Recent advances on proton-neutron pairing and quartet correlations in nuclei, Session II

Summary Talk

My goal:

My goal:

ESNT Workshop on Recent Advances on Proton-Neutron pairing… Sept 2-6, 2019

My goal:

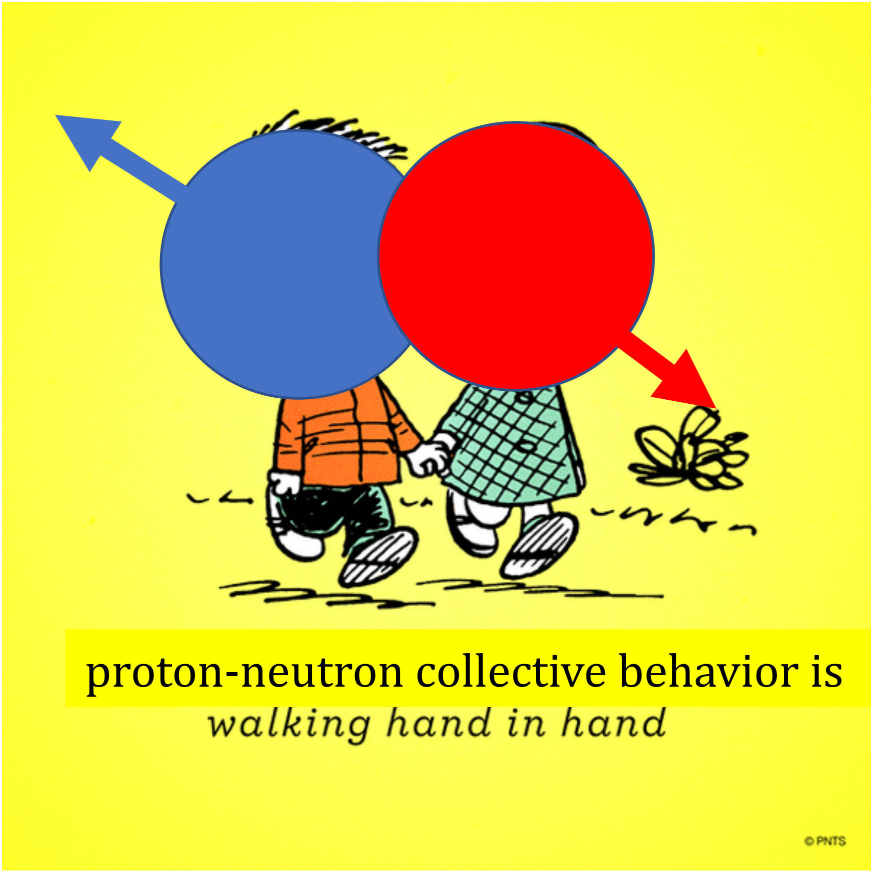
Find correlations and clustering of ideas among the talks

Workshop themes

Simple pictures of cooperative behavior

Workshop themes

Simple pictures of cooperative behavior

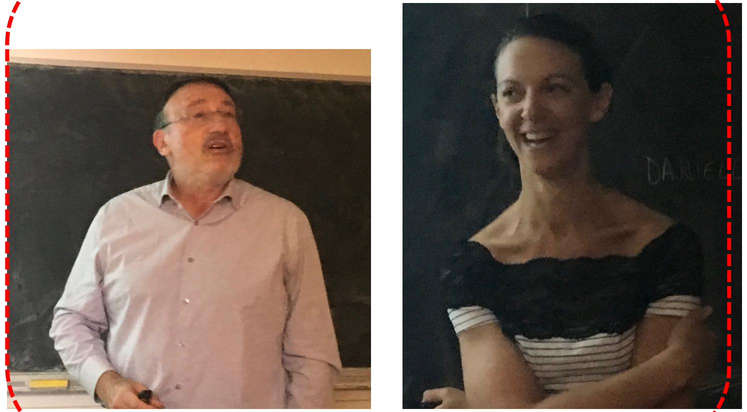


Workshop themes

Keep in mind
this is a 'mean-field' summary,
that is,
I won't get all the high-resolution details,
but instead focus on, well,
the average picture….

Evidence for pairing/ p-n pairing /clustering

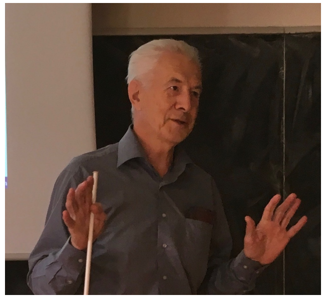
theory cluster

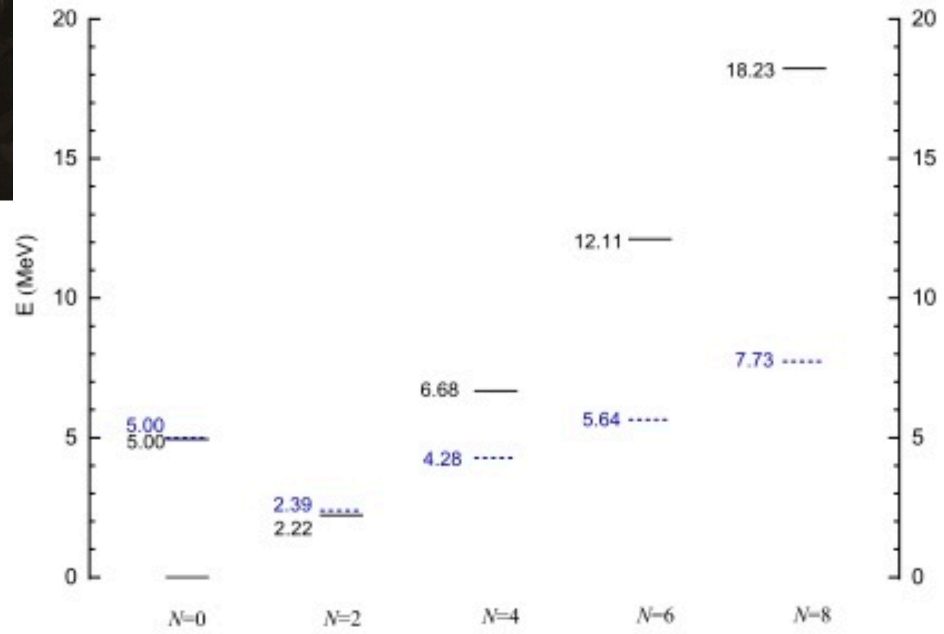


experimental pair
(correlation in momentum
not coordinate space…)

