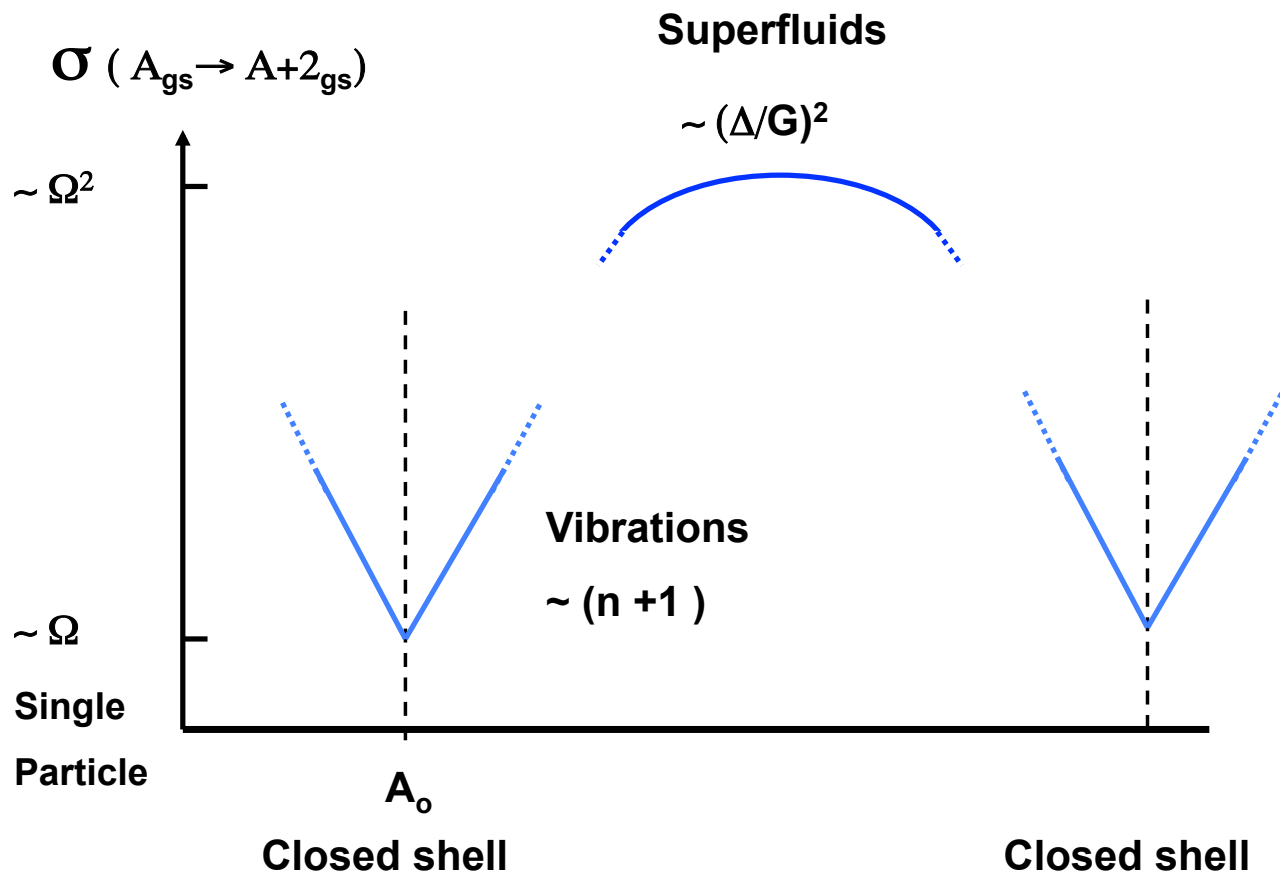
Surface interaction



PHYSICAL REVIEW C 85, 034317 (2012)

