NEUTRON-PROTON CORRELATION PHENOMENA IN THE HEAVIEST TZ 0 NUCLEI

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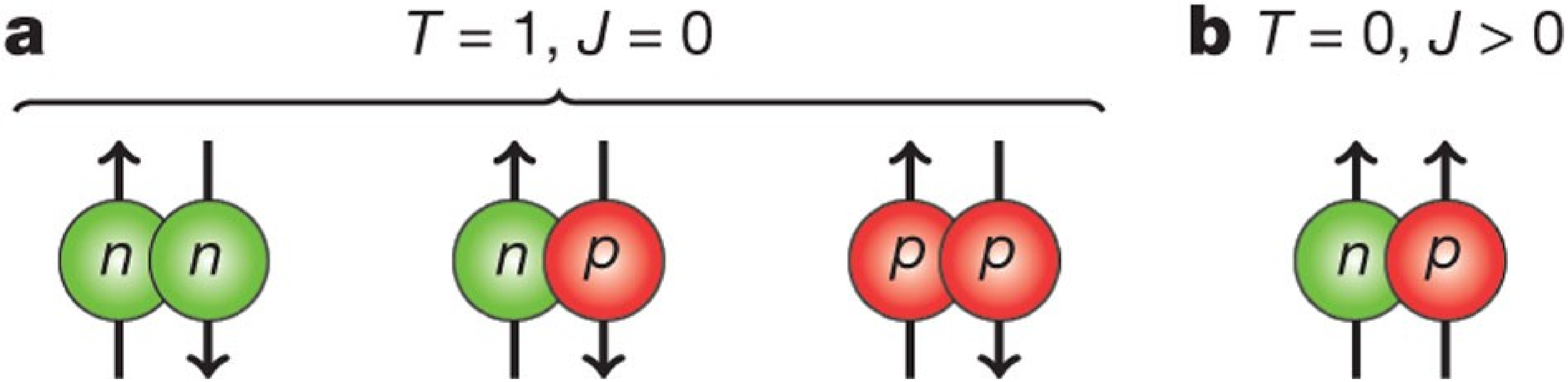
What is the nature of nuclear pair correlations in N = Z nuclei? *

- A long-standing, open question in nuclear structure physics
- Answer *will not* come from one experiment but a few key complementary approaches

* Do we need to clarify the definition of pairing? Often, BCS-type of pair correlations involving many single-particle states (away from closed shells) in the low-spin coupling limit are implicitly assumed but various definitions are used in the literature!

Neutron-proton pairing in N = Z nuclei

ISOVECTOR **ISOSCALAR**



When approaching N=Z, ”normal” pair correlations may remain or even be extended as neutrons and protons occupy identical quantum states

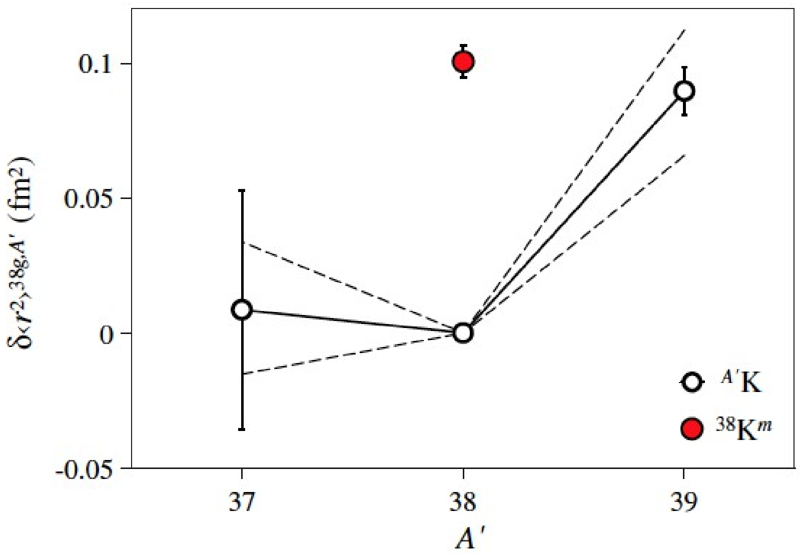
- Binding energies in e-e and o-o nuclei indicate that **T=1 *np* pairing** is dominant, no evidence for a T=0 (deuteron-like) pair condensate **up to around A 60**

- Comparison of spectroscopy data with mean-field calculations for A=60-76 nuclei also suggests the presence of a strong isovector (T=1) *np* pair field at low spin, but no evidence for T=0 pairing.

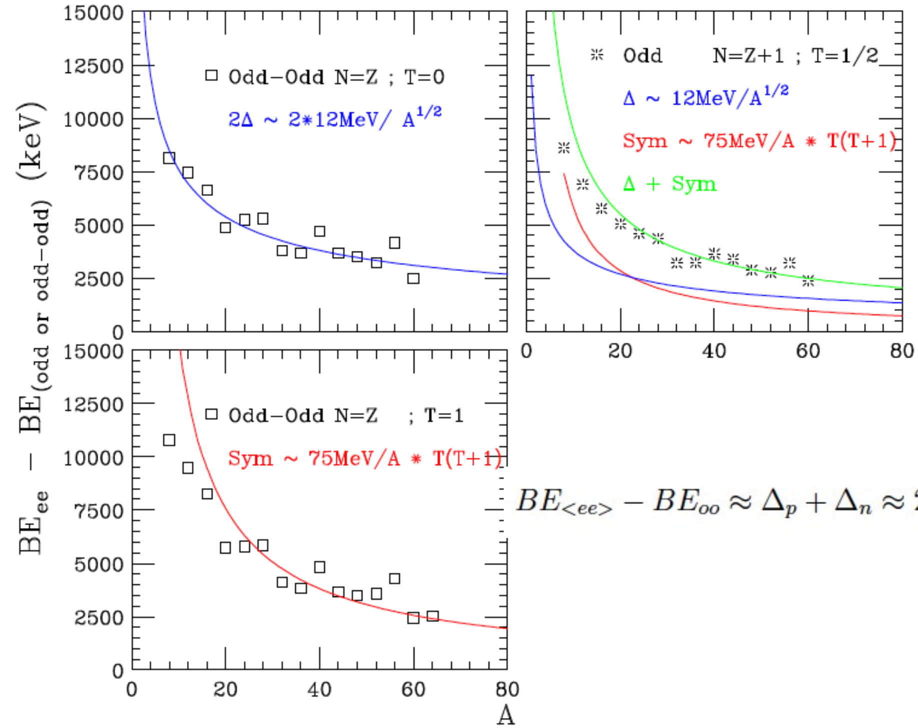
P. Vogel, Nucl. Phys. A662 (2000) 148,
A.O. Macchiavelli et al PRC 61 (2000) 014303R
A Afanasjev, S Frauendorf, Phys. Rev. C 71, 064318 (2005)
S. Frauendorf, A.O. Macchiavelli, Prog. in Particle and Nuclear Physics 78, 24 (2014)

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

Evidence for *isovector* np pairing is claimed from nuclear binding energies, rotational alignments, charge radii etc



"Proton-Neutron Pairing Correlations in the Self-Conjugate Nucleus 38*K* Probed via a Direct Measurement of the Isomer Shift", Bissell et al., PRL 113, 052502 (2014)



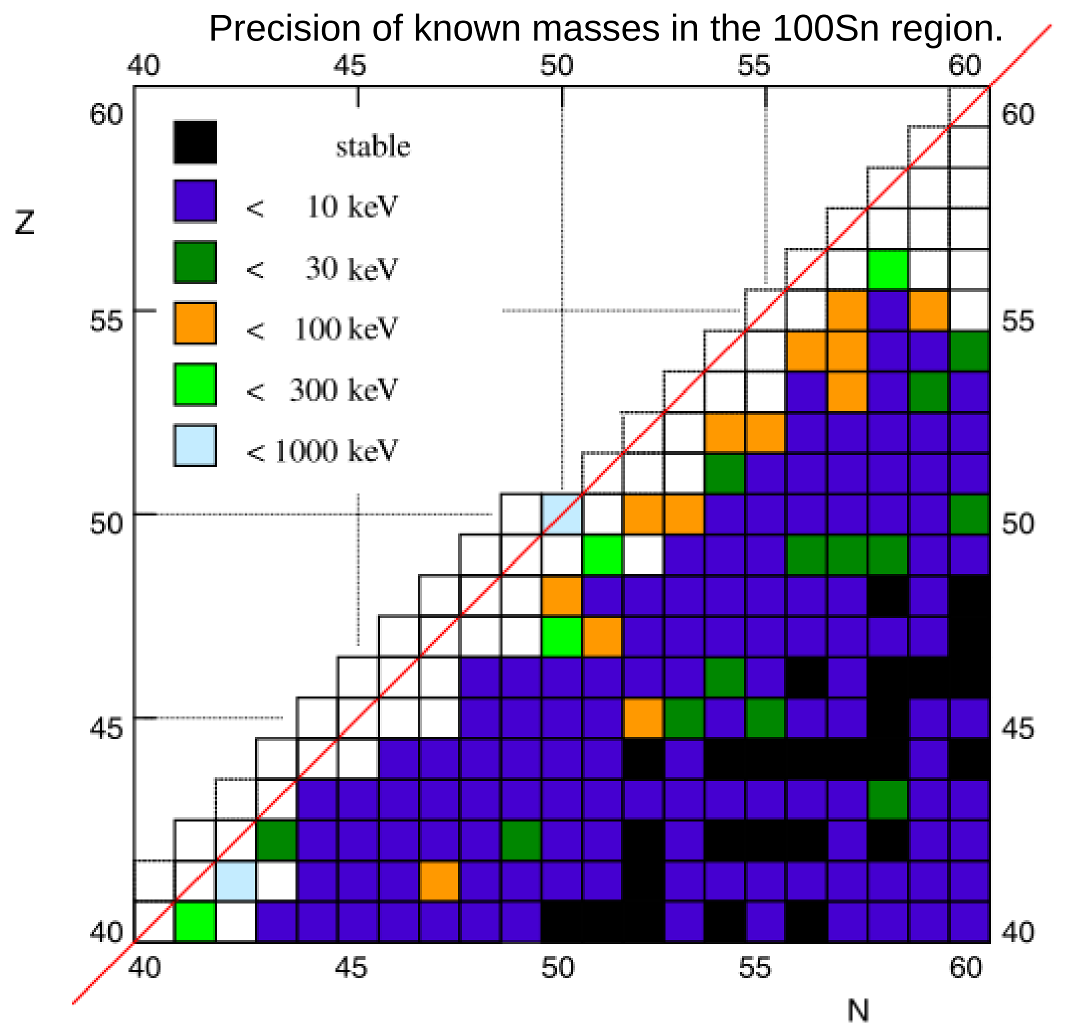
$$BE_{<ee>} - BE_{oo} \approx \Delta_p + \Delta_n \approx 2\Delta$$

Figure 25: Summary of binding energy differences for nuclei along the $N = Z$ line.

"Overview of neutron-proton pairing"
Frauendorf, S., Macchiavelli, A.O. Progress in Particle and Nuclear Physics 78, 24-90 (2014)

"Excludes" *T*=0 pairing in g.s
Note: Data end at *N*=*Z* 30!
Symmetry energy?
"In our view, there is no obvious relation to the presence of isoscalar pair correlations."

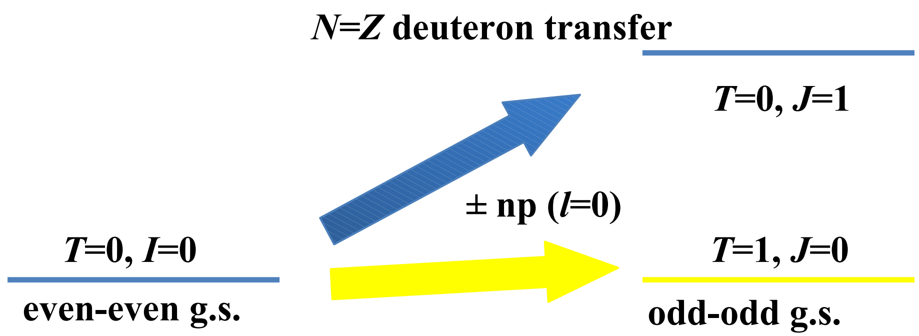
Precison mass data is crucially lacking for N=Z!



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

S. Frauendorf, A.O. Macchiavelli
"Overview of np pairing" Prog in Nucl and Part Phys 78, 24 (2014)

Data: Show clear evidence for an isovector np condensate as expected from isospin invariance.
Conclude: a **ground-state** condensate of deuteron-like pairs appears quite elusive and suggest that pairing collectivity in the T=0 channel may only show in the form of a phonon, at least up to mass ~ 60.
Future: 1) Precision mass measurements beyond mass 60
2) Use direct reactions (exclusive measurements), adding or removing an np pair, as the most promising tool to provide a definite answer to this intriguing question.



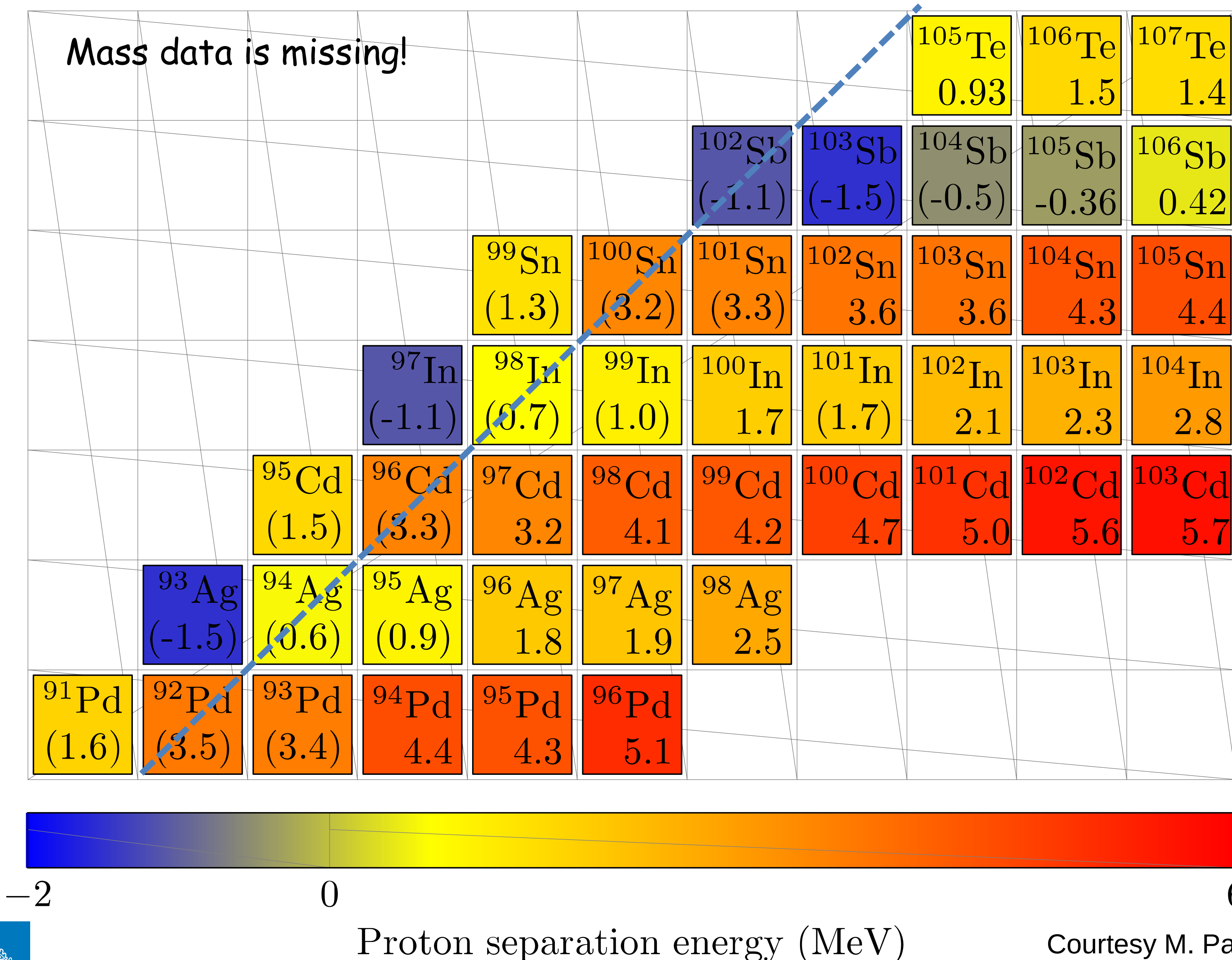
ISSUES:

1) Need for (reaction) theory to develop clear predictions
2) Will be many years before intense beams of 80Zr, 84Mo, 88Ru, 92Pd etc are available for such studies
3) Only probes ground-state or low-spin correlations

What else could we look for? Pairing at finite angular momentum

- Properties of deformed N=Z nuclei (delayed alignments, B(E2) values)

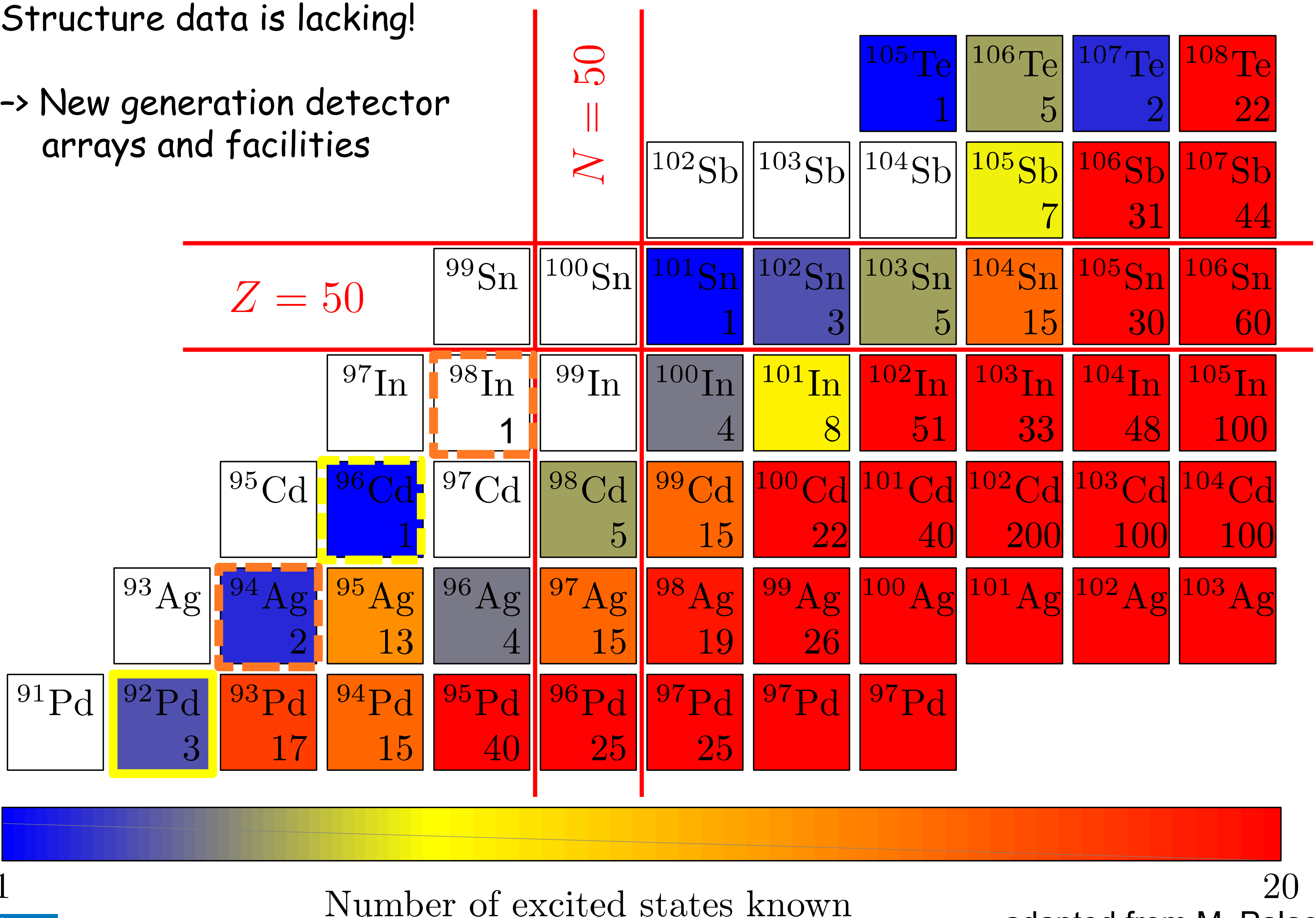
T=1 pairing is suppressed by the Coriolis effect in high-spin states
The T=0 coupling is less affected by the Coriolis anti-pairing effect and will still be active and could become dominant as I increases



Courtesy M. Palacz

Structure data is lacking!