Evidence for pairing/ p-n pairing /clustering

Energies of the 0^+ T=0 states in ^{56}Ni



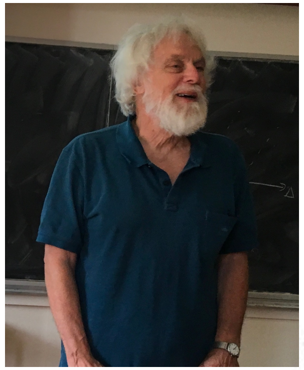


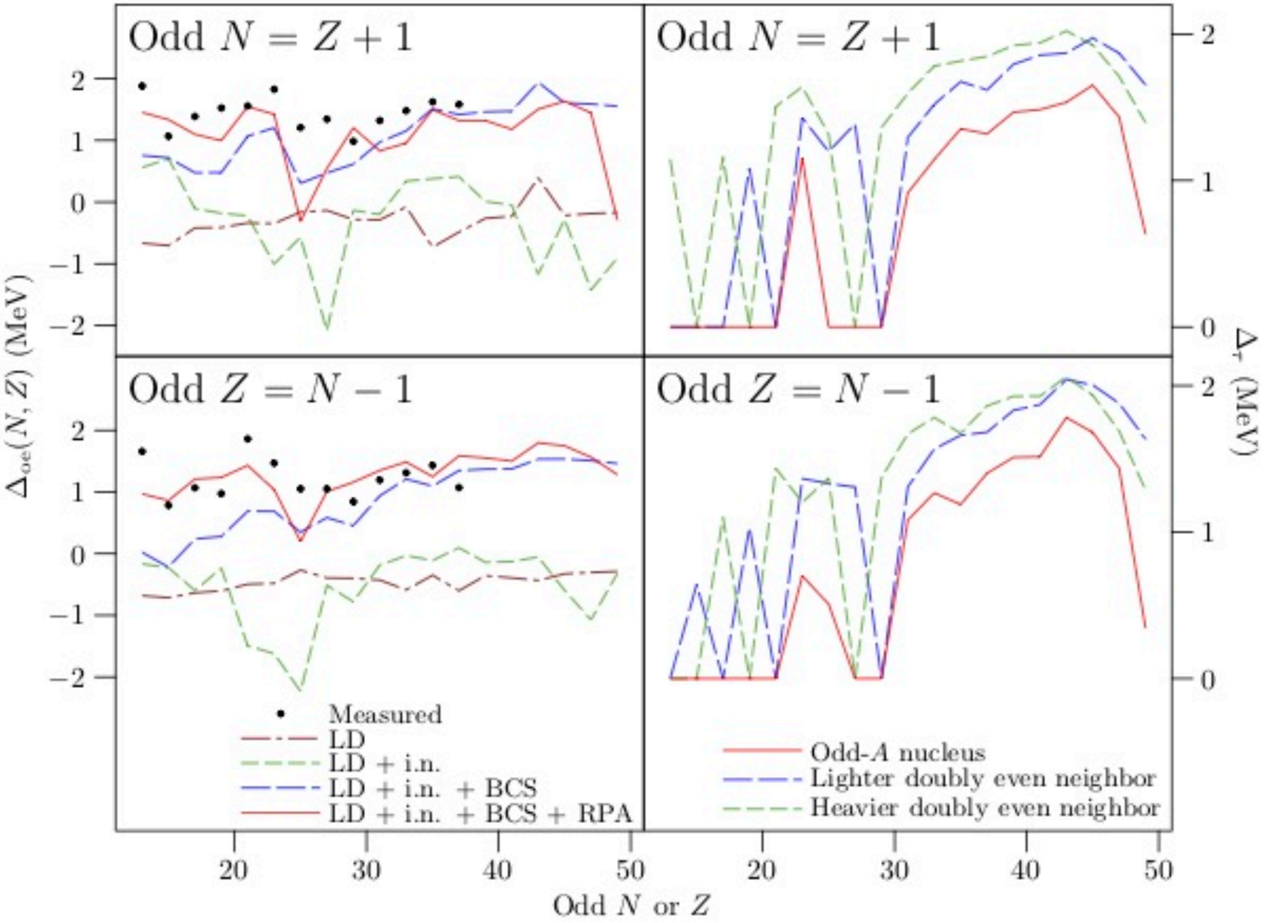
Pairing "rotations" and "vibrations" in spectra

$G_1 = \frac{14.4}{A}$MeV is fixed to reproduce the energy of the pairing vibrational state in ^{56}Ni at 5 MeV. d=0.6 for ^{56}Ni

Evidence for pairing/ p-n pairing /clustering

Results for $Z = N - 1$





pair vibrations and odd-even mass differences

Evidence for pairing/ p-n pairing /clustering

EFFECT OF QUADRUPLE CORRELATIONS IN LIGHT NUCLEI

V G SOLOVIEV
Joint Institute of Nuclear Research, Dubna, USSR

Received 25 December 1959

"quadruple"= two interacting pn pairs

Fingerprints of alpha-like (quadruple) correlations

1) Extracting a pn pair from a even-even N=Z nucleus costs more energy than adding to it a pn pair

^{22}Na ← 22.1 MeV — ^{24}Mg — 13.6 Mev → ^{26}Al — 24.4 MeV — ^{28}Si

2) Extracting one neutron from a even-even N=Z nucleus costs more energy than from neighbouring nuclei

