

Search for np pairing in collectively rotating $N \sim Z$ systems (case ^{88}Ru , ^{87}Tc)

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KTH Royal Institute of Technology

International Workshop
” Ab initio Nuclear Pairing Properties”

Espace de Structure et de réactions Nucléaires Théorique (ESNT), at CEA-Saclay, 13-21 May, 2025

Le plat du jour

- Introduction
- Brief overview of experimental probes of np pairing
- Evolution of pairing isospin modes with angular momentum along $N=Z$
- The heaviest deformed $N \sim Z$ systems: ^{88}Ru and ^{87}Tc

50 years 1975 - 2025

Nobel Prize in Physics 1975



Photo from the Nobel Foundation archive.

Aage Niels Bohr

Prize share: 1/3



Photo from the Nobel Foundation archive.

Ben Roy Mottelson

Prize share: 1/3



Photo from the Nobel Foundation archive.

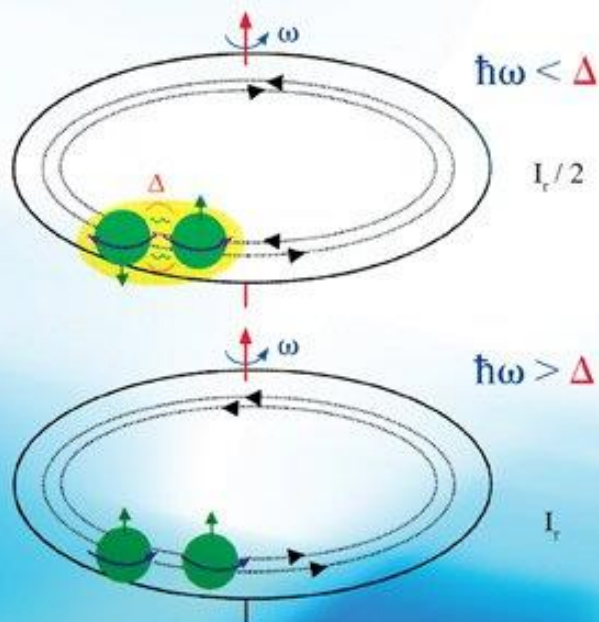
Leo James Rainwater

Prize share: 1/3

The Nobel Prize in Physics 1975 was awarded jointly to Aage Niels Bohr, Ben Roy Mottelson and Leo James Rainwater "for the discovery of the connection between collective motion and particle motion in atomic nuclei and the development of the theory of the structure of the atomic nucleus based on this connection"

Fifty Years of Nuclear BCS

Pairing in Finite Systems

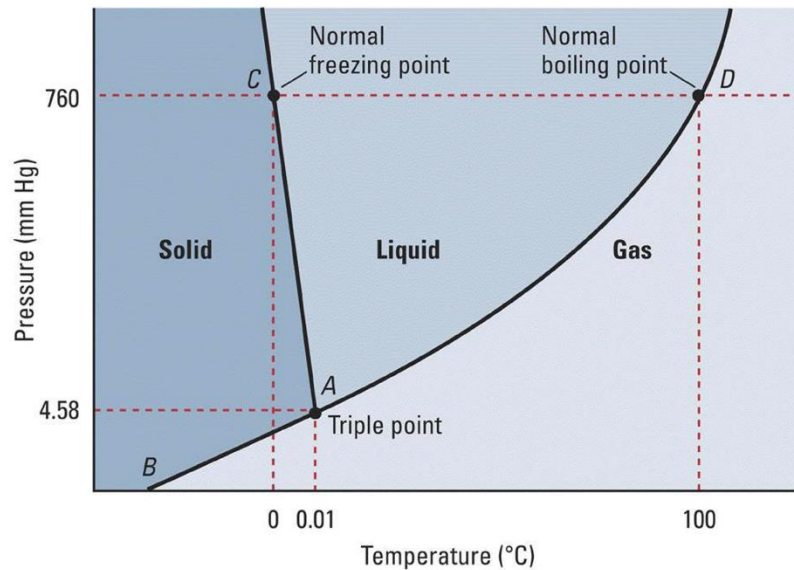


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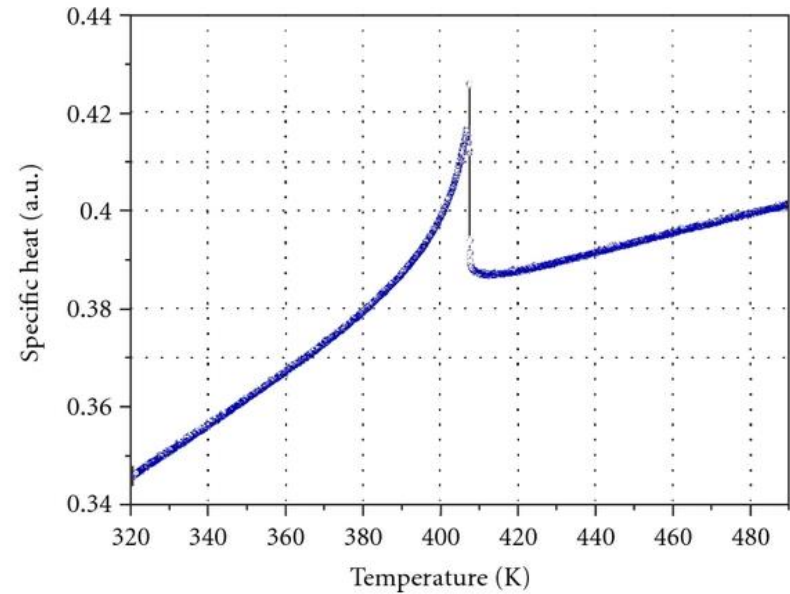
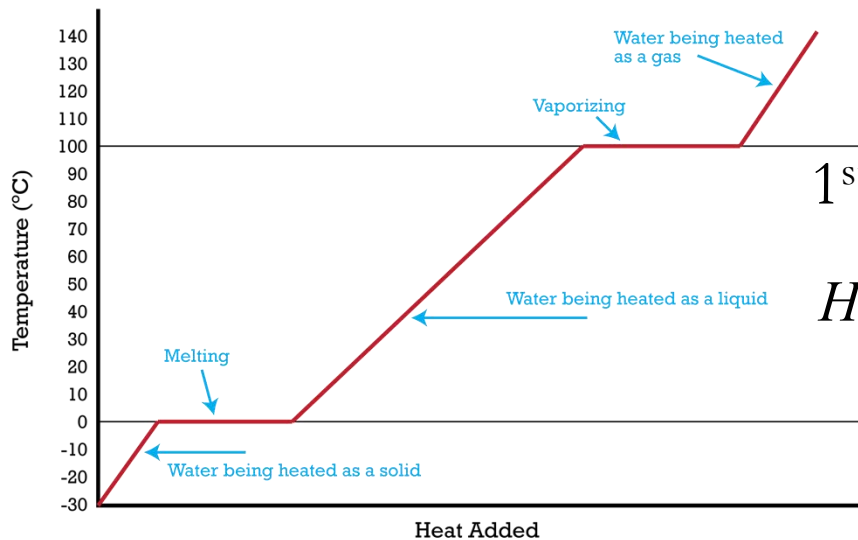
 World Scientific

<https://doi.org/10.1142/8526> (2013)

Phases of matter - phase transitions



Heating Curve for Water at 1.00 atm Pressure



Temperature dependence of specific heat of BaTiO₃ single crystal around the paraelectric-ferroelectric phase transition point T_c
S. Grabovsky, M. Takesada, A. Onodera et al., Annual Meeting of Physical Society of Japan, March 2012

1st order phase transition:

$$H(\lambda) = (1 - \eta)H_0 + \eta H_1 \quad \eta - \text{"control" parameter}$$

$$\frac{d \langle H(\eta) \rangle}{d\eta} \text{ discontinuity at } \eta = \eta_{cr}$$

Letters to the Editor

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Bound Electron Pairs in a Degenerate Fermi Gas*

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Physics Department, University of Illinois, Urbana, Illinois

(Received September 21, 1956)

IT has been proposed that a metal would display superconducting properties at low temperatures if the one-electron energy spectrum had a volume-independent energy gap of order $\Delta \simeq kT_c$, between the ground state and the first excited state.^{1,2} We should like to point out how, primarily as a result of the exclusion principle, such a situation could arise.

Consider a pair of electrons which interact above a quiescent Fermi sphere with an interaction of the kind that might be expected due to the phonon and the screened Coulomb fields. If there is a net attraction between the electrons, it turns out that they can form a bound state, though their total energy is larger than zero. The properties of a noninteracting system of such

$= (1/V) \exp[i(\mathbf{k}_1 \cdot \mathbf{r}_1 + \mathbf{k}_2 \cdot \mathbf{r}_2)]$ which satisfy periodic boundary conditions in a box of volume V , and where \mathbf{r}_1 and \mathbf{r}_2 are the coordinates of electron one and electron two. (One can use antisymmetric functions and obtain essentially the same results, but alternatively we can choose the electrons of opposite spin.) Defining relative and center-of-mass coordinates, $\mathbf{R} = \frac{1}{2}(\mathbf{r}_1 + \mathbf{r}_2)$, $\mathbf{r} = (\mathbf{r}_2 - \mathbf{r}_1)$, $\mathbf{K} = (\mathbf{k}_1 + \mathbf{k}_2)$ and $\mathbf{k} = \frac{1}{2}(\mathbf{k}_2 - \mathbf{k}_1)$, and letting $\mathcal{E}_K + \epsilon_k = (\hbar^2/m)(\frac{1}{4}K^2 + k^2)$, the Schrödinger equation can be written

$$(\mathcal{E}_K + \epsilon_k - E)a_k + \sum_{\mathbf{k}'} a_{\mathbf{k}'} (\mathbf{k} | H_1 | \mathbf{k}') \times \delta(\mathbf{K} - \mathbf{K}') / \delta(0) = 0 \quad (1)$$

where

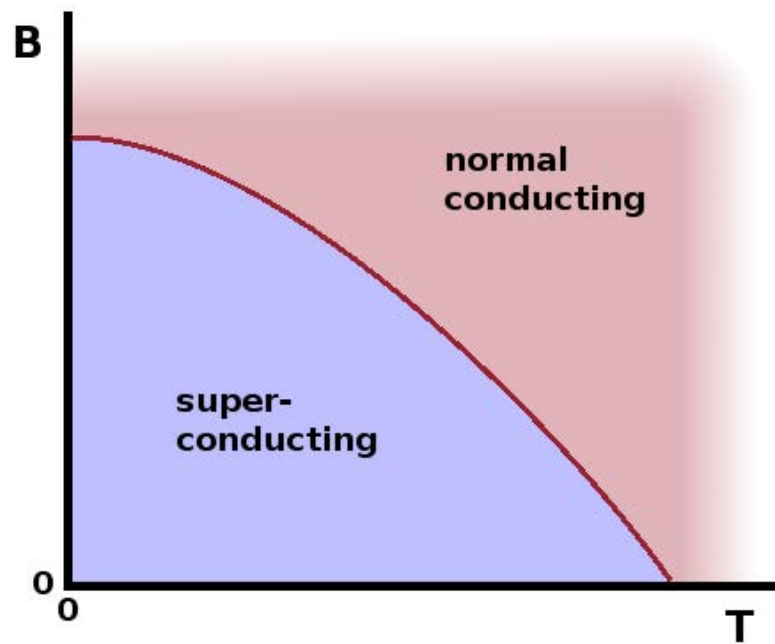
$$\begin{aligned} \Psi(\mathbf{R}, \mathbf{r}) &= (1/\sqrt{V}) e^{i\mathbf{K} \cdot \mathbf{R}} \chi(\mathbf{r}, K), \\ \chi(\mathbf{r}, K) &= \sum_{\mathbf{k}} (a_{\mathbf{k}}/\sqrt{V}) e^{i\mathbf{k} \cdot \mathbf{r}}, \end{aligned} \quad (2)$$

and

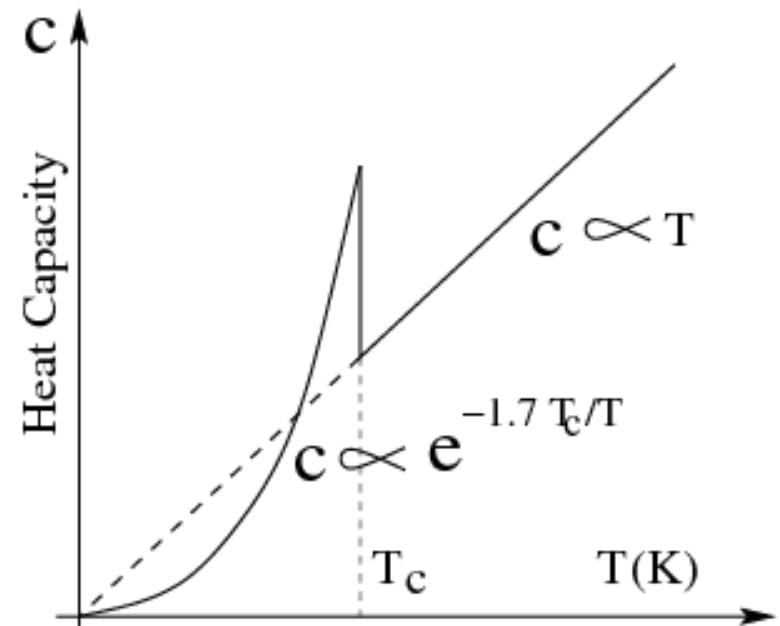
$$(\mathbf{k} | H_1 | \mathbf{k}') = \left(\frac{1}{V} \int d\mathbf{r} e^{-i\mathbf{k} \cdot \mathbf{r}} H_1 e^{i\mathbf{k}' \cdot \mathbf{r}} \right)_{0 \text{ phonons}}.$$

We have assumed translational invariance in the metal. The summation over \mathbf{k}' is limited by the exclusion principle to values of k_1 and k_2 larger than q_0 , and by the delta function, which guarantees the conservation of the total momentum of the pair in a single scattering. The K dependence enters through the latter restriction.

Bardeen and Pines³ and Fröhlich⁴ have derived approximate formulas for the matrix element $(\mathbf{k} | H_1 | \mathbf{k}')$; it is thought that the matrix elements for which the two electrons are confined to a thin energy shell near the Fermi surface, $\epsilon_1 \simeq \epsilon_2 \simeq \epsilon_F$, are the principal ones



<http://users.aber.ac.uk>



Can we observe something similar in atomic nuclei?

THE PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 114, NO. 6

JUNE 15, 1959

Possible Superfluidity of a System of Strongly Interacting Fermions*†

L. N. COOPER,‡ R. L. MILLS, AND A. M. SESSLER

The Ohio State University, Columbus, Ohio

(Received January 30, 1959)

The possible superfluidity of a system of strongly interacting fermions is investigated on the assumption that an adequate description of the system in its "normal" state is given by independent fermions in a momentum-dependent potential. On the basis of this assumption we have investigated whether a correlated wave function of the form used by Bardeen, Cooper, and Schrieffer minimizes the ground-state energy. The nonzero terms in the expectation value of the Hamiltonian contain the modified kinetic energy and the full two-body potential between the fermion pairs. An integral equation is obtained in configuration space for the correlation function between pairs. This integral equation is meaningful even for potentials with hard cores, and a nonzero solution implies the existence of a superfluid state. A variational method is devised which provides a criterion for superfluidity and a lower bound for the transition temperature into the superfluid state. We find that a repulsive hard core does not in principle forbid the existence of a superfluid state, but whereas in the absence of a hard core an attractive two-body potential always leads to a superfluid state at sufficiently low temperatures, in the presence of a repulsive core there appears to be a critical strength of attraction needed to form a superfluid state. When the variational principle is applied to liquid He^3 or to nuclear matter, it is found for a wide class of trial functions that the system does not become a superfluid.

I. INTRODUCTION

THE fact that a system of fermions can become a superfluid is demonstrated by the observed behavior of the electron gas in many metals at low temperatures. It seems natural then to inquire whether or not other systems of fermions might display similar properties, and what the criterion for such behavior would be. This question is of particular interest because of recent conjectures¹ that nuclear matter might be superfluid in the sense that for an infinite medium there would be an energy gap between the ground state and the lowest single particle excitations. It has been further conjectured that this might show up for a finite nucleus as the explanation for the abnormally large single-particle excitation energy of even-even nuclei. Whether or not He^3 , the other well-known Fermi fluid, has a

superfluid phase at low temperatures has been a matter of concern since the discovery of the λ transition in He^4 and London's conjecture² that Bose statistics are crucial to the formation of the superfluid phase.

We have attempted to treat this question by taking over to an arbitrary system of fermions what appears to have worked very well for the electron gas. There the introduction of pair correlations into the wave function and the approximation that only pairs of given total spin and total momentum are strongly correlated was sufficient to account for the observed properties of the superconducting phase. In making this same assumption for an arbitrary system of fermions we have had to assume that in some sense the "normal" fluid could be described in an uncorrelated approximation. The situation in this regard, for a fermion system such as the nucleus, is much less clear than the corresponding situation in a metal where the lattice plays such a dominant rôle.

This basic conjecture of our procedure, the description of the normal fluid as a Fermi gas in a momentum-dependent potential, is discussed in Sec. II. In the third

* Supported in part by the National Science Foundation.

† A preliminary account of this work was presented at the *Kamerlingh-Onnes Conference on Low-Temperature Physics, Leiden, Netherlands, June, 1958* (Suppl. Physica 24, September, 1958).

‡ Present address: Brown University, Providence, Rhode Island.

¹ Bohr, Mottelson, and Pines, *Phys. Rev.* **110**, 936 (1958); C. De Dominicis and P. C. Martin, *Bull. Am. Phys. Soc. Ser. II*, **3**, 224 (1958).

² F. London, *Nature* **163**, 694 (1949).

Thermal and electromagnetic properties of ^{166}Er and ^{167}Er

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A. Voinov

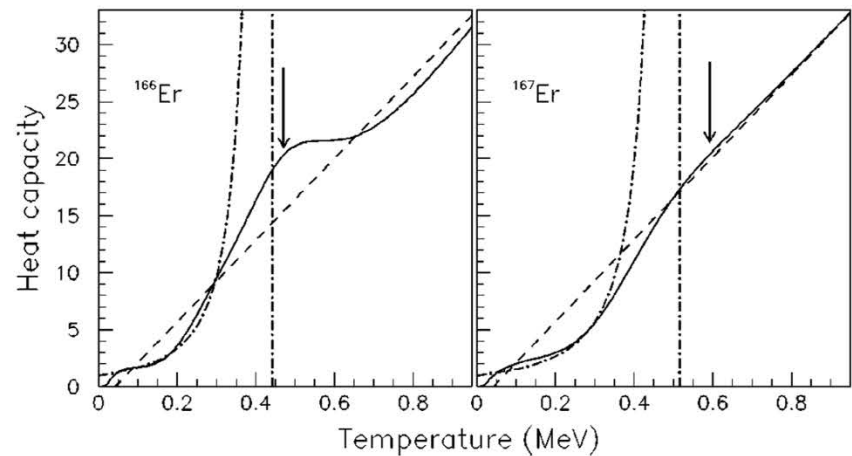
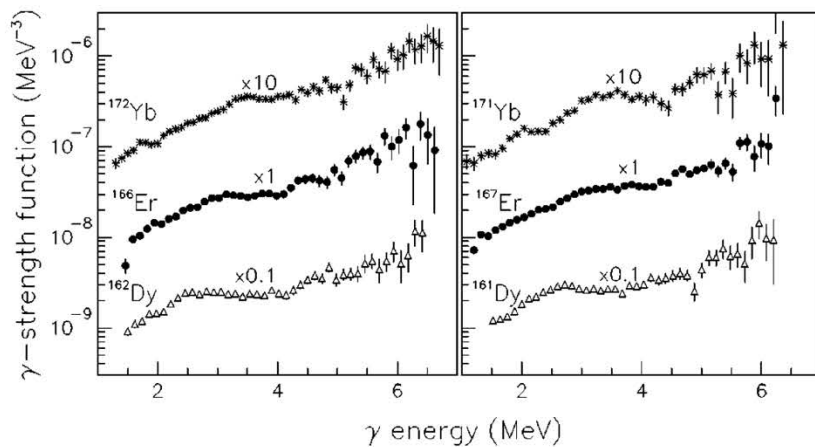
Frank Laboratory of Neutron Physics, Joint Institute of Nuclear Research, RU-141980 Dubna, Moscow region, Russia

(Received 30 October 2000; published 6 March 2001)

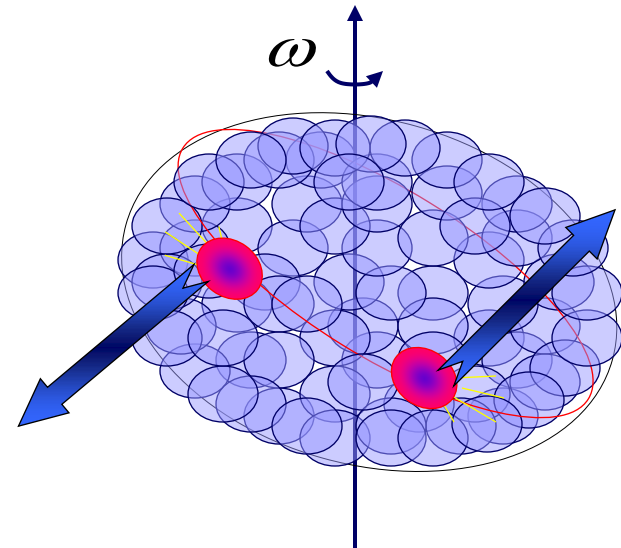
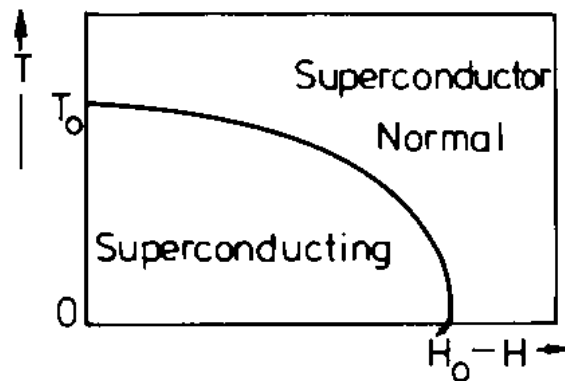
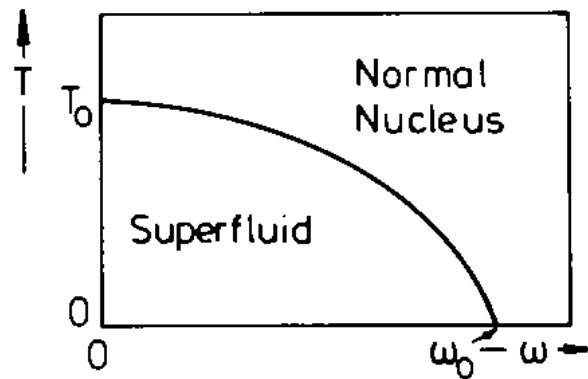
The primary γ -ray spectra of ^{166}Er and ^{167}Er are deduced from the $(^3\text{He}, \alpha\gamma)$ reaction and the $(^3\text{He}, ^3\text{He}'\gamma)$ reaction, respectively, enabling a simultaneous extraction of the level density and the γ -ray-strength function. Entropy, temperature, and heat capacity are deduced from the level density within the microcanonical and canonical ensembles, displaying signals of a phaselike transition from the pair-correlated ground state to an uncorrelated state at $T_c \sim 0.5$ MeV. The γ -ray-strength function displays a bump around $E_\gamma \sim 3$ MeV, interpreted as the pygmy resonance.