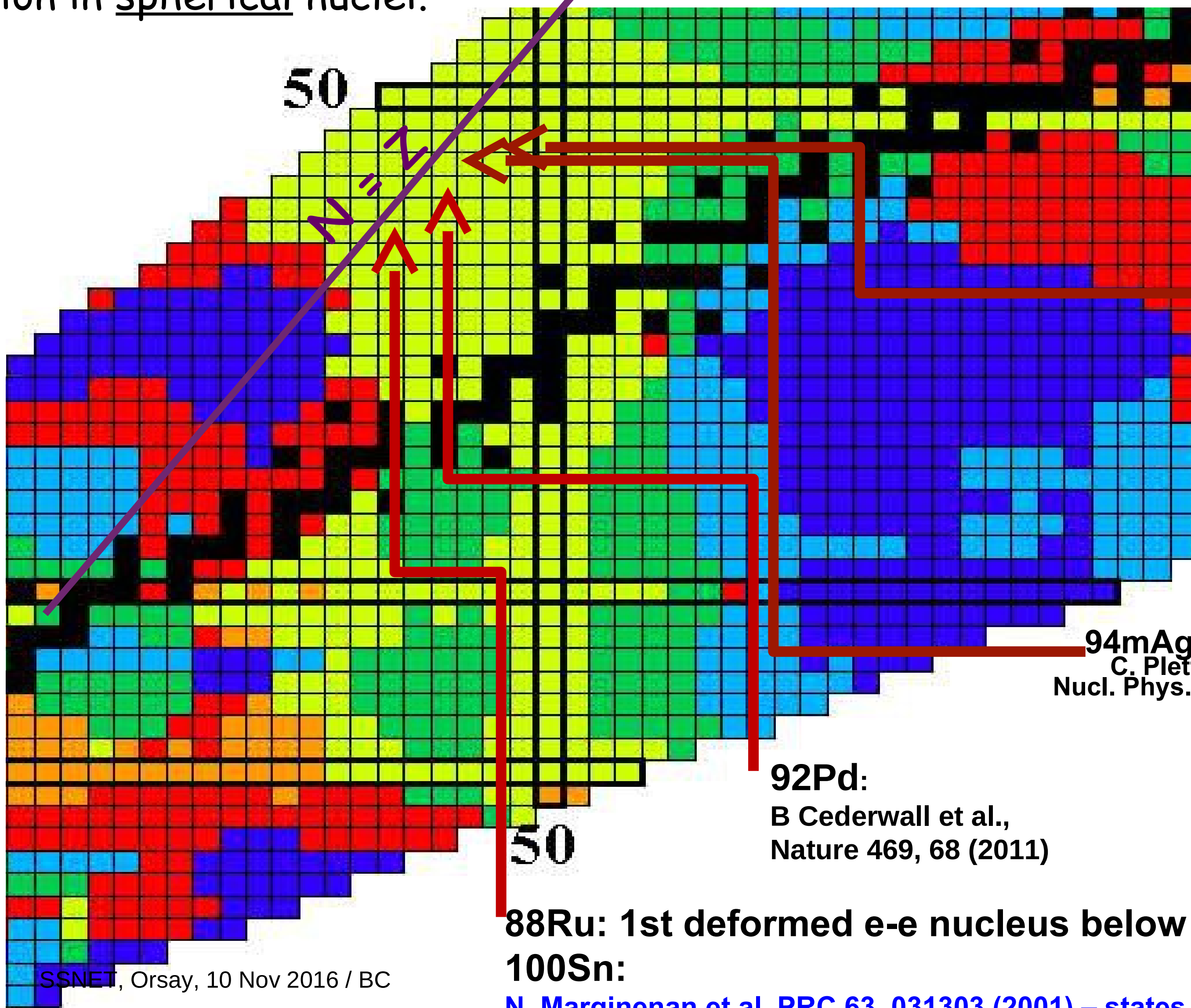
-> New generation detector arrays and facilities



adapted from M. Palacz

Evidence for strong isoscalar np correlations

As yet there is no data that definitively supports the presence of T=0 np BCS type pairing condensate, but clear evidence for influence of T=0 np interaction in <u>spherical</u> nuclei.



96mCd (16+)
B S Nara Singh et al., PRL 107, 172501 (2011)

P.J. Davies et al IoP talk + to be Published (2016)

94mAg (21+)
C. Plettner et al.
Nucl. Phys. A733, 20 (2004)

92Pd:
B Cederwall et al.,
Nature 469, 68 (2011)

88Ru: 1st deformed e-e nucleus below 100Sn:
N. Marginenan et al, PRC 63, 031303 (2001) – states to 8+

Strong T=0 neutron-proton (np) pair correlations may lead to something different from a BCS-type of pairing condensate:

"Isoscalar spin-aligned coupling scheme" *

predicted for N=Z nuclei in an "island"
of spherical nuclei close below 100Sn.

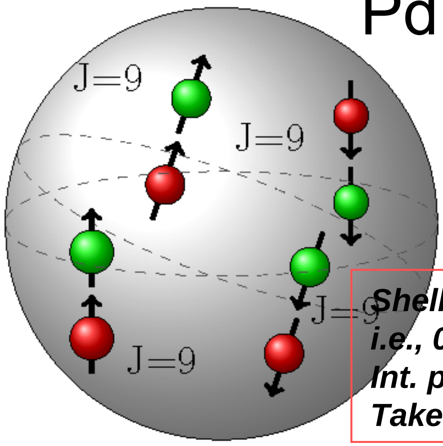
- Characteristic signature of "vibrational-like" yrast energies and "rotational-like" B(E2) strengths. B(E2;0+→ 2+)s develop differently compared with standard seniority scheme along isotopic chain as N→ Z

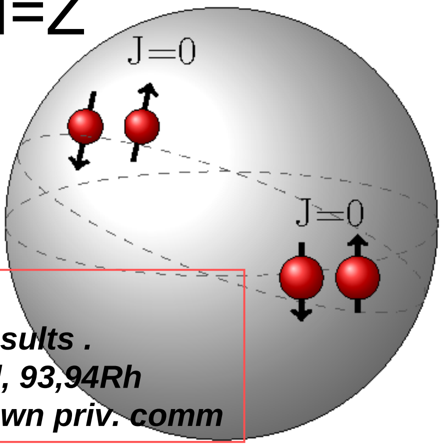
- A manifestation of strong np-pair correlations different from pairing in the BCS sense

* 'Evidence for a spin-aligned neutron-proton paired phase from the level structure of 92Pd'
B. Cederwall et al., Nature **469**, 68 (2011)

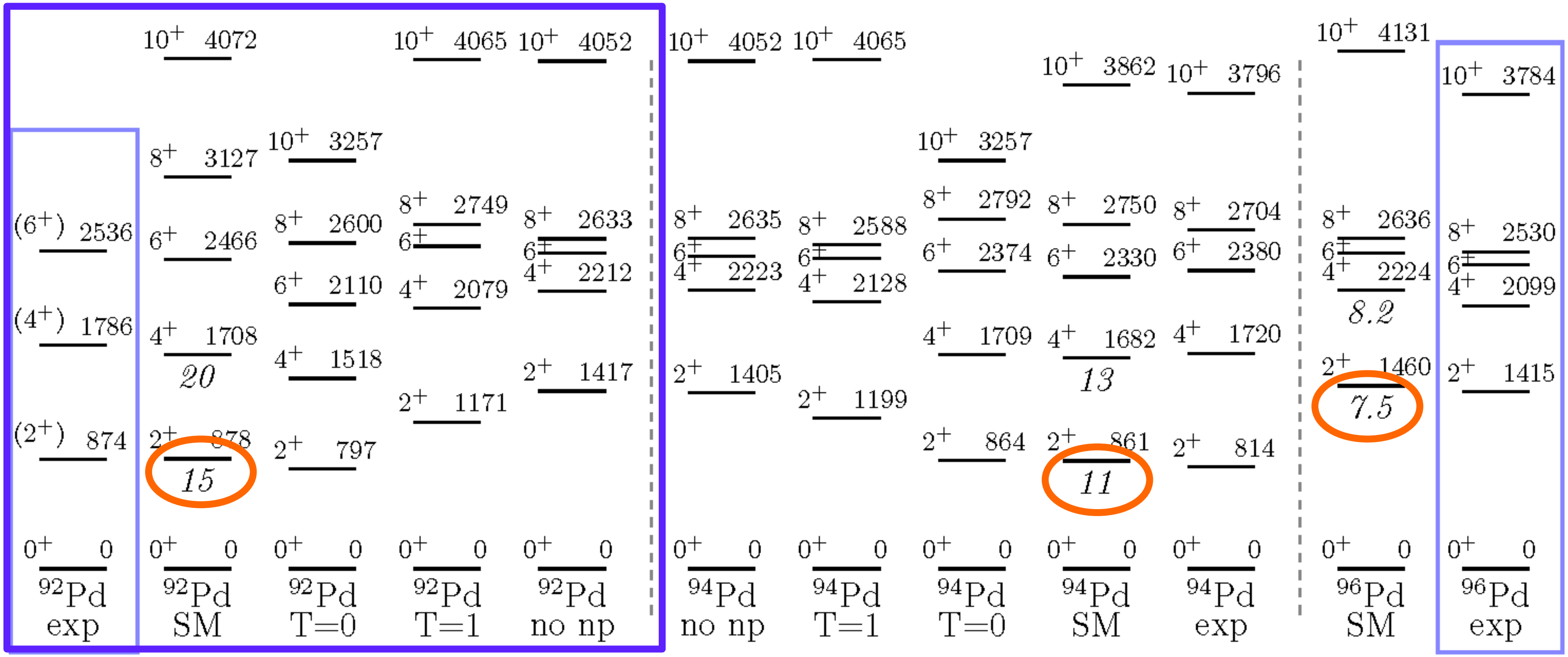
'Spin-aligned neutron-proton pair mode in atomic nuclei'
C. Qi, **J. Blomqvist**, T. Bäck, B. Cederwall, A. Johnson, R. J. Liotta, and R. Wyss
Phys. Rev. C 84, 021301 (2011)

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





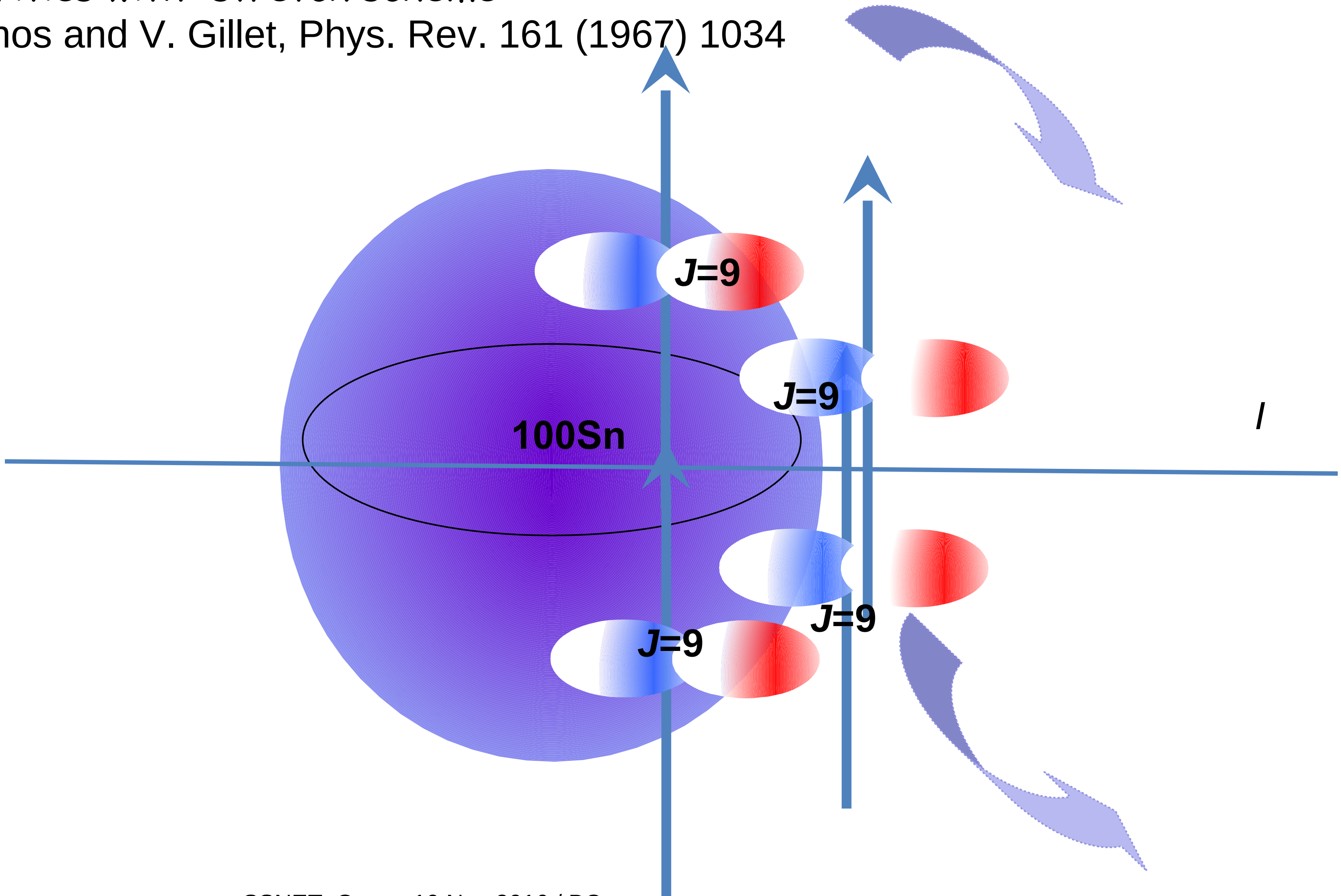
Shell model calculations performed in several model spaces, i.e., 0g9/2, 0g9/2-1p1/2 and 0g9/2-1p1/2-0f5/2-1p3/2 with similar results . Int. parameters determined to reproduce exp energies in 94,95Pd, 93,94Rh Taken from Lisetskiy et al, Phys.Rev.C70,044314(2004); B.A Brown priv. comm



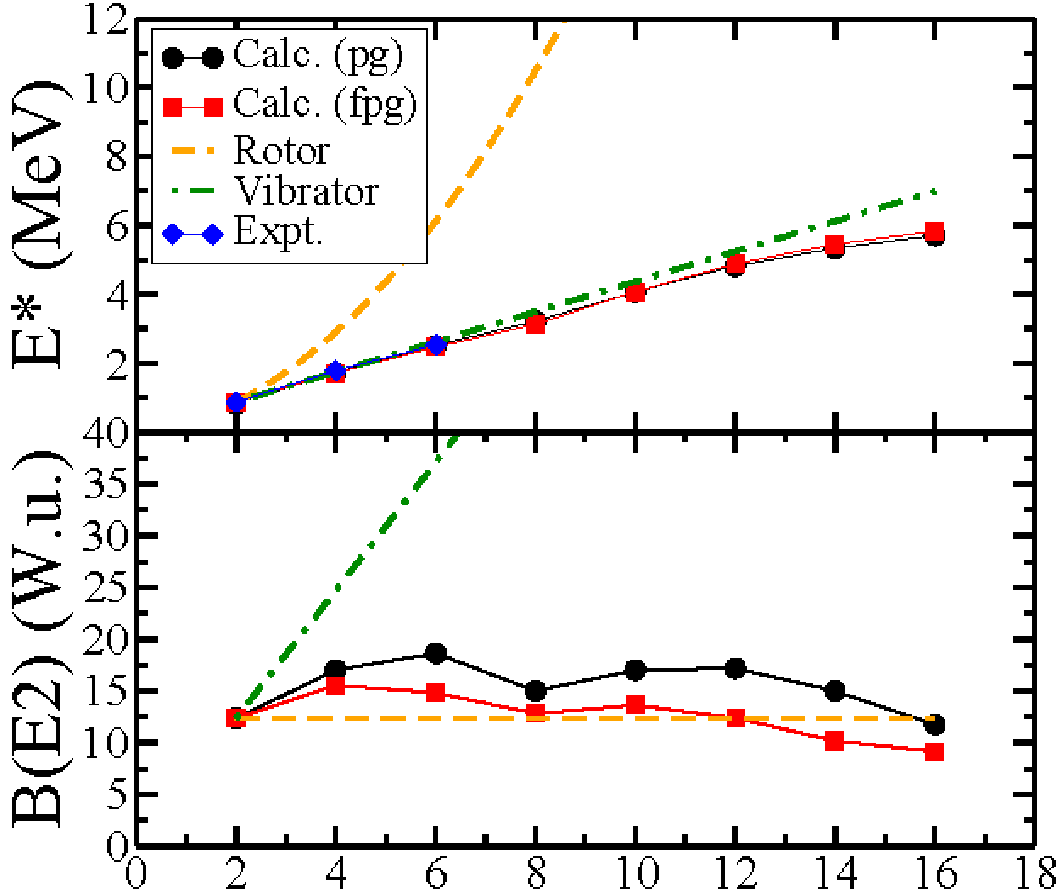
From B. Cederwall et al., Nature **469**, 68 (2011)

Generation of angular momentum in the isoscalar spin-aligned coupling scheme (92Pd)

Similarities with "stretch scheme"
M. Danos and V. Gillet, Phys. Rev. 161 (1967) 1034



“Unique” signature of spin-aligned T=0 coupling scheme ?