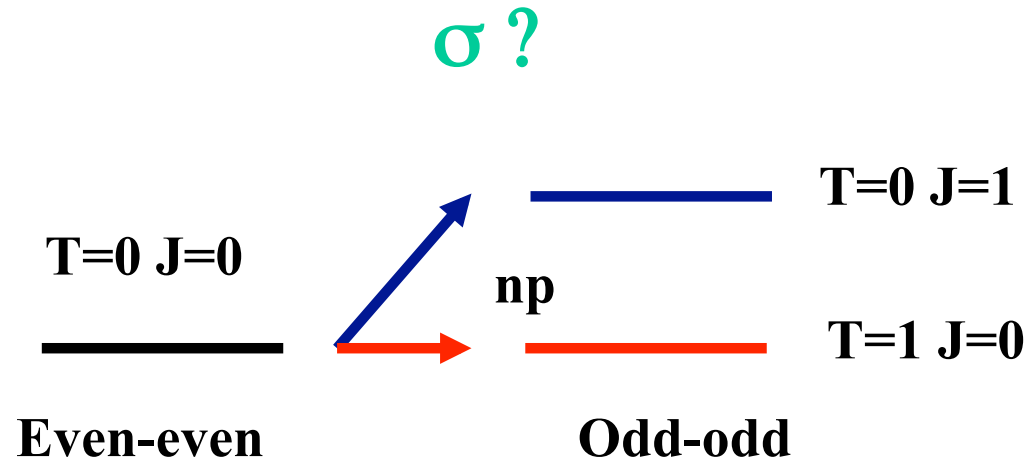
Pair-transfer probability in open- and closed-shell Sn isotopes

M. Grasso,¹ D. Lacroix,² and A. Vitturi^{3,4}



Systematic relative measurements and within a given nucleus.

$(^3\text{He}, p)$ Transfer Reactions

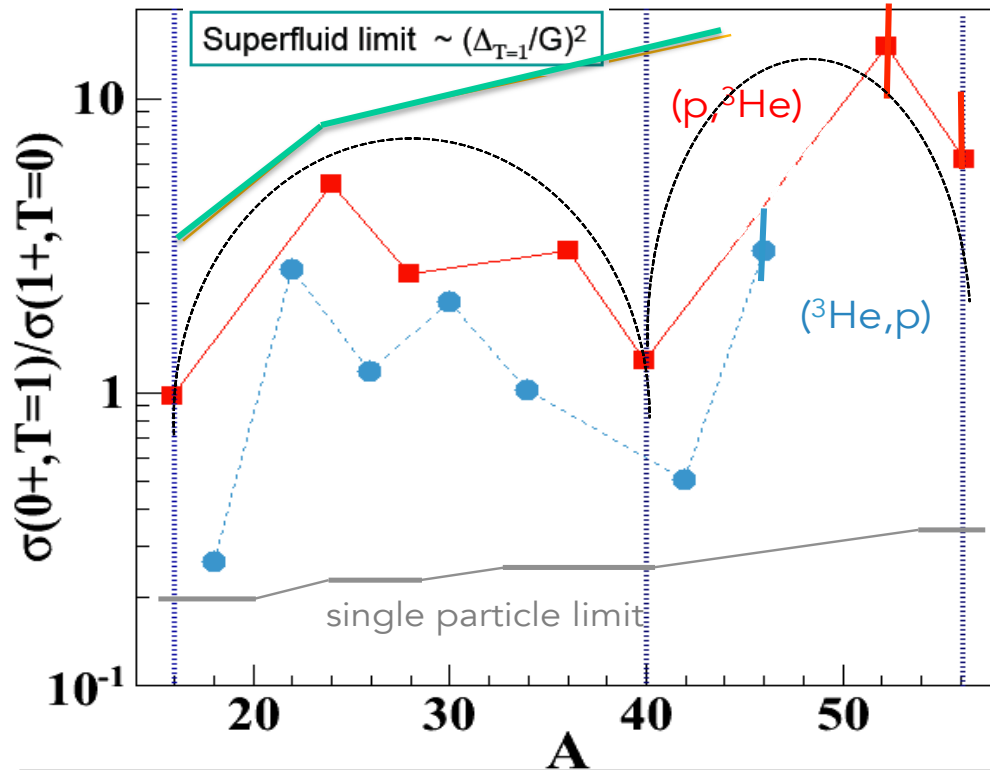


$(^3\text{He}, p)$ - $L=0$ transfer

Measure the np transfer cross section to $T=1$ and $T=0$ states

Both absolute $\sigma(T=0)$ and $\sigma(T=1)$ and relative $\sigma(T=0) / \sigma(T=1)$ tell us about the character and strength of the correlations