PHYSICAL REVIEW C **63** 044309

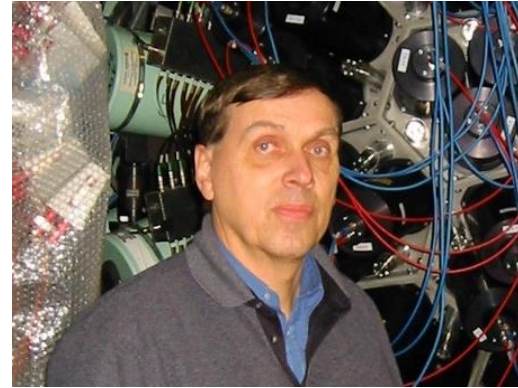
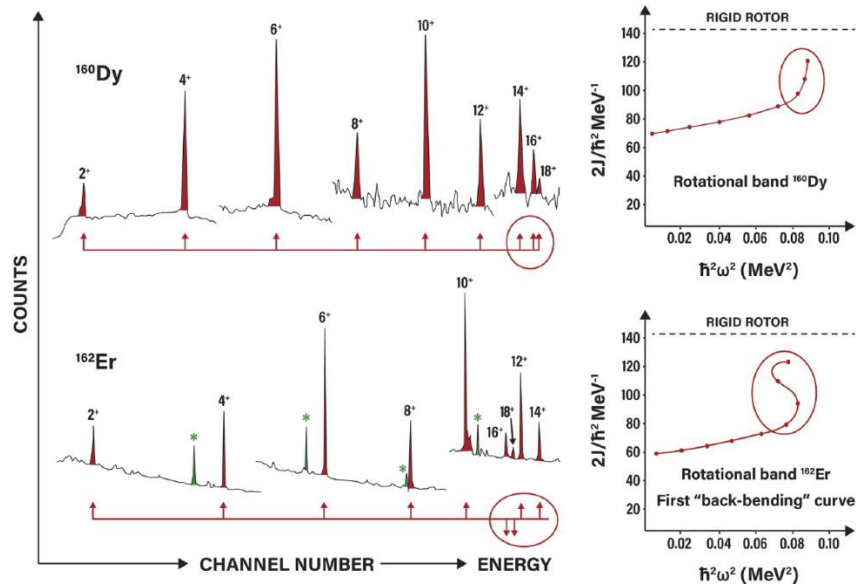
PHYSICAL REVIEW C **63** 044309



Similarly to a magnetic field on a superconductor, the rotational motion of a **deformed** nucleus counteracts the isovector-coupled ($J=0$) superfluid phase by breaking time-reversed nn or pp pairs. (Coriolis anti-pairing effect)



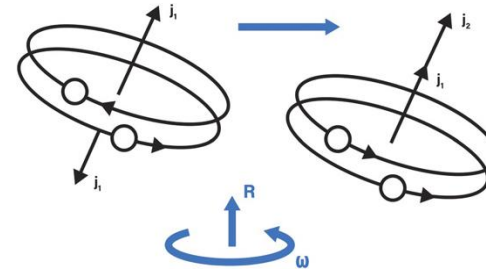
Rotational alignments (“backbending”) in deformed nuclei: a sensitive probe of pairing strength



Arne Johnson
1944-2023



Frank Stephens
1931-2024



Note: The “Backbending” effect (A. Johnson et al., 1971) is not a complete phase transition. In the finite nuclear system the paired and unpaired phases are mixed after the first alignment (“Stockholm, S-band”) (F.S. Stephens and R.S. Simon, 1972).

A. Johnson, H. Ryde, and J. Sztarkier, Phys. Lett. B34, 605 (1971)

A. Johnson, H. Ryde, S. A. Hjorth, Nuc. Phys. A179, 753 (1972)

F. S. Stephens and R. S. Simon. Nuc. Phys. A183, 257 (1972)

Standard description of rotational bands for decades:
Cranked Deformed Shell Model (Nilsson/WS)+ BCS (isovector pairing)

Configuration interaction (shell model) description of collective rotation
possible in some cases, e.g. ^{48}Cr

Physical Review Letters

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Backbending Mechanism of ^{48}Cr

Kenji Hara¹, Yang Sun², and Takahiro Mizusaki³

Show more

Phys. Rev. Lett. **83**, 1922 – Published 6 September, 1999

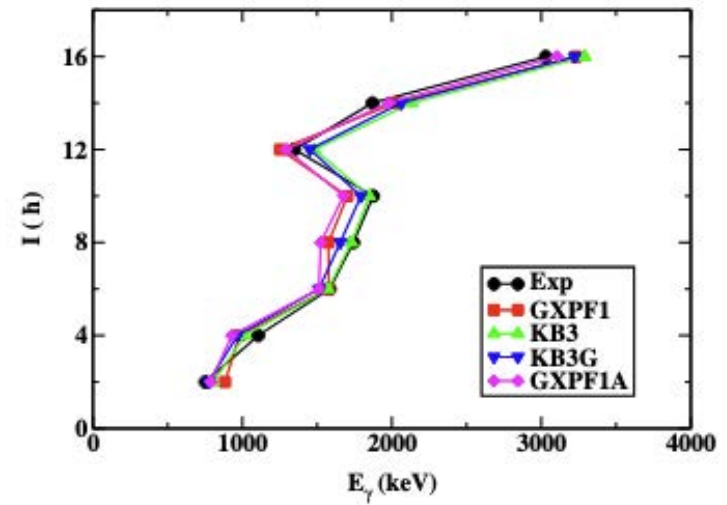
DOI: <https://doi.org/10.1103/PhysRevLett.83.1922>

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Abstract

The mechanism of backbending in ^{48}Cr is investigated in terms of the projected shell model and the generator coordinate method. It is shown that both methods are reasonable shell model truncation schemes. These two quite different quantum mechanical approaches lead to a similar conclusion that the backbending is due to a band crossing involving an excited band which is built on simultaneously broken neutron and proton pairs in the "intruder" subshell $f_{7/2}$. It is pointed out that this type of band crossing is usually known to cause the second backbending in rare-earth nuclei.

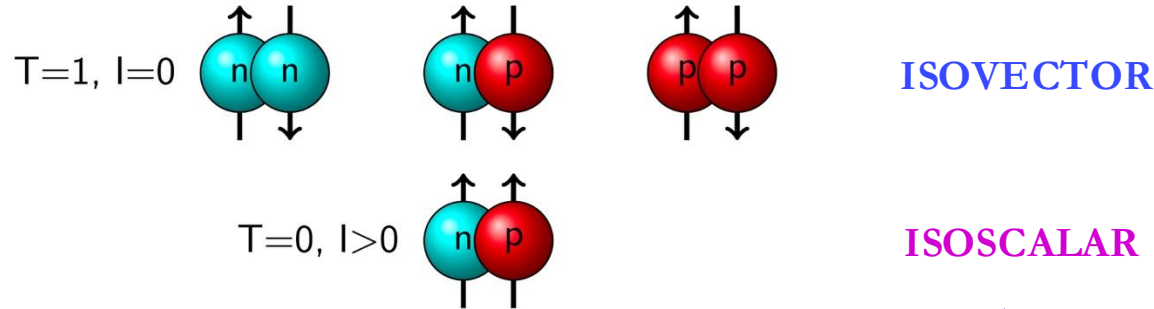


Y.R., R.P.S., Proc. DAE Symp. on Nucl. Phys. 66 (2022)

Neutron-proton pairing in $N \approx Z$ nuclei - experimental probes

Isospin NN pairing modes in $N \sim Z$ nuclei

- a unique possibility for nuclei due to the coupling of two Fermi liquids

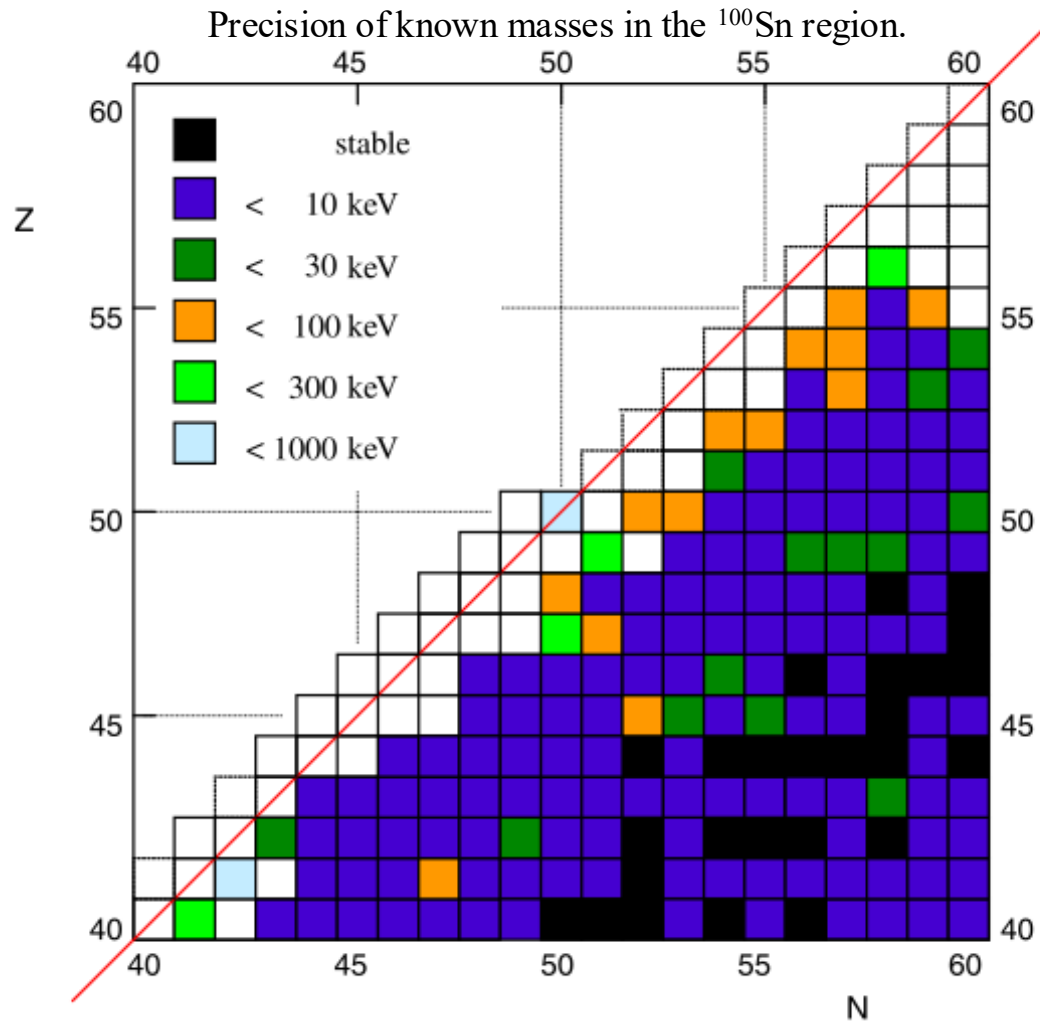


- Masses - binding energies in e-e and o-o nuclei indicate that **$T=1$ np pairing** is dominant, no evidence for a $T=0$ (deuteron-like) pair condensate **up to around $A \approx 60$. Need for accurate mass measurements in heavier $N=Z$ systems**
- np (deuteron) pair transfer reactions
- GT Beta decay strengths
- Other radioactive decay modes: (alpha) proton???
- The above methods **probe ground-state or low-spin correlations**
- Spectral properties of spherical $N=Z$ nuclei near closed shells –deviations from classical s.p. behavior (e.g. ^{92}Pd – isoscalar spin-aligned coupling*)
- **Rotational properties of deformed nuclei**

We know the isoscalar effective NN interaction is strongly attractive but can it produce a correlated np pairing condensate?

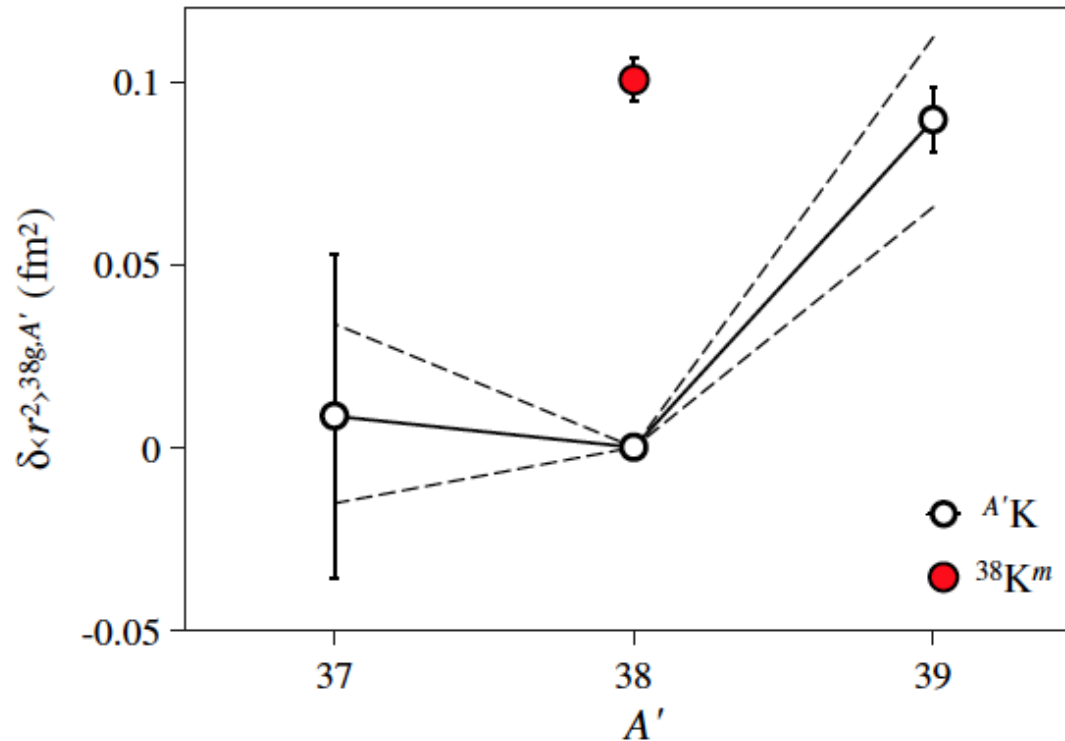
S. Frauendorf and A. Macchiavelli, Prog. Part. Nucl. Phys. 78, 24 (2014)

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



T. Faestermann, M. Górska, and H. Grawe, Prog. Part. Nucl. Phys. 69, 85 (2013)

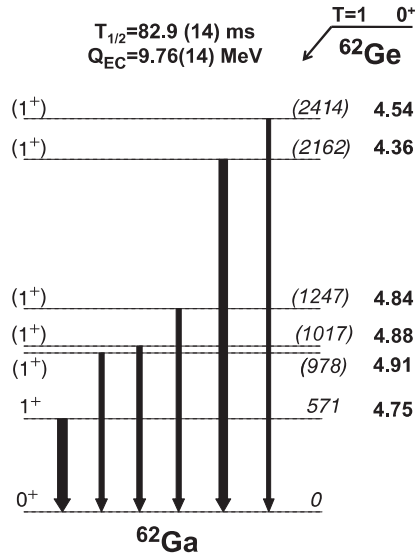
Evidence for *isovector* np pairing from nuclear charge radius



“Proton-Neutron Pairing Correlations in the Self-Conjugate Nucleus ^{38}K Probed via a Direct Measurement of the Isomer Shift”

M.L. Bissell et al., PRL 113, 052502 (2014)

GT (beta decay) strengths



“Hindered Gamow-Teller Decay to the Odd-Odd $N = Z$ ^{62}Ga :
Absence of Proton-Neutron $T=0$ Condensate in $A = 62$ ”,
E. Grodner et al., PRL 113, 092501 (2014)

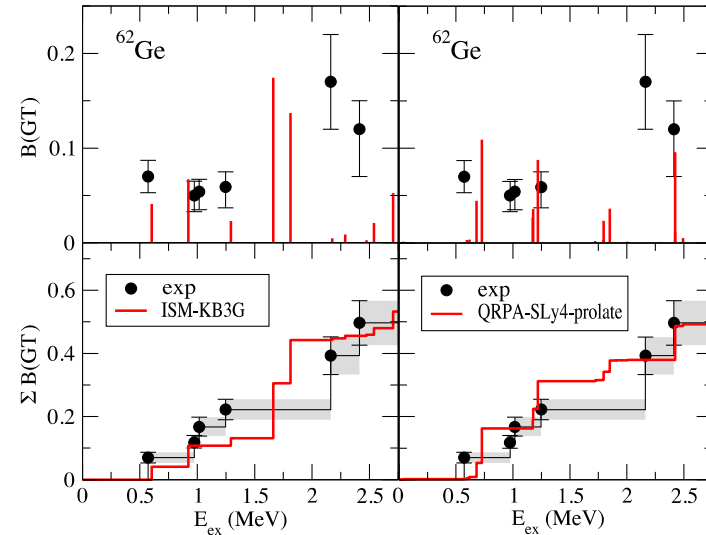
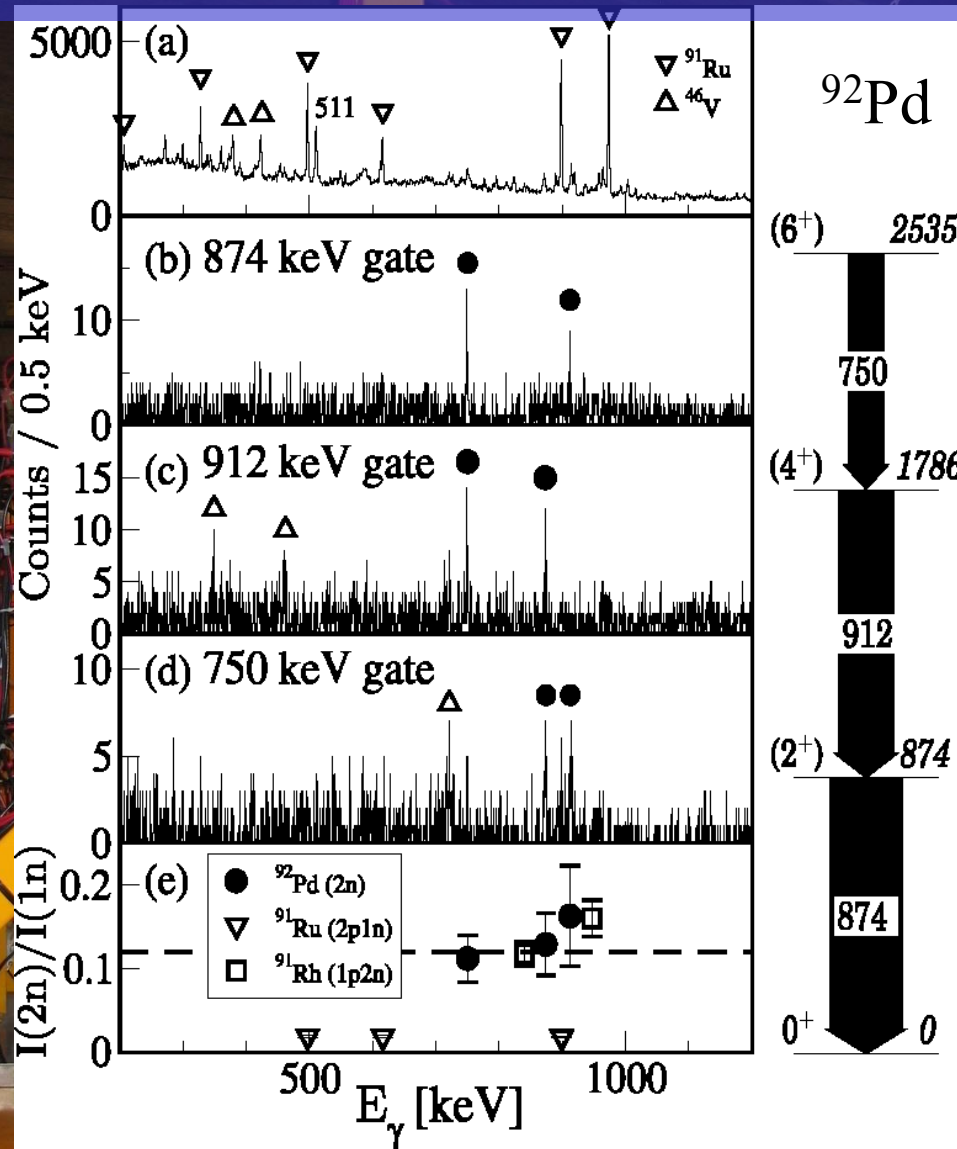
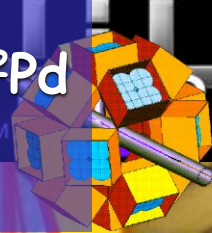


FIG. 4 (color online). Experimental (black) and calculated (red) single level $B(\text{GT})$ and accumulated $B(\text{GT})$ values for the ^{62}Ge to ^{62}Ga β decay. Left panels use the ISM approach using the KB3G interaction and right panels use the QRPA approach using the SLy4 interaction. Experimental uncertainty corridors are indicated in gray.