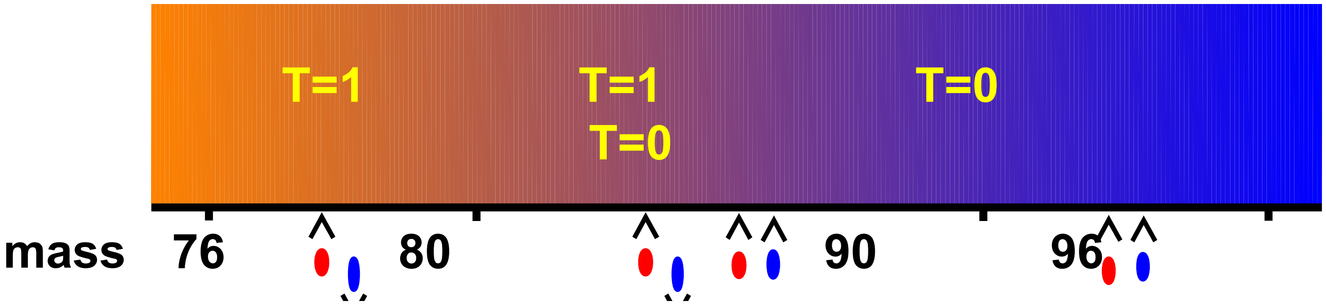


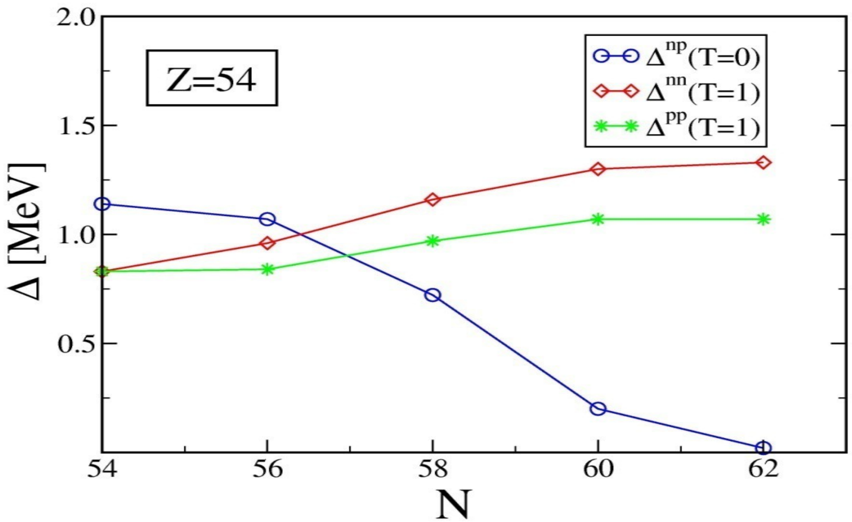
Upper: Shell model spectra of 92Pd
calculated within the 1p3/20f5/21p1/20g9/2 space [10] (fpg) and the 1p1/20g9/2 space (pg).
Lower: B(E2; I → I − 2) values in 92Pd calculated within the fpg and pg spaces. The two dashed lines show the predictions of the geometric collective model normalized to the 2+1 state

C.Qi, J.Blomqvist, T.Bäck, B. Cederwall, A. Johnson, R. J. Liotta, and R. Wyss, PRC 84, 021301(R) (2011)

Predictions for neutron-proton pairing in **deformed** N = Z nuclei

A. L. Goodman , PRC 60, 014311 (1999) –
studies of ground states of e-e A = 76-96, N = Z nuclei



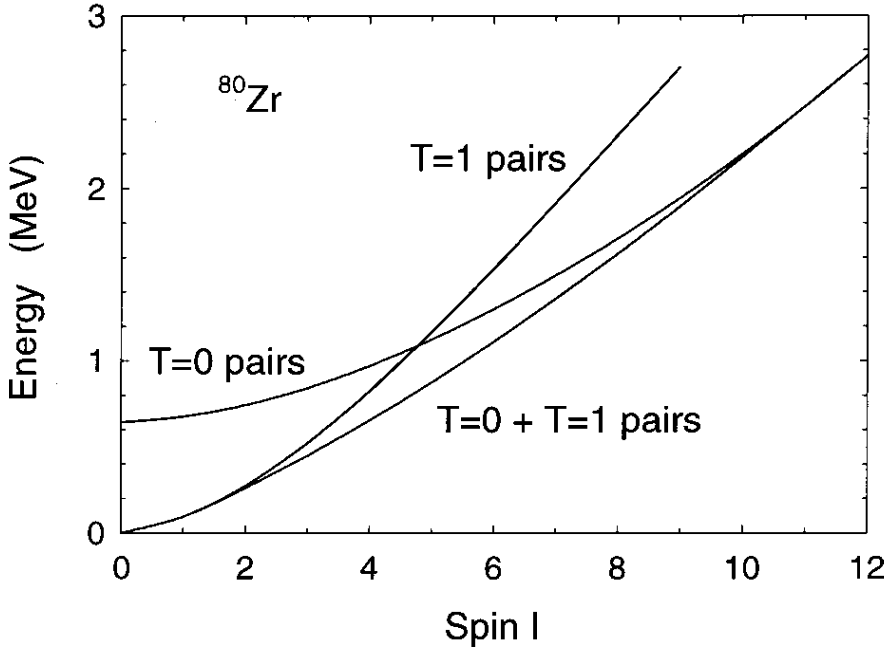


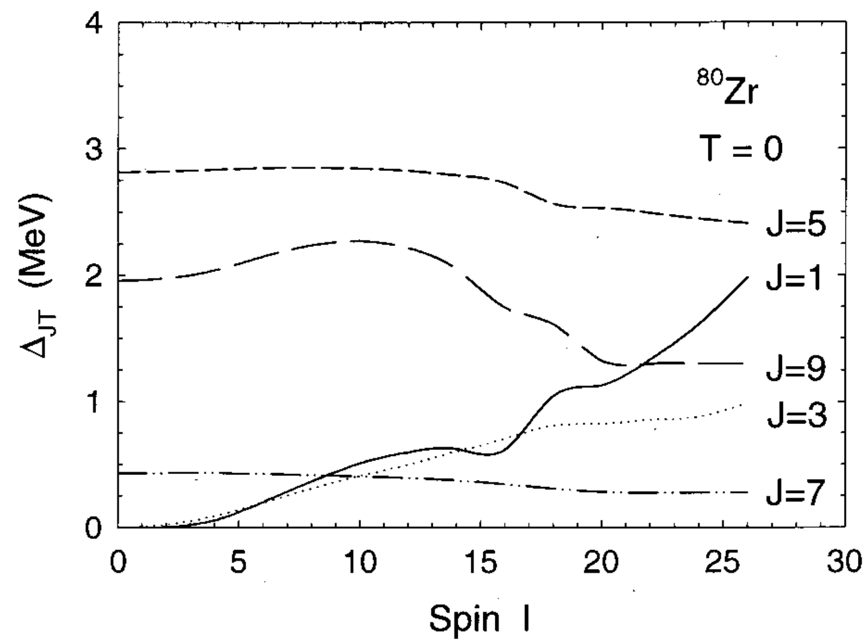
W. Satula,R.Wyss, Phys. Rev. Lett. 86, 4488 (2001)

The isoscalar (np) pair gap is predicted to increase sharply as N ! Z

Isospin-generalized HFB theory

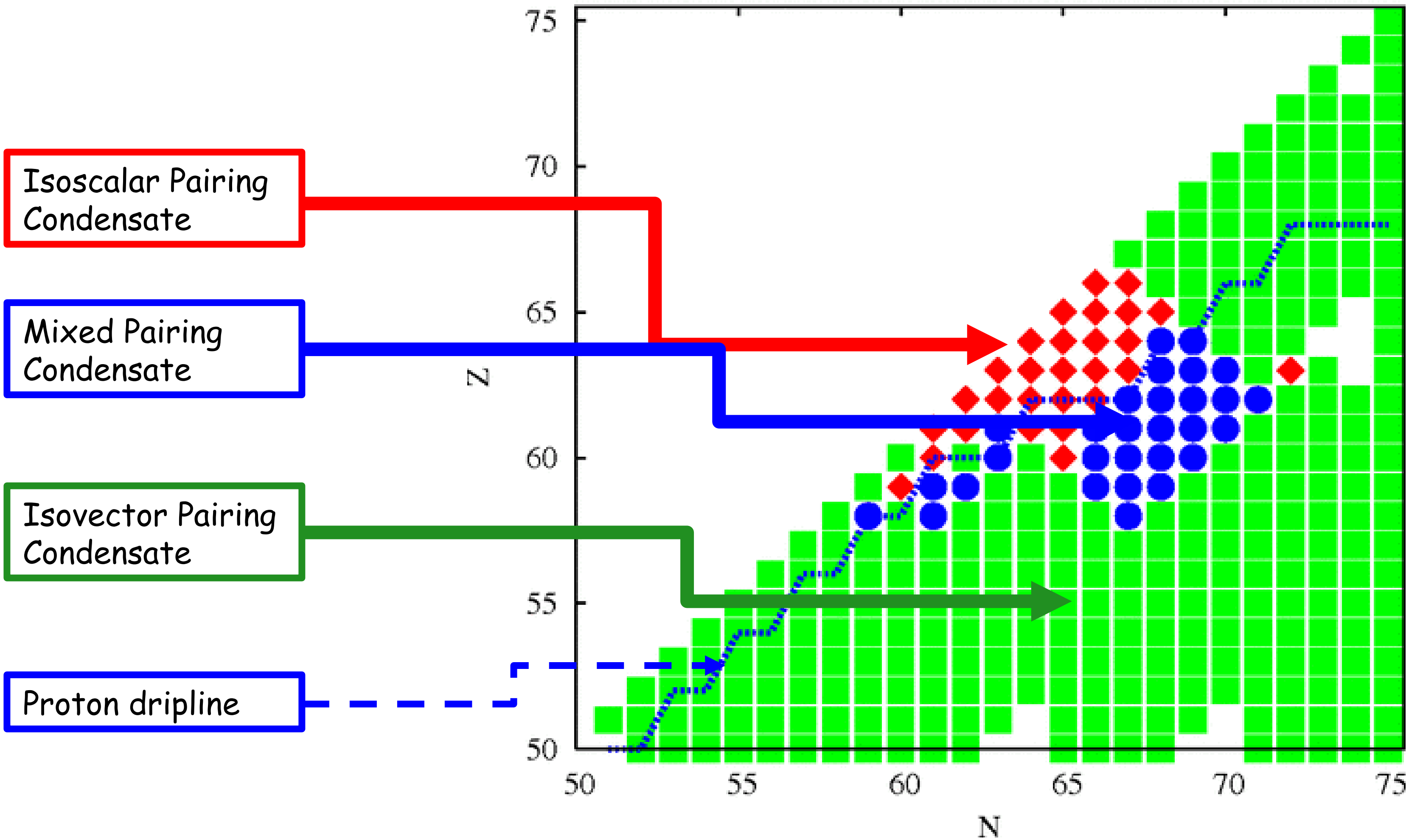
"*T* = 0 and *T* = 1 pairing in rotational states of the *N* = *Z* nucleus 80Zr"
A. L. Goodman, PRC 63, 044325 (2001)





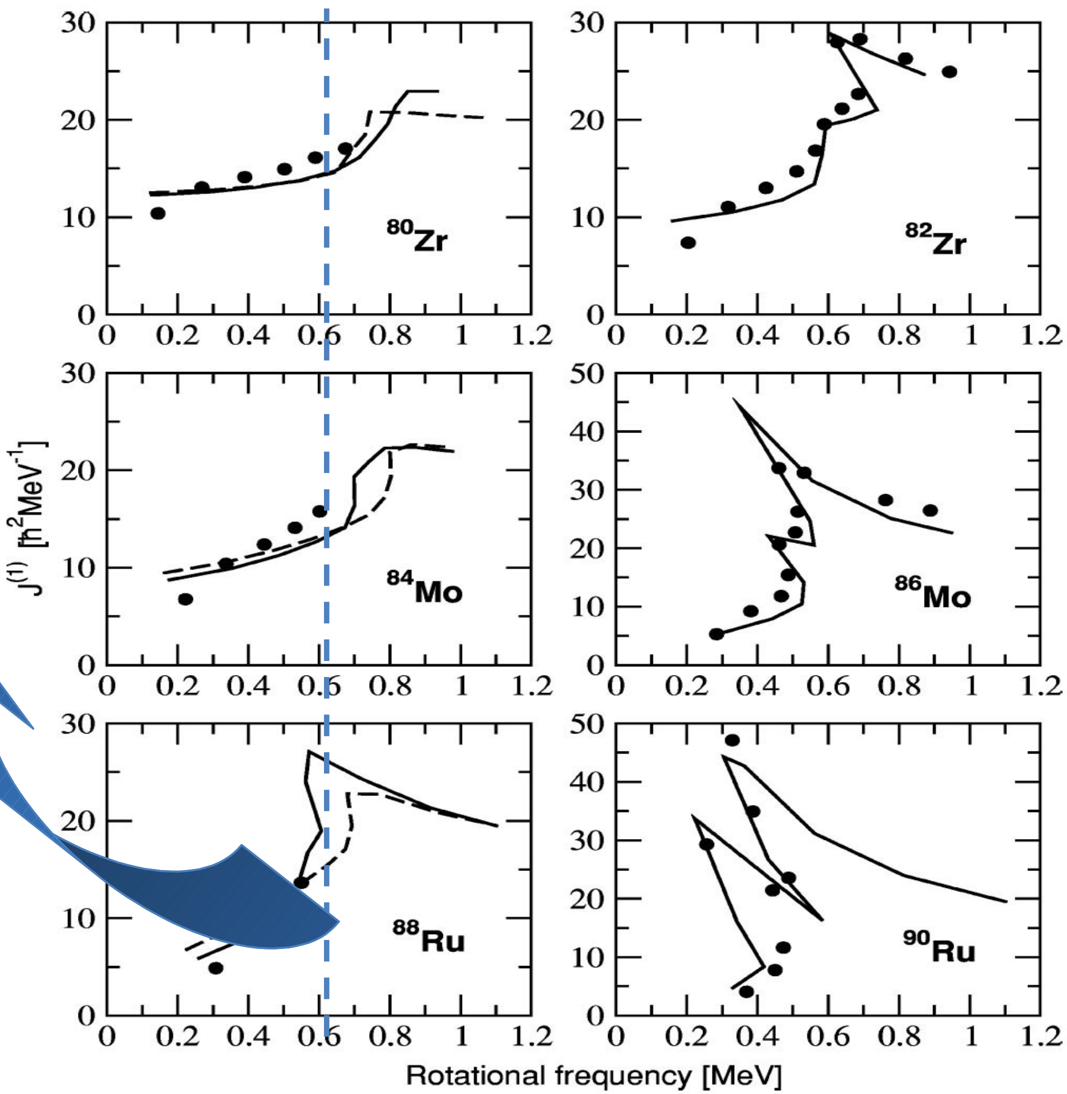
$\Delta_{=} \quad =$

“Mixed-Spin Pairing Condensates in Heavy Nuclei“
A. Gezerlis, G. F. Bertsch, and Y. L. Luo, Phys. Rev. Lett. 106, 252502 (2011)



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

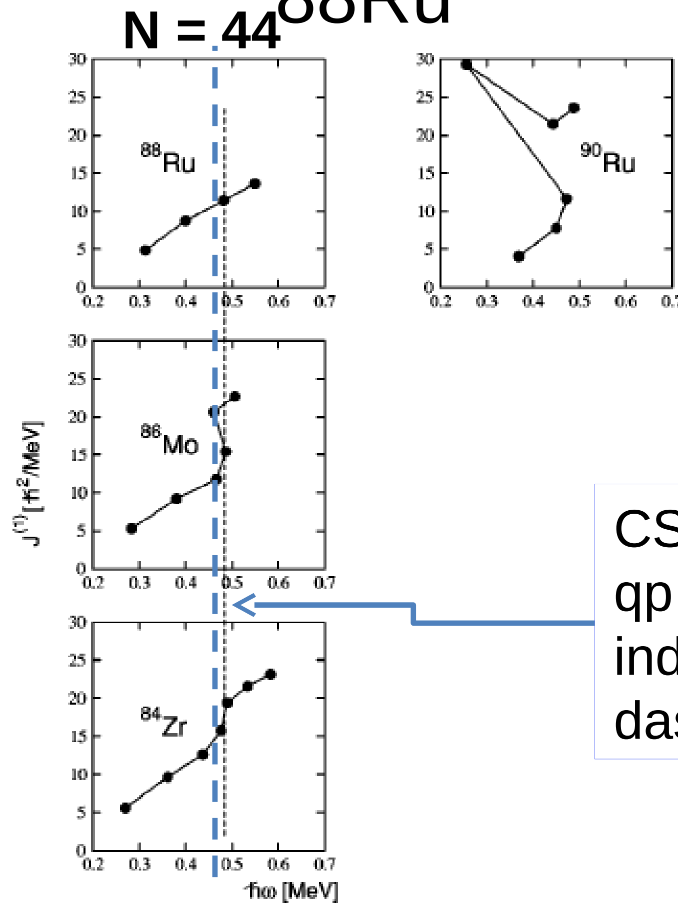
PSM ____________
PSM with enhanced np res. int._ _ _ _ _



Data end crucially here!