Systematic of ($^3\text{He}, p$) and ($p, ^3\text{He}$) $N=Z$ nuclei

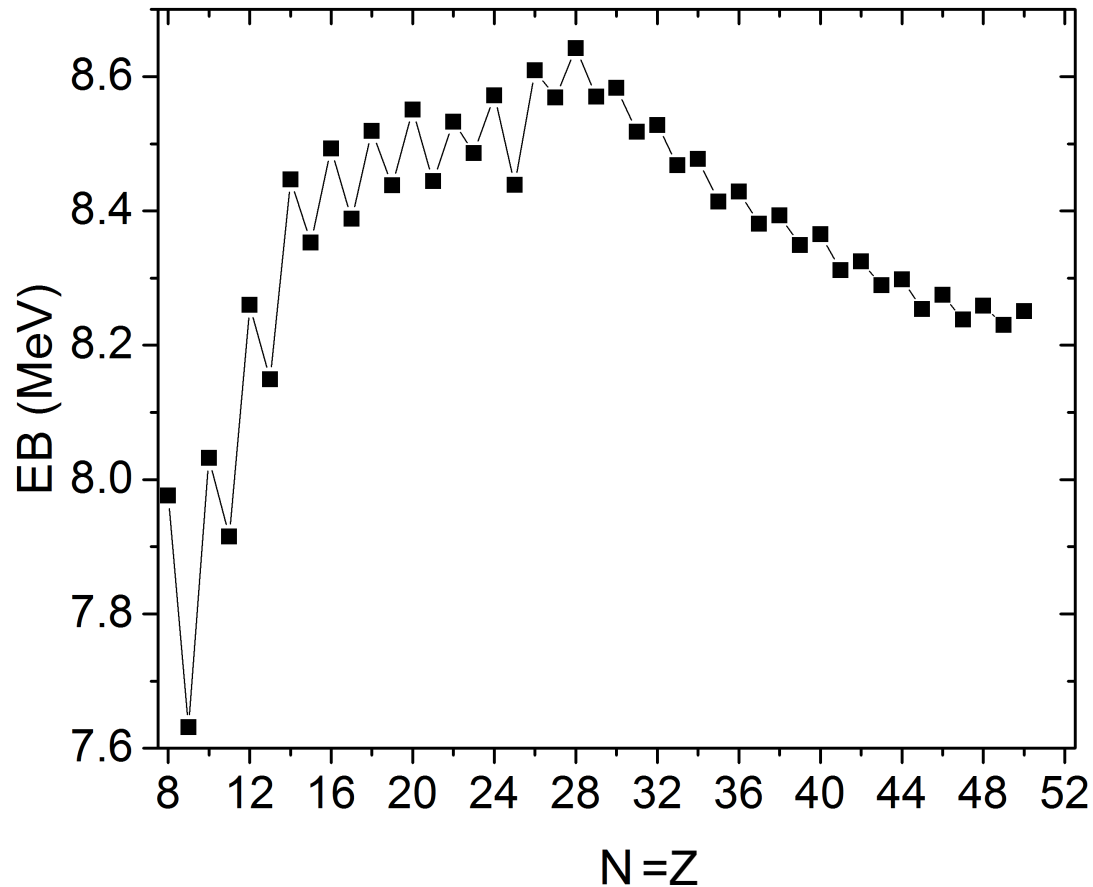


Single-particle estimate $\sim (\text{spin}) \times (^3\text{He}) \times (\text{LS} \rightarrow \text{jj})$

Ratio between the cross sections for transfer of an IV pair and an IS pair from e-e 0^+_1 to the 0^+_1 and the 1^+_1 states in the o-o.

- Only N-projected mean field or simple 1 or 2 shell model calculations for transfer matrix elements on the market.
- Realistic Shell Model not yet applied to pair transfer. However, the correlation energies provide a good estimate.
- Measurement of absolute enhancement is difficult
- Ratio of IS/IV enhancement is easier and interesting because the IV strength is well established from the energies.

Quarteting



The N=Z e-e nuclei are 50-100 keV more bound than the o-o ones.