“Search for a new kind of superfluidity built on collective proton-neutron pairs with aligned spin is performed studying the Gamow-Teller decay of the $T = 1, J^\pi = 0^+$ ground state of ^{62}Ge into excited states of the odd-odd $N = Z$ nucleus ^{62}Ga . Individual Gamow-Teller transition strengths agree well with theoretical predictions of the interacting shell model and the quasiparticle random phase approximation. The absence of any sizable low-lying Gamow-Teller strength in the reported beta-decay experiment supports the hypothesis of a negligible role of coherent $T = 0$ proton-neutron correlations in ^{62}Ga . “

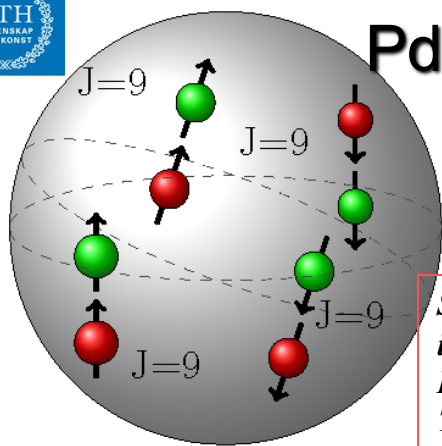
Observation of excited states in the $N=Z=46$ nucleus ^{92}Pd

EXOAM + Neutron Wall + Diamant experiment

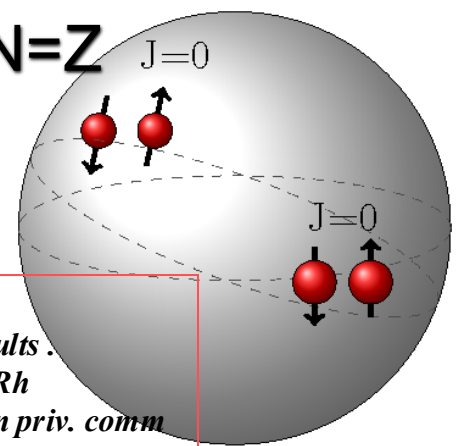


B. Cederwall et al., Nature **469**, 68 (2011)

Pd energy level systematics near N=Z - effects of np interactions



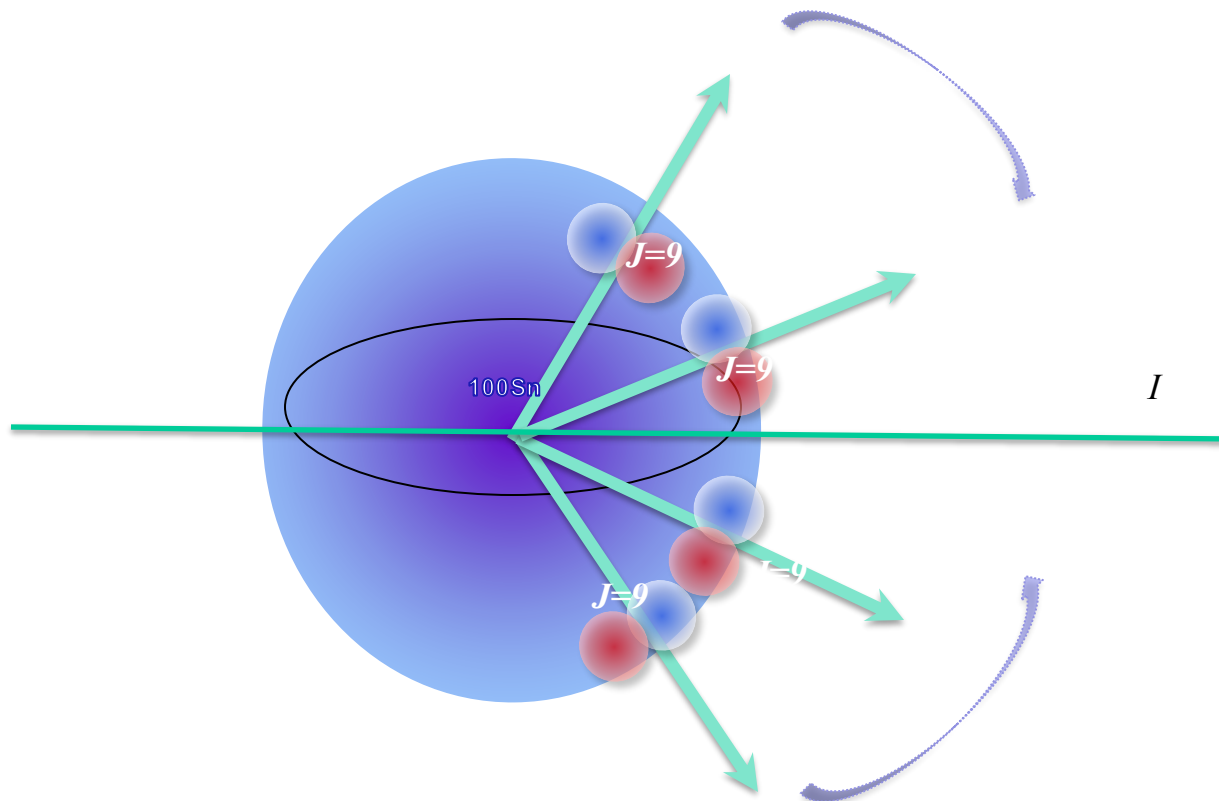
Shell model calculations performed in several model spaces, i.e., 0g9/2, 0g9/2-1p1/2 and 0g9/2-1p1/2-0f5/2-1p3/2 with similar results. Int. parameters determined to reproduce exp energies in $^{94,95}\text{Pd}$, $^{93,94}\text{Rh}$ Taken from Lisetskiy et al, Phys.Rev.C70,044314(2004); B.A Brown priv. comm.



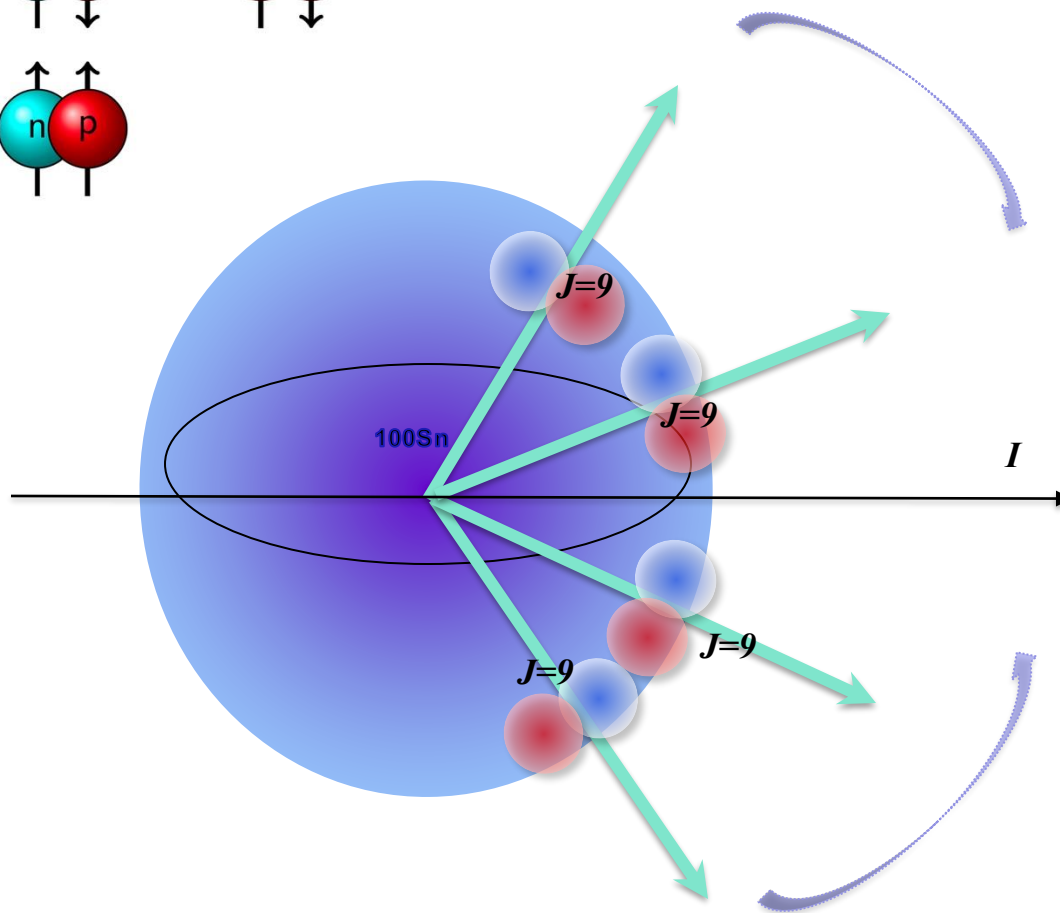
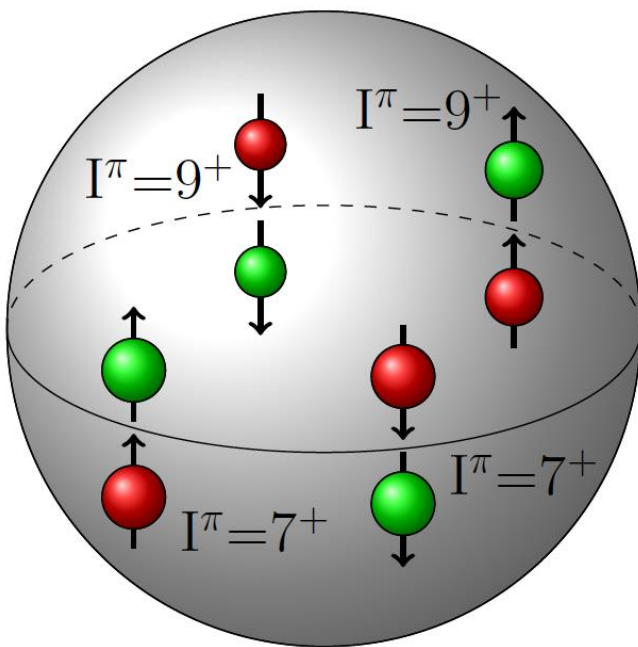
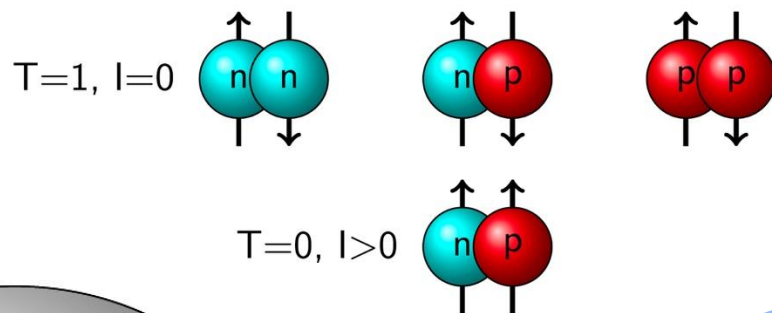
$10^+ \quad \underline{4072}$					$10^+ \quad \underline{4065}$	$10^+ \quad \underline{4052}$	$10^+ \quad \underline{4052}$	$10^+ \quad \underline{4065}$	$10^+ \quad \underline{3862}$			$10^+ \quad \underline{3796}$	$10^+ \quad \underline{4131}$	$10^+ \quad \underline{3784}$
$8^+ \quad \underline{3127}$					$10^+ \quad \underline{3257}$		$10^+ \quad \underline{3257}$			$10^+ \quad \underline{3257}$				
$(6^+) \quad \underline{2536}$	$6^+ \quad \underline{2466}$	$8^+ \quad \underline{2600}$	$8^+ \quad \underline{2749}$	$8^+ \quad \underline{2633}$	$8^+ \quad \underline{2635}$	$8^+ \quad \underline{2588}$	$8^+ \quad \underline{2792}$	$8^+ \quad \underline{2750}$	$8^+ \quad \underline{2704}$	$8^+ \quad \underline{2636}$	$8^+ \quad \underline{2530}$			
$(4^+) \quad \underline{1786}$	$6^+ \quad \underline{2110}$	$4^+ \quad \underline{2079}$	$6^+ \quad \underline{2212}$	$4^+ \quad \underline{2212}$	$6^+ \quad \underline{2223}$	$6^+ \quad \underline{2128}$	$6^+ \quad \underline{2374}$	$6^+ \quad \underline{2330}$	$6^+ \quad \underline{2380}$	$6^+ \quad \underline{2224}$	$6^+ \quad \underline{2099}$			
$(2^+) \quad \underline{874}$	$4^+ \quad \underline{1708}$	$4^+ \quad \underline{1518}$	$2^+ \quad \underline{1417}$	$2^+ \quad \underline{1171}$	$2^+ \quad \underline{1405}$	$2^+ \quad \underline{1199}$	$4^+ \quad \underline{1709}$	$4^+ \quad \underline{1682}$	$4^+ \quad \underline{1720}$	8.2	$2^+ \quad \underline{1460}$	$2^+ \quad \underline{1415}$		
	20							13			7.5			
	$2^+ \quad \underline{878}$	$2^+ \quad \underline{797}$					$2^+ \quad \underline{864}$	$2^+ \quad \underline{861}$	$2^+ \quad \underline{814}$					
	15							11						
$0^+ \quad \underline{0}$	$0^+ \quad \underline{0}$	$0^+ \quad \underline{0}$	$0^+ \quad \underline{0}$	$0^+ \quad \underline{0}$	$0^+ \quad \underline{0}$	$0^+ \quad \underline{0}$	$0^+ \quad \underline{0}$	$0^+ \quad \underline{0}$	$0^+ \quad \underline{0}$	$0^+ \quad \underline{0}$	$0^+ \quad \underline{0}$	$0^+ \quad \underline{0}$	$0^+ \quad \underline{0}$	$0^+ \quad \underline{0}$
^{92}Pd	^{92}Pd	^{92}Pd	^{92}Pd	^{92}Pd	^{94}Pd	^{94}Pd	^{94}Pd	^{94}Pd	^{94}Pd	^{94}Pd	^{96}Pd	^{96}Pd	^{96}Pd	^{96}Pd
exp	SM	T=0	T=1	no np	no np	T=1	T=0	SM	exp		SM	exp		

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

Spherical $N \sim Z$ systems: Generation of angular momentum in the isoscalar
spin-aligned coupling scheme (^{92}Pd)
(not a np pairing **condensate** in the traditional sense)



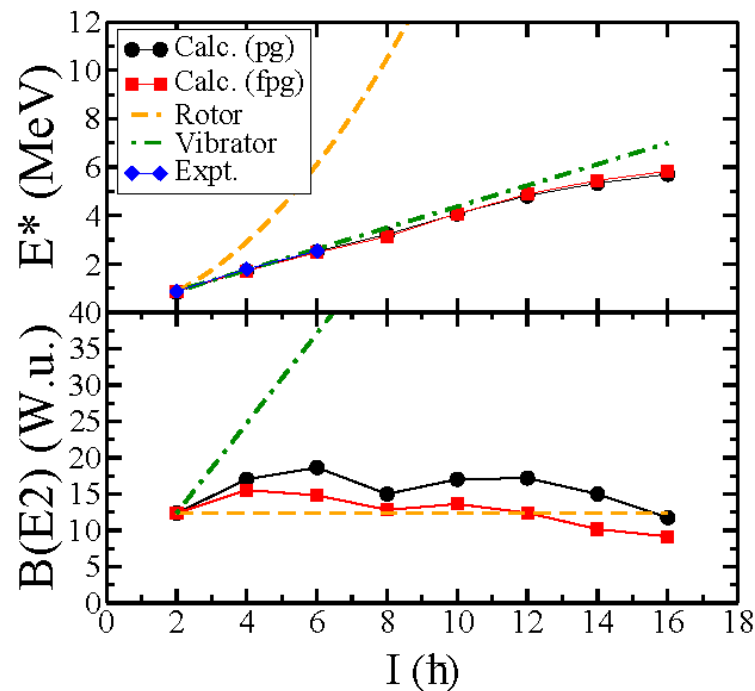
Spherical $N \sim Z$ systems: Generation of angular momentum in the isoscalar spin-aligned coupling scheme (^{92}Pd)



Isoscalar paired phase in ^{92}Pd ?

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

Angular momentum response of spectra and transition rates in the isoscalar spin-aligned coupling scheme (^{92}Pd)



Upper: Shell model spectra of ^{92}Pd

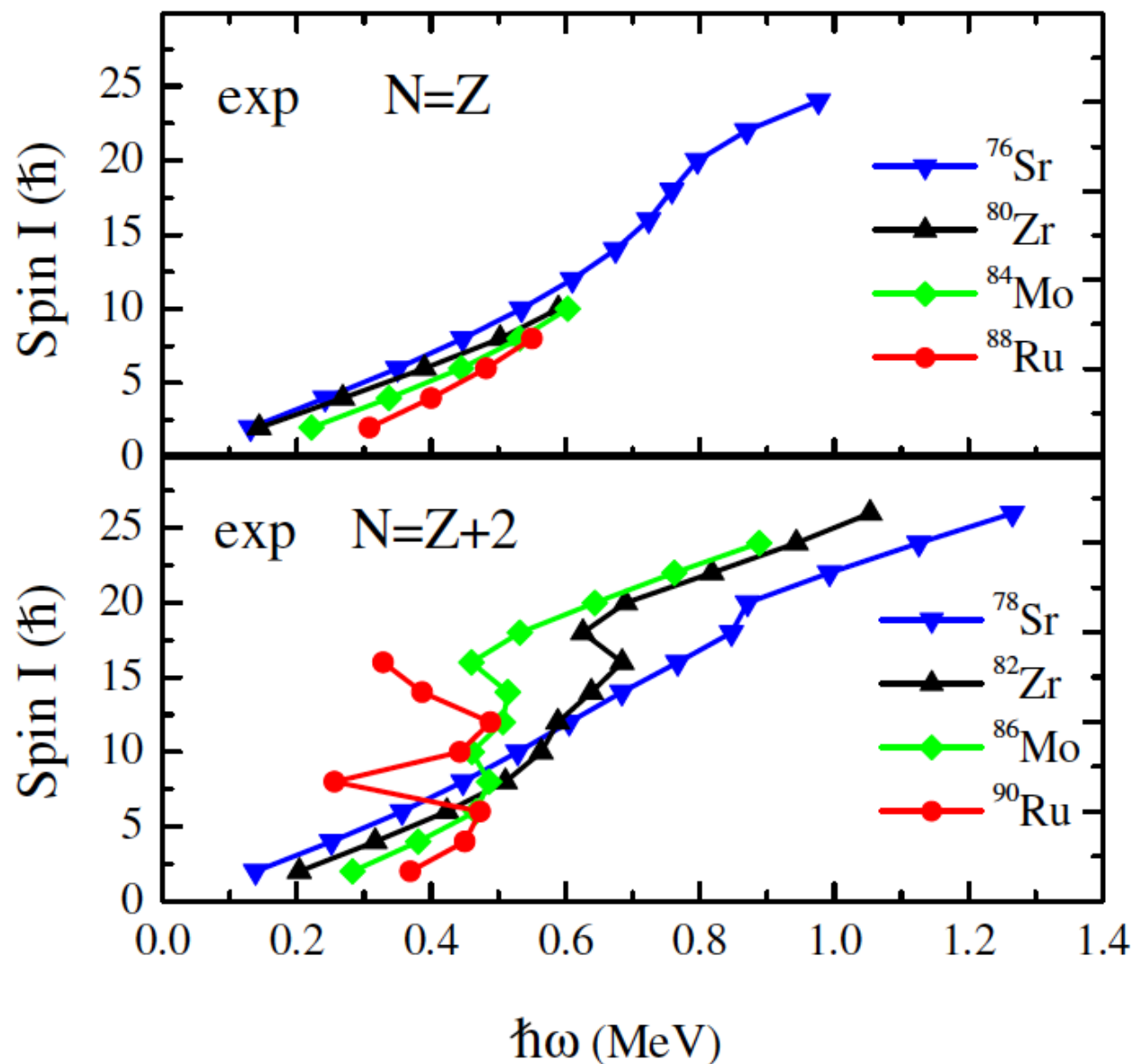
calculated within the $1p_{3/2}0f_{5/2}1p_{1/2}0g_{9/2}$ space [10] (fpg) and the $1p_{1/2}0g_{9/2}$ space (pg).