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

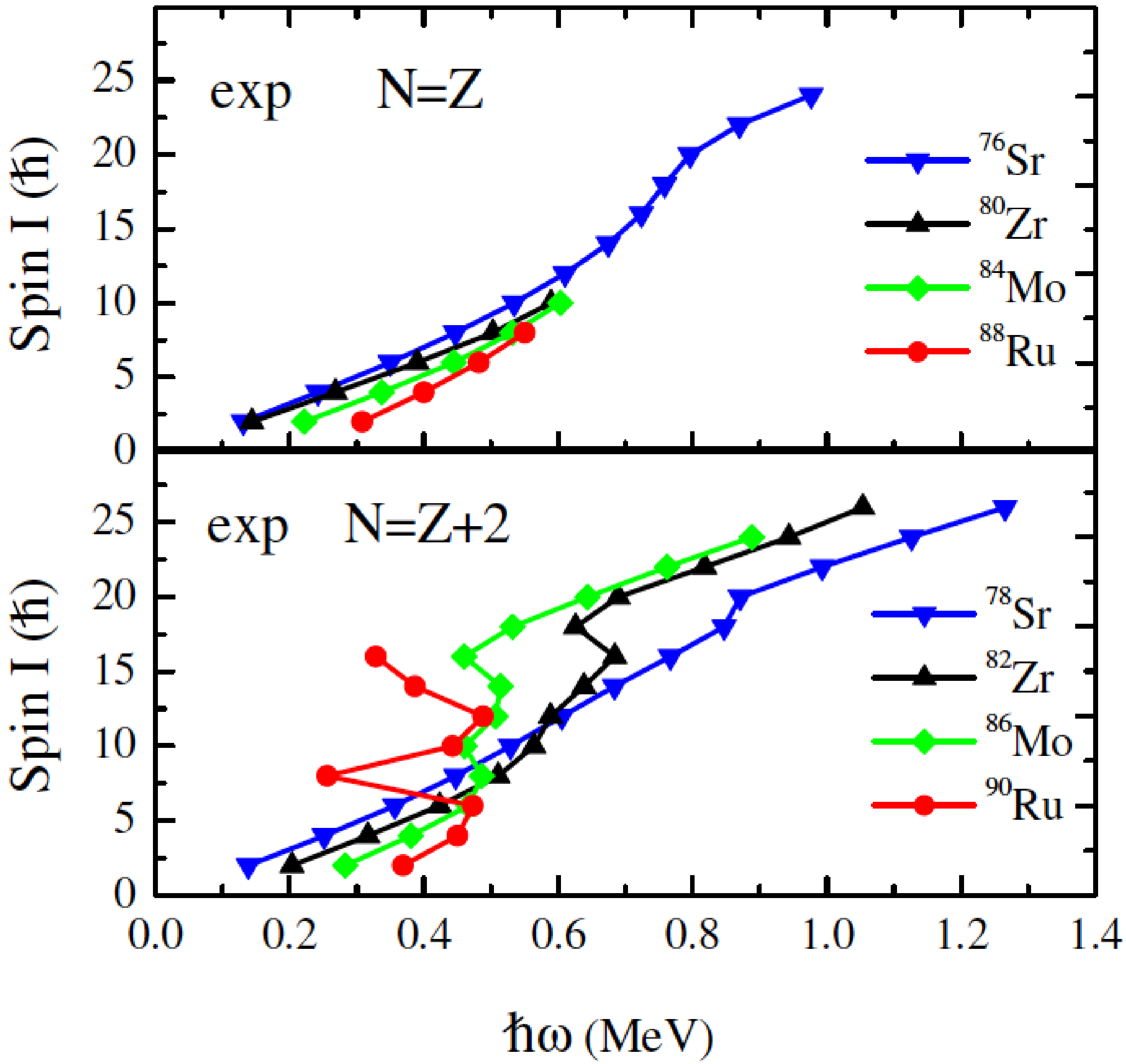
Spectroscopy as a probe of T=0 pairing in deformed 88Ru



CSM predictions of 1st qp band xing frequencies indicated by the vertical dashed line

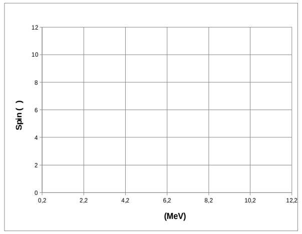
Data tentatively suggest that there is a shift in the alignment frequency of the g9/2 quasiparticles for the N=Z=44 nucleus 88Ru with respect to (a) the T 0 cases and (b) predictions from CSM calculations including standard T=1 BCS pairing.
Need data in the spin 10-16 range to test if there is a delayed alignment that can be accounted for within the normal T=1 pairing scheme or if T=0 pairing must be invoked

Experimental I vs systematics



Taken from Kaneko, Sun and de Angelis, Nucl. Phys. A957, 144 (2017)

Example of theory predictions for 88Ru
”Standard” LSSM calculation* for 88Ru, C. Qi, KTH *
” Nilsson-SU3 self-consistency in heavy N = Z nuclei” Zuker, Poves, Nowacki and Lenzi
Predict similar ”alignment” of angular momentum, **at variance with expt!**



*See F.G. Moradi et al., Phys. Rev. C89, 014301 (2014), JUN45 int. taken from
M. Honma, T. Otsuka, T. Mizusaki, and M. Hjorth-Jensen, Phys. Rev. C 80, 064323 (2009).
Zuker, Poves, Nowacki and Lenzi , Phys. Rev. C92, 024320 (2015) (JUN45 int)

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Nuclear Physics A 957 (2017) 144–153
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Enhancement of high-spin collectivity in $N = Z$ nuclei by the isoscalar neutron–proton pairing

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Abstract

Pairing from different fermions, neutrons and protons, is unique in nuclear physics. The fingerprint for the isoscalar $T = 0$ neutron–proton (np) pairing has however remained a question. We study this exotic pairing mode in excited states of rotating $N \approx Z$ nuclei by applying the state-of-the-art shell-model calculations for ^{88}Ru and the neighboring ^{90,92}Ru isotopes. We show that the $T = 0$ np pairing is responsible for the distinct rotational behavior between the $N = Z$ and $N > Z$ nuclei. Our calculation suggests a gradual crossover from states with mixed $T = 1$ and $T = 0$ pairing near the ground state to those dominated by the $T = 0$ np pairing at high spins. It is found that the $T = 0$ np pairing plays an important role in enhancing the high-spin collectivity, thereby reducing shape variations along the $N = Z$ line.

Keywords: Neutron–proton pairing; Isospin invariance; $N = Z$ nuclei; High-spin states; Large-scale shell model

Predictions for 88Ru

New shell model (PMMU) interaction developed for *fpg9/2d5/2* model space including explicit pairing interaction*

PMMU: H = Ho + HP + HM + Hm :

Ho = s.p, HP = pairing

HM = multipole, contains QQ + OO components

Hm = monopole term

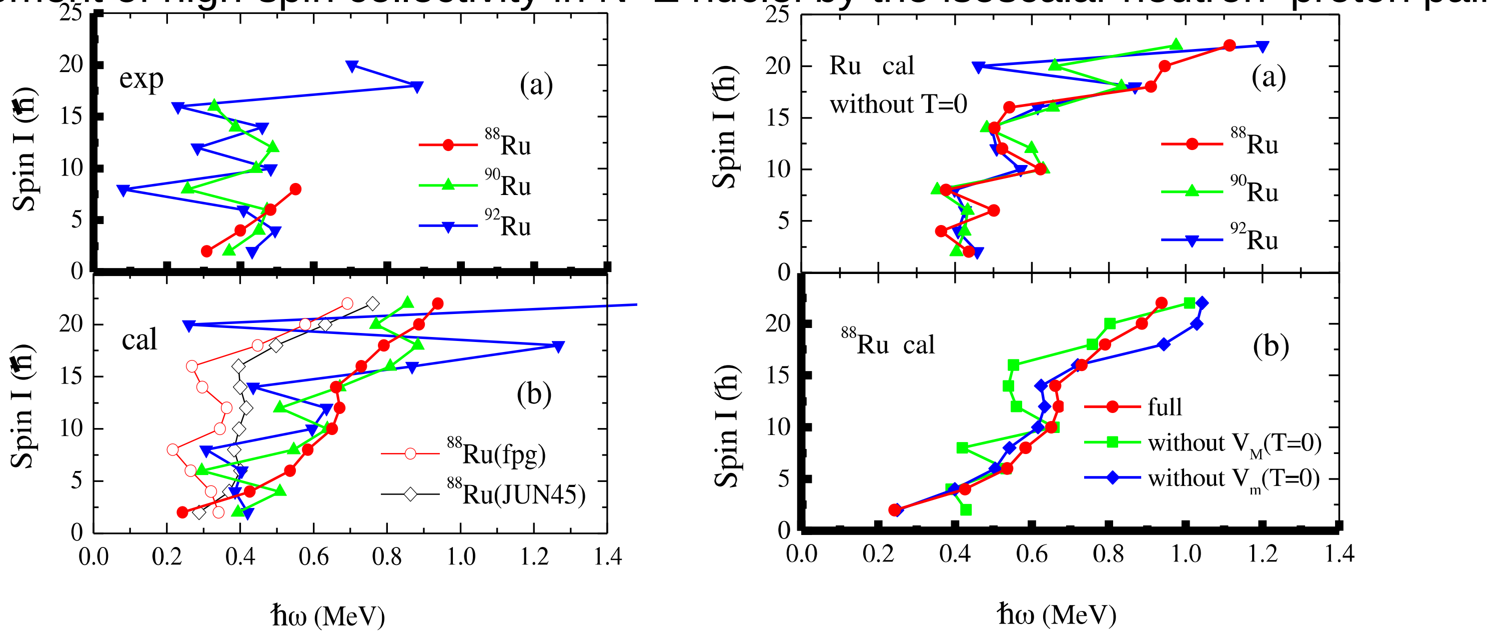
$$H = H_0 + H_P + H_M + H_m^{MU},$$

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

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

- K. Kaneko, T. Mizusaki, Y. Sun, and S. Tazaki, Phys. Rev. C89, 011302(R) (2014) and Kaneko, Sun and de Angelis, Nucl. Phys. A957, 144 (2017)

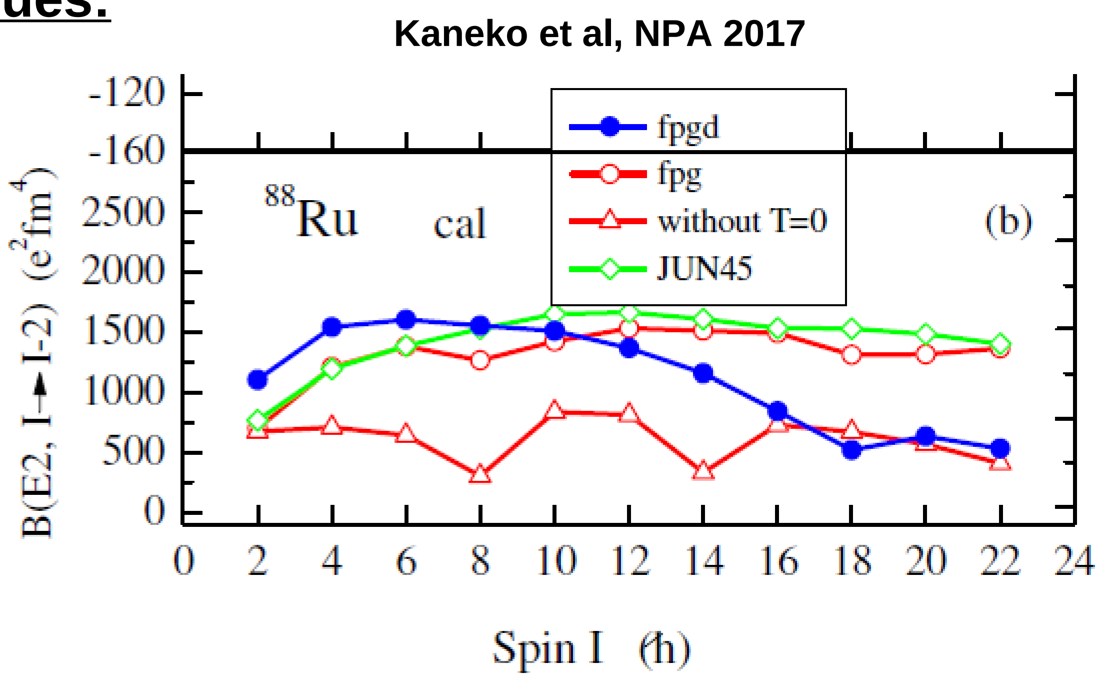
"Enhancement of high-spin collectivity in N=Z nuclei by the isoscalar neutron–proton pairing"



Note: Without the *T = 0 np* pairing, the smooth pattern in 88Ru disappears and its rotational behaviour is as violent as 90,92Ru. **QQ np T=0 is most important in 88Ru**.

Predictions for 88Ru

B(E2) values:

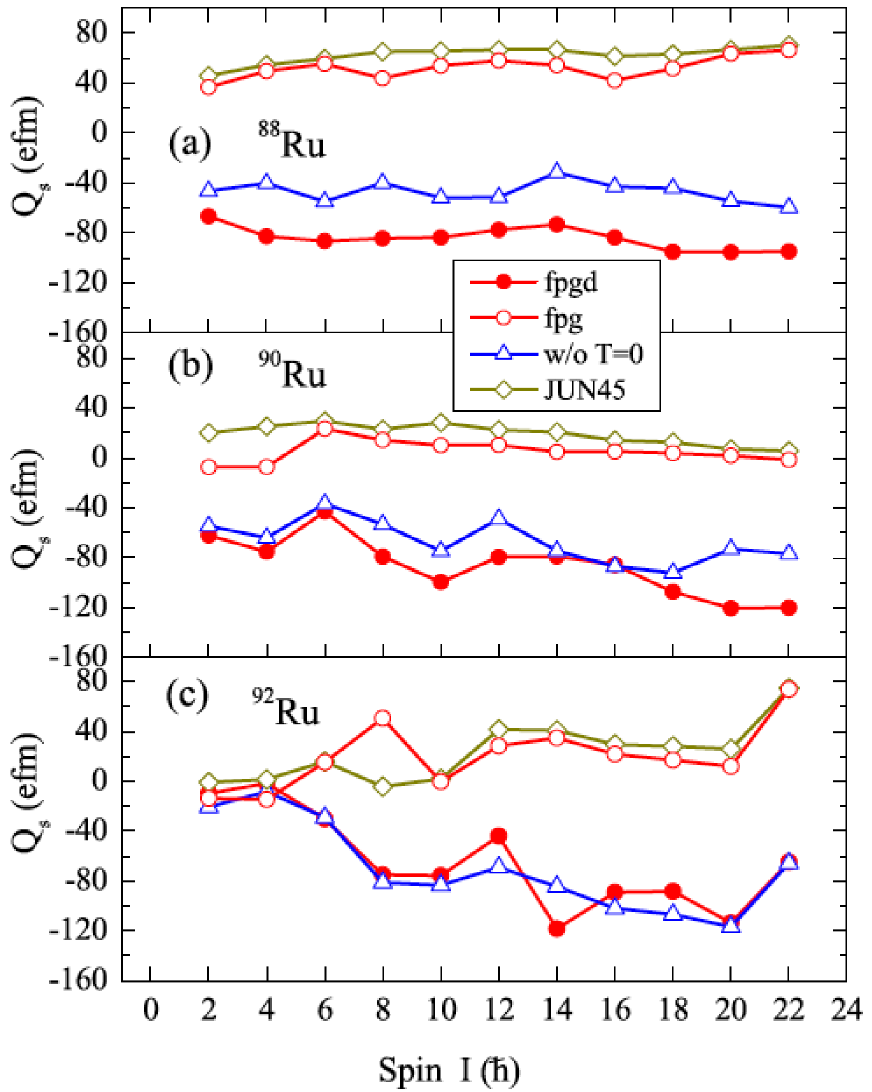


The calculations suggest that the *T = 0 np* pairing enhances the collectivity.

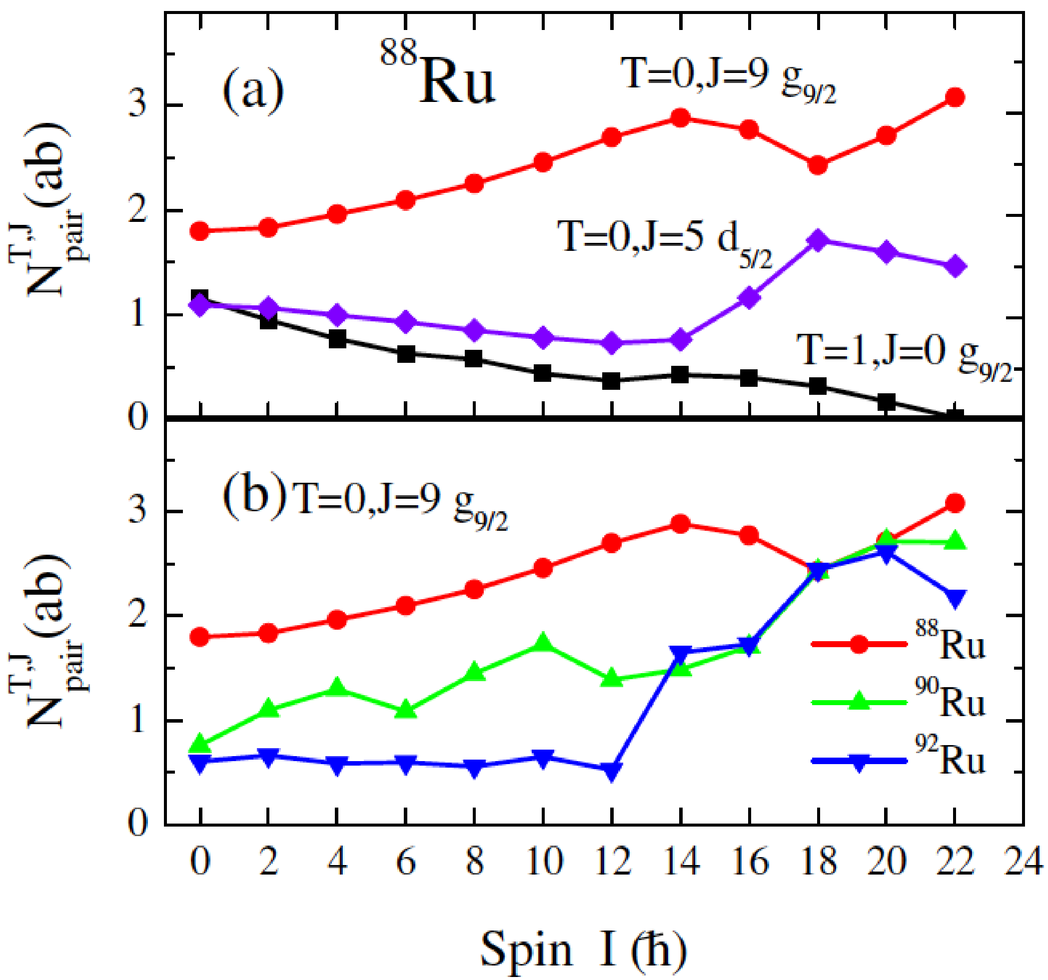
Decrease of *B(E2)* at high spins in the *pfgd* calculation is due to structure changes resulting from the transfer of the *T = 0* pairs from the g9/2 to the d5/2 orbit.