Isospin conservation and quarteting

$$H = \sum_i \varepsilon_i (N_i^{(\nu)} + N_i^{(\pi)}) + \sum_{ij,\tau} V(i,j) P_{i,\tau}^+ P_{j,\tau}$$

$$P_{i1}^+ \propto \nu_i^+ \nu_{\bar{i}}^+ \quad P_{i-1}^+ \propto \pi_i^+ \pi_{\bar{i}}^+ \quad P_{i0}^+ \propto \nu_i^+ \pi_{\bar{i}}^+ + \pi_i^+ \nu_{\bar{i}}^+$$

non-collective quartets

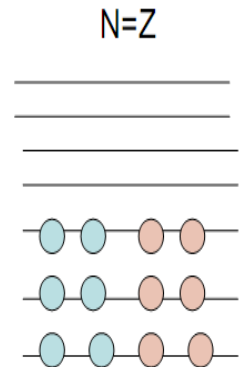
$$Q_{ij}^+ = [P_{i\tau}^+ P_{j\tau'}^+]^{T=0} \propto P_{\nu\nu,i}^+ P_{\pi\pi,j}^+ + P_{\pi\pi,i}^+ P_{\nu\nu,j}^+ - P_{\nu\pi,i}^+ P_{\nu\pi,j}^+$$

collective quartet

$$Q^+ = \sum_{ij} x_{ij} [P_{i\tau}^+ P_{j\tau'}^+]^{T=0}$$

quartet condensate

$$|QCM\rangle = |Q^{+n_q}\rangle \rightarrow \quad (\text{has } T=0, J=0)$$



Quartet condensation and Cooper pairs

$$|QCM\rangle = Q^{+n_q} |-\rangle \quad Q^+ = \sum_{ij} x_{ij} [P_{i\tau}^+ P_{j\tau'}^+]^{T=0}$$

$$Q^+ = 2\Gamma_{\nu\nu}^+ \Gamma_{\pi\pi}^+ - \Gamma_{\nu\pi}^+ \Gamma_{\nu\pi}^+ \quad \Gamma_{\tau}^+ = \sum_i x_i P_{i,\tau}^+ \quad \text{collective pairs}$$

$$|QCM\rangle = (2\Gamma_{\nu\nu}^+ \Gamma_{\pi\pi}^+ - \Gamma_{\nu\pi}^+ \Gamma_{\nu\pi}^+)^{n_q} |-\rangle$$

‘coherent’ mixing of condensates formed by nn, pp and pn pairs

$$|PBCS0\rangle \propto (\Gamma_{\nu\pi}^{+2})^{n_q} |-\rangle \quad |PBCS1\rangle \propto (\Gamma_{\nu\nu}^+ \Gamma_{\pi\pi}^+)^{n_q} |-\rangle$$

calculations

$$\delta_x < QCM | H | QCM \rangle = 0$$

method of recurrence relations

Quartet condensation versus pair condensation

$$H = \sum_i \varepsilon_i N_i + \sum_{ij} V_{J=0}^{T=1}(i, j) \sum_t P_{it}^+ P_{jt}$$

pairing forces extracted from SM interactions

$$|QCM\rangle \equiv (Q^+)^{n_q} | - \rangle \quad |PBCS1\rangle \propto (\Gamma_{\nu\nu}^+ \Gamma_{\pi\pi}^+)^{n_q} | - \rangle \quad |PBCS0\rangle \propto (\Gamma_{\nu\pi}^{+2})^{n_q} | - \rangle$$

	SM	QCM	PBCS1	PBCS0
²⁰ Ne	9.173	9.170 (0.033%)	8.385 (8.590%)	7.413 (19.187%)
²⁴ Mg	14.460	14.436 (0.166%)	13.250 (8.368%)	11.801 (18.389%)
²⁸ Si	15.787	15.728 (0.374%)	14.531 (7.956%)	13.102 (17.008%)
³² S	15.844	15.795 (0.309%)	14.908 (5.908%)	13.881 (12.389%)
⁴⁴ Ti	5.973	5.964 (0.151%)	5.487 (8.134%)	4.912 (17.763%)
⁴⁸ Cr	9.593	9.569 (0.250%)	8.799 (8.277%)	7.885 (17.805%)
⁵² Fe	10.768	10.710 (0.539%)	9.815 (8.850%)	8.585 (20.273%)
¹⁰⁴ Te	3.831	3.829 (0.052%)	3.607 (5.847%)	3.356 (12.399%)
¹⁰⁸ Xe	6.752	6.696 (0.829%)	6.311 (6.531%)	5.877 (12.959%)
¹¹² Ba	8.680	8.593 (1.002%)	8.101 (6.670%)	13.064 (13.064%)