Lower: $B(E2; I \rightarrow I - 2)$ values in ^{92}Pd calculated within the fpg and pg spaces. The two dashed lines show the predictions of the geometric collective model normalized to the 2^+_1 state

C.Qi, J.Blomqvist, T.Bäck, B. Cederwall, A. Johnson, R. J. Liotta, and R. Wyss,

PRC 84, 021301(R) (2011)

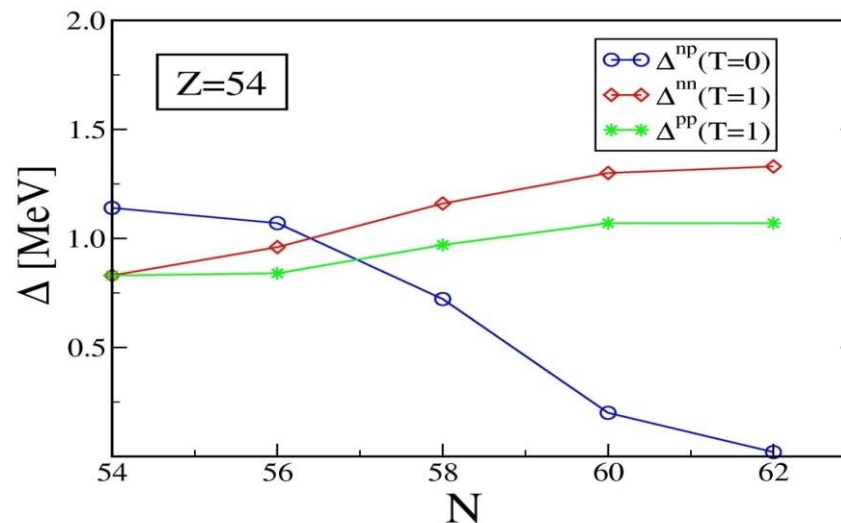
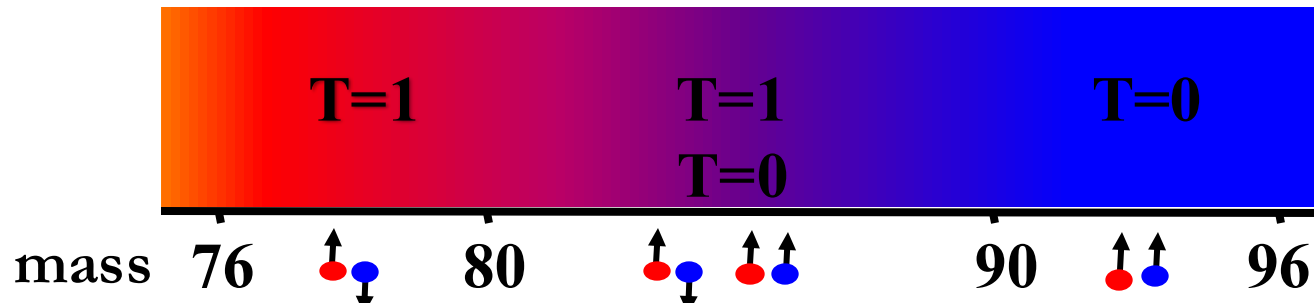
Experimental I vs ω in deformed $N \sim Z$ nuclei



Theory predictions for neutron-proton pairing in the heaviest *deformed* $N \sim Z$ nuclei

A. L. Goodman , PRC 60, 014311 (1999)

Isospin-generalized BCS-HFB predictions for ground states of e-e $A = 76-96$, $N = Z$ nuclei



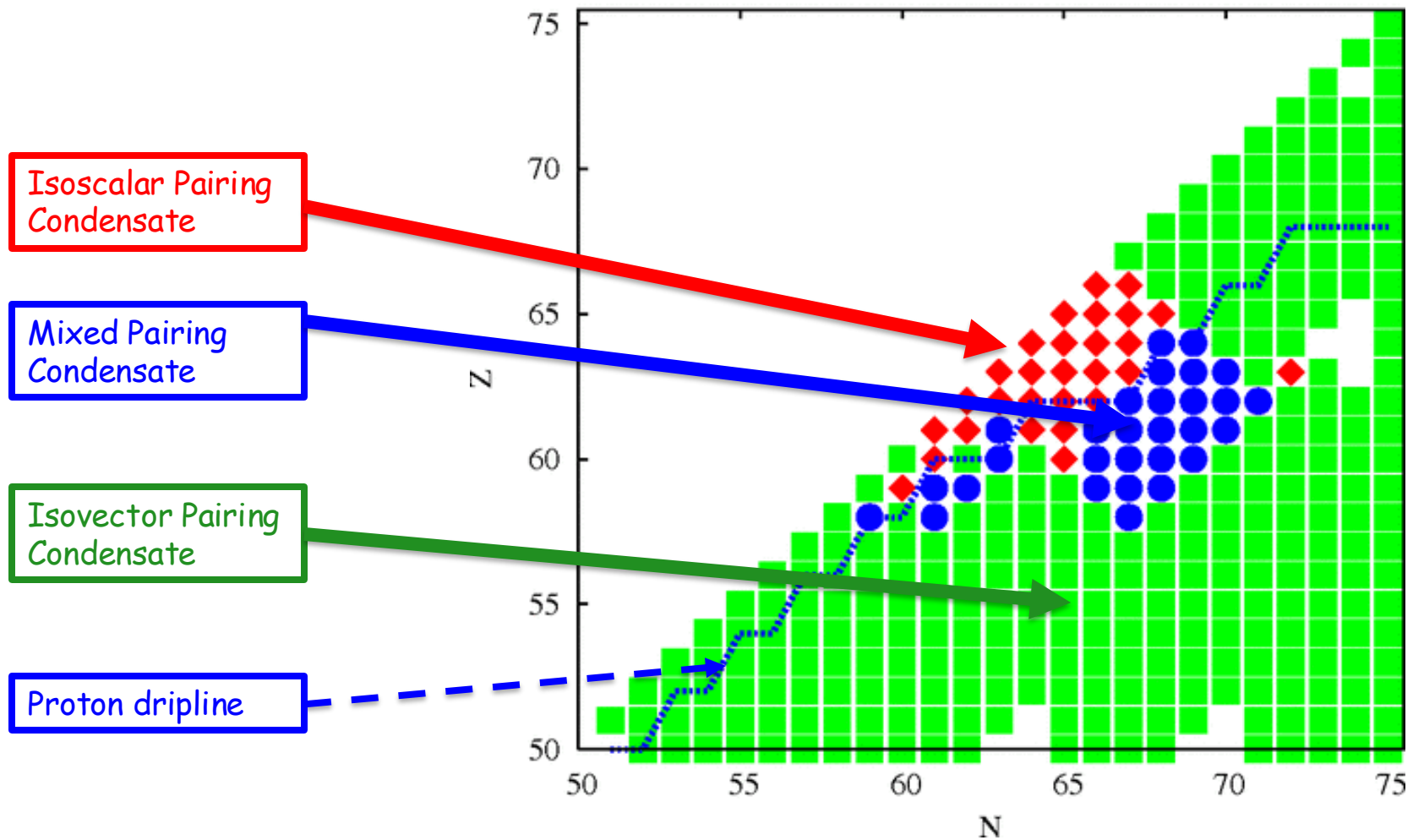
W. Satula, R. Wyss,
Phys. Rev. Lett. Vol. 86,
4488 (2001)

”Isocranking”: The isoscalar (np) pair gap is predicted to increase sharply as $N \rightarrow Z$

“Mixed-Spin Pairing Condensates in Heavy Nuclei”

A. Gezerlis, G. F. Bertsch, and Y. L. Luo

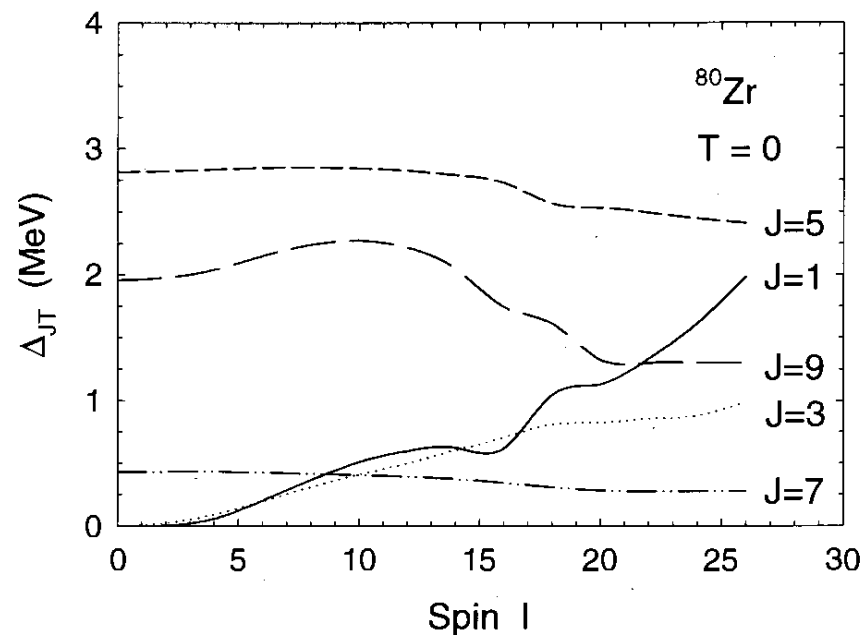
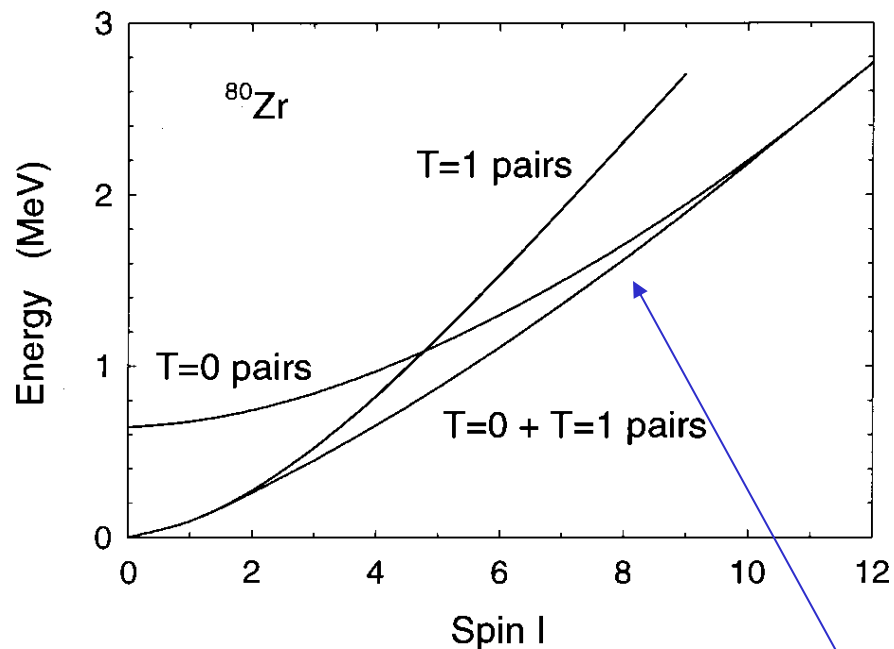
Phys. Rev. Lett. 106, 252502 (2011)



Note: predicted isoscalar pairing condensate coincides with region of maximum collectivity

“ $T = 0$ and $T = 1$ pairing in rotational states of the $N = Z$ nucleus ^{80}Zr ”

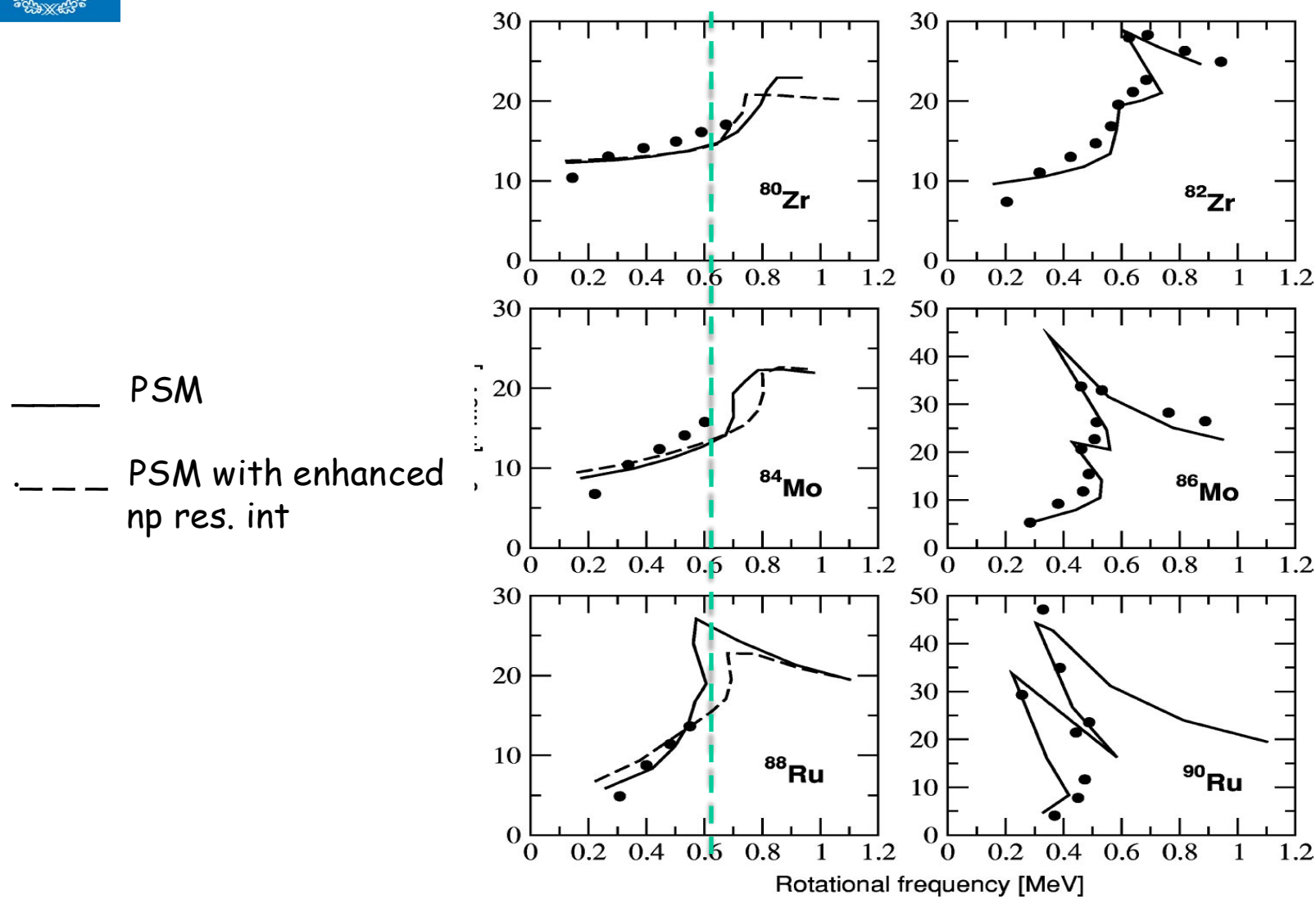
A. L. Goodman, PRC 63, 044325 (2001)



$\Delta =$

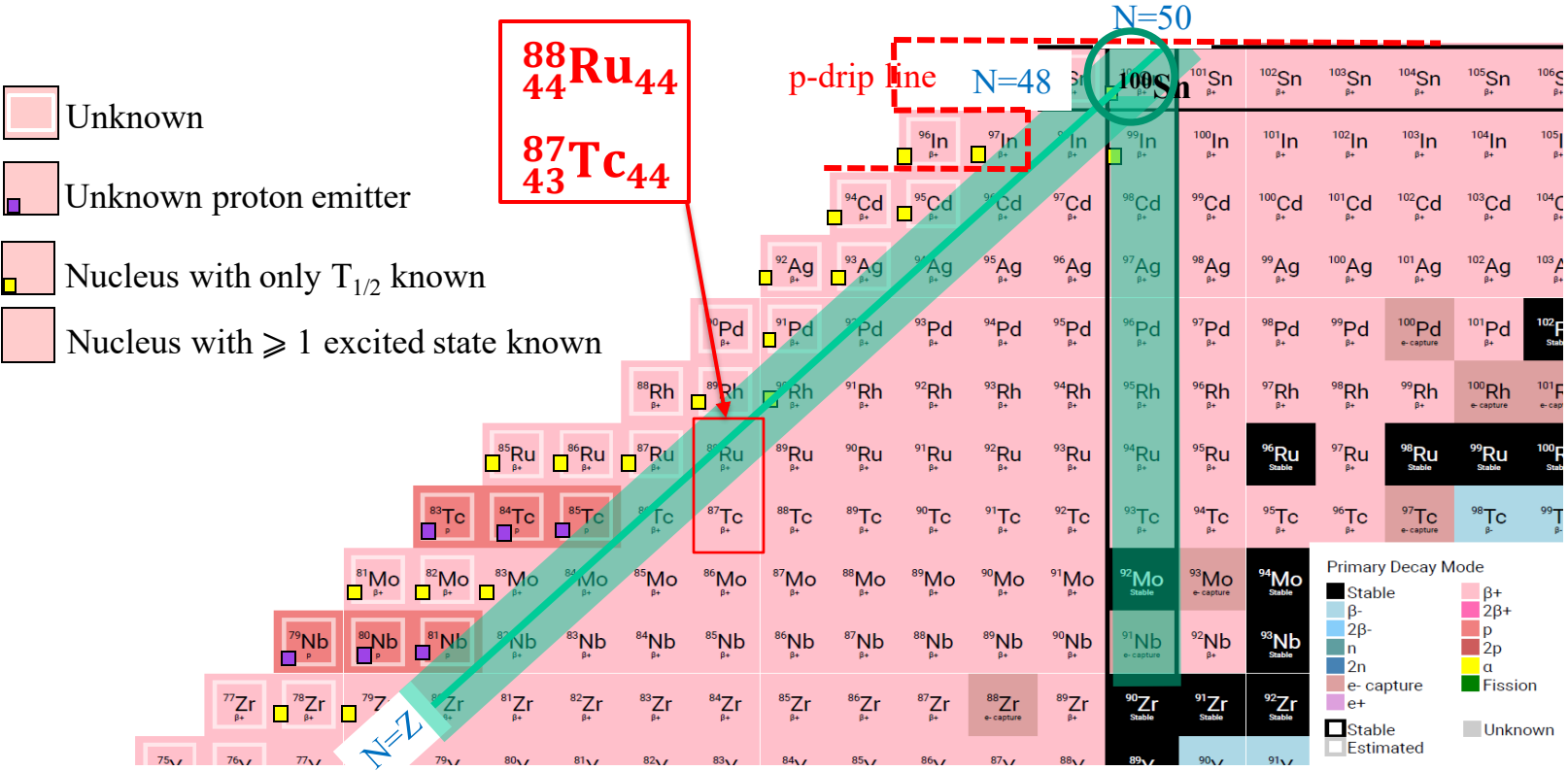
$T=1$ pairing is suppressed by the Coriolis effect in high-spin states
The $T=0$ coupling is less affected by the Coriolis anti-pairing effect and will still be active and could become dominant as I increases

Delayed (or absent) paired ($T=1$) bandcrossings in deformed $N=Z$ nuclei?