LSSM calculations using the PMMU int. in 88Ru and Tz=1,2 isotopes: "Qs"

K. Kaneko et al. / Nuclear Physics A 957 (2017) 144–153

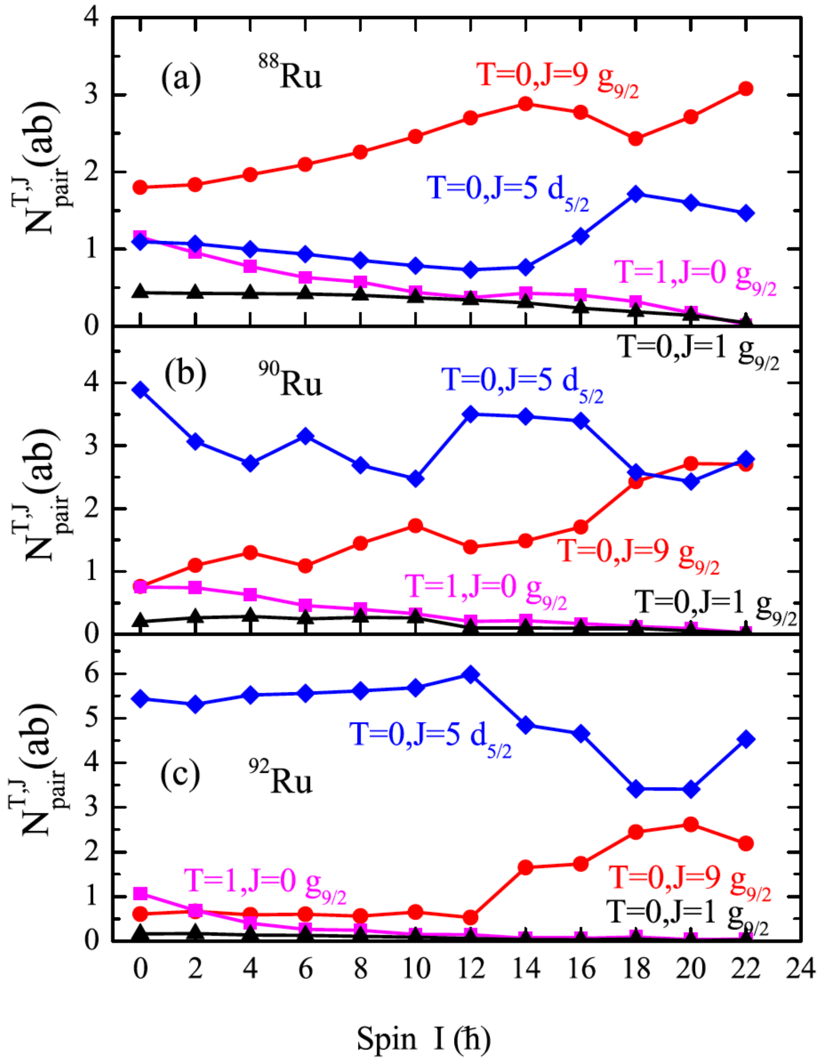


LSSM calculations and np pairing in 88Ru and Tz=1,2 isotopes: "Number of pairs"
Kaneko, Sun and de Angelis, NPA 2017



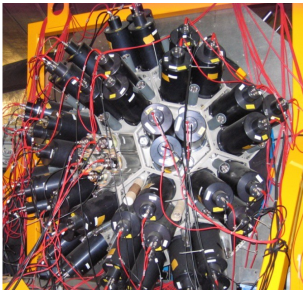
LSSM calculations and np pairing in 88Ru and Tz=1,2 isotopes: "Number of pairs"

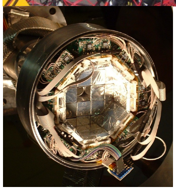
K.| Kaneko et al. / Nuclear Physics A 957 (2017) 144–153



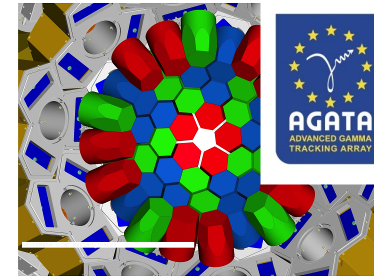
Calculated numbers of pairs in different spin and isospin states in 88,90,92Ru. For 88Ru similar to "Spin-aligned coupling scheme, B. Cederwall et al., Nature (London) 469, 68 (2011)C. Qi, et al., Phys. Rev. C 84, 021301(R) (2011).

Note: 88Ru is deformed while 90,92Ru are «spherical»!

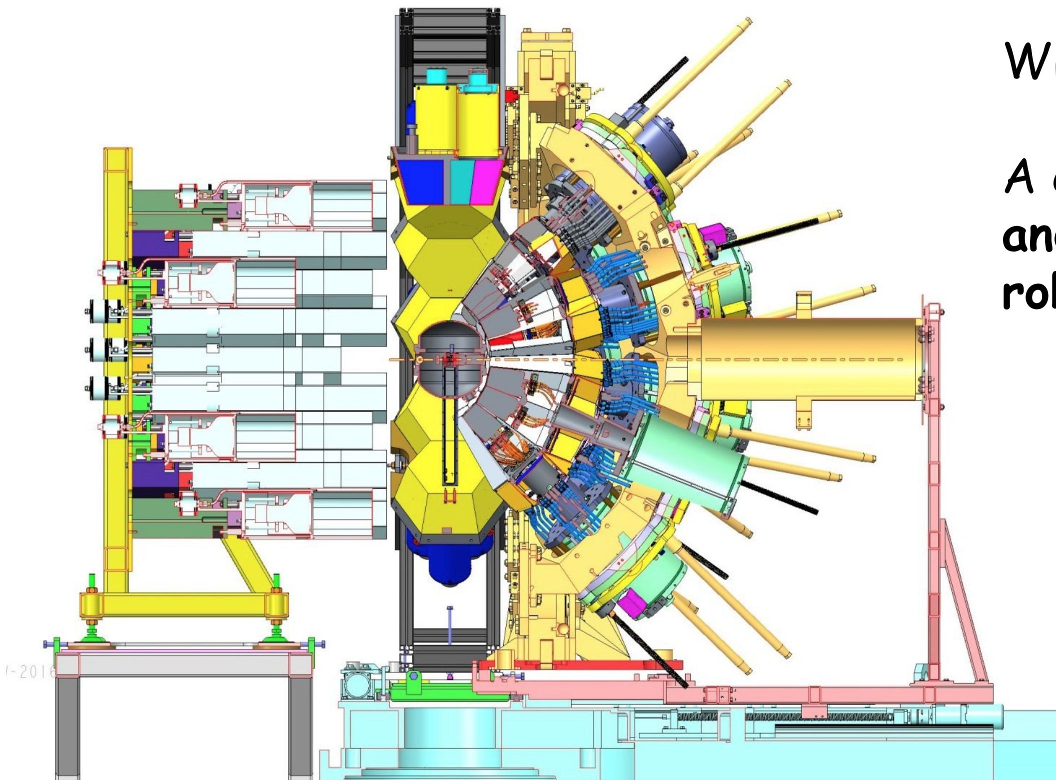




AGATA EXPERIMENT
or GANIL campaign (36 UTs)



Reaction: 36Ar+54Fe ! 88Ru+2n (Ebeam = 115 MeV)
(more forward focussing of neutrons compared with 32S+58Ni)
AGATA+NEDA/NWALL+DIAMANT
Degrading of the beam from CSS1 = 3.8MeV/A ! 3.3MeV/A in S or near target

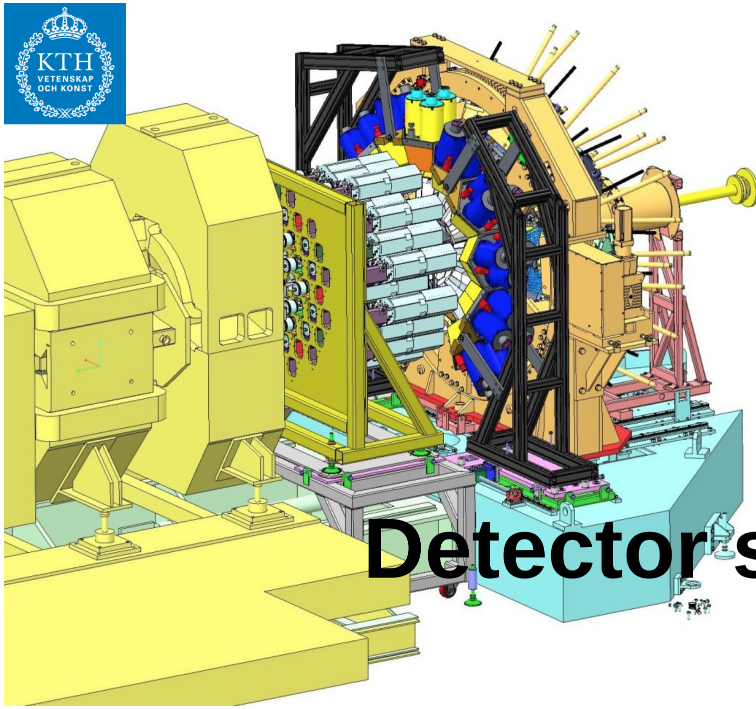


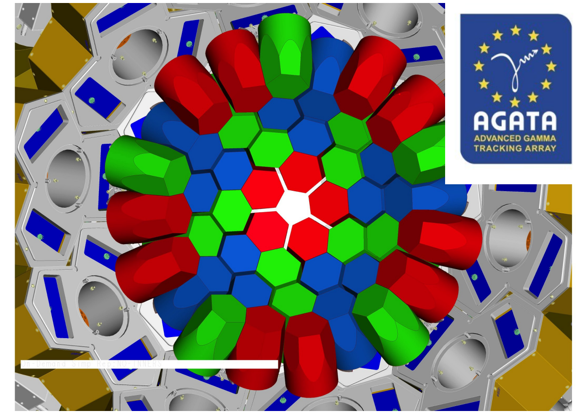
Will T=0 pairing appear in 88Ru?

A challenge for expt
and for theory to develop robust observables!

Thank You

Backup slides





Detector systems and performance:

AGATA close conf. ph ~ 0.10 (compared with (E =1.3 MeV) ~ 0.03 GASP)

NEUTRON WALL+NEDA (1n) ~ 0.30; (”clean” 2n) ~ 0.045 (c.f. (1n) ~ 0.03 n-RING)

DIAMANT CsI(Tl) array (p) ~ 0.50 ( ) ~ 0.40 (similar to ISIS)

(any) ~ 0.66➔ veto eff iciency for particle mult. 2 is 88%

<u>PERFORMANCE GAIN</u> compared with GASP/n-RING/ISIS* <u>2n ~ 200</u>

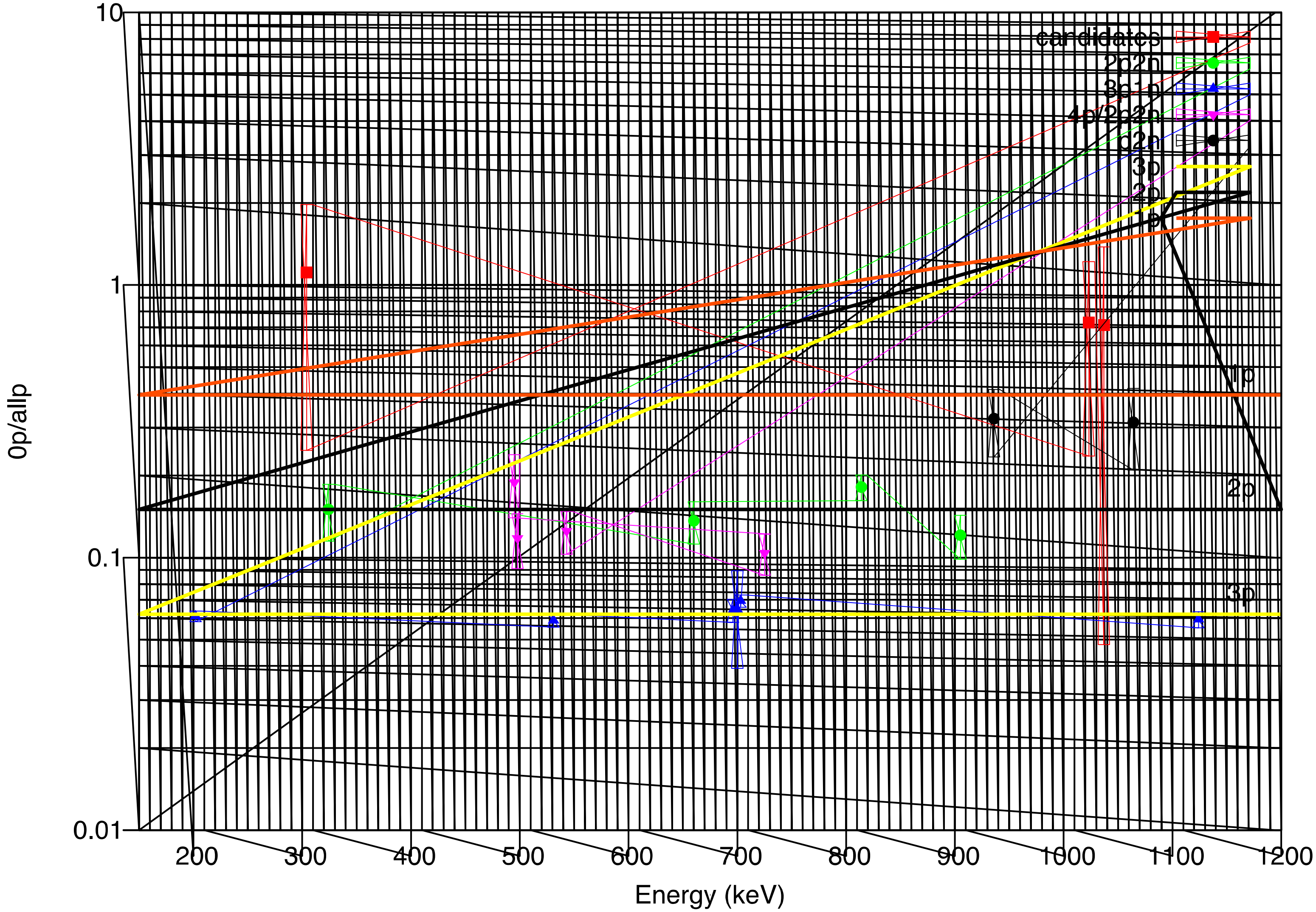
n ~ 50

n ~ 500

n-RING had too low eff iciency for 2n-detection: <u>huge advantage to use clean 2n selection</u>