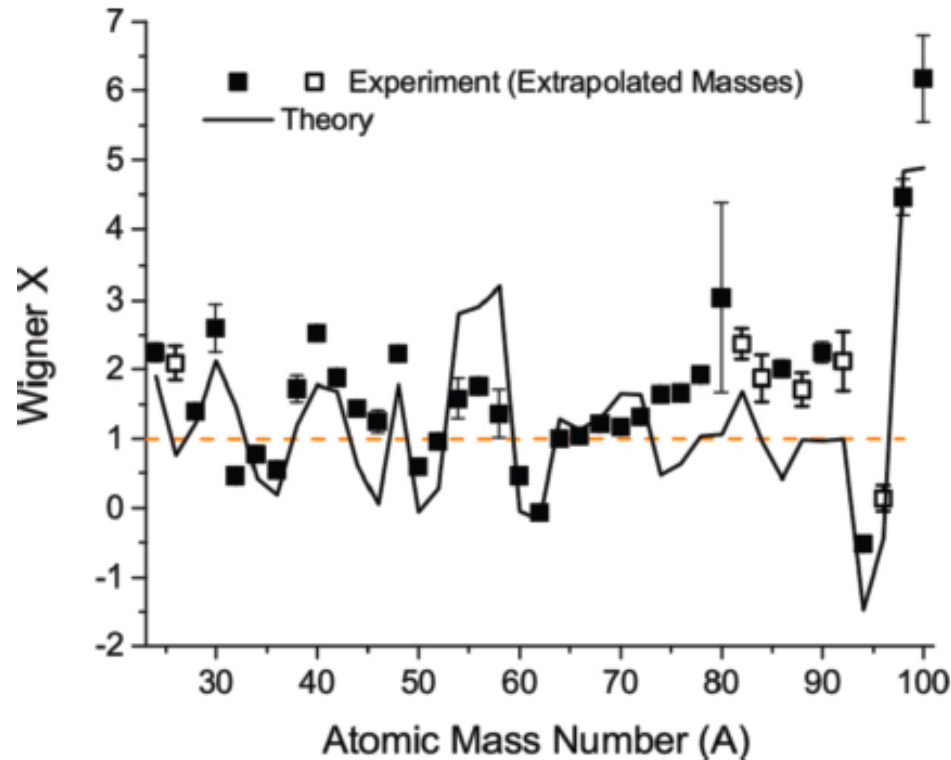
- Conclusions
- *T=1 pairing is accurately described by quartets, not by pairs*
 - *there is not a pure condensate of isovector pn pairs in N=Z nuclei*

States with good isospin always contain a mixture of $\Gamma\pi\pi$, $\Gamma\nu\nu$, $\Gamma\pi\nu$.

How different are $P_{TM=0}P_A|T=1\text{ MF}\rangle$ and $|QCM\rangle$?

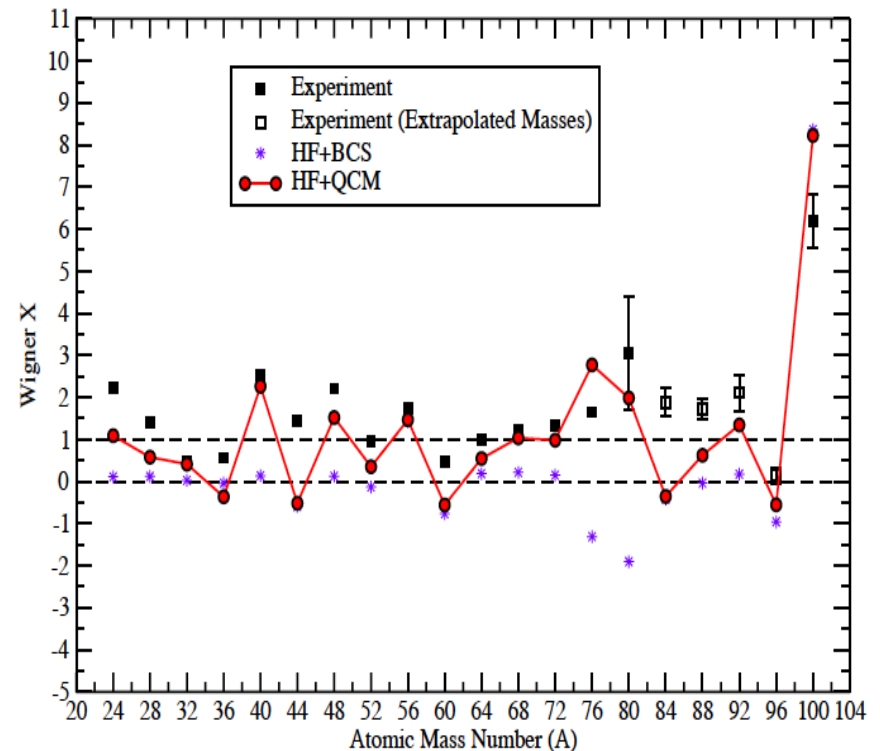
Wigner energy: comparison with earlier calculations