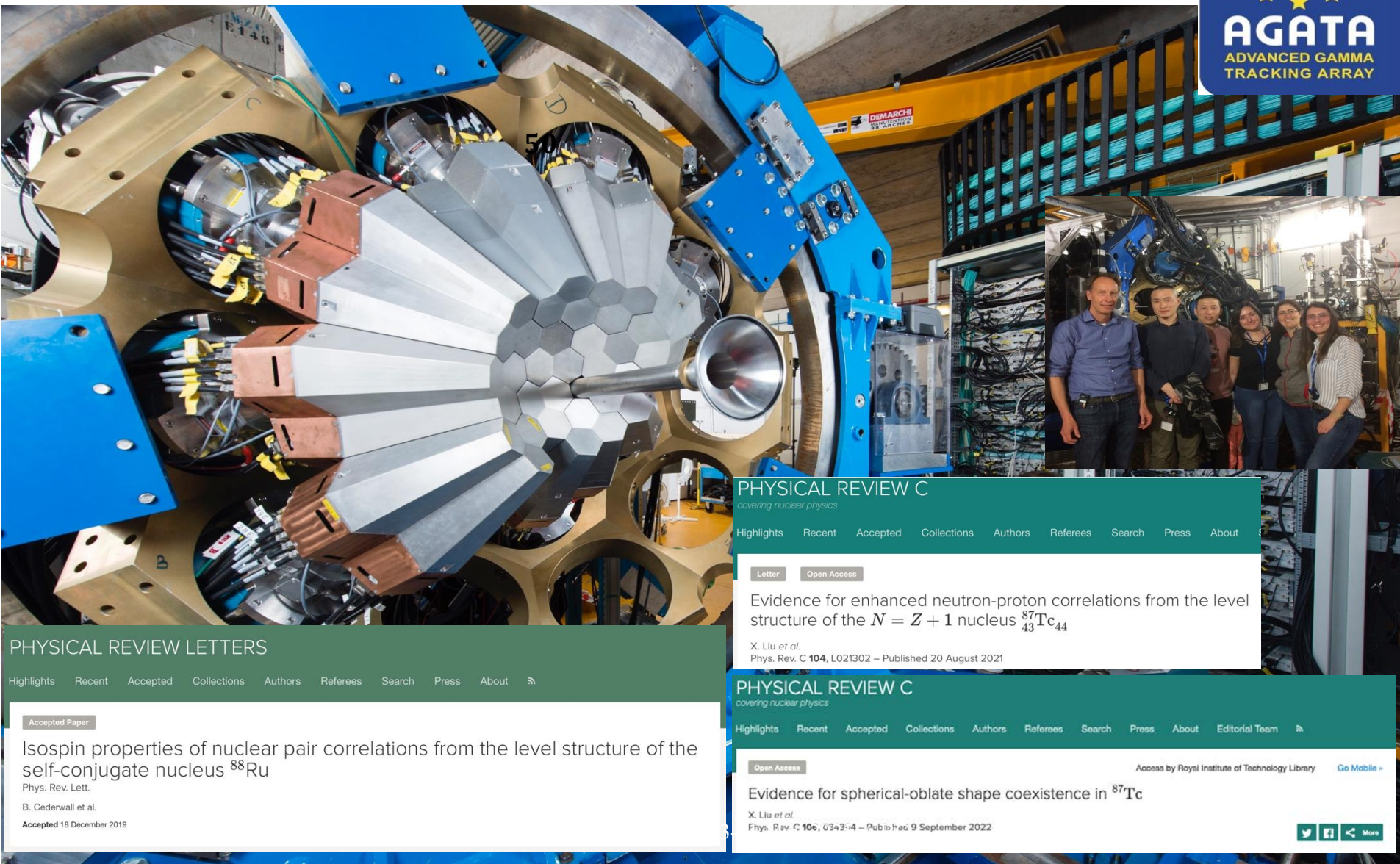


N. Marginenan *et al.*, Phys. Rev. C 65, 051303R (2002)

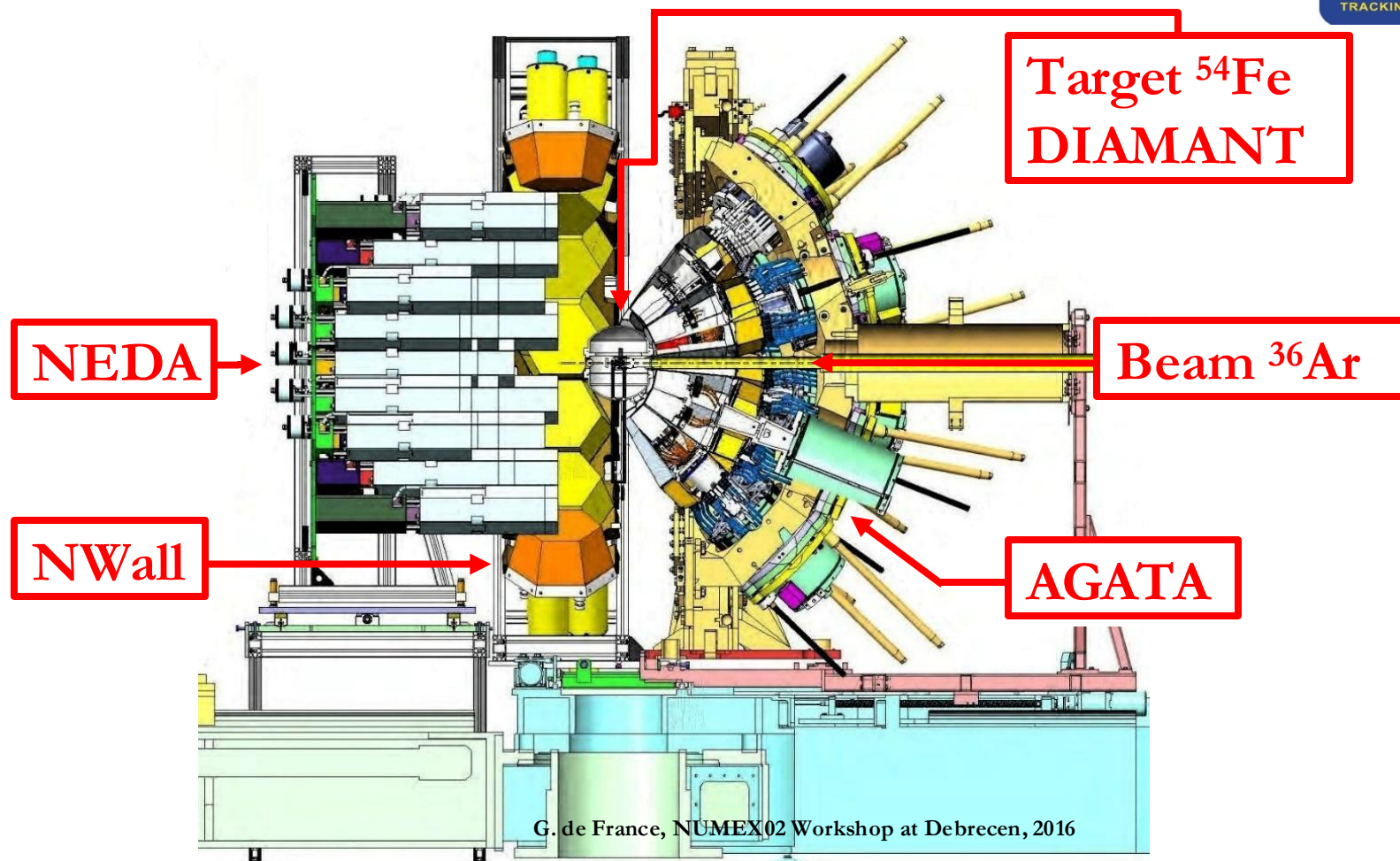
Beam: ^{36}Ar (115 MeV, 5 ~ 10 pA)
 Target: ^{54}Fe (99.58%, 6 mg/cm²)
 Main contaminations: ^{16}O from oxidation, ^{56}Fe (0.40%)
 Fusion-evaporation reactions of interest:
 $^{36}\text{Ar}(^{54}\text{Fe}, 2n)^{88}\text{Ru}$
 $^{36}\text{Ar}(^{54}\text{Fe}, 2n1p)^{87}\text{Tc}$



Experiment

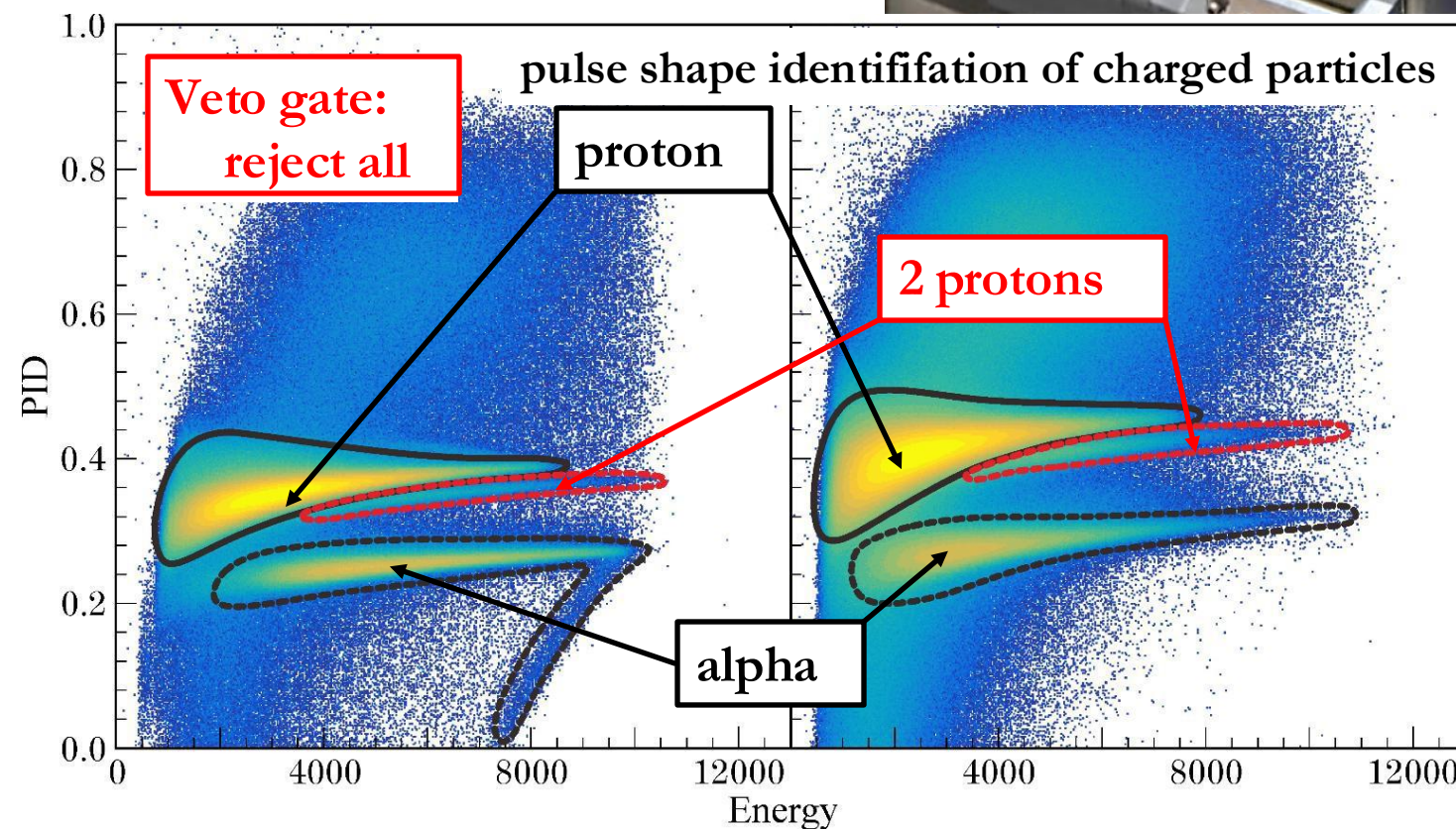
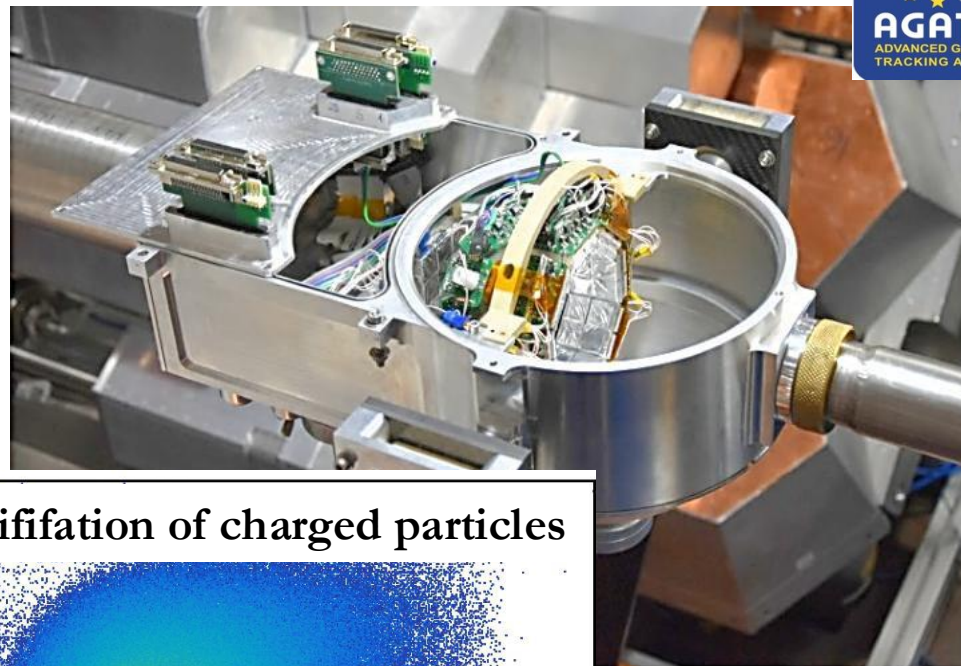


Experimental Setup



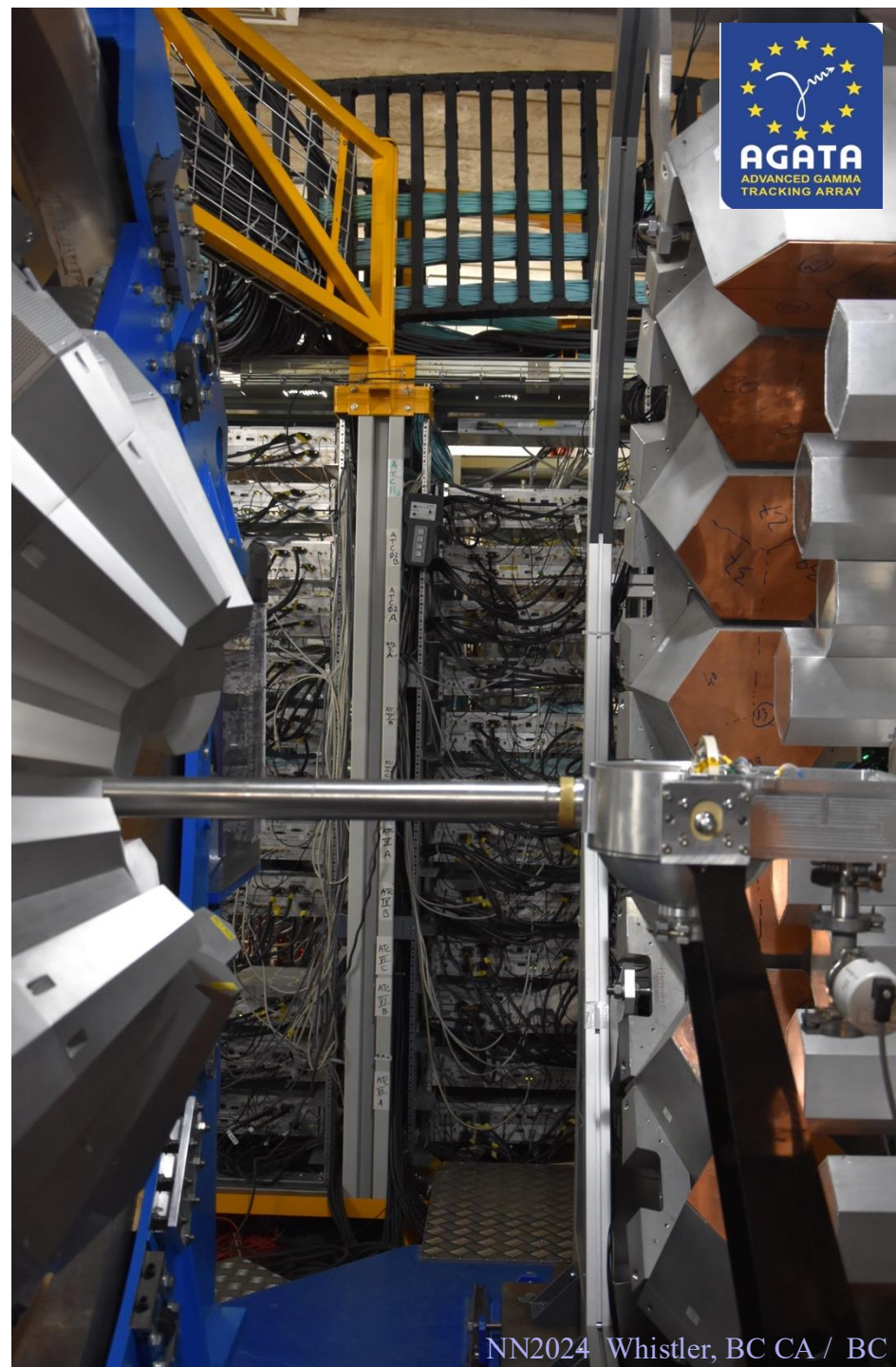
DIAMANT charged particle array

- 60 CsI(Tl) Detectors
- $\sim 2\pi$ Coverage
- E, T, PID
- Slave Mode
- $\epsilon_p \sim 40\%$, $\epsilon_\alpha \sim 25\%$

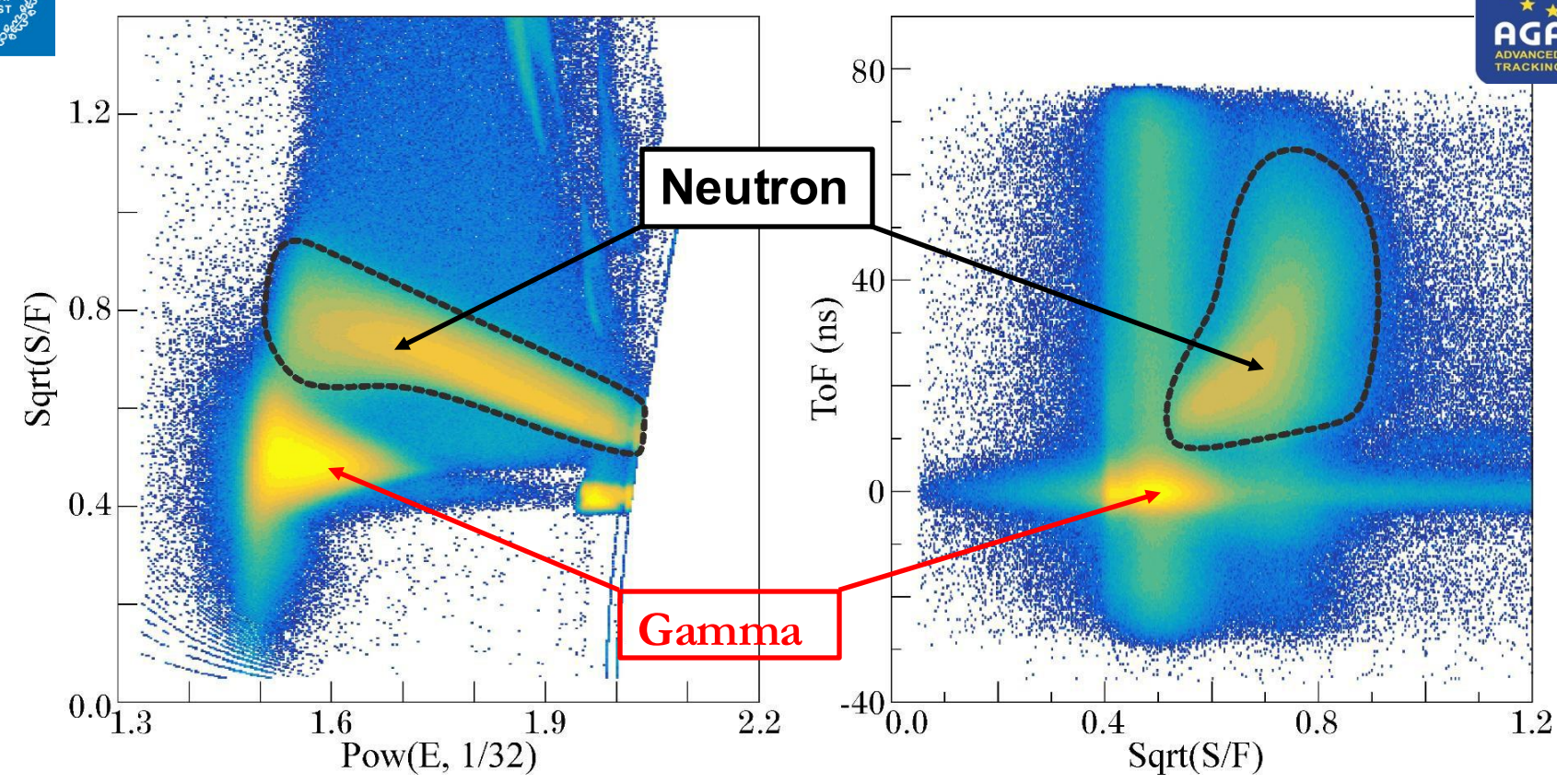


NEDA & NWall

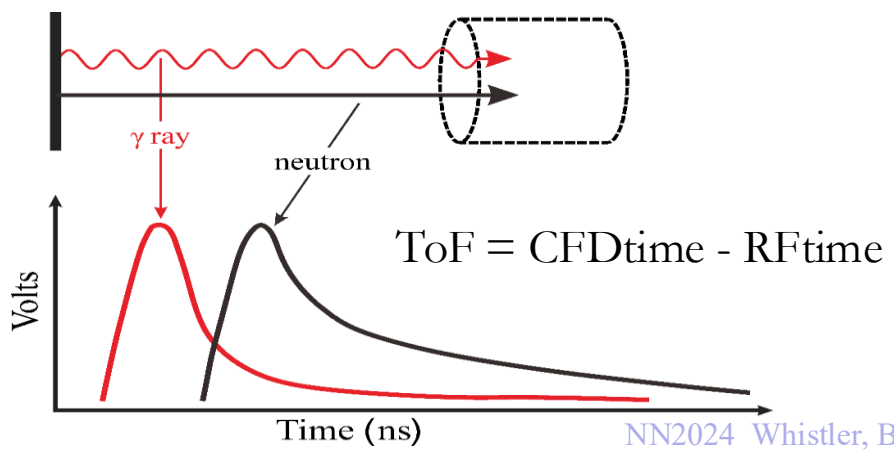
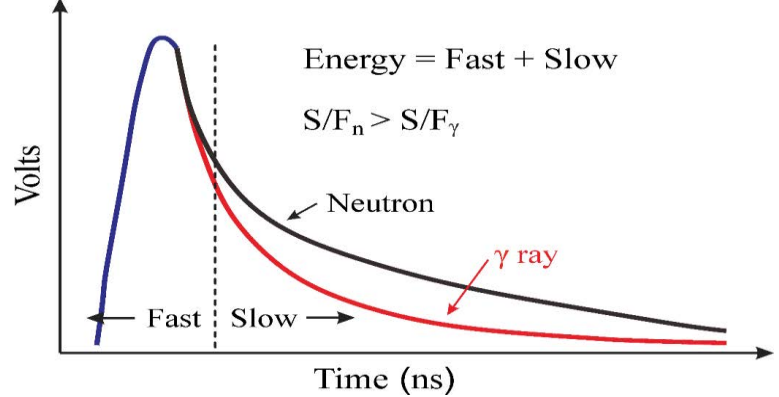
- Organic liquid scintillator cells
- 54 NEDA & 14 NWall
- $\sim 1.6\pi$ Coverage
- Pulse Shape
- Trigger: $\gamma\gamma$ - n (*neutron-like*)