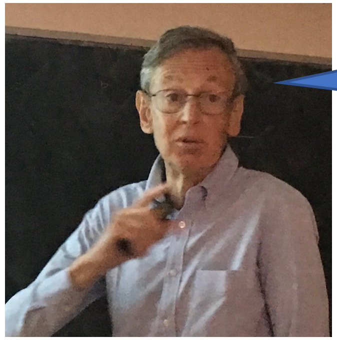
$B(^{24}Mg)-B(^{23}Mg) = 16.6$ MeV

$B(^{25}Mg) - B(^{24}Mg) = 7.3$ Mev

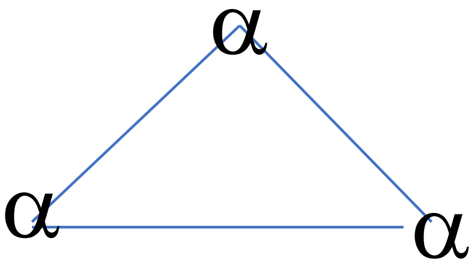
$B(^{26}Mg)-B(^{25}Mg) = 11.3$ Mev

to brake a quadruple (quartet) in pairs takes about 4-5 MeV

Evidence for pairing/ p-n pairing /clustering

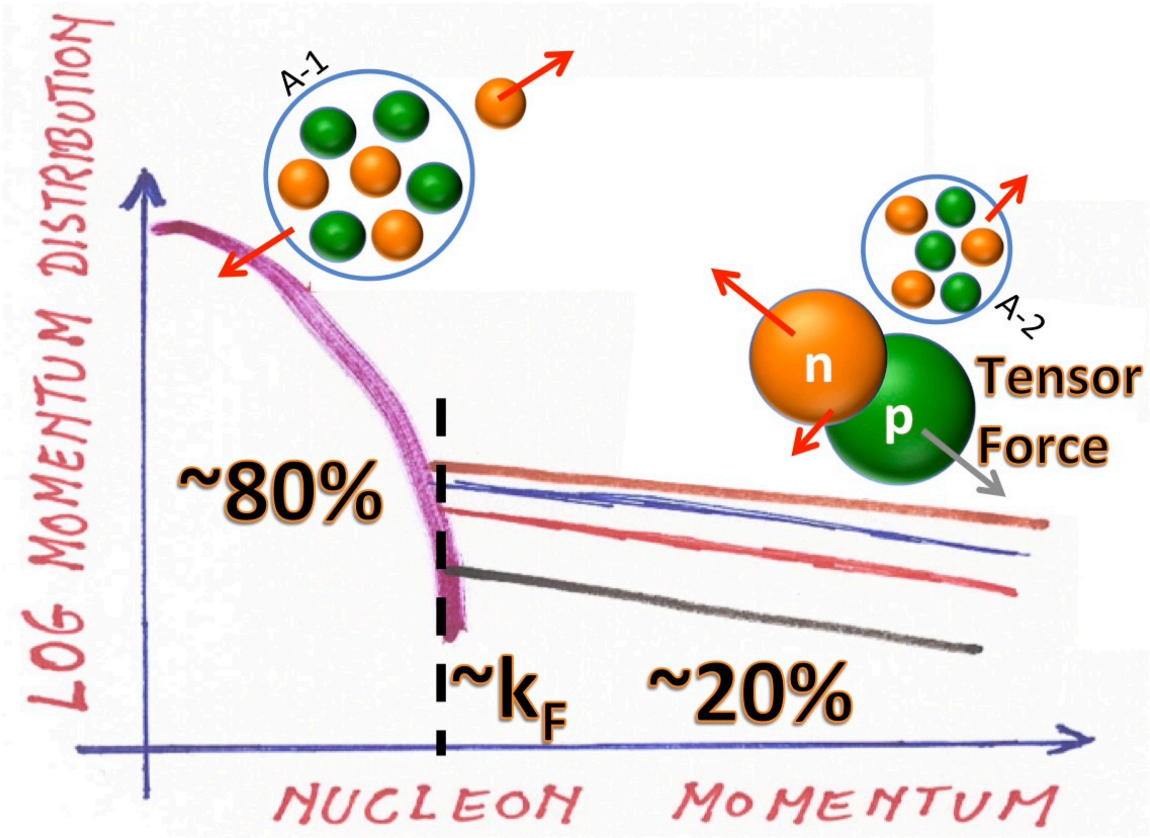


Band structure (0+ 2+, 3-,) and transition densities in inelastic α-^{12}C shows evidence of D3h discrete symmetry



Evidence for pairing/ p-n pairing /clustering

A high-momentum tail is attributed to SRCs between a pair of strongly interacting nucleons; a value of about 20% SRC contribution was indirectly inferred.



Duer, Nature (2018); Cohen, PRL (2018); Hen, RMP (2017); Hen, Science (2014); Hen, PLB (2013) Korover, PRL (2014); Fomin, PRL (2012); Subedi, Science (2008); Piasetzky, PRL (2007); Egiyan, PRL (2006)

(weakly coupled experimental talk)

Evidence for pairing/ p-n pairing /clustering

+ bonus round on ^{40}Mg...

(weakly coupled experimental talk)

Evidence for pairing/ p-n pairing /clustering

Experimental searches for strong p-n pair correlations in (p,^{3}He) transfer reactions (T=0 pairing seems weaker in *pf* shell than *sd*)

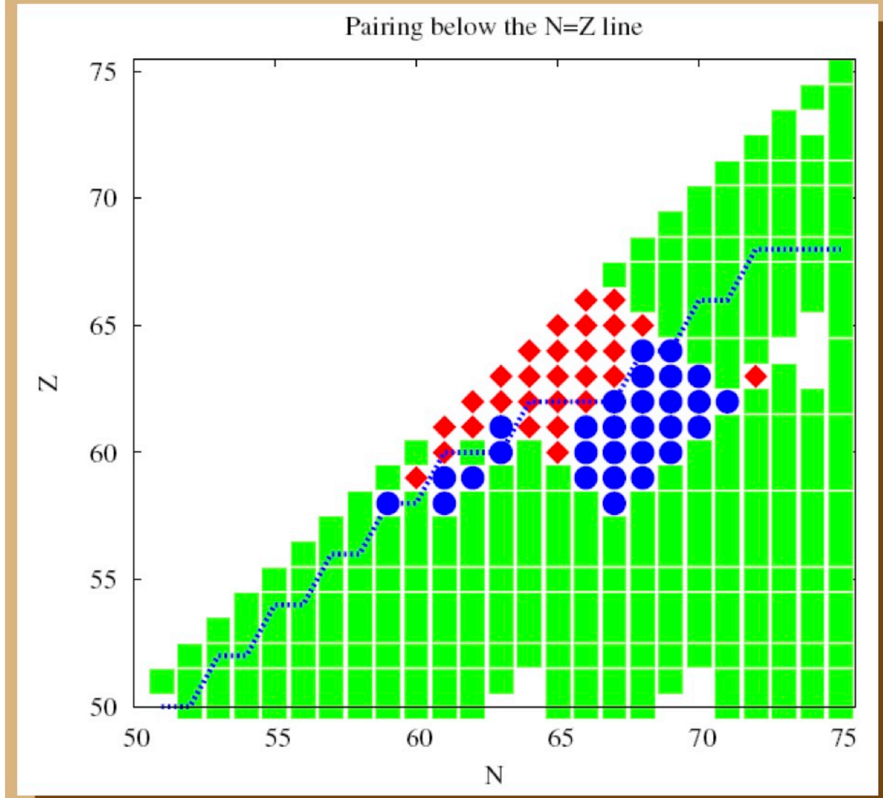
and proposed tests for α-quartets via (6Li,d) or (7Li,t) transfer reactions

What drives pairing and clustering?