$$H_V = \sum_k \epsilon_k \hat{N}_k - G_V \sum_{kk', \tau} \hat{P}_{k, \tau}^+ \hat{P}_{k', \tau} + C \vec{T} \cdot \vec{T}$$



Bentley & Frauendorf PRC(2013)

$$H_V = \sum_k \epsilon_k \hat{N}_k - G_V \sum_{kk', \tau} \hat{P}_{k, \tau}^+ \hat{P}_{k', \tau}$$



Negrea & Sandulescu PRC(2014)

Isvector (J=0) pairing versus isoscalar (J=1) pairing

$$|QM\rangle = \prod_{\nu=1}^{N_Q} Q_{\nu}^{\dagger} |0\rangle. \quad Q_{\nu}^{\dagger} = Q_{\nu}^{\dagger(iv)} + Q_{\nu}^{\dagger(is)}$$

$$|is\rangle = \prod_{\nu=1}^{N_Q} Q_{\nu}^{\dagger(is)} |0\rangle \quad |iv\rangle = \prod_{\nu=1}^{N_Q} Q_{\nu}^{\dagger(iv)} |0\rangle$$

Correlation energies (% deviations from QM)

		QM	iv	is	$\langle QM iv \rangle$	$\langle QM is \rangle$	$\langle iv is \rangle$
IS/IV	^{20}Ne	15.985	14.402 (9.9%)	15.130 (5.35%)	0.884	0.953	0.843
IS	^{24}Mg	28.625	23.269 (18.71%)	26.925 (5.94%)	0.650	0.910	0.336
IS	^{28}Si	35.386	28.896 (18.34%)	33.377 (5.68%)	0.590	0.910	0.341
IS	^{32}S	38.844	33.958 (12.58%)	37.881 (2.48%)	0.640	0.974	0.587
IV	^{44}Ti	7.02	6.27 (10.6%)	4.92 (30%)	0.90	0.68	0.3
IV	^{48}Cr	11.624	10.59 (8.9%)	7.38 (36.5%)	0.906	0.497	0.22
IS/IV	^{52}Fe	13.823	12.814 (7.3%)	9.98 (27.83%)	0.927	0.753	0.74
IV	^{104}Te	3.147	3.041 (3.37%)	1.549 (50.78%)	0.978	0.489	0.314
IV	^{108}Xe	5.495	5.240 (4.64%)	2.627 (52.19%)	0.958	0.354	0.234
IV	^{112}Ba	7.035	6.614 (5.98%)	4.466 (36.52%)	0.939	0.375	0.376

T=1 and T=0 pairing correlations **always** coexist

&

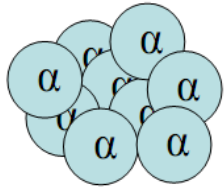
difficult to disentangle

T=1 correlations dominate, some T=0 correlations \longleftrightarrow **T=1 condensate+dynamical T=0**

Alpha-like quartetting versus alpha clustering

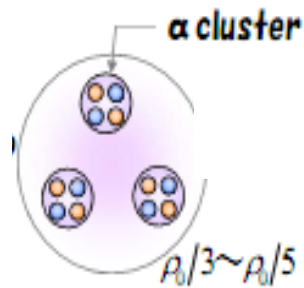
unified microscopic treatment ?

Quartetting



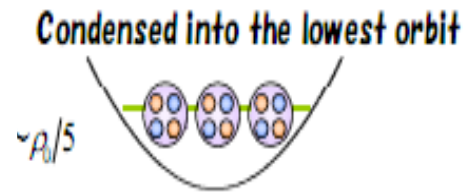
ground state

Alpha-clustering



excited states

Alpha condensation ?



Hoyle state in ^{12}C ?