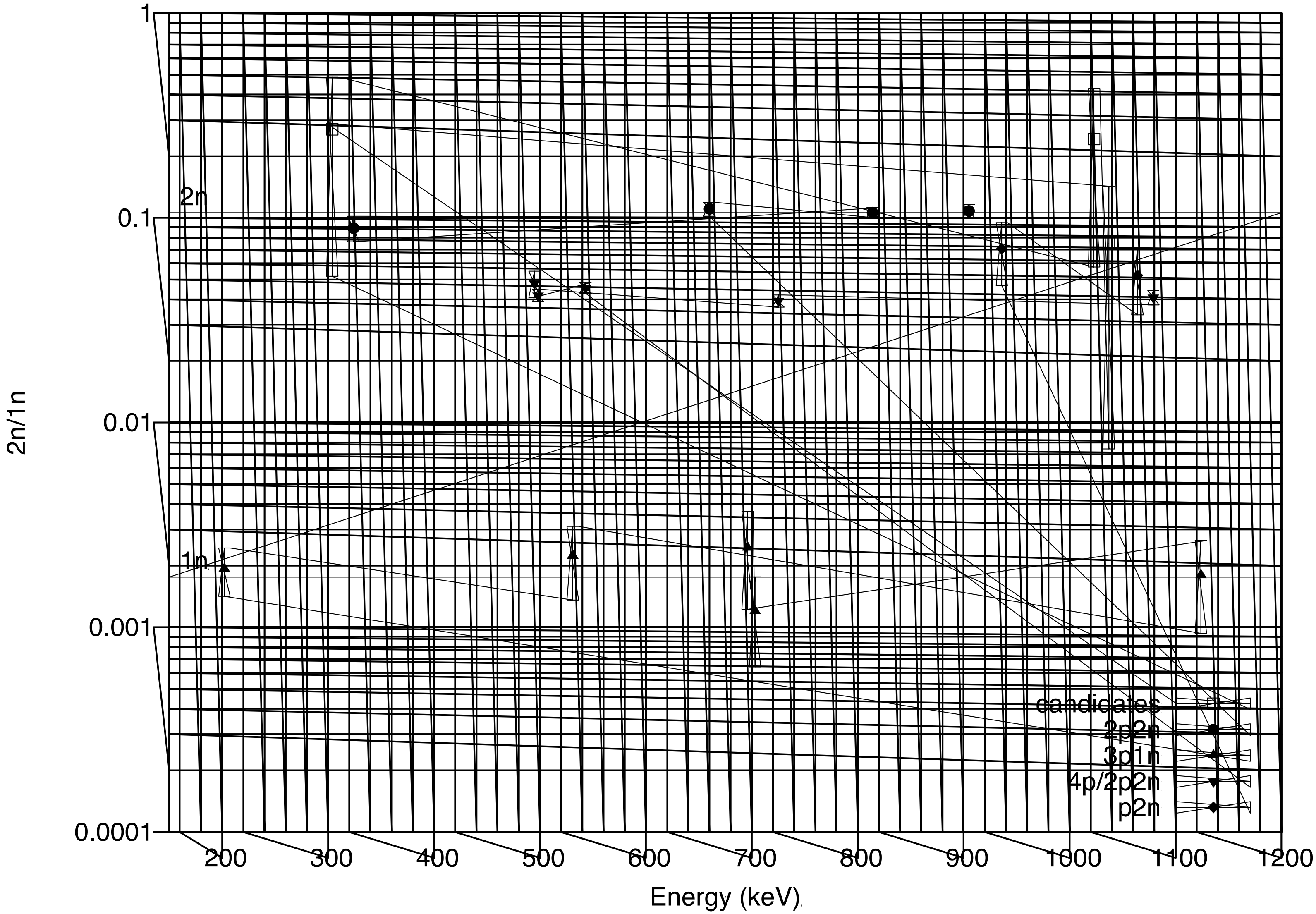
Results (preliminary) E623, 96Cd

U. Jakobsson et al., KTH



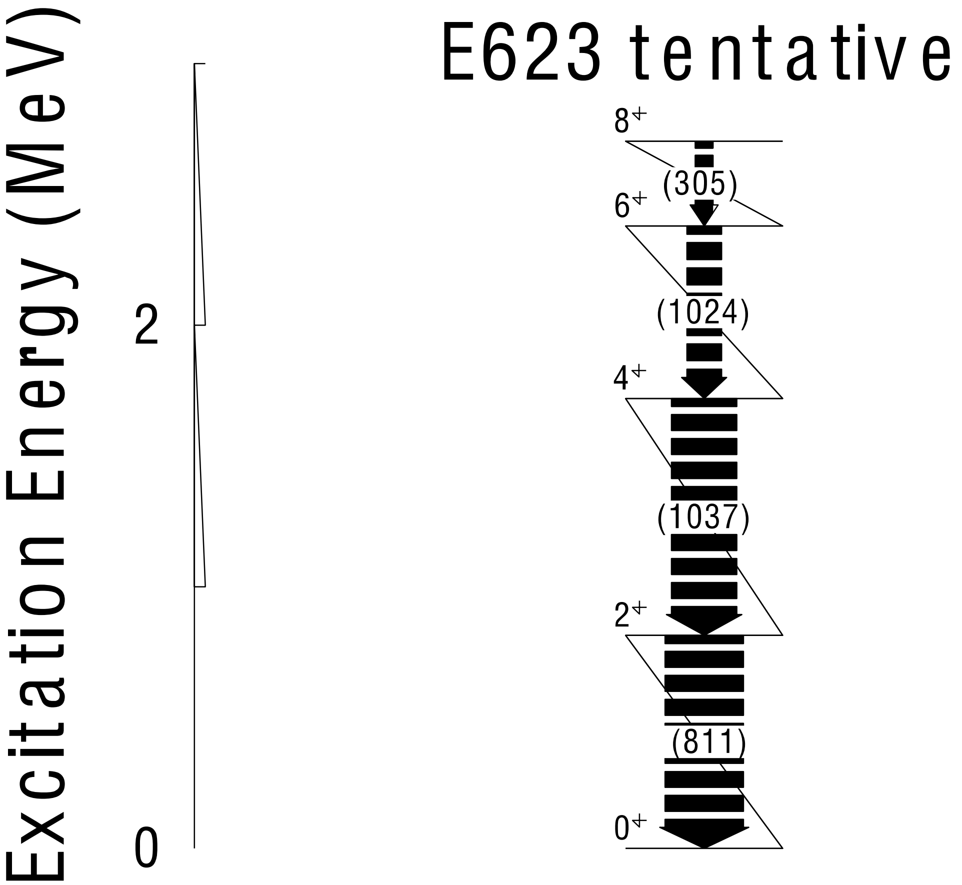
Results (preliminary) E623, 96Cd

U. Jakobsson et al., KTH



Results (preliminary) E623, 96Cd

U. Jakobsson et al., KTH



Results (preliminary) E623, 96Cd

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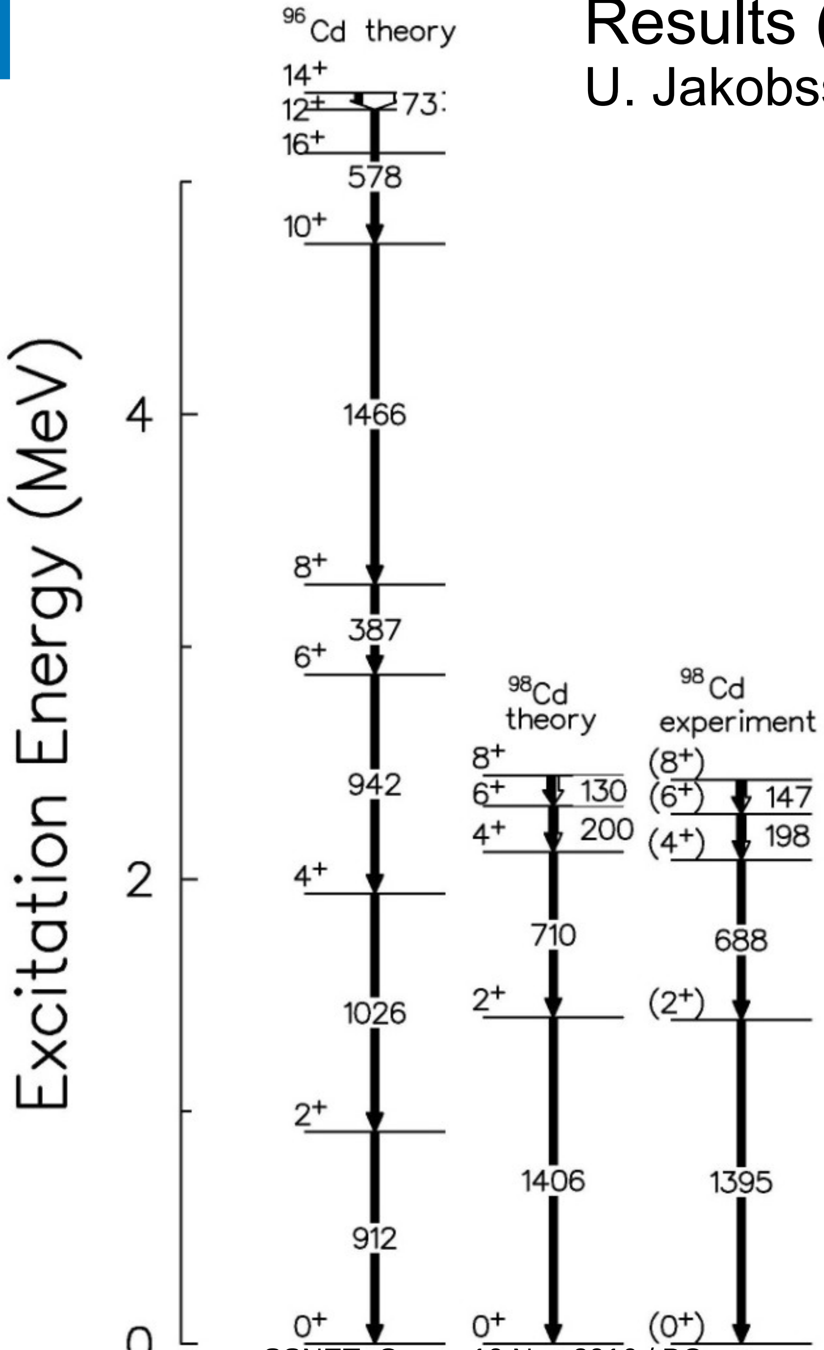
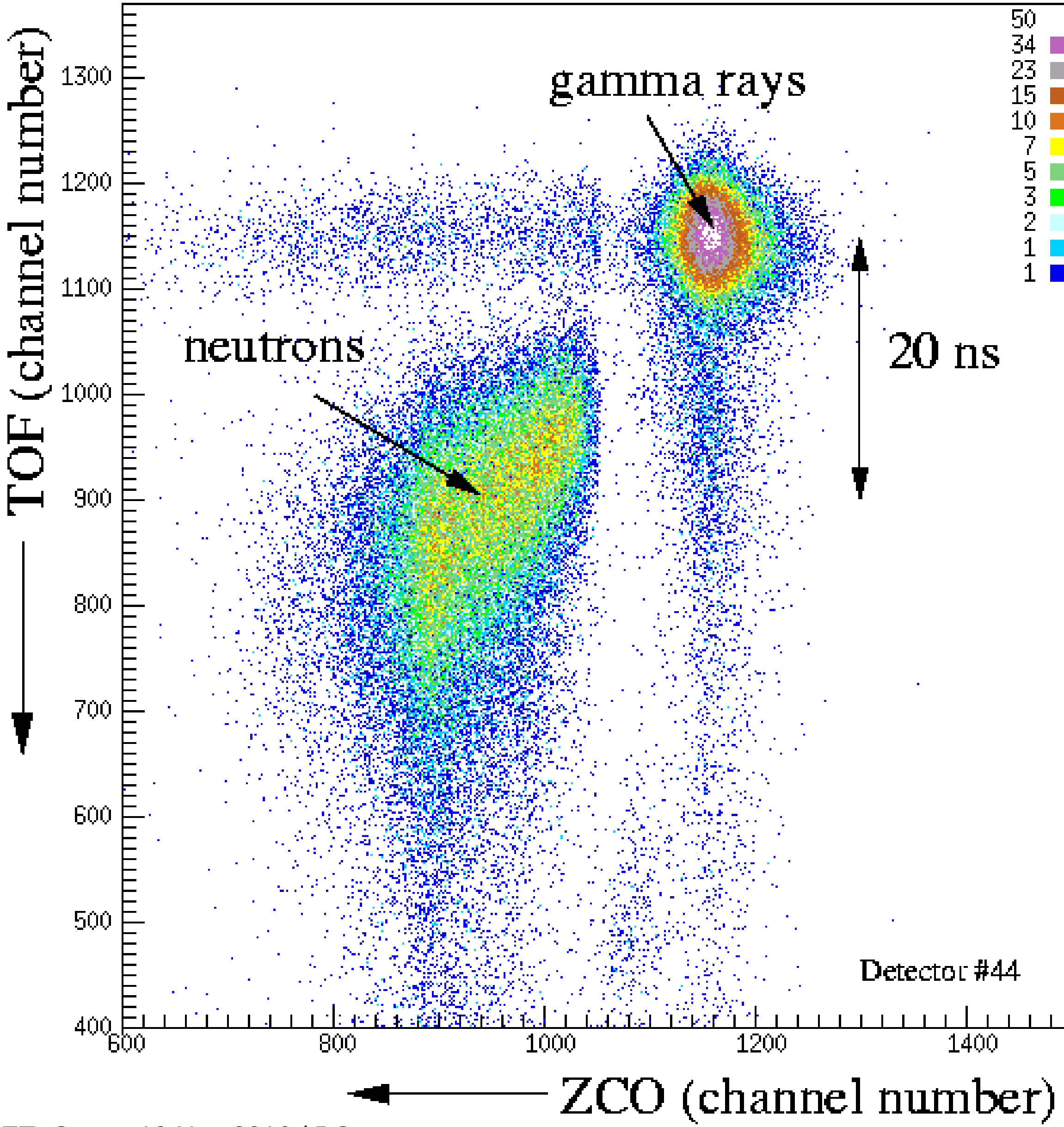
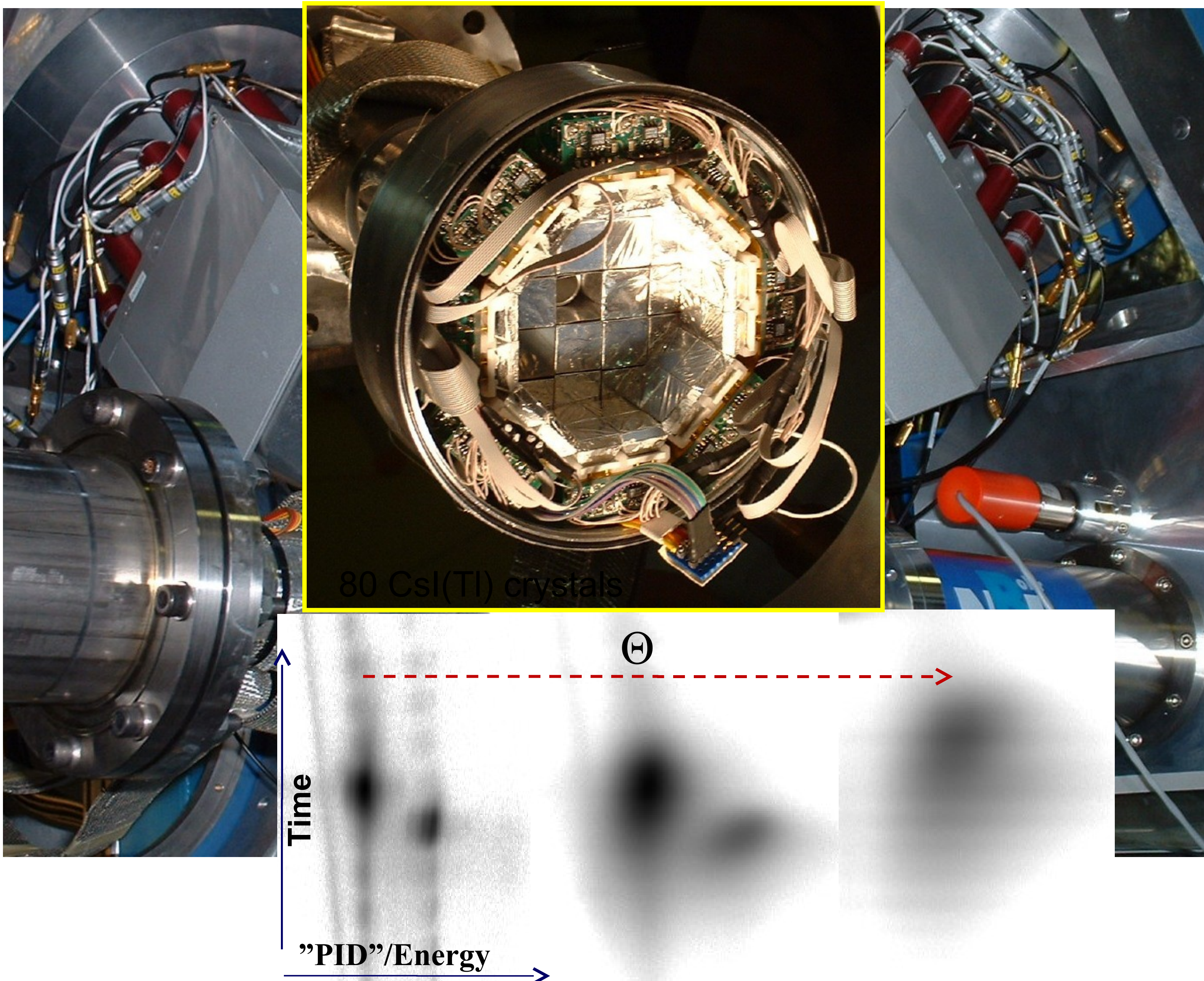


Neutron-gamma separation using the TOF vs. ZCO method

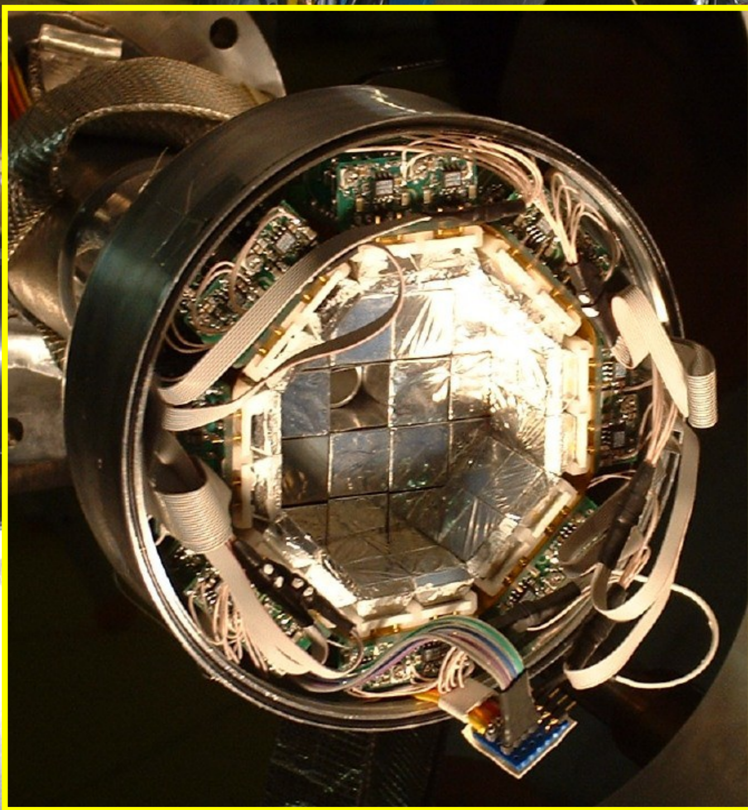


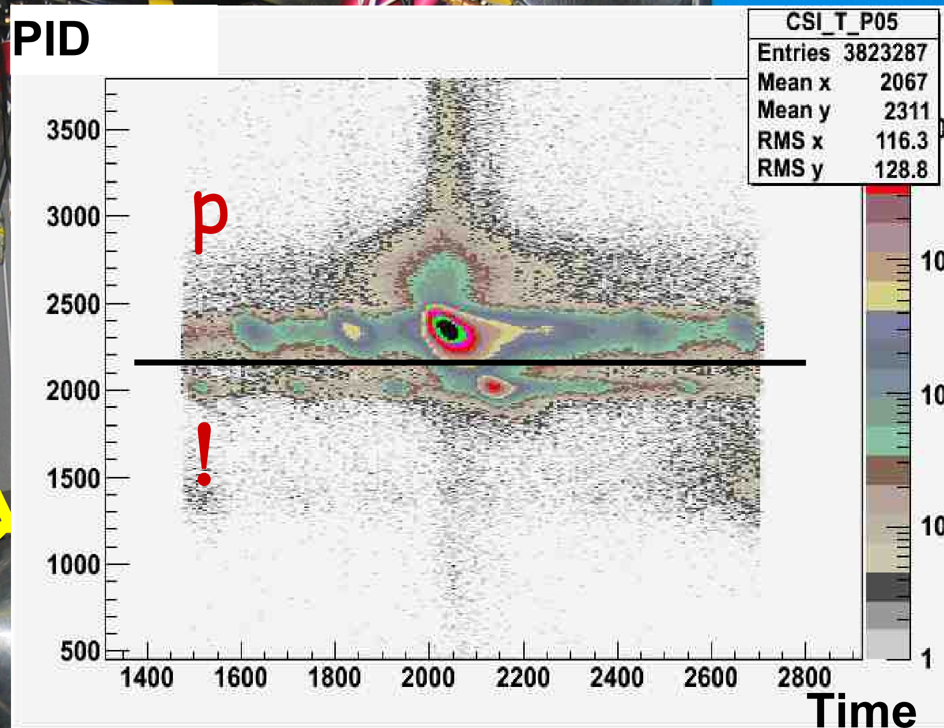
DIAMANT charged particle array – veto and control