(a diffuse cluster with long-range correlations..?)

What drives pairing and clustering?

Pairing in heavy nuclei (A~130)



Correlation energies

- Blue line: proton drip
- Green: spin-singlet
- Red: spin-triplet
- Blue: mixed-spin
- Spin-triplet pairing persists off N=Z line
- Mixed-spin pairing appears to be energetically stable (note: no deformation)

A. Gezerlis, G. F. Bertsch, and Y. L. Luo, Phys. Rev. Lett. **106**, 252502 (2011)

What drives pairing and clustering?

Clustering occurs in states near continuum: residue of (g.s.) A–α scattering resonances

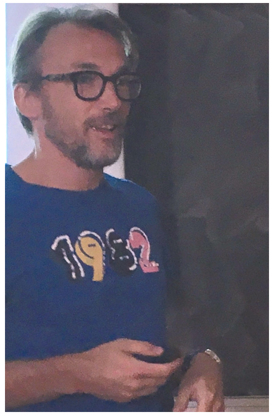
What drives pairing and clustering?

Deformation and low density drives scattering

(not orthogonal to Volya)

How can we better model nuclei?

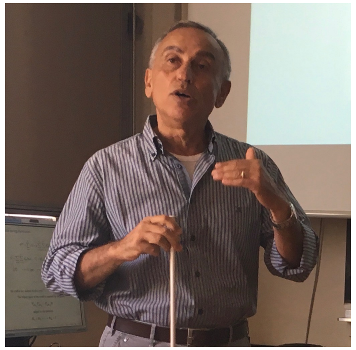
“Mean-field” + projection


(coupled via tensor force)



What the shell model can teach us



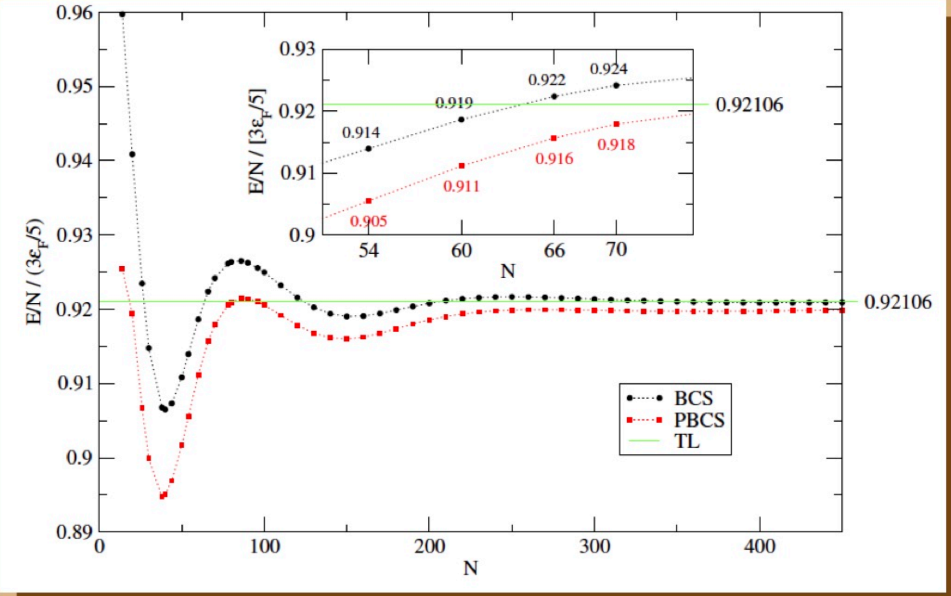
Condensing the shell model to pairs & quartets

How can we better model nuclei?

"Mean-field" + projection

BCS in a box: symmetry restoration

$$|\psi_N\rangle = \int_0^{2\pi} \frac{d\phi}{2\pi i} e^{-iM\phi} \prod_{\mathbf{k}} \left(u_{\mathbf{k}} + e^{i\phi} v_{\mathbf{k}} \hat{p}^\dagger_{\mathbf{k}} \right) |0\rangle$$



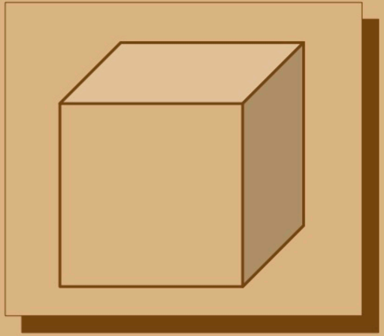
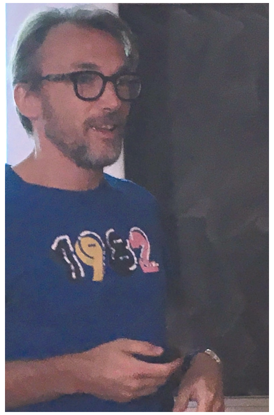


Figure by George Palkanoglou

How can we better model nuclei?

"Mean-field" + projection



Extend the reach of successful theories (coupled-cluster, MBPT) by symmetry breaking -> restoration

So far only U(1) (number)
but SU(2) (deformation) promised!

How can we better model nuclei?

"Mean-field" + projection

When driven to large deformation, we can (sometimes) see clusters arise in projected mean-field calculations

How can we better model nuclei?

"Mean-field" + projection

Use SO(8) model to test VBP vs VAP

Pairing coexistence seen by the VAP approach!

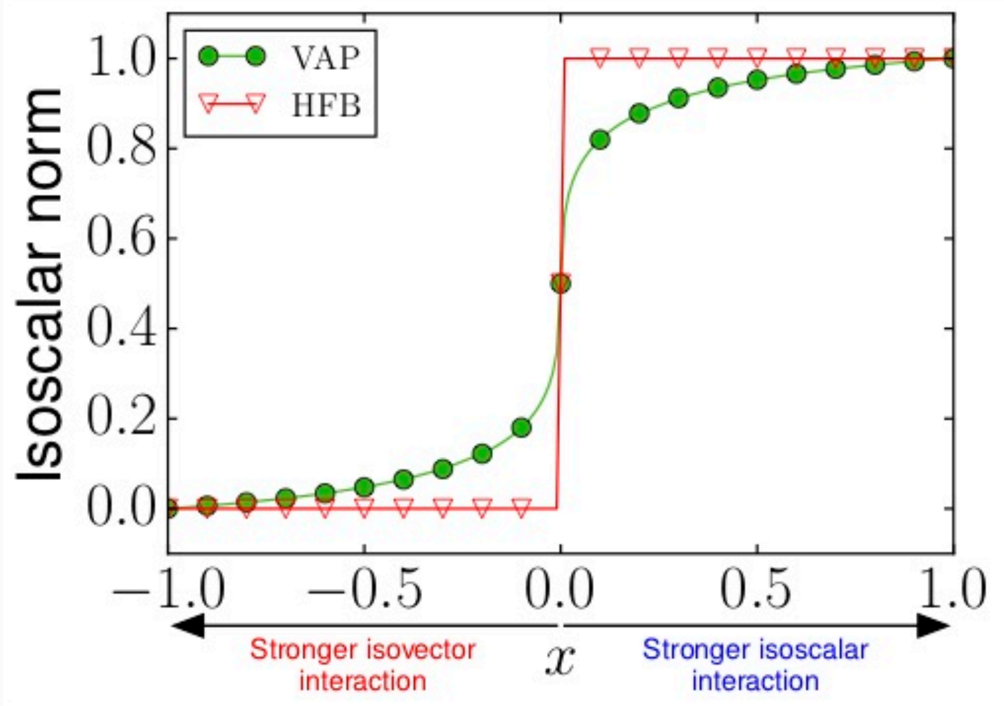


Figure 5: Norm of isoscalar pairs (contribution to the total wavefunction of the nucleus) as a function of the tuning parameter x obtained from VAP and PAV (HFB) methods.

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How can we better model nuclei?

"Mean-field" + projection

Spin & isospin projection seem most important!

Importance of the separate symmetry restorations

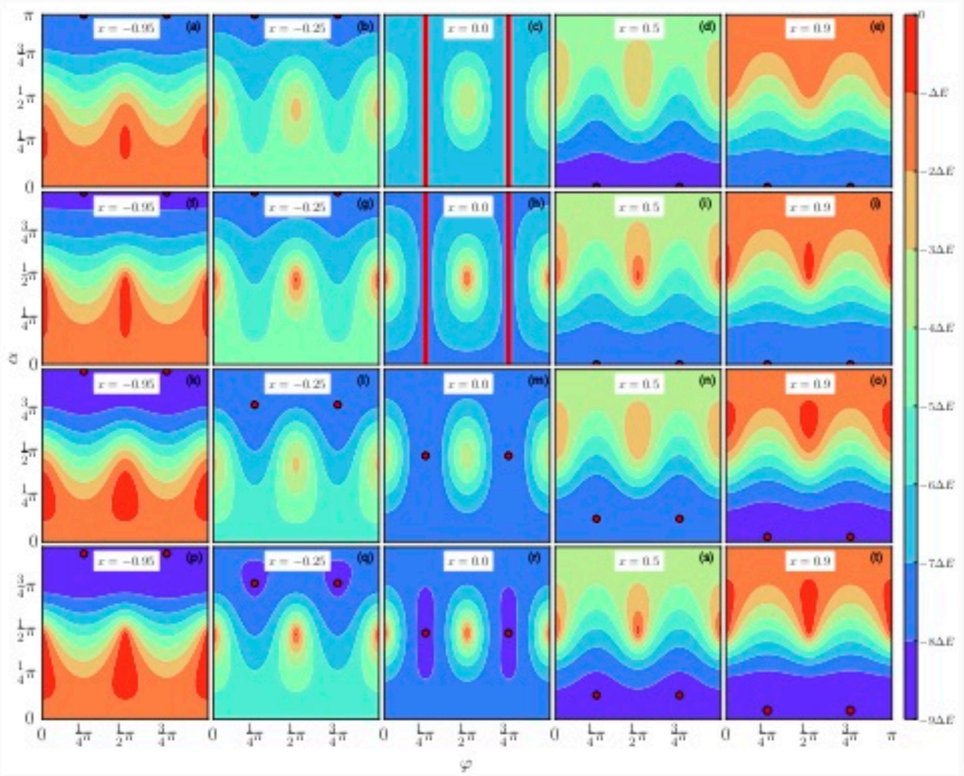
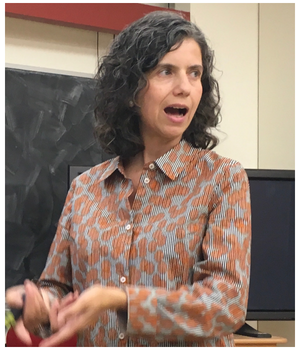


Figure 6: HFB (first row), particle-number restored (second row), spin plus isospin restored (third row) and particle number, spin and isospin restored (fourth row) energy surfaces.

How can we better model nuclei?

"Mean-field" + projection



Importance of tensor force

Introduction

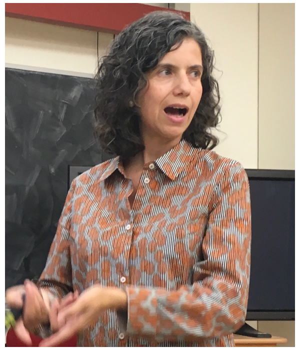
- Otsuka *et al.* showed that shell evolution cannot be studied without tensor force
  Phys. Rev. Lett. **95**, 232502 (2005)
- They proposed a new parametrization for the Gogny force including a tensor-isospin term → GT2
  Phys. Rev. Lett. **97**, 162501 (2006)

μ (fm)	W (MeV)	B (MeV)	H (MeV)	M (MeV)
0.7	2311	−3480	2962	−2800
1.2	−339	388	−370	260

W_0=160 MeV fm^5 $x_0 = 1$ $\alpha = 1/3$

How can we better model nuclei?