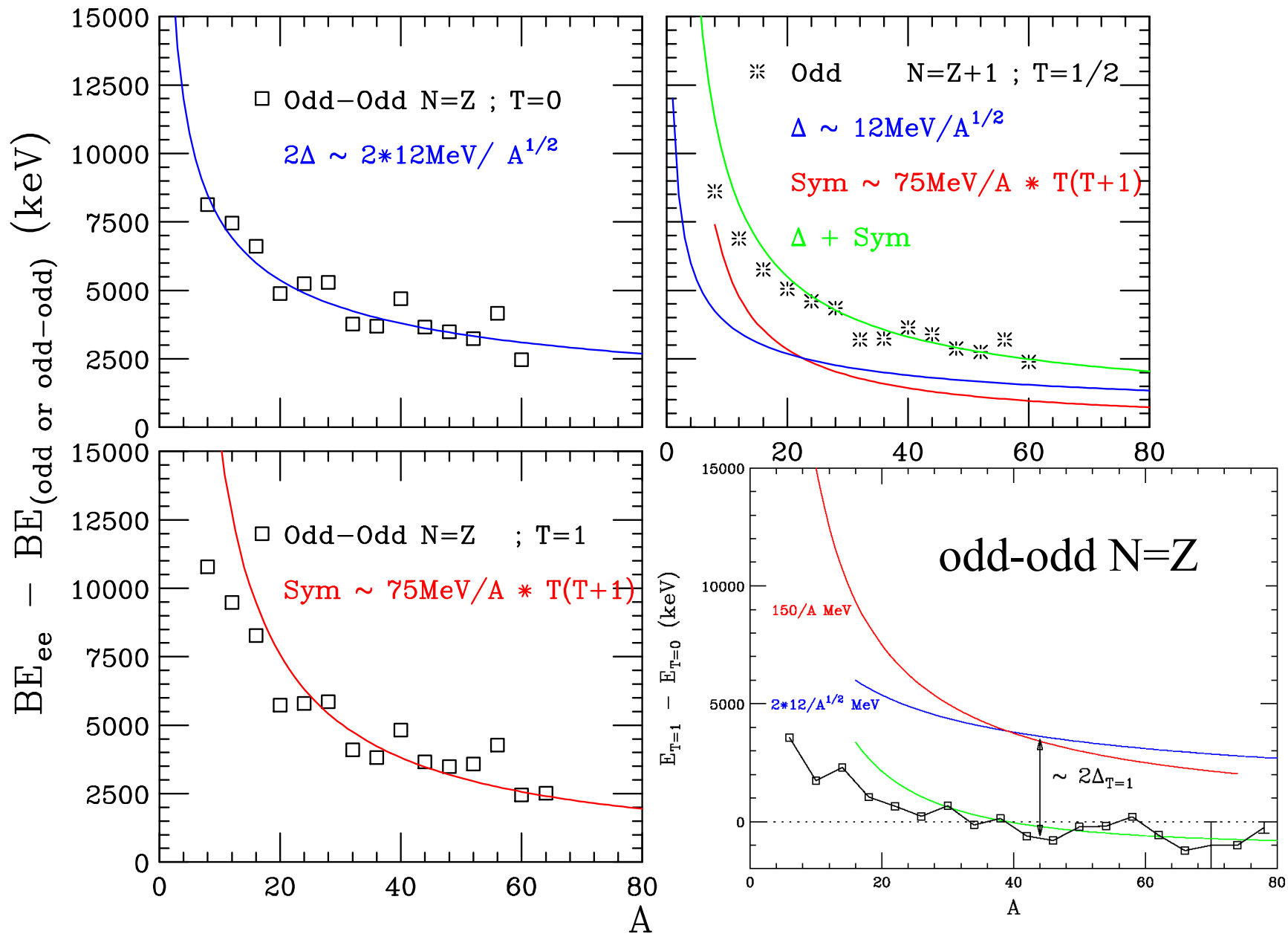
Ab initio Monte Carlo calculations in light $N=Z$ nuclei

ground state of $N=Z$ nuclei are close to a phase transition
between an alpha boson condensate and a quantum liquid