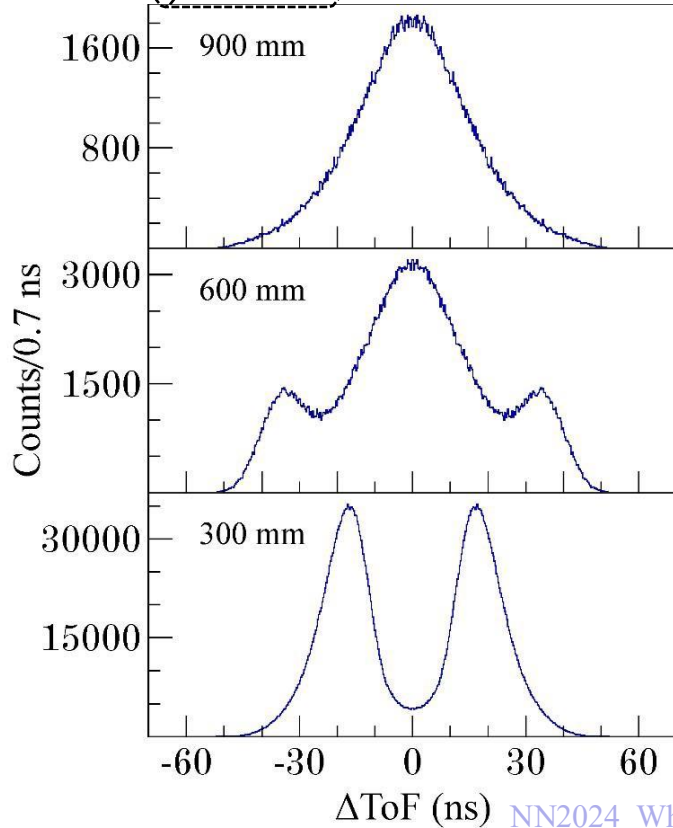
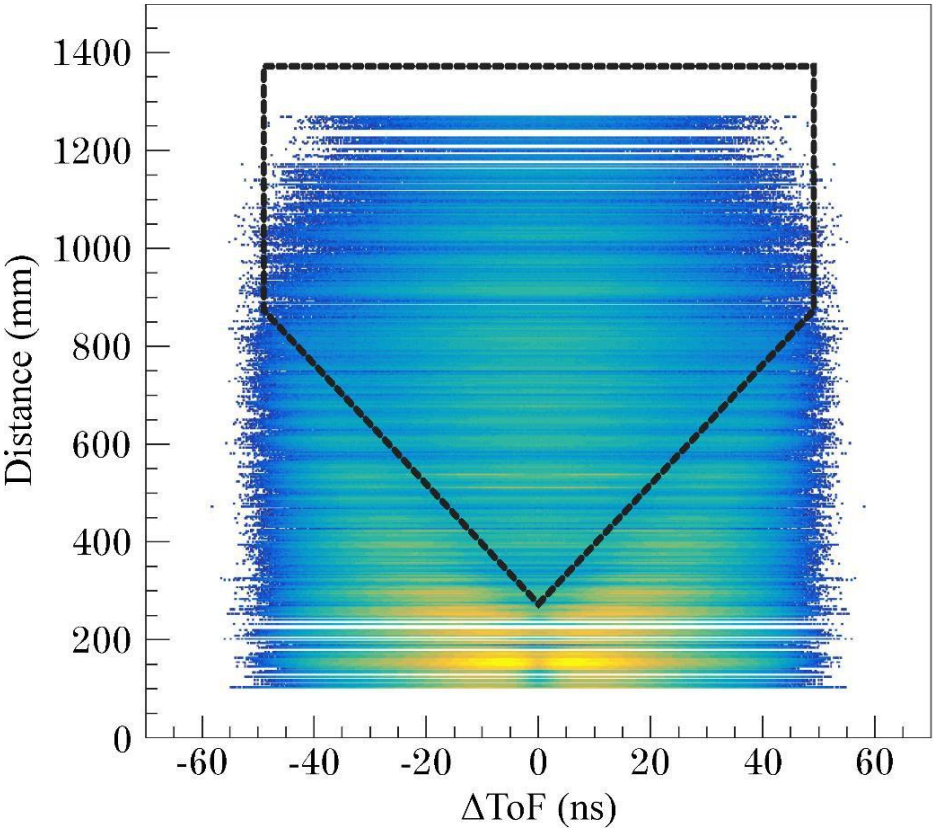
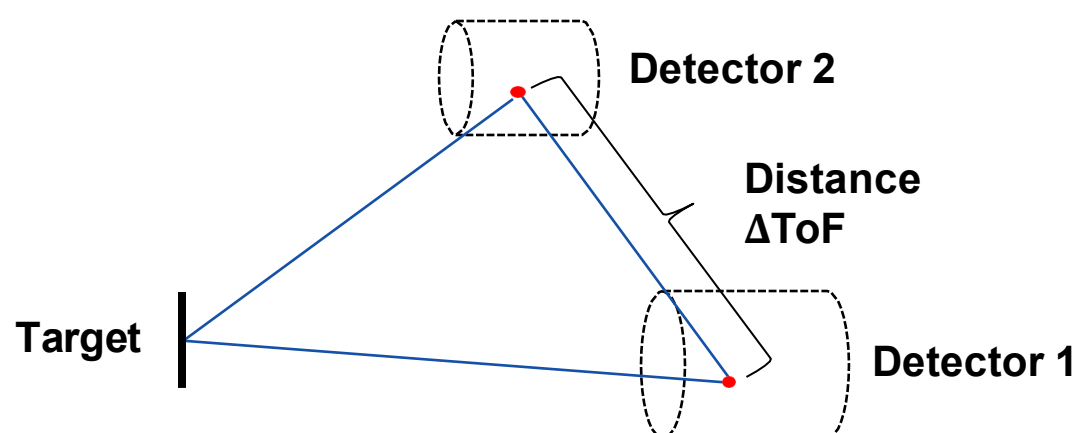
Neutron- γ Discrimination

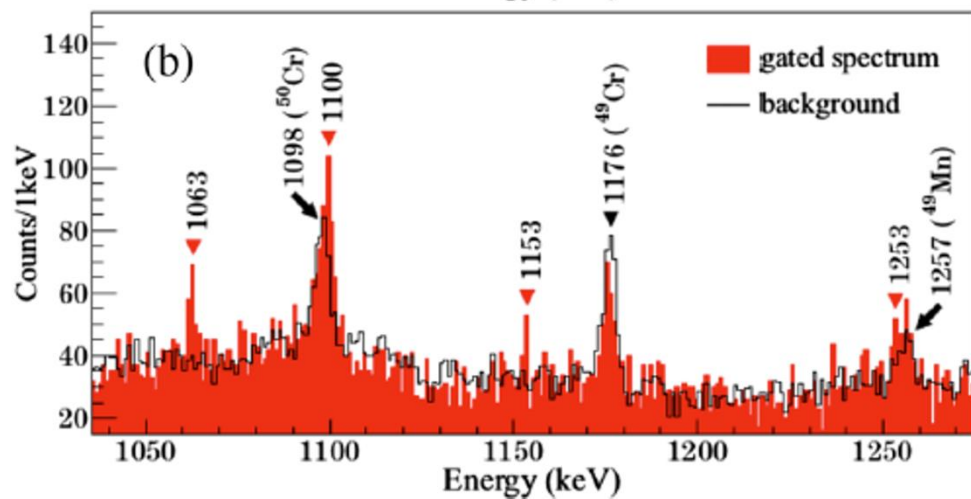
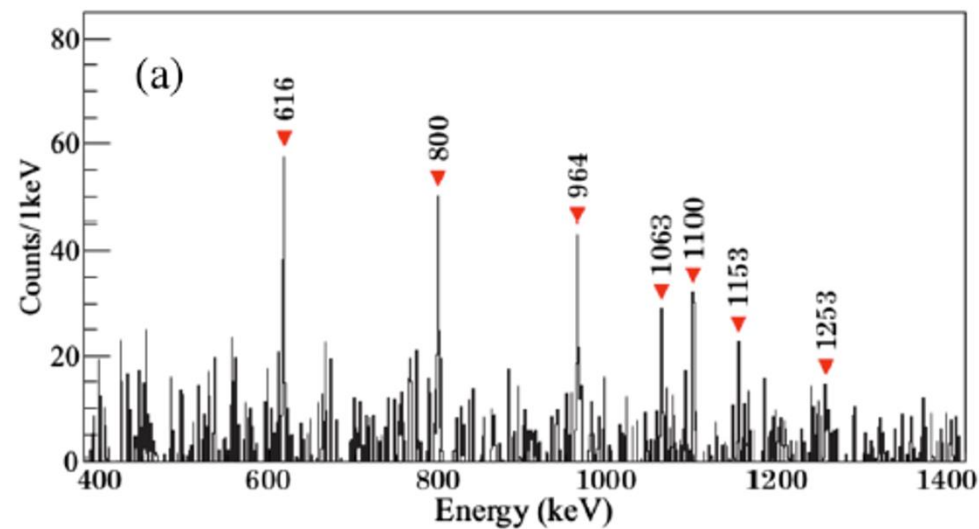


PSD: Charge Comparison Method

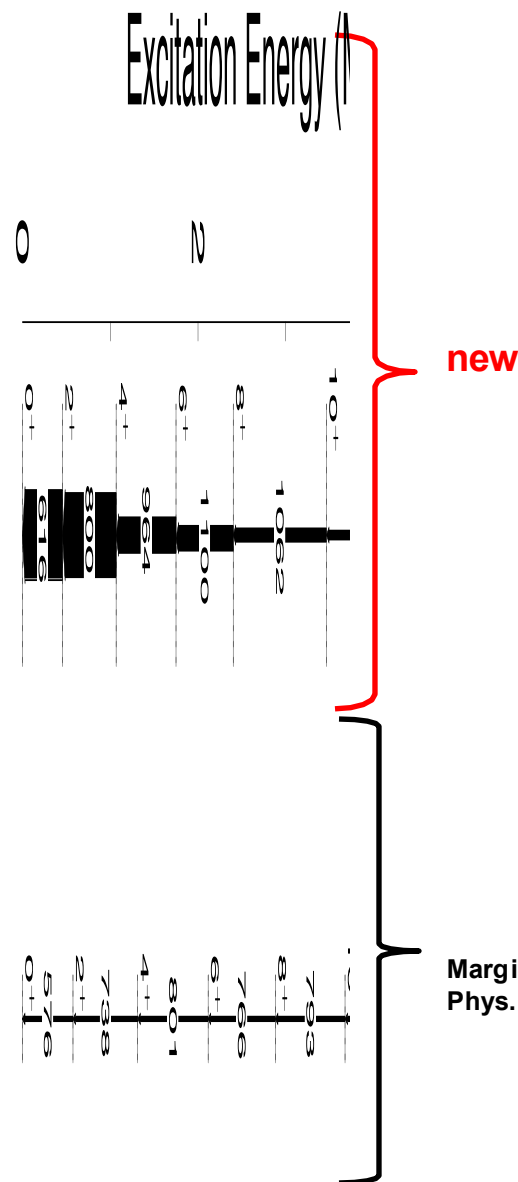


Neutron scatter rejection critical for identifying weak 2n- and 3n-emission reaction channels

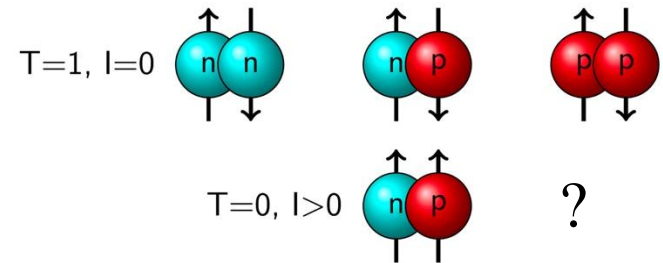
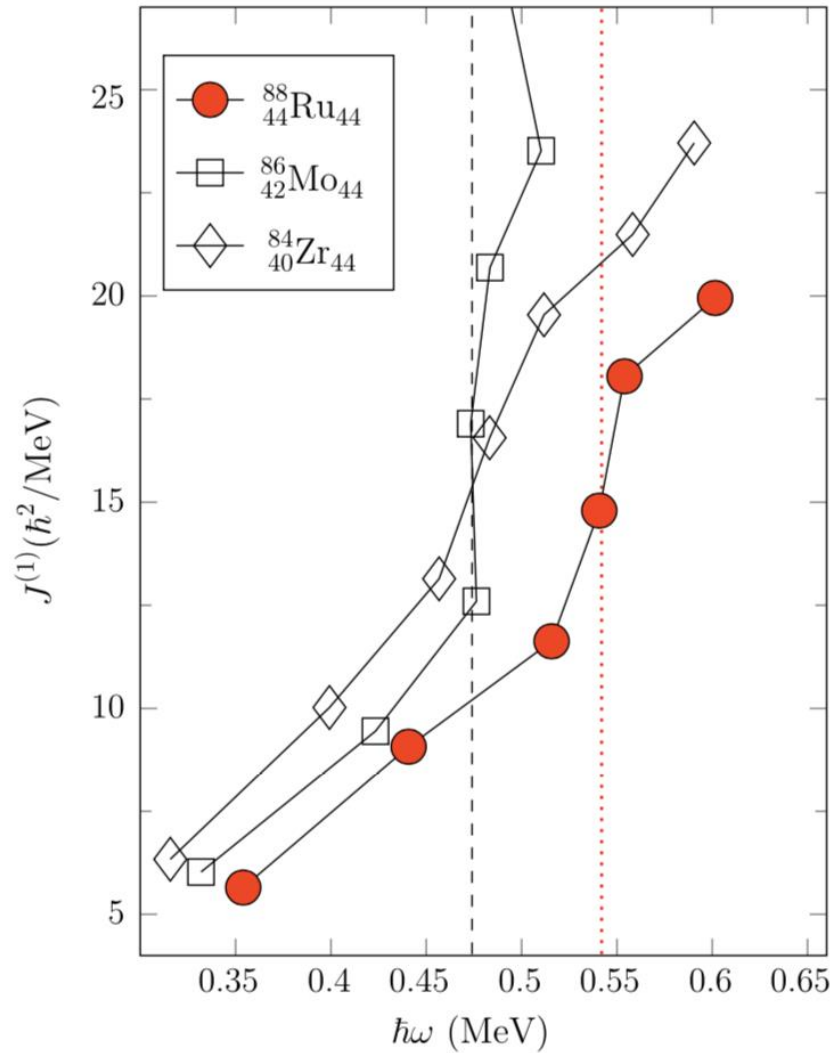




Taken from B. Cederwall, X Liu et al, PRL 124 062501 (2020)



N=44 isotones



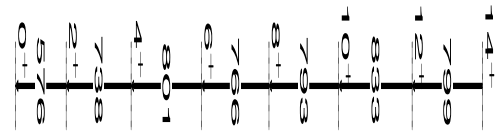
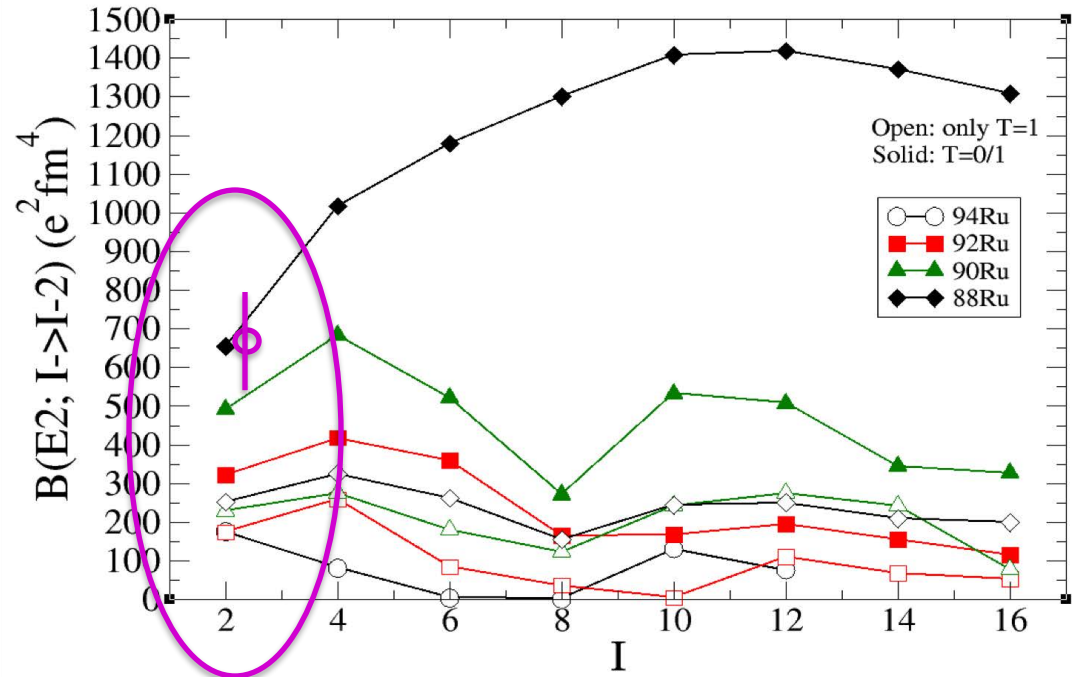
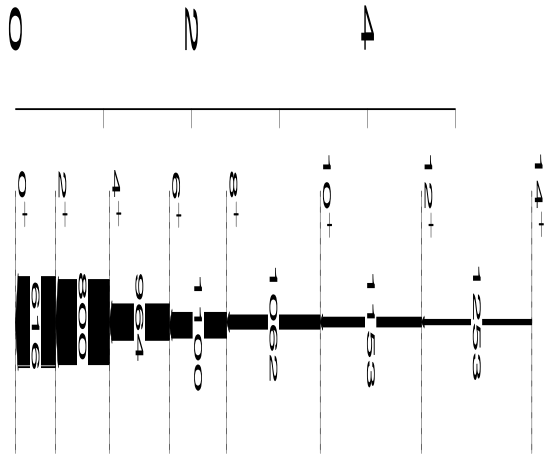
LSSM calculations: $T=0$ correlations drive collectivity, but how?

- Is this an effect of isoscalar (quadrupole) pairing?