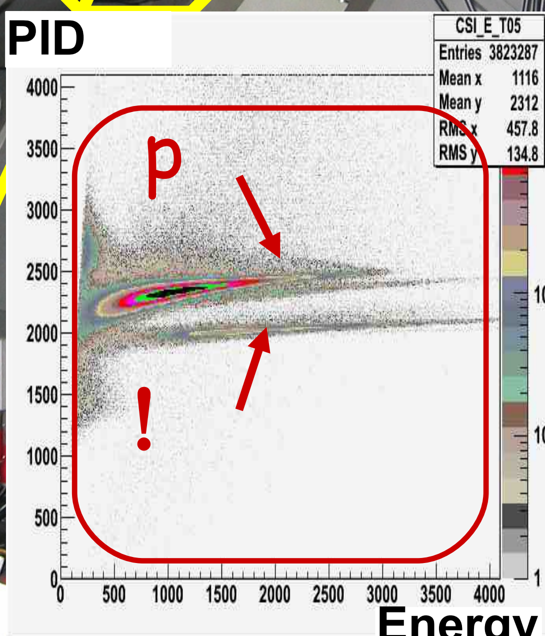


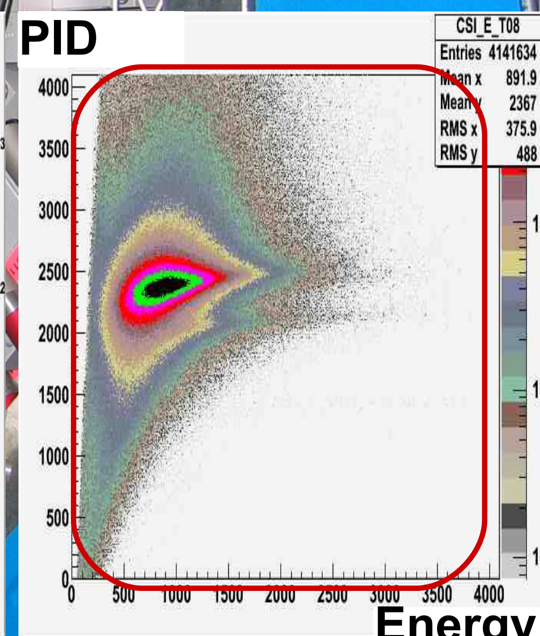
DIAMANT

Charged particle array at EXOGAM



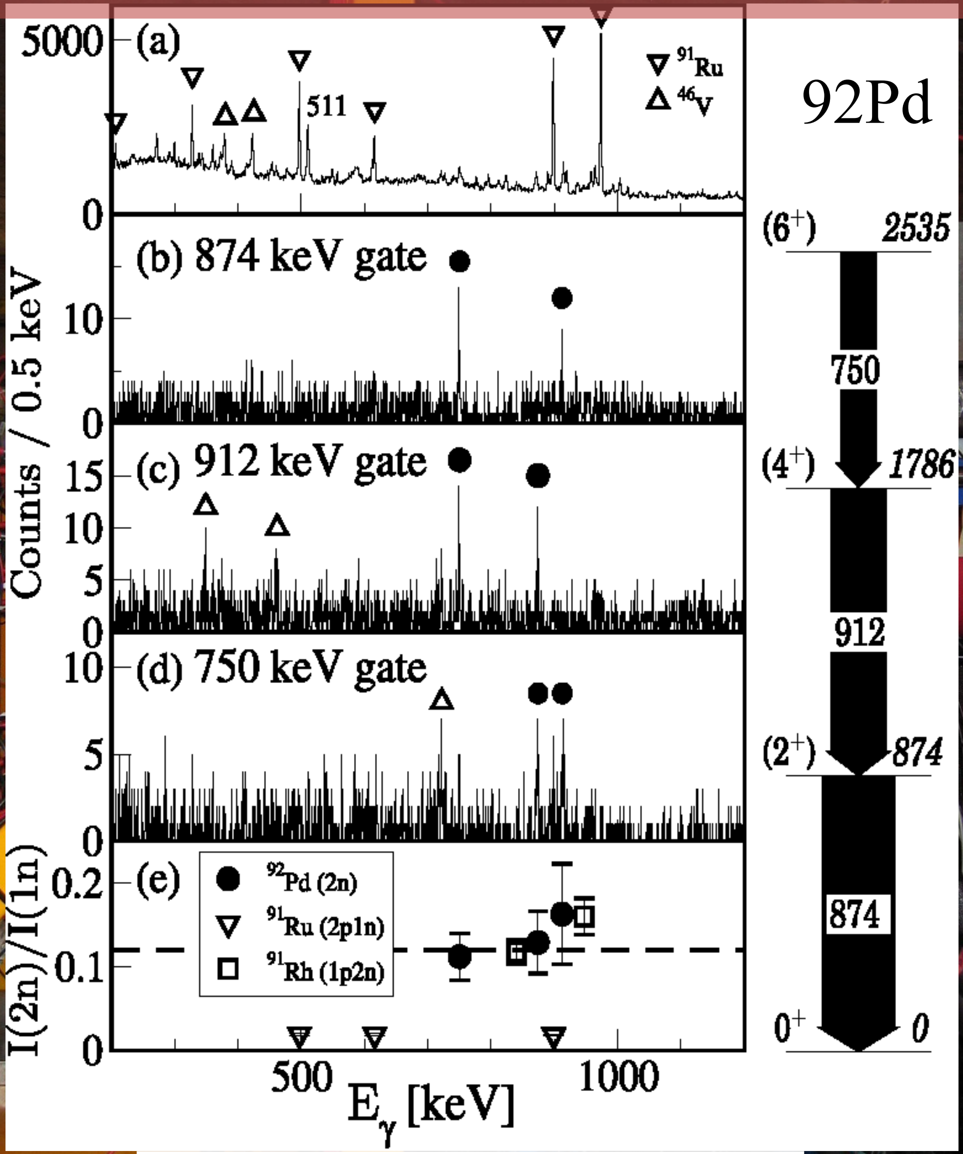




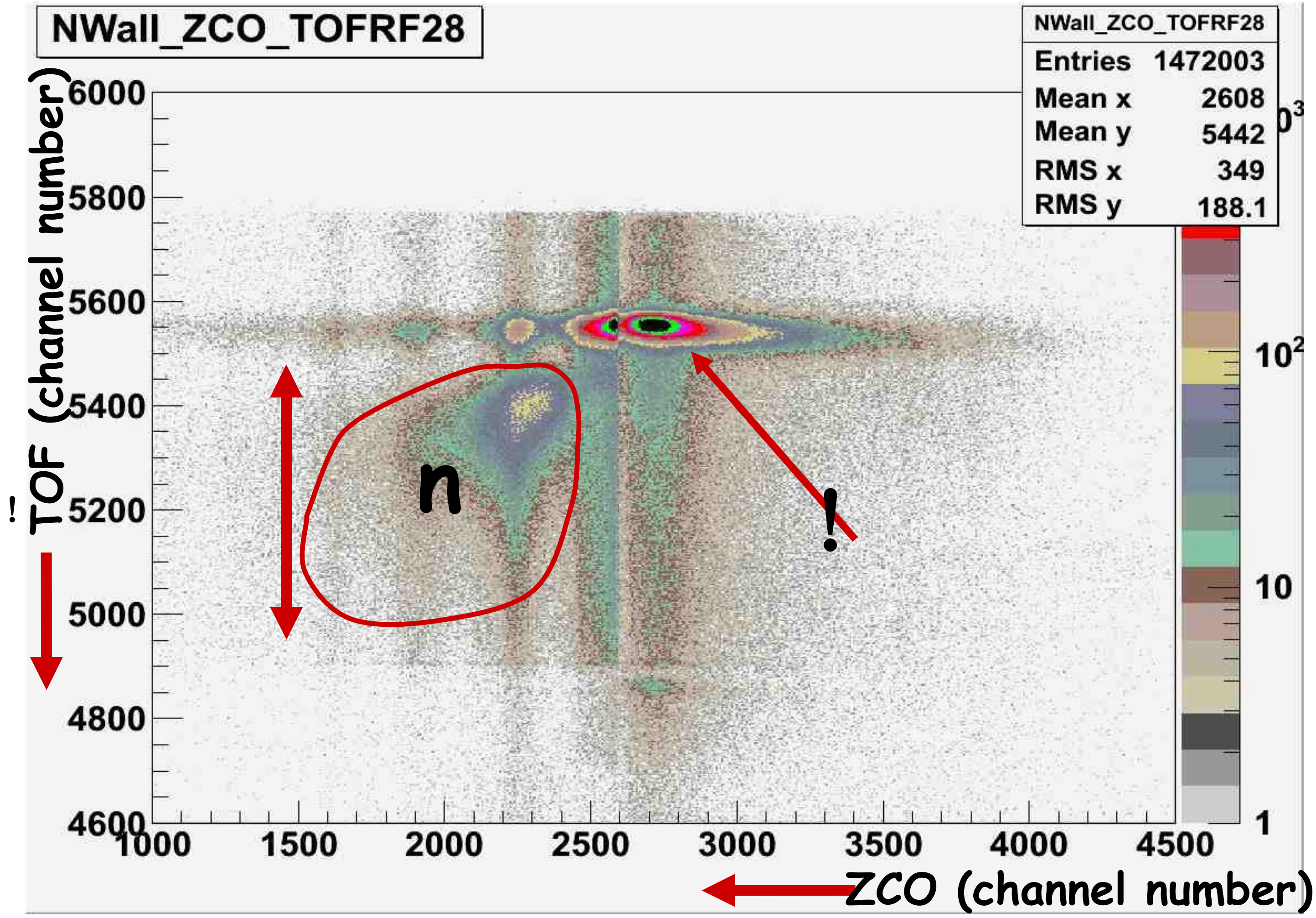


Observation of excited states in the N=Z=46 nucleus 92Pd

EXOGAM + Neutron Wall + Diamant experiment



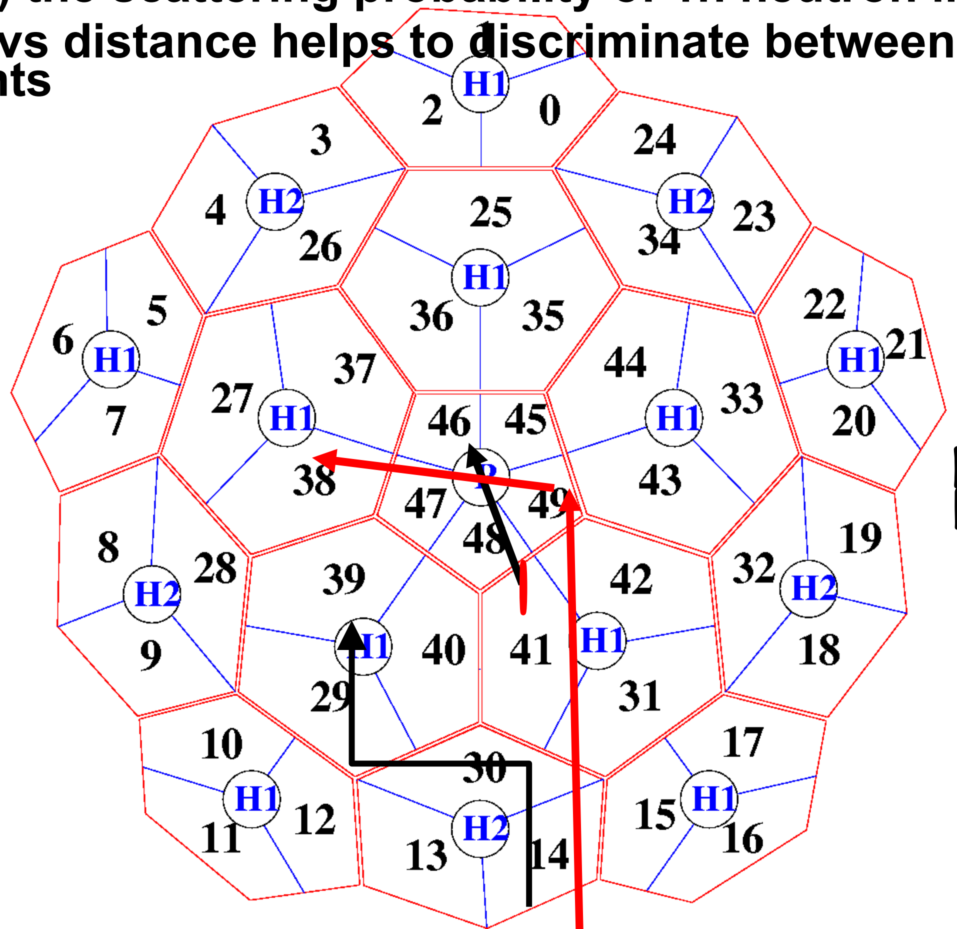
B. Cederwall et al., Nature **469**, 68 (2011)



γ-neutron misidentification probability: 0.12%

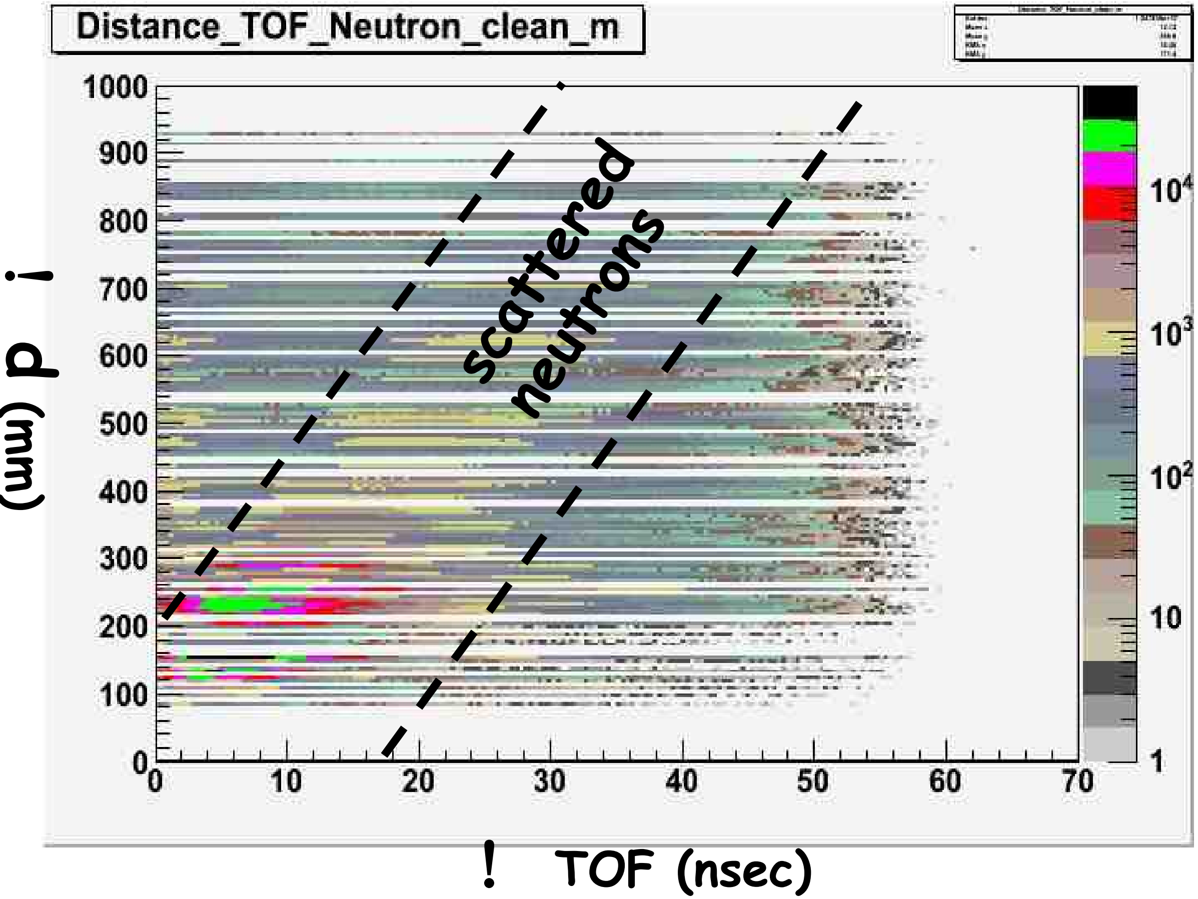
orrection of neutron multiplicity

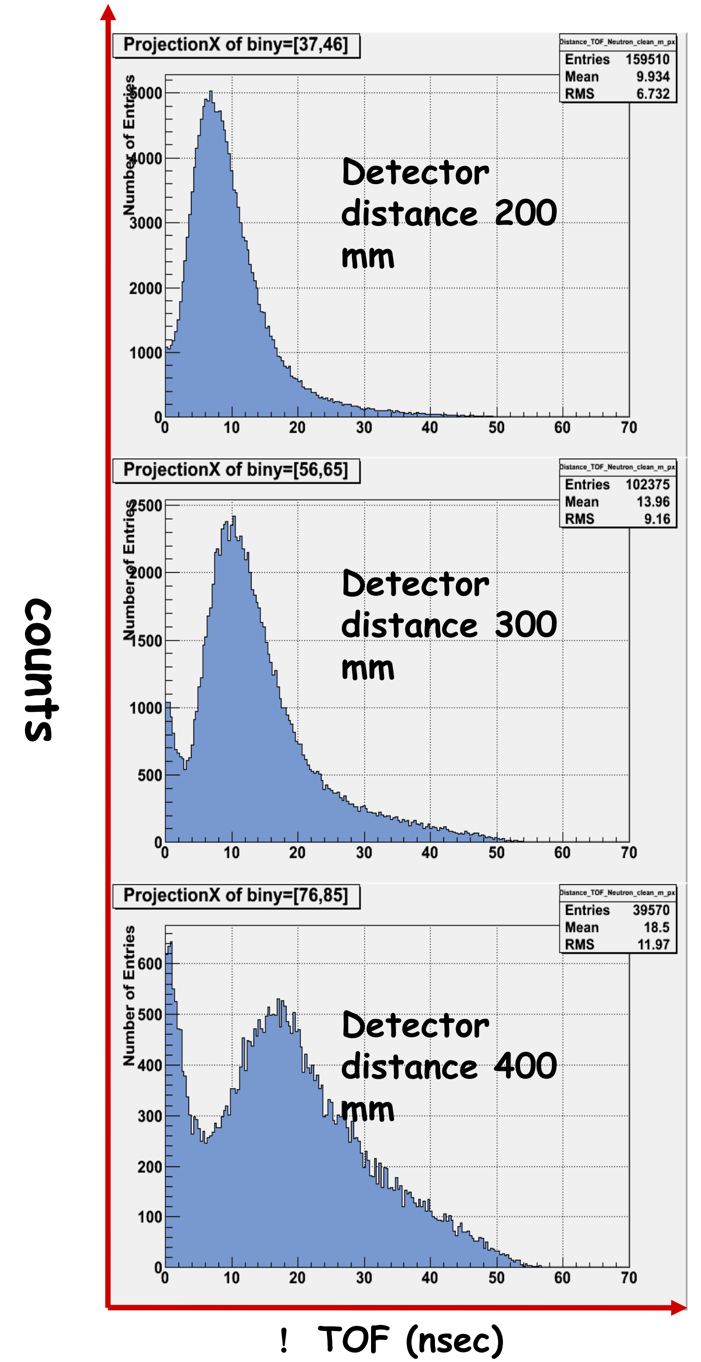
For 91Ru (2pn) the scattering probability of 1n neutron in 2n channel: 12%
Cut on TOF vs distance helps to discriminate between 2n events and 1n-scattered events



Neutron Scattering between detectors

The TOF parameter reveals scattered neutrons





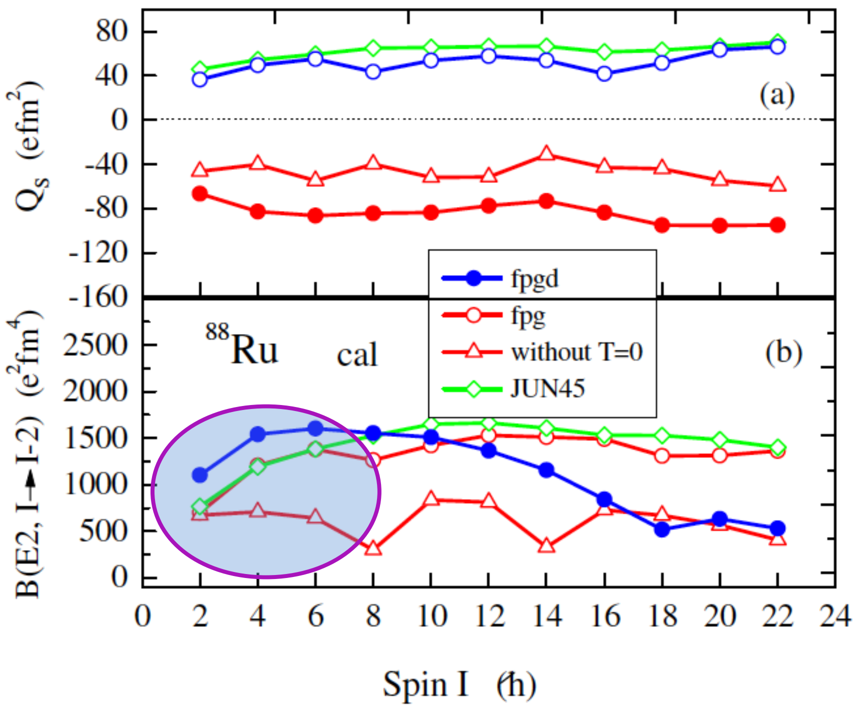
Rejection efficiency of 1n-scattered neutrons

for 91Ru (2pn): 87%

for 12C(36Ar, pn)46V: 75%

and 73% of true 2n events are preserved.