S. Elhatisari et al, arXiv: 1602.04539 (2016); Nature 528, 111 (2015)

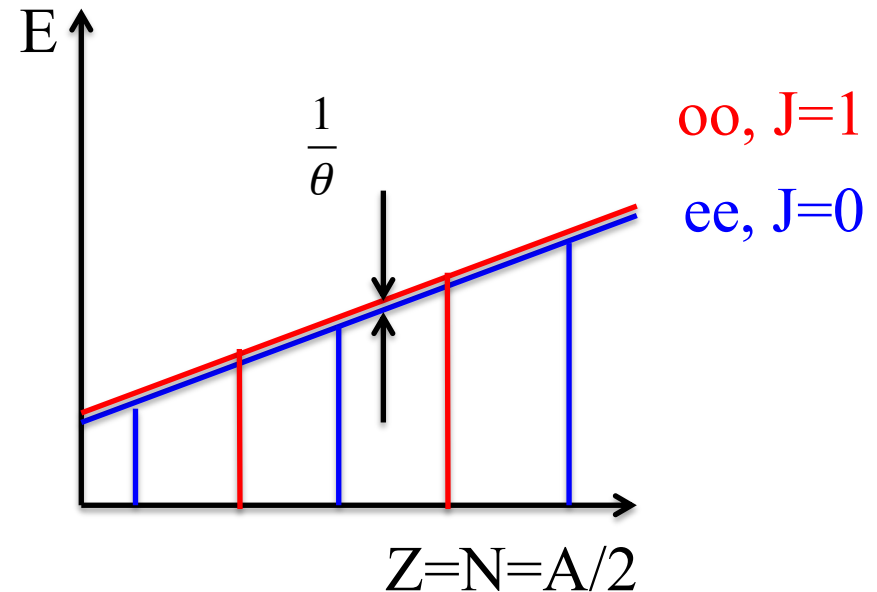
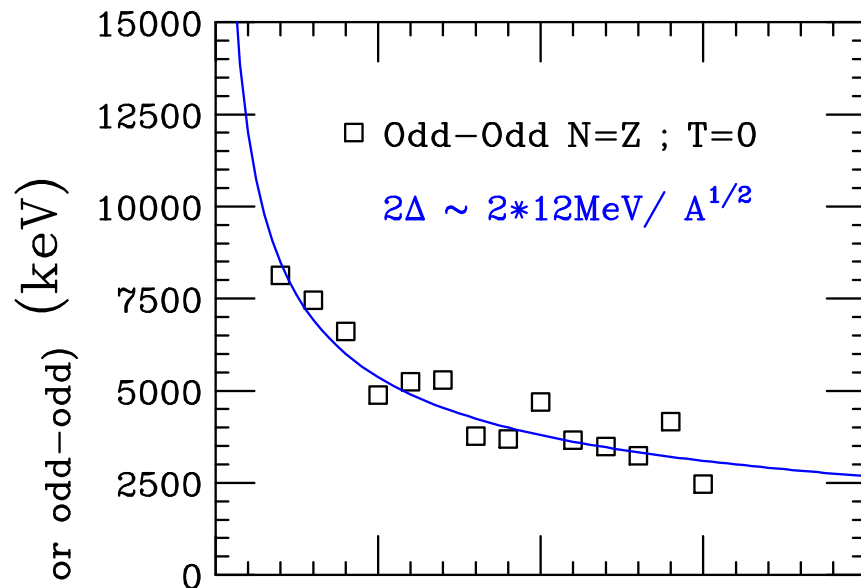
Summary

- The pn isovector pairing has to be as strong as the pp and nn pairing for symmetry reasons. No additional parameter to adjust.
- Mean field results: either IV or IS. IV for $200 > A > 40$. Below, IV or IS depends on deformation. Above, IS.
- Experimental energies consistent with strong IV (iso rotational bands). Coexisting IS pair vibrations likely.
- Scarce data on ratio IS/IV from pair transfer data. IV dominates.
- Eight-level and large-scale shell models: strong IV + weak IS.
- Pair correlation energies and two-particle transfer matrix elements from large-scale shell model of interest (only 2 studies so far).
- Quartet correlations from large-scale shell model of interest.



$T=1$ pair gap + isorotational energy account for the $N \approx Z$ binding energies ⁵⁶

T=0 condensate generates pair-rotational bands:
 Regular sequence of ground states include the odd-odd nuclei



The experimental
 T=0 odd-odd states do
 not join a pair-rotational band

$$\frac{J(J+1)}{2\theta} \quad \theta \text{ large,}$$

cranking, Shell Model