"Mean-field" + projection



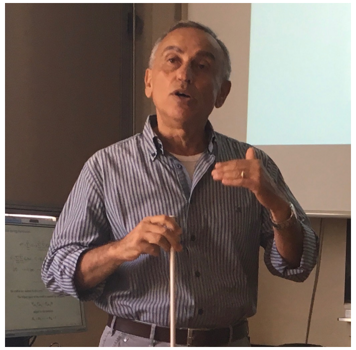
Preliminary results in mirror nuclei

2^+ and 4^+ excitations for mirror nuclei: O isotopes

Nucleus	excited state	D1S	D1ST2a	D1M	D1MTd	exp
^{18}O	2^+	2.409	2.615	2.324	2.691	1.982
	4^+	3.452	3.677	3.196	3.575	3.554
^{18}Ne	2^+	1.787	1.973	1.697	2.027	1.887
	4^+	2.703	2.912	2.467	2.811	3.338
^{20}O	2^+	2.342	2.509	2.233	2.554	1.67
	4^+	3.493	3.690	3.191	3.535	3.57
^{20}Mg	2^+	1.633	1.809	1.528	1.832	1.65
	4^+	2.627	2.825	2.363	2.685	3.70
^{22}O	2^+	2.839	2.936	2.447	2.716	3.199
	4^+	4.067	4.430	3.423	3.876	
^{22}Si	2^+	2.212	2.325	1.920	2.121	
	4^+	3.477	3.722	2.936	3.329	

How can we better model nuclei?

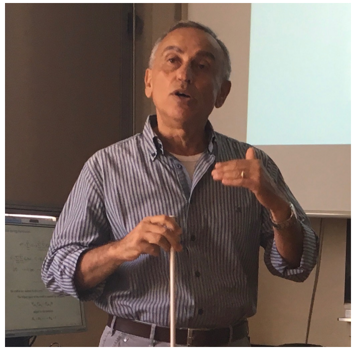
What the shell model can teach us



Condensing the shell model to pairs & quartets

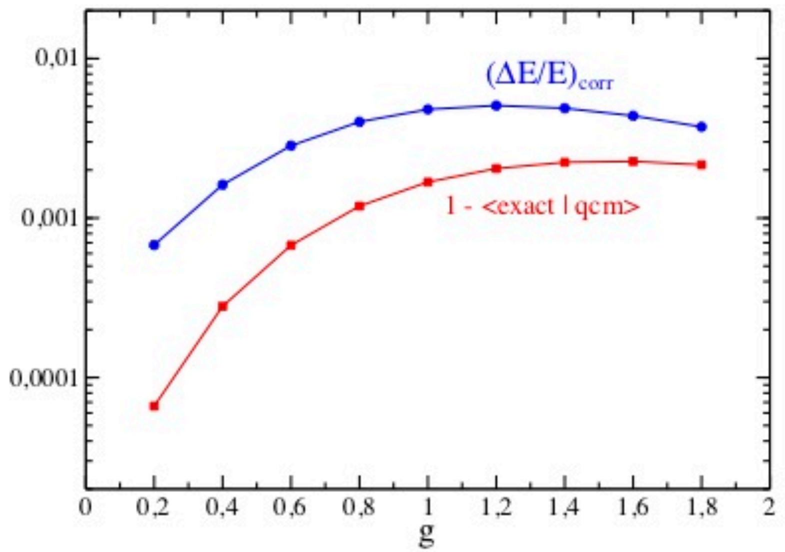
How can we better model nuclei?

Condensing the shell model to pairs & quartets



qcm vs exact results

6 protons and 6 neutrons over 6 equispaced levels



How can we better model nuclei?

Condensing the shell model to pairs & quartets

Quartet condensation versus pair condensation for isovector & isoscalar pairing

$$H=\sum_{ij}\varepsilon_i N_i+\sum_{ij}V^{T=1}_{J=0}(i,j)\sum_{\tau} P^+_{i\tau}P_{j\tau}+\sum_{ij}V^{T=0}_{J=1}(i,j)\sum_{\sigma} D^+_{i\sigma}D_{j\sigma}$$

$$(Q^+)^{n_q}|-> \qquad (\Gamma^+_{\nu\nu}\Gamma^+_{\pi\pi})^{n_q}|-> \qquad (\Gamma^+_{\nu\pi})^{2n_q}|-> \qquad =(\Delta_0^+)^{2n_q}|0\rangle$$

	QCM	PBC1	$PBCS0_{iv}$	$PBCS0_{is}$
^{20}Ne	15.985 (-)	14.011 (12.35%)	13.664 (14.52%)	13.909 (12.99%)
^{24}Mg	28.595 (0.24%)	21.993 (23.35%)	20.516 (28.50%)	23.179 (19.22%)
^{28}Si	35.288 (0.57%)	27.206 (23.58%)	25.293 (28.95%)	27.740 (22.19%)
^{44}Ti	7.019 (-)	5.712 (18.62%)	5.036 (28.25%)	4.196 (40.22%)
^{48}Cr	11.614 (0.21%)	9.686 (16.85%)	8.624 (25.97%)	6.196 (46.81%)
^{52}Fe	13.799 (0.42%)	11.774 (15.21%)	10.591 (23.73%)	6.673 (51.95%)
^{104}Te	3.147 (-)	2.814 (10.58%)	2.544 (19.16%)	1.473 (53.19%)
^{108}Xe	5.489 (0.20%)	4.866 (11.61%)	4.432 (19.49%)	2.432 (55.82%)
^{112}Ba	7.017 (0.34%)	6.154 (12.82%)	5.635 (20.17%)	3.026 (57.13%)

- quartet condensation wins over Cooper pair condensates
- T=1 and T=0 pairing correlations always coexist in quartets

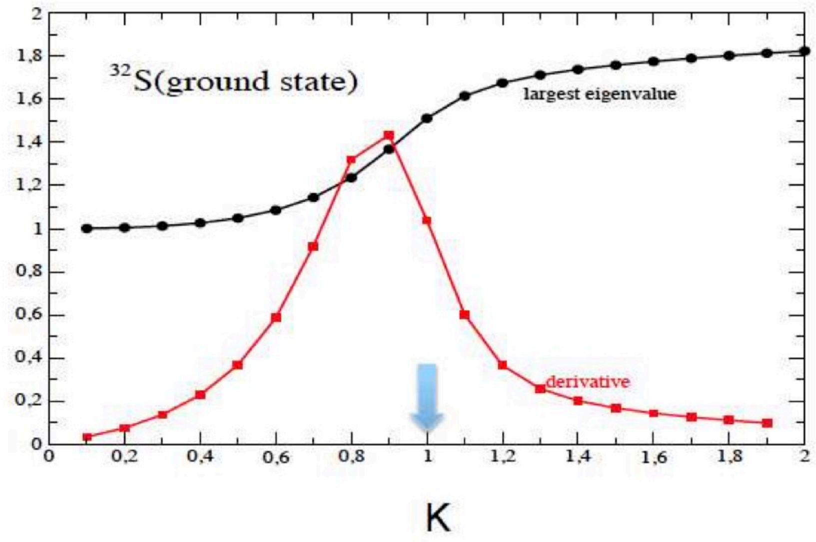
M. Sambataro and N.S, Phys. Rev C93, 054320 (2016)

How can we better model nuclei?