LSSM calculations and np pairing in 88Ru: Transition rates



T1/2theo=26 ps

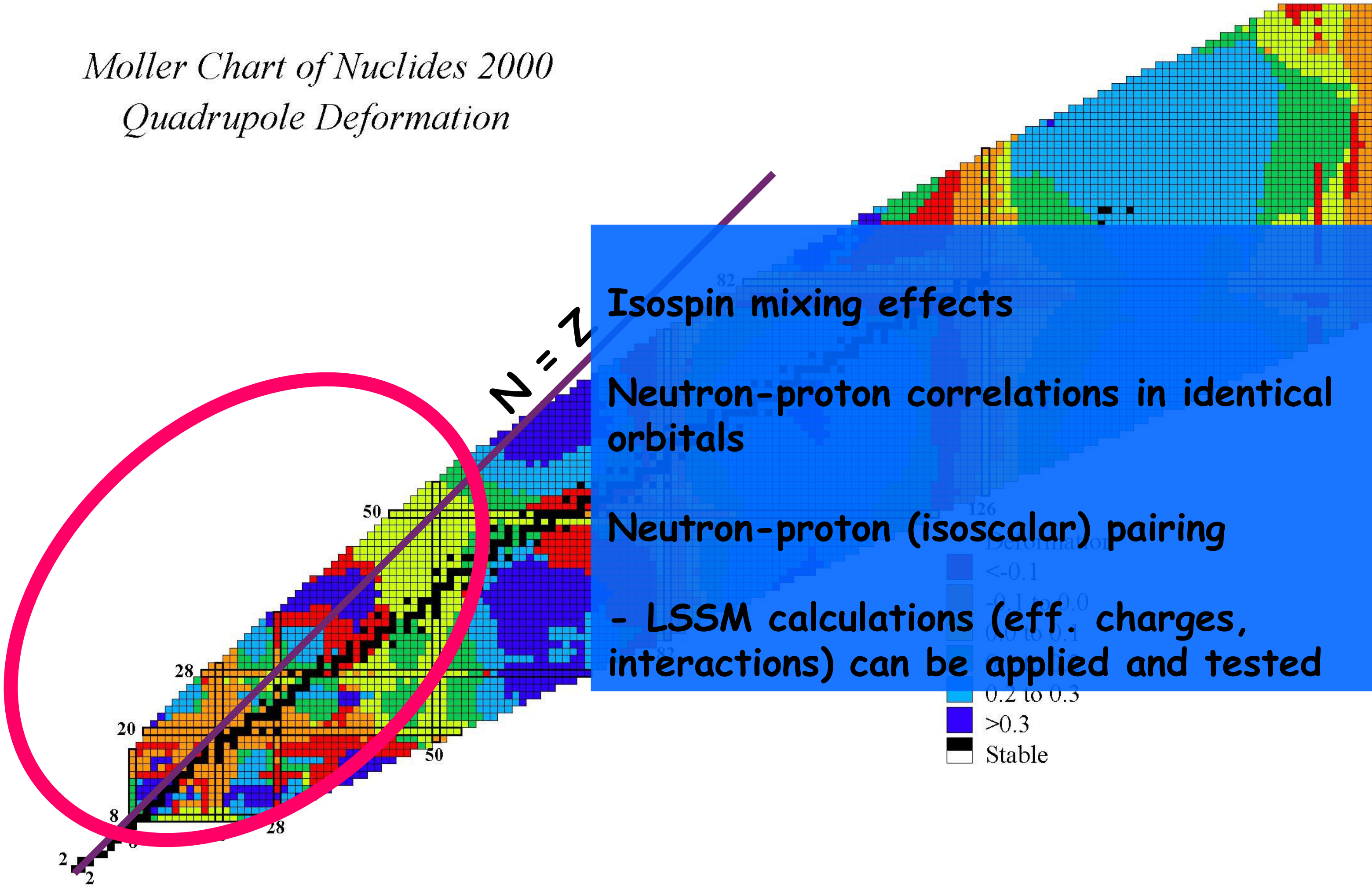
Note: ep =1.5 e en =1.1 e

Kaneko, Sun and de Angelis, submitted to PLB

JUN45, ep =1.5 e en =0.5 e

C. Qi, priv. com

Spectroscopy and lifetime measurements as probes of neutron-proton correlations around 100Sn



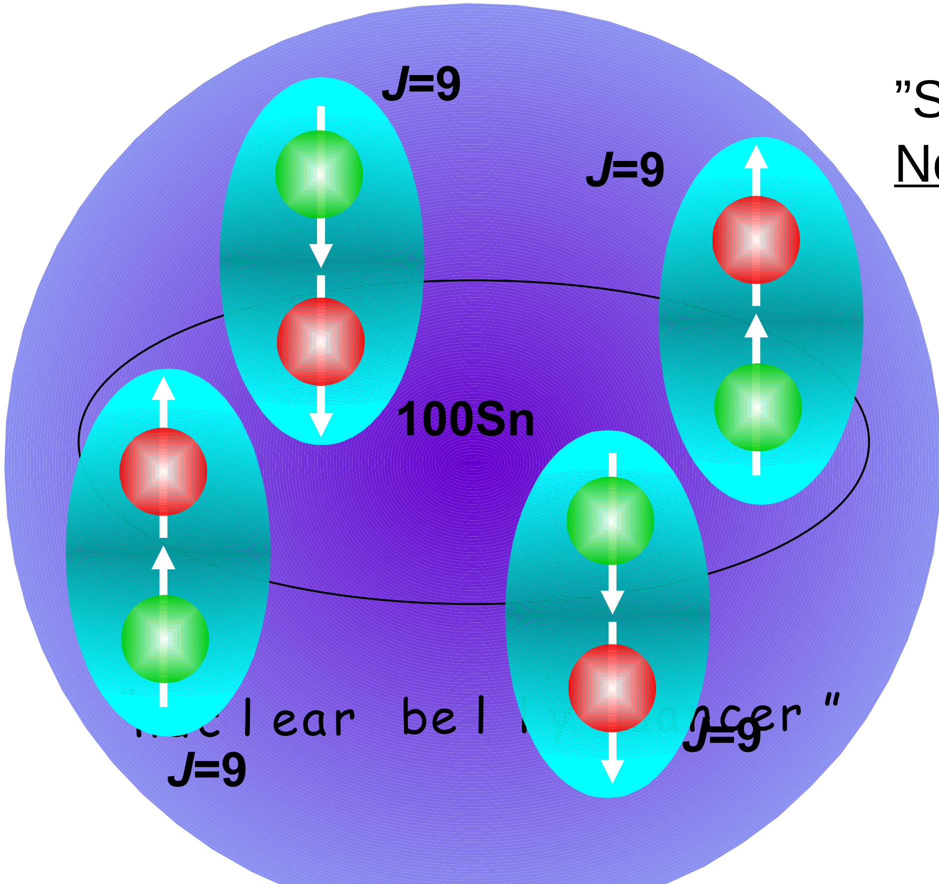
Isospin mixing effects

Neutron-proton correlations in identical orbitals

Neutron-proton (isoscalar) pairing

- LSSM calculations (eff. charges, interactions) can be applied and tested

Strong residual np interactions ➔ Spin-aligned T=0 np coupling scheme for N=Z nuclei below 100Sn



"Spin-aligned *T*=0 np paired phase"

Not pairing as a BCS condensate

The diagonal SM interaction matrix element that corresponds to the isoscalar νπ(g9/2)2 aligned np pair (*J*π = 9+),
*V*9 = ‹g29/2;*J*=9|V|g29/2;*J*=9›,
is strongly attractive, with *V*9 ħ –2 MeV

igned isoscalar np coupling:

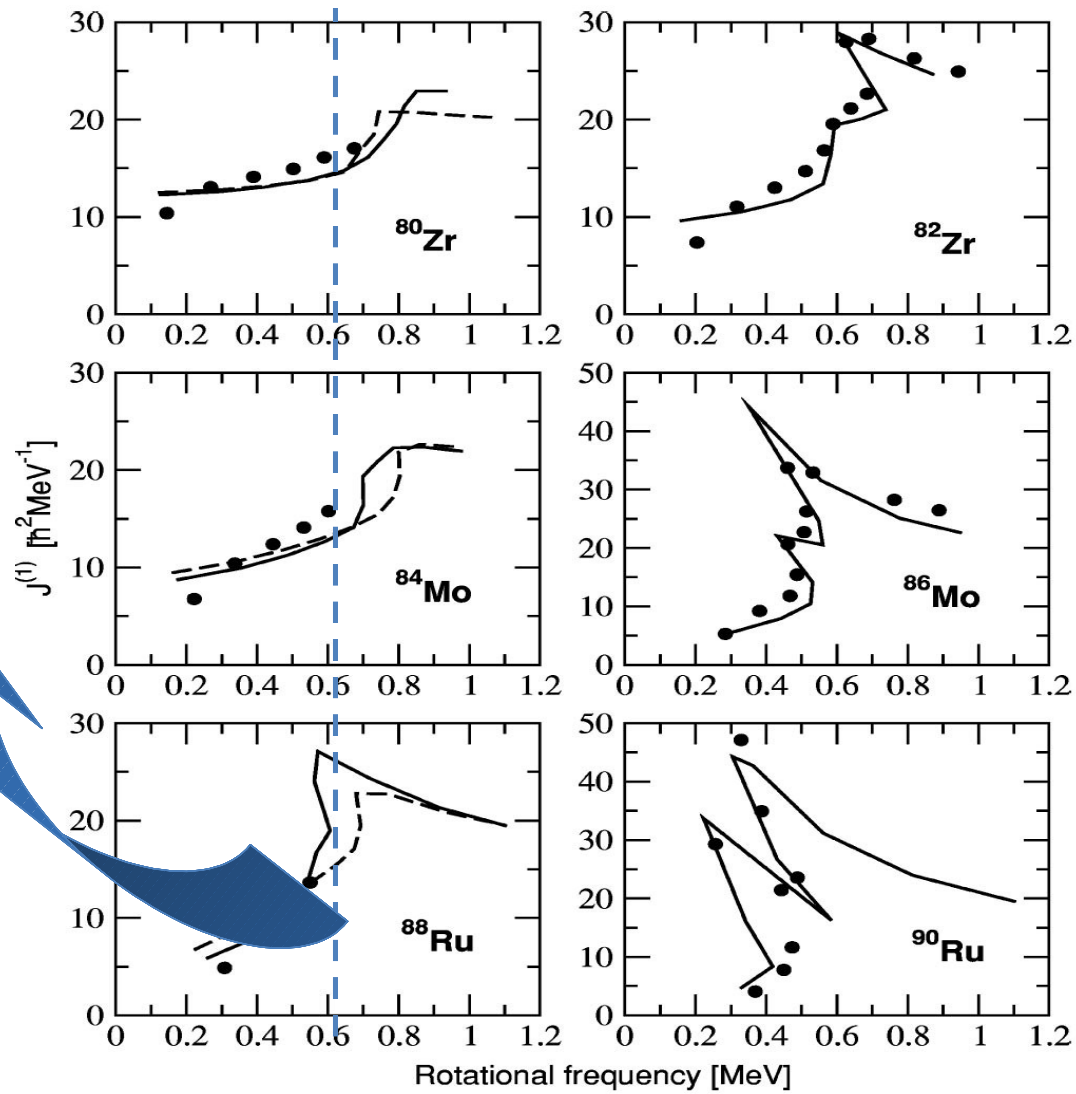
G.S. dominated by a component [({νg 9/2-1 x πg 9/2-1}9+)2]0+ x [({νg 9/2-1 x πg 9/2-1}7+)2

fferent from the standard textbook description of the ground states in even-even nuclei!

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

PSM ____________

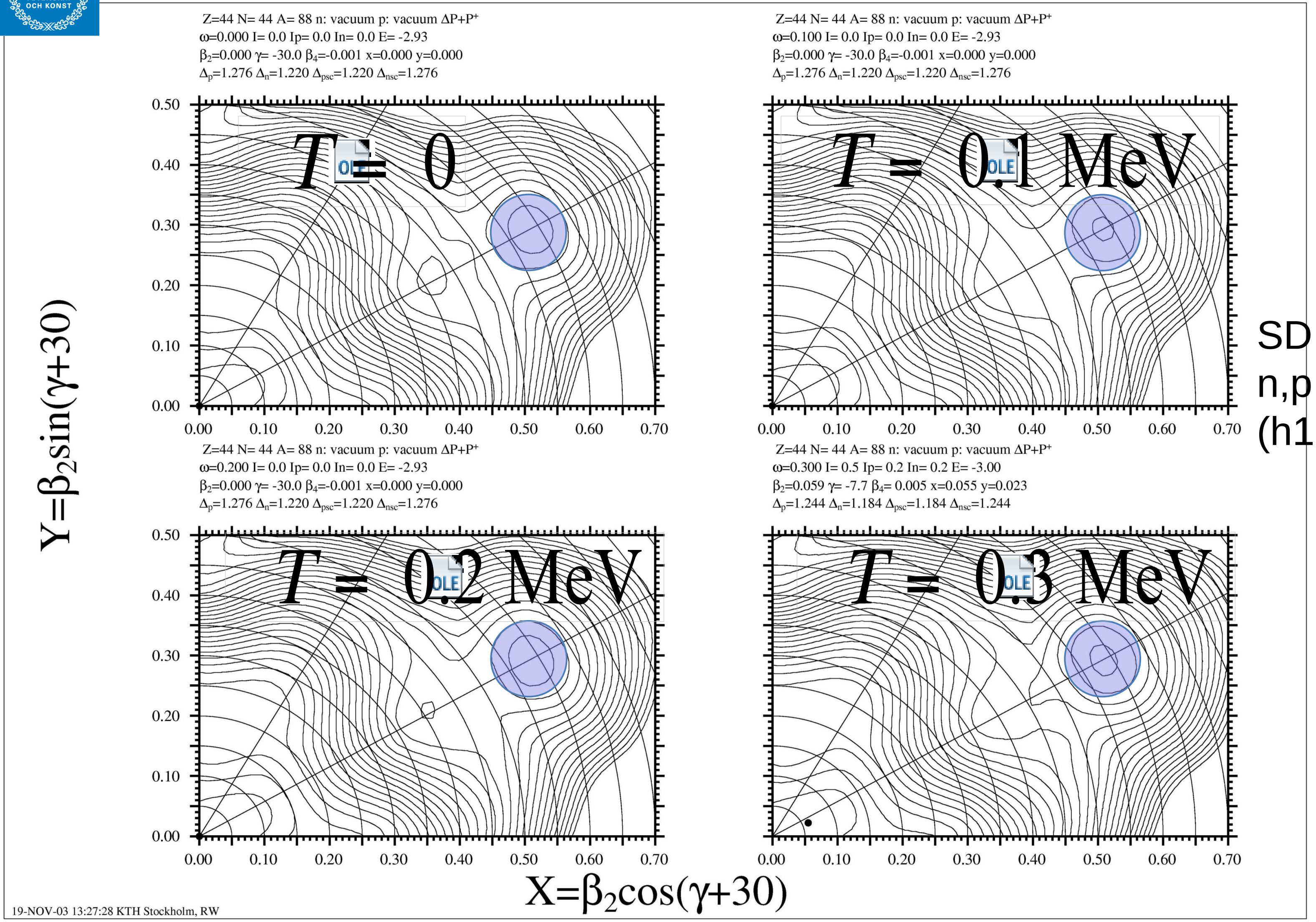
PSM with enhanced np res. int._ _ _ _ _



Data end crucially here!

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

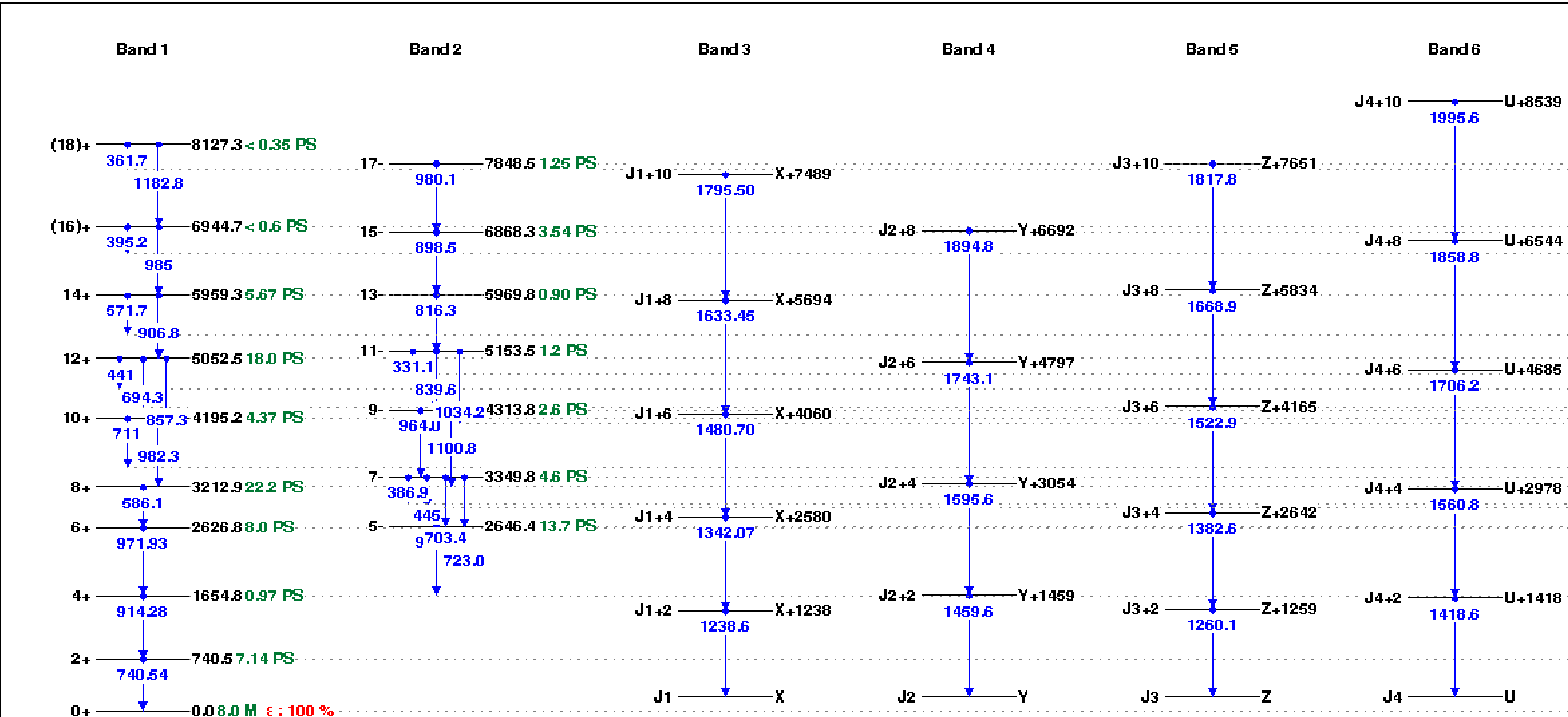
Predictions for 88Ru



SD config. involves n,p high-j intruder (h11/2) orbits.

"Doubly-magic" superdeformed N = Z = 44 88Ru?
Deep SD minumum down to zero rot frequency, low excitation energy (actually yrast at low spin!) – need to test beyond mean-field structure models!

Expected lifetimes



Energy scaling only →~ factor two longer lifetimes in 88Ru yrast band

$^{88}_{42}Mo_{46}$