Excitation Energy (MeV)

$B(E2)$ measurements are critical

New results from GRETINA@FRIB (M. Bentley et al., in preparation)



JUN45 interaction, fpg model space effective charges $e_p = 1.5e$ and $e_n = 0.8e$
Chong Qi, priv. comm

^{88}Ru SM

LSSM calculations: JUN45 with (slightly) adjusted QQnp

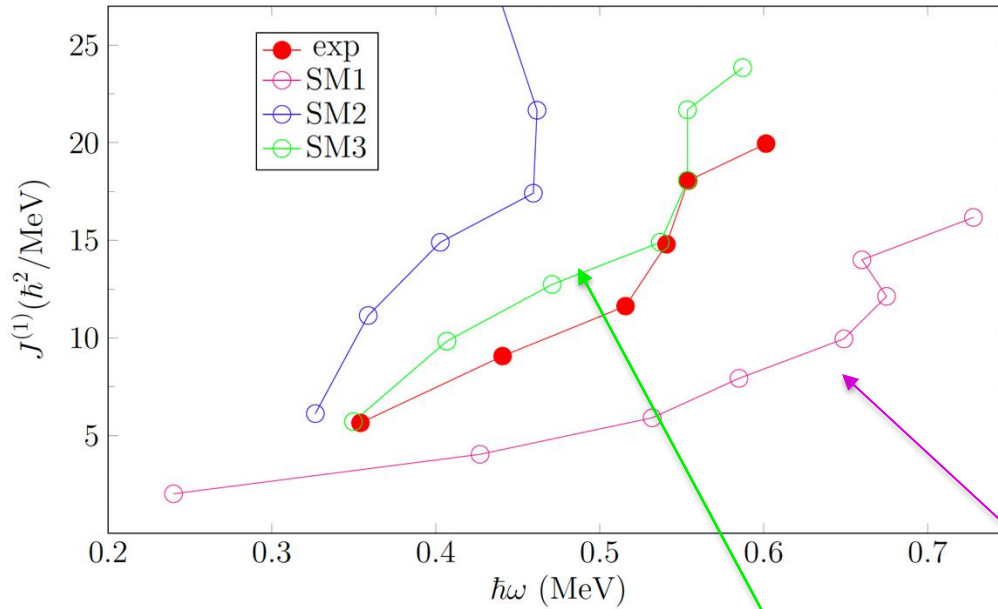


FIG. 2: (Color online) Experimental and theoretical values (filled and open symbols, respectively) for the kinematical moment of inertia ($J^{(1)}$) of the ground-state band in $^{88}\text{Ru}_{44}$. The experimental data is from this work and the theoretical predictions are taken from the work of Kaneko et al. [29] (SM1) and LSSM calculations performed in this work (SM2 and SM3). See text for details.

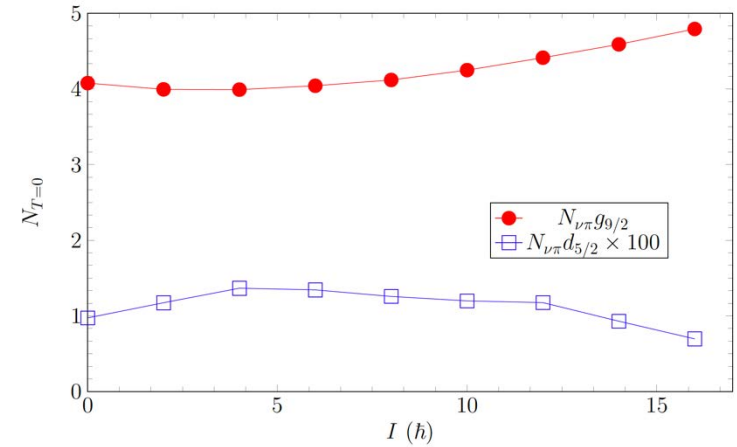
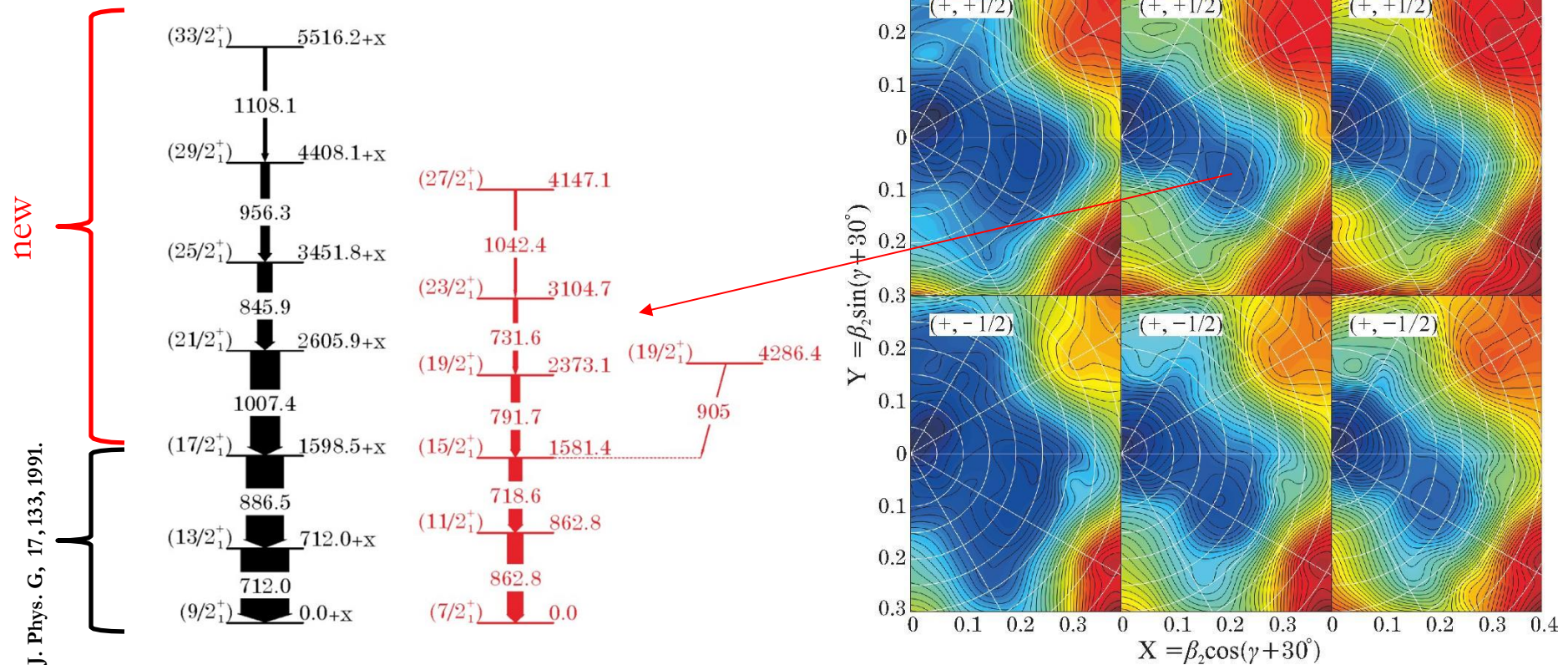


FIG. 3: (Color online) Calculated numbers of isoscalar np pairs in the $g_{9/2}$ and $d_{5/2}$ orbitals for $^{88}\text{Ru}_{44}$ as a function of total angular momentum. See text for details.

PMMU

JUN45 with QQnp \rightarrow 1.09 x QQnp_0

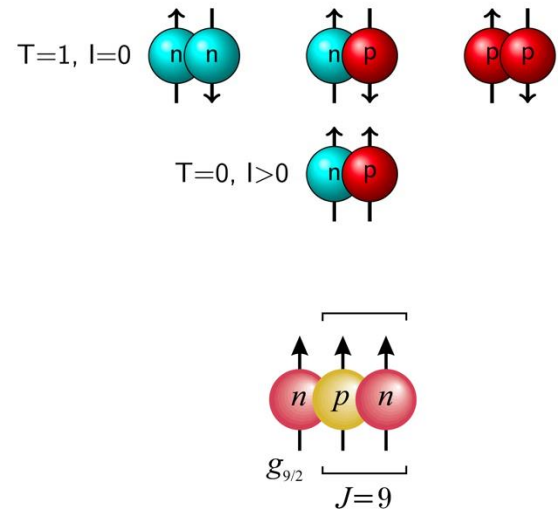
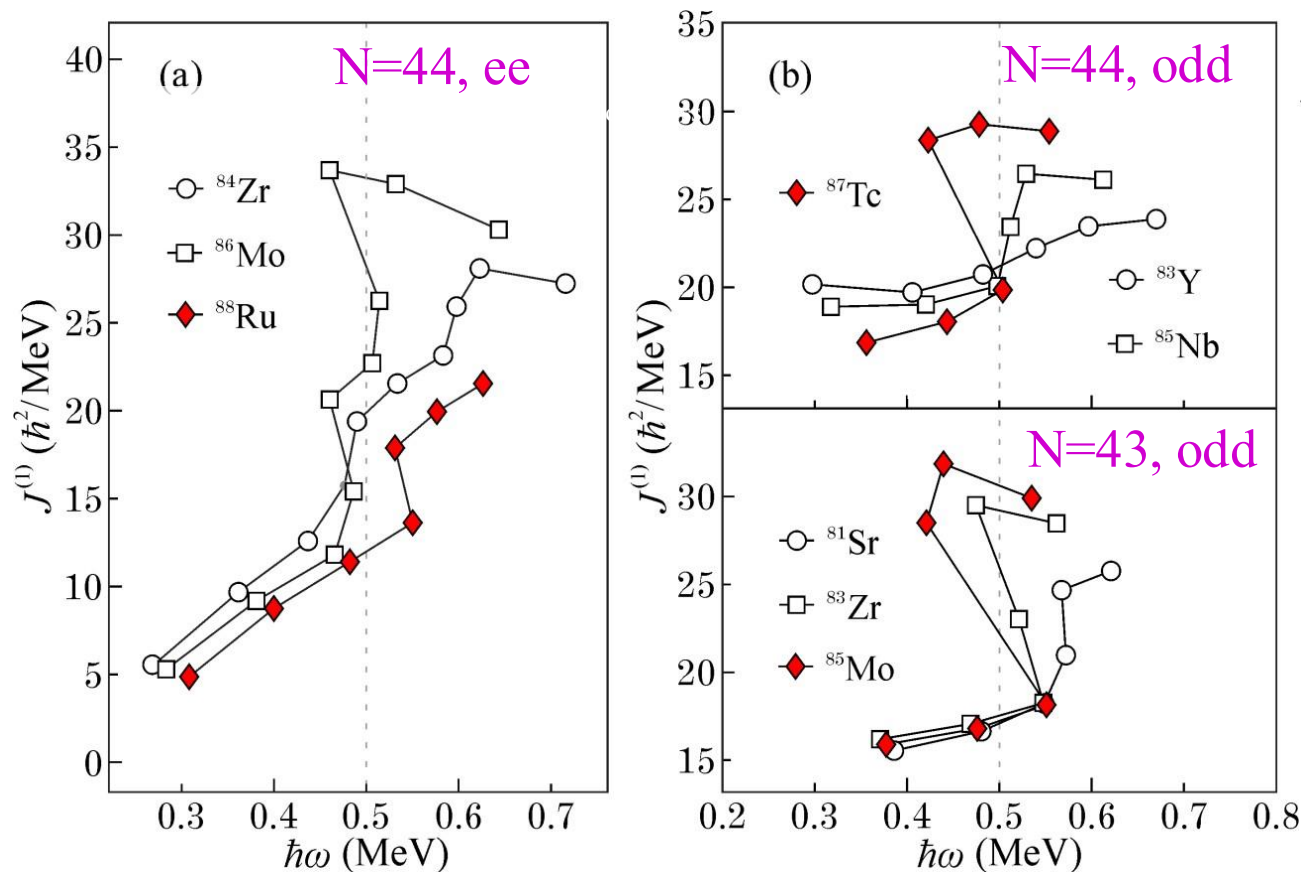
Extension of the ground state ($\pi g_{9/2}$) band and new oblate band in the $T_Z=1/2$ nucleus ^{87}Tc



X. Liu, B. Cederwall, Ö. Aktas et al, PRC 104 L021302 (2021)

X. Liu, B. Cederwall, Ö. Aktas et al, PRC 106 034304 (2022)

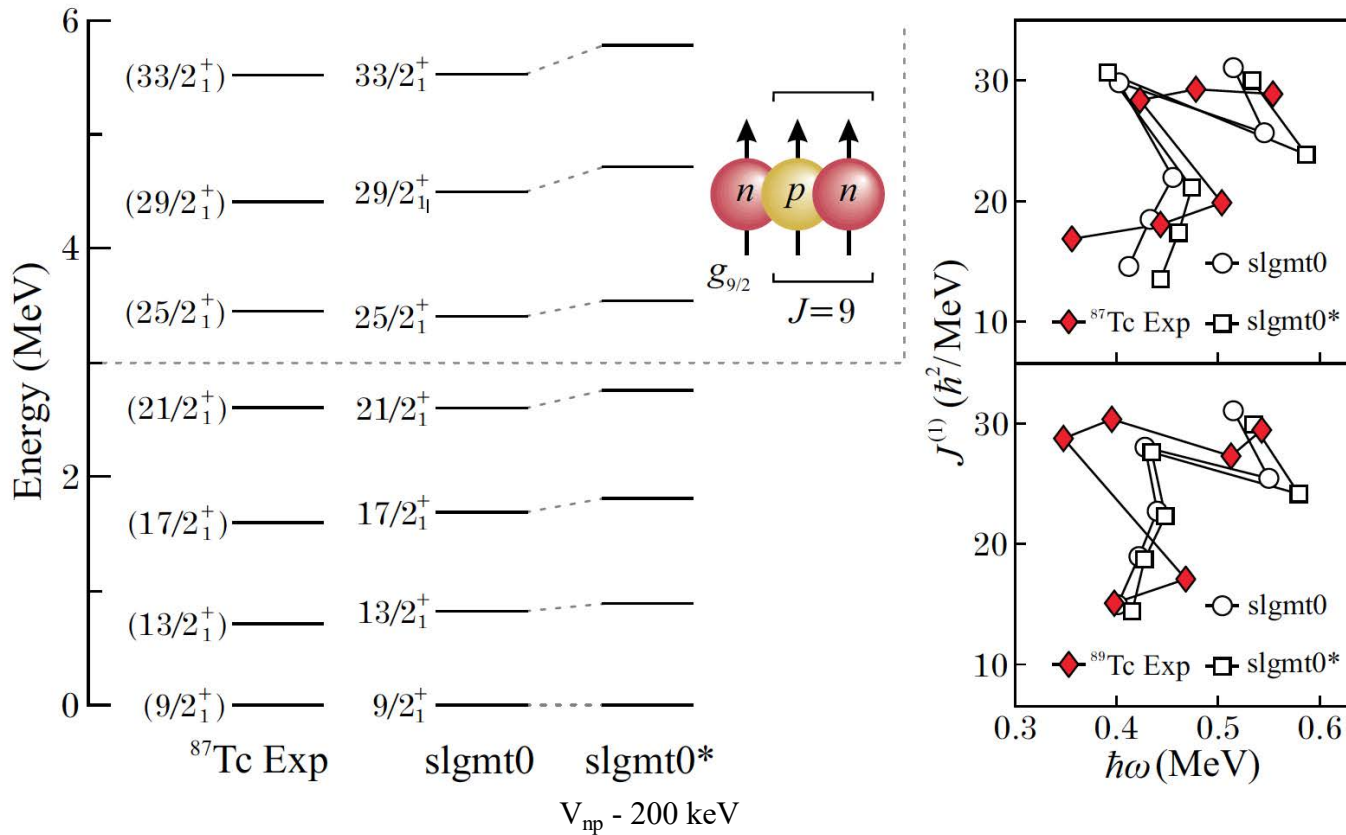
Pairing isospin modes in deformed $N \sim Z$ nuclei – odd-even vs even-even



B. Cederwall et al, PRL 124 062501 (2020)

X. Liu et al, PRC 104 L021302 (2021)

Shell model calculation for ^{87}Tc ($T_Z=1/2$) – effect of spin-aligned np pairs (V_{np})



X. Liu et al, PRC 104 L021302 (2021)

F. J. D. Serduke, R. D. Lawson, and D. H. Gloeckner, Nucl. Phys. A 256, 45 (1976)

Odd-mass $N \sim Z$ ($T_Z=1/2$) nuclei:

- Odd valence particle contributes constructively to isoscalar np pairing correlations "spin-dependent effective 3-N" interaction as opposed to "blocking" effect in pure isovector case?
- Increase of structural difference between 1qp and 3qp configuration reduces interaction strength in the band crossing?


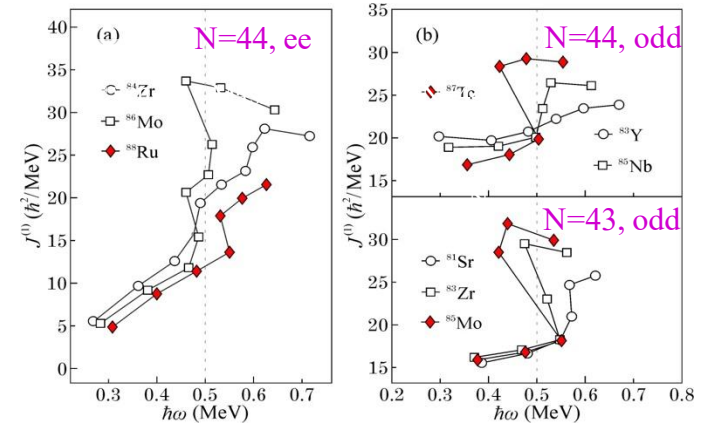
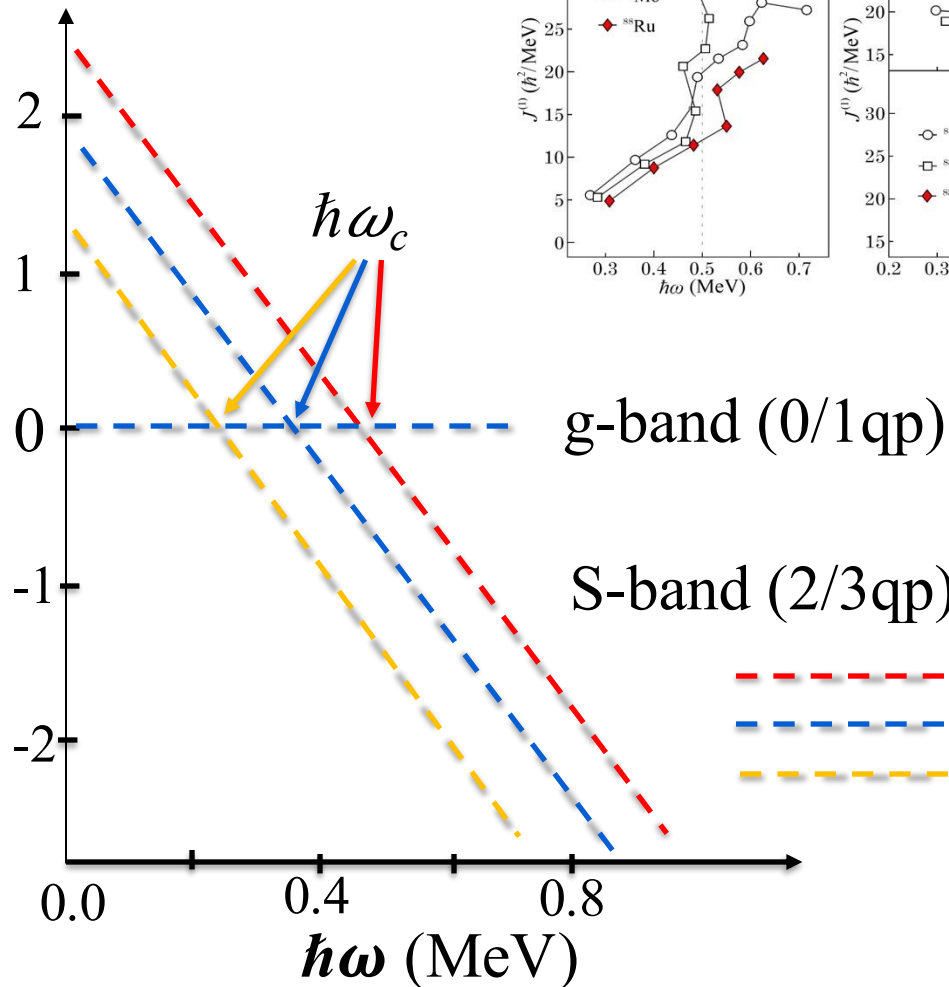
Influence of pairing isospin modes in deformed $N \sim Z$

– odd-A vs even-even cases (naïve picture)

$$h' = h_0 + h_{pair} - \omega j_x$$

e' (MeV)

iv pairing gap "2Δ"