Condensing the shell model to pairs & quartets

Evolution of the largest eigenvalue of 4-body density matrix: ^{32}S

$$H = \sum_i \varepsilon_i (N_i^{(n)} + N_i^{(p)}) + k \sum_{ii',jj',J',T'} V_{JT}(ii';jj')[A^{+}_{ii'J'T'} A_{jj'J'T'}]^{J=0,T=0}$$



Indication of a fast transition towards a quartet condensate !

How can we better model nuclei?

Condensing the shell model to pairs & quartets

Need to include interplay with deformation…
start with simple pairing in deformed (Nilsson)
single-particle basis

How can we better model nuclei?

What the shell model can teach us

How can we better model nuclei?

What the shell model can teach us

Simple shell-model calculations, even in single-j shell, illustrate competition between deformation and pairing

Giving alpha clusters a little "boost" describes cluster states very well

Entropy may make supercomputers unnecessary

Last but far from least: Can cluster emissions tells us something?

A cluster unto himself….

Despite early hope for heavy cluster emissions as a signature of superheavy nuclei,

even for superheavies, α-decay always dominates

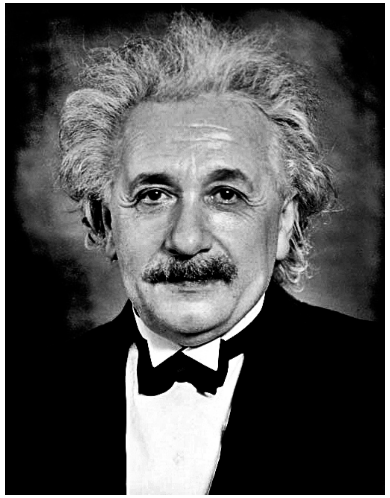
What lessons do we learn?
Final thoughts

What lessons do we learn?
Final thoughts

"How do you keep track of all those electrons?"

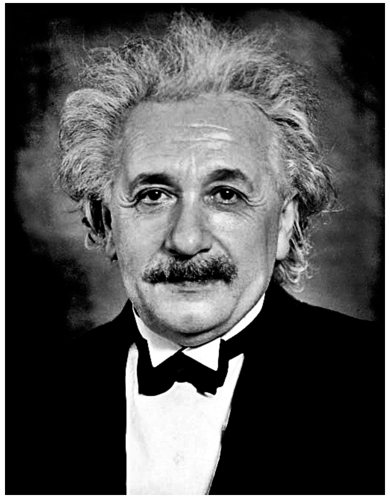
What lessons do we learn?
Final thoughts

"Everything should be made as simple as possible, but no simpler."



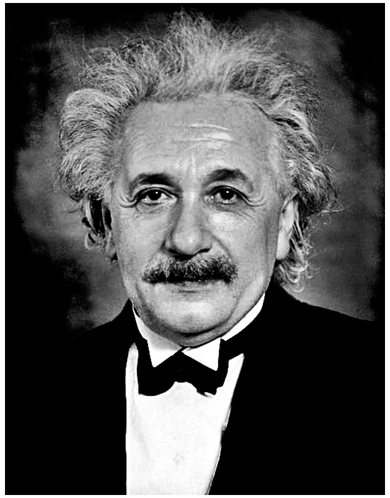
What lessons do we learn?
Final thoughts

But when is something "too simple"?



What lessons do we learn?
Final thoughts

It depends upon the question you're asking!



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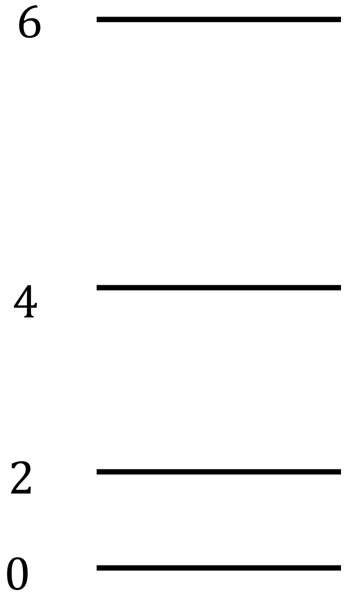
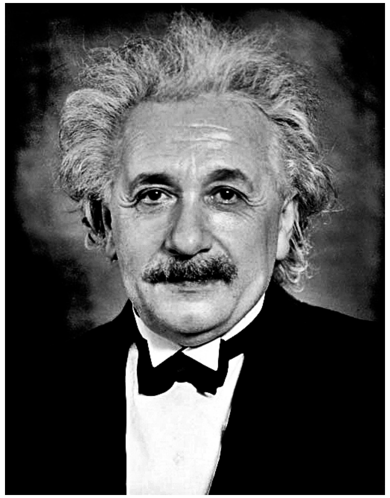


The absolute g.s. energy of a rotational band isn’t important…



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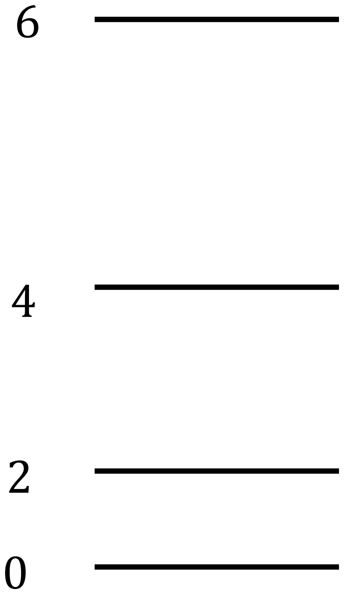
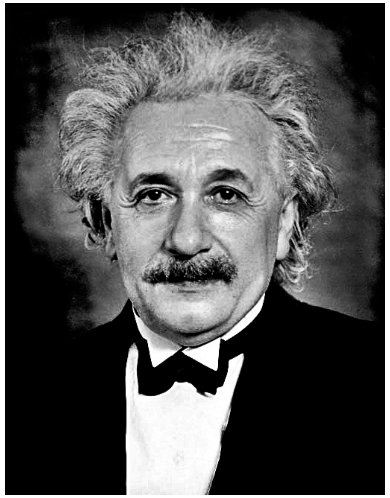


The absolute g.s. energy of a rotational band isn't important…
… unless you need the Q-value.



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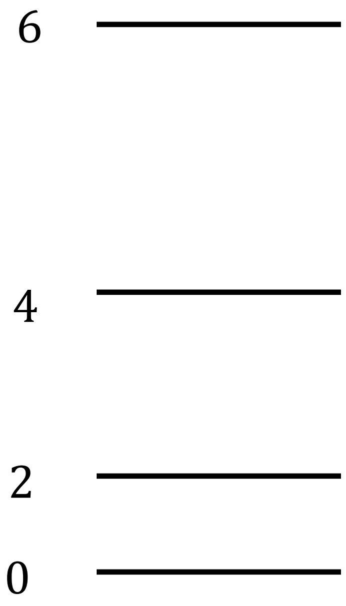
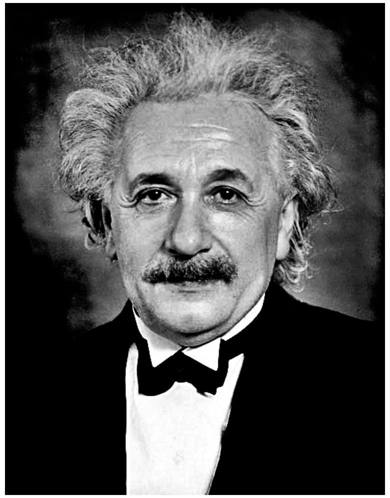


The absolute g.s. energy of a rotational band isn't important…
… unless you need the Q-value.

Only relative g.s. energies are important…



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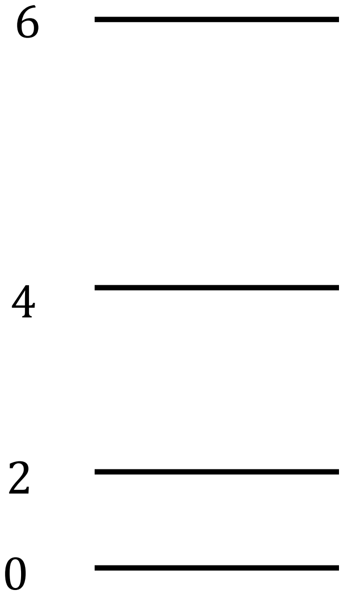
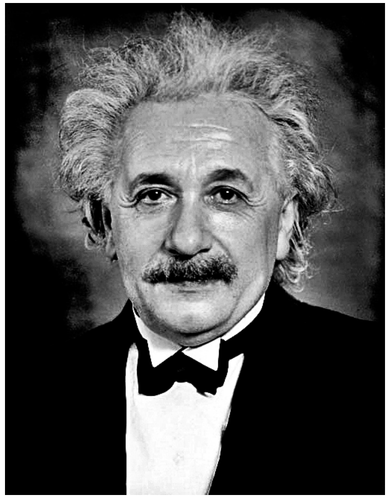


The absolute g.s. energy of a rotational band isn't important…
… unless you need the Q-value.

Only relative g.s. energies are important…
… unless you need the equation of state for neutron stars!



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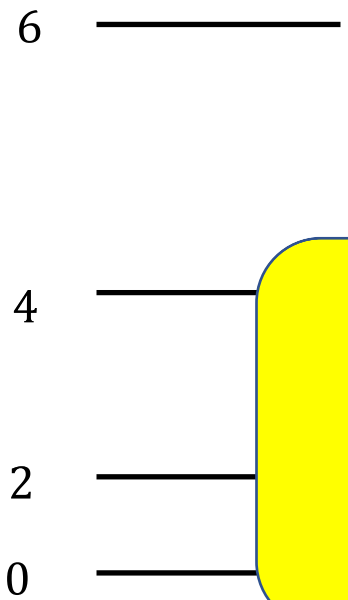
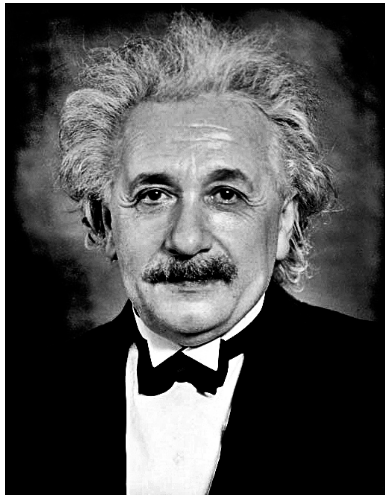


The absolute g.s. energy of a rotational band isn't important…

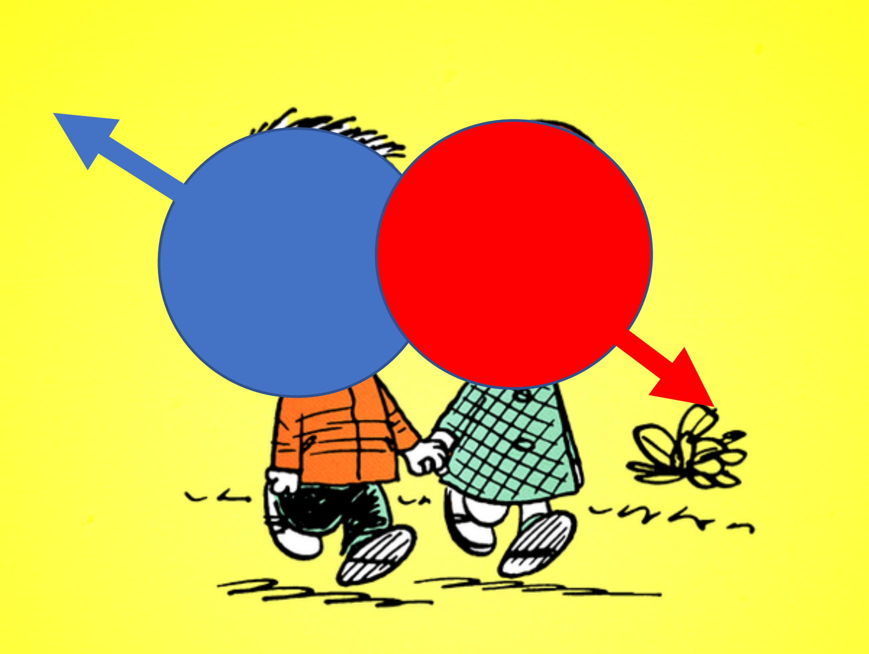
ortant…

of state for neutron sta…

"Simple" and "important" are **relative** terms!



To summarize the summary:



Happiness is…. simple models of complex behavior!