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Does the nuclear ground state have a temperature? and other questions

Calvin W. Johnson

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Many-body correlations, phase transitions, and clustering, Saclay, Sept 2026



OUTLINE

Prelude: What do we mean by ‘temperature’?

Part 1: Configuration temperature

Part 2: Proton-neutron temperature

Part 3: Assumption-free evidence for clusters



THE “SHELL MODEL”

A.K.A., CONFIGURATION-INTERACTION

We solve the many-body problem
as a matrix eigenvalue equation

$$\hat{H}|\Psi\rangle = E|\Psi\rangle$$

by expanding in a basis of shell-model configurations

$$|\Psi\rangle = \sum_{\alpha} c_{\alpha} |\alpha\rangle \quad \begin{array}{l} \text{(either with fixed } J_z=M: M\text{-scheme} \\ \text{or with fixed total } J: J\text{-scheme)} \end{array}$$

Occupation-representation of a Slater determinant
 $|00010110111\rangle$

Because we have an explicit representation of the wave function, we can ask detailed questions, often in many different ways!



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What do we mean by ‘temperature’?



What do we mean by ‘temperature’?

The Boltzmann distribution says the probability to find the system in a given state is proportional to

$$\exp(-E / T)$$

this in turn is related to

$$\frac{1}{T} = \frac{dS}{dE}$$



OUTLINE

Prelude: What do we mean by ‘temperature’?

Part 1: Configuration temperature