- $iv + is$ pairing, ee
- iv pairing
- $iv + is$ pairing, odd

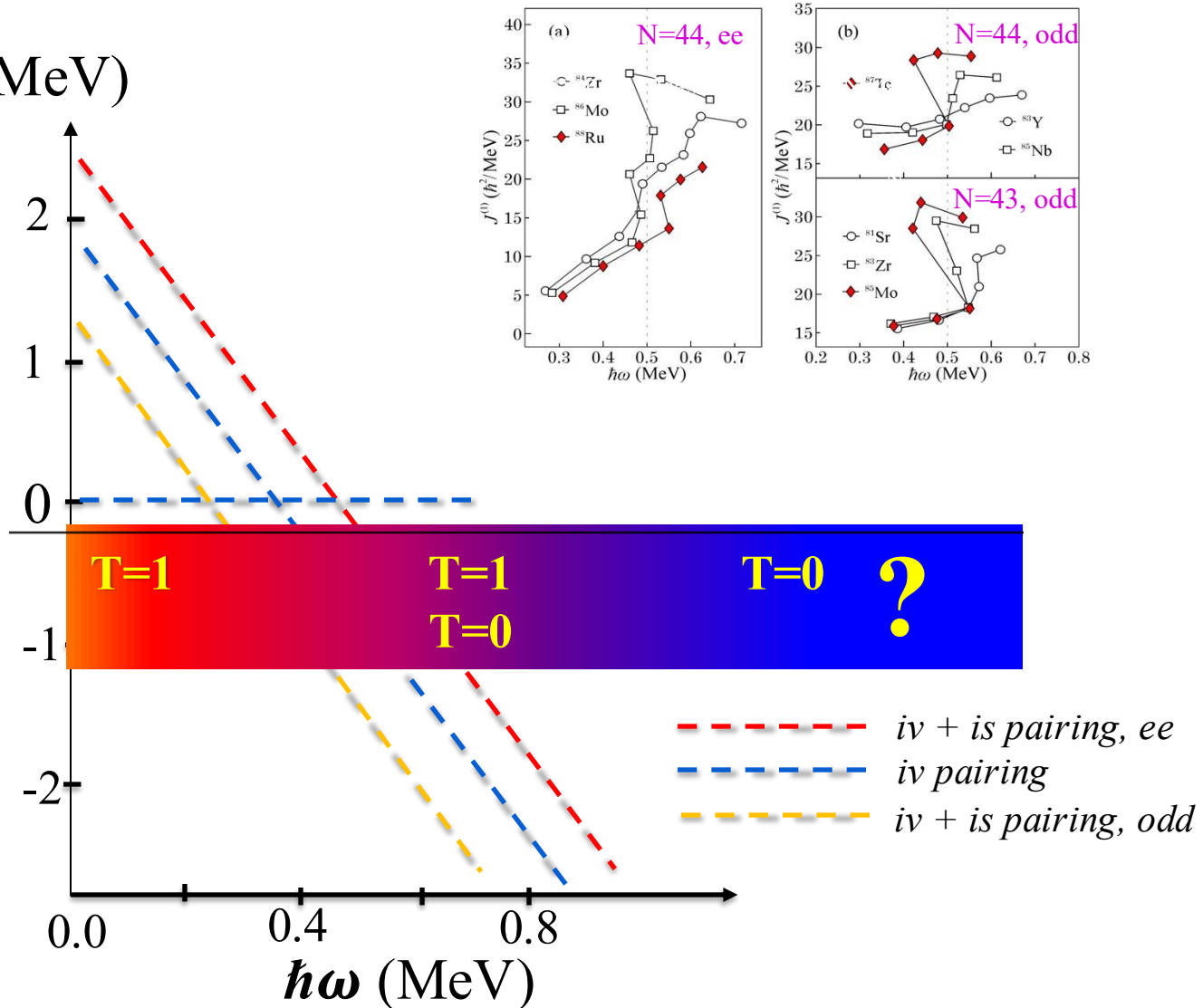
Influence of pairing isospin modes in deformed $N \sim Z$

– odd-A vs even-even cases (naïve picture)

$$h' = h_0 + h_{pair} - \omega j_x$$

e' (MeV)

iv pairing gap "2Δ"



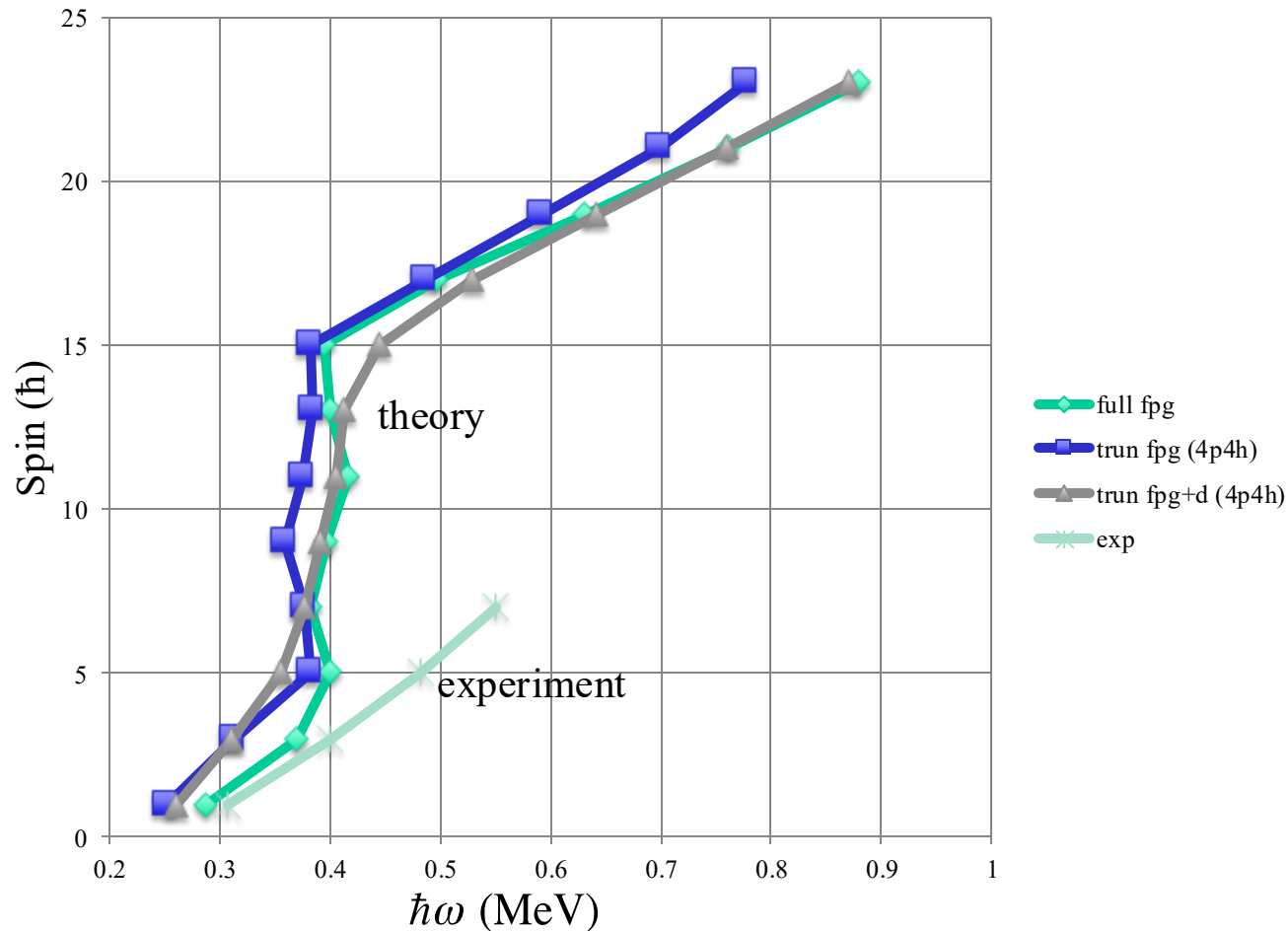
Summary

- Intermediate-angular momentum states in the heaviest deformed $N \sim Z$ nuclei ^{88}Ru and ^{87}Tc have been observed with AGATA + ancillary detectors (NEDA/NWALL, DIAMANT)
- In ^{88}Ru , the rotational frequency for the configuration change between the ground-state and qp-aligned structures indicates a "delay" wrt standard calculations and expt data in neighboring $T_z=1$ isotones, in agreement with theoretical predictions for enhanced isoscalar np correlations.
- For, the $T_z=1/2$ isotone, ^{87}Tc , we observe an earlier band crossing frequency compared with the neighboring $N=44$ and $N=43$ odd-mass nuclei for the yrast band built on the $\pi g_{9/2}$ ground state
- \therefore IV band crossing frequencies show opposite behavior as $T_z \rightarrow 0$ for ee and oe systems
- a new signature for enhanced IS pair correlations in these $N \sim Z$ systems?

Thanks to the AGATA collaboration, GANIL, NEDA, DIAMANT teams!

Predictions for ^{88}Ru

"Standard" SM calculations* for ^{88}Ru predict similar "alignment" of angular momentum



* F.G. Moradi et al., Phys. Rev. C89, 014301 (2014)

LSSM predictions for ^{88}Ru with interaction including an explicit pairing term (PMMU)

PMMU: $H = H_o + H_p + H_M + H_m$:

H_o = s.p, H_p = pairing

H_M = multipole, contains QQ + OO components

H_m = monopole term

$$H = H_0 + H_P + H_M + H_m^{MU},$$

$$H_0 = \sum_{\alpha} \epsilon_{\alpha} c_{\alpha}^{\dagger} c_{\alpha}, \quad H_P = - \sum_{J=0,2} \frac{1}{2} g_J \sum_{M\kappa} P_{JM1\kappa}^{\dagger} P_{JM1\kappa}$$

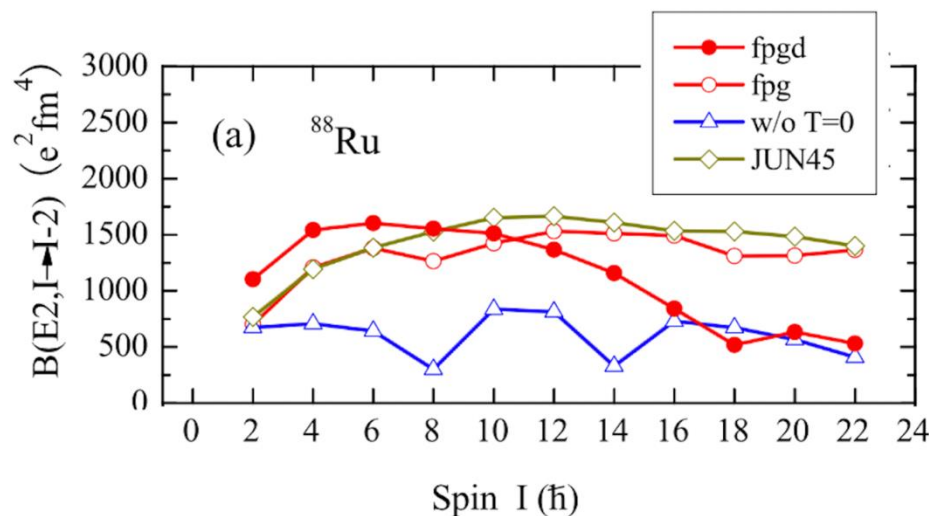
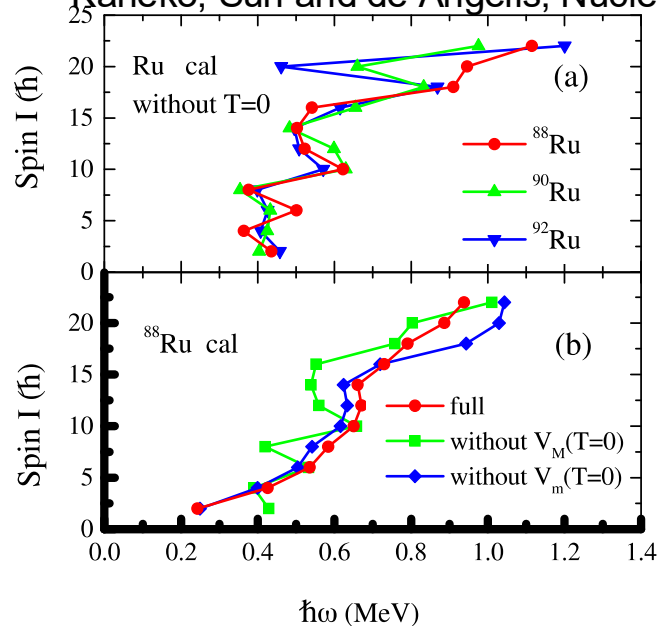
$$H_M = -\frac{1}{2} \chi_2 \sum_M : Q_{2M}^{\dagger} Q_{2M} : - \frac{1}{2} \chi_3 \sum_M : O_{3M}^{\dagger} O_{3M} :$$

$$H_m^{MU} = \sum_{a \leq b, T} V_m^{MU}(ab, T) \sum_{JMK} A_{JMTK}^{\dagger}(ab) A_{JMTK}(ab),$$

K. Kaneko, T. Mizusaki, Y. Sun, and S. Tazaki, Phys. Rev. C89, 011302(R)

(2014)

Kaneko, Sun and de Angelis, Nuclear Physics A957, 144-153 (2017)



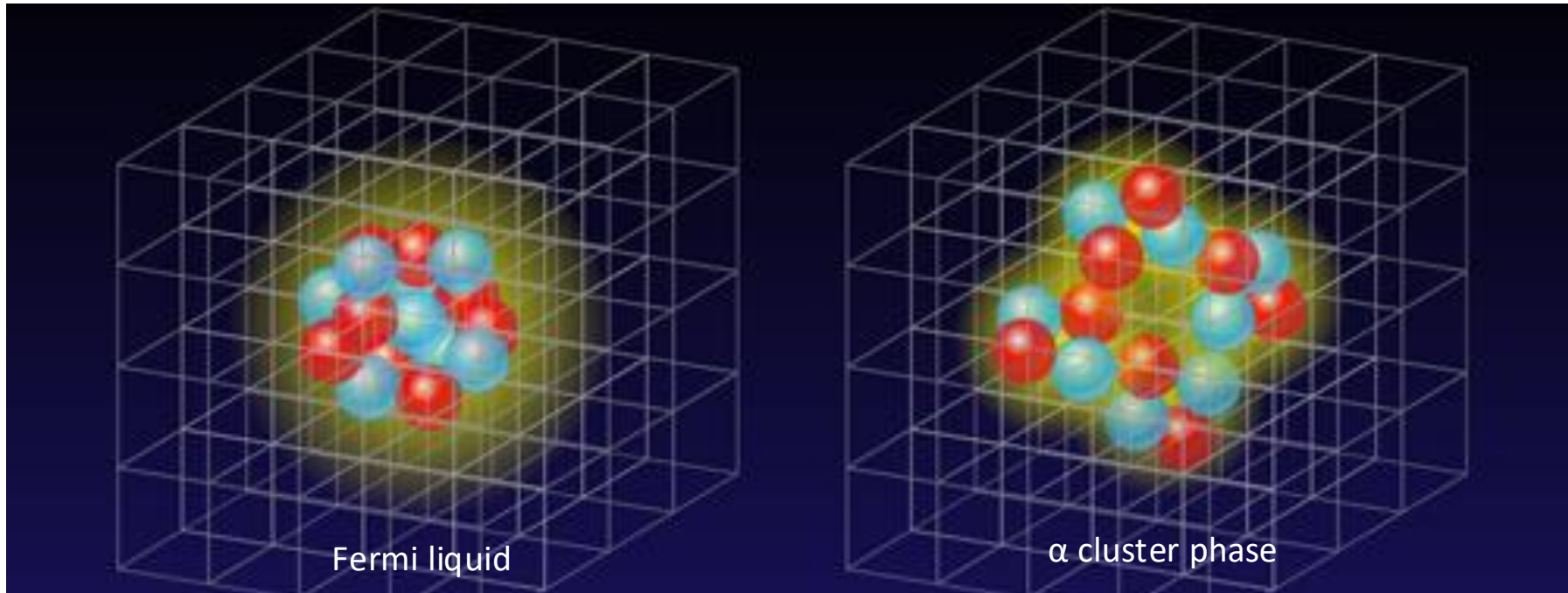
effective charges $e_p=1.5e$ and $e_n=1.1e$

Note: Without the $T=0$ np pairing, the smooth pattern in ^{88}Ru disappears and it lacks rotational behaviour as for $^{90,92}\text{Ru}$. **The np QQ T=0 is most important in the PMMU for driving the collective strength**

Thank You

Backup

Other exotic phases of nuclear matter - quartetting and α -particle condensation



PRL **117**, 132501 (2016)

 Selected for a **Viewpoint** in *Physics*
PHYSICAL REVIEW LETTERS

week ending
23 SEPTEMBER 2016



Nuclear Binding Near a Quantum Phase Transition

Serdar Elhatisari,¹ Ning Li,² Alexander Rokash,³ Jose Manuel Alarcón,¹ Dechuan Du,² Nico Klein,¹ Bing-nan Lu,²
Ulf-G. Meißner,^{1,2,4} Evgeny Epelbaum,³ Hermann Krebs,³ Timo A. Lähde,² Dean Lee,⁵ and Gautam Rupak⁶



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journal homepage: www.elsevier.com/locate/ppnp



Review

Overview of neutron–proton pairing

S. Frauendorf^a, A.O. Macchiavelli^{b,*}

^a Department of Physics, University Notre Dame, Notre Dame, IN 46556, United States

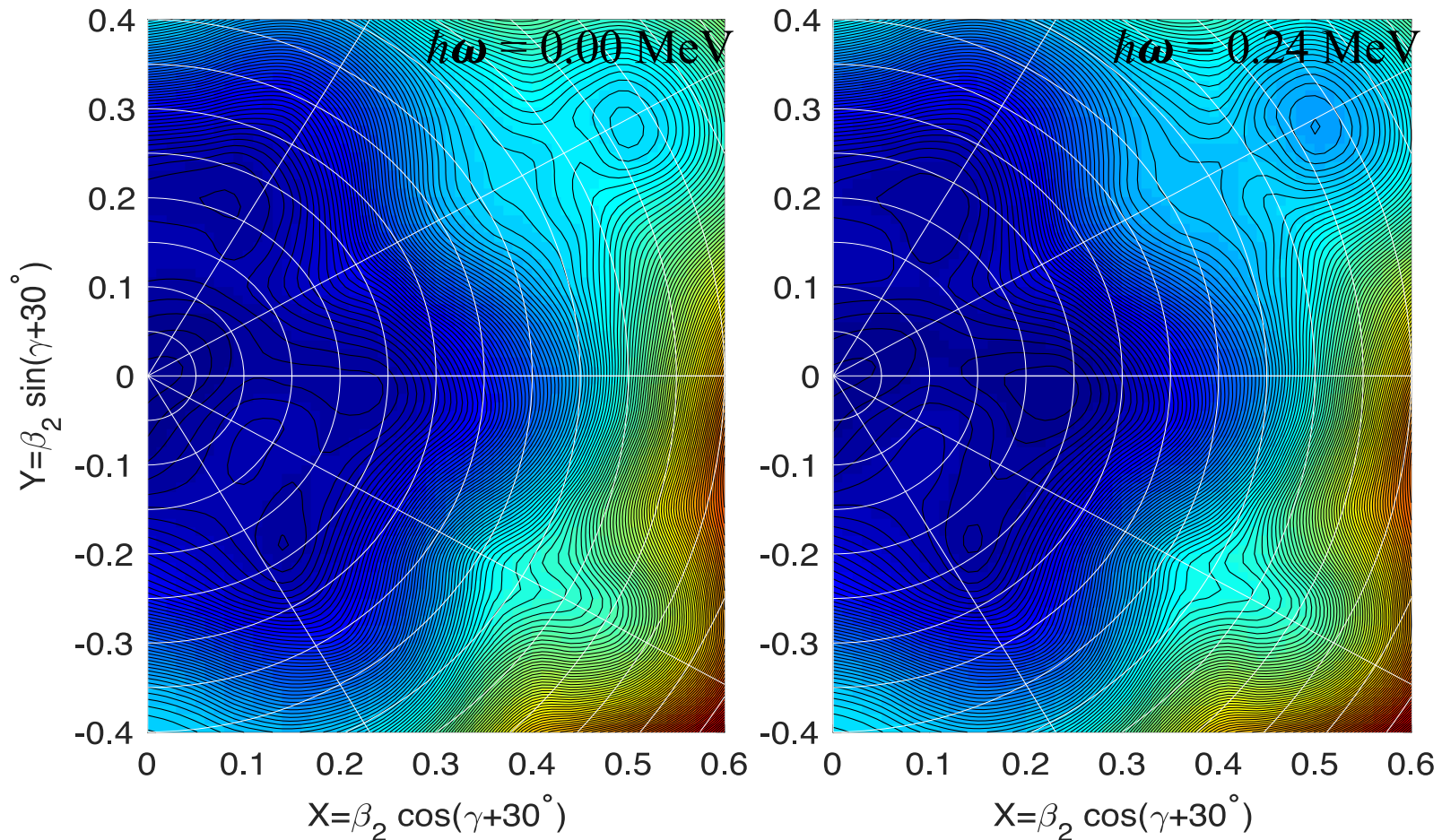
^b Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States



Deviations of experimental spectra from pure isovector calculations have been repeatedly suggested as possible evidence for the existence of an isoscalar pair field. In our opinion, such evidence is not significant. The calculated moments of inertia are close to experiment, both in the paired and unpaired regimes. This is consistent with Shell Model calculations, which find moderate isoscalar correlations that do not change the moments of inertia enough to be significant. Calculated band crossing frequencies also agree with experiment within the uncertainty margin of the applied approaches. The early evidence for a delay of the crossing between the g- and s bands (first backbend) in $N = Z$ nuclei has been disproved by more recent experiments. Moreover some delay is also predicted within an isovector scenario, which is also within the general margin of uncertainty. The spin-aligned regime suggested by the Shell Model studies may represent certain isoscalar correlations, the nature of which has still to be understood. Experimental evidence does not exist, because the relevant data on energies and $B(E2)$ values for $N = Z \geq 44$ have yet to be measured.

Strutinsky-type PES calculations * with standard isovector pairing
(total Routhian surface (TRS) approach)

Note: do not produce deformed ground-state shape
(but pronounced superdeformed minimum appears already at zero rot. frequency!)



* W. Nazarewicz, R. Wyss, A. Johnson, Nuclear Physics A 503(2), 285 (1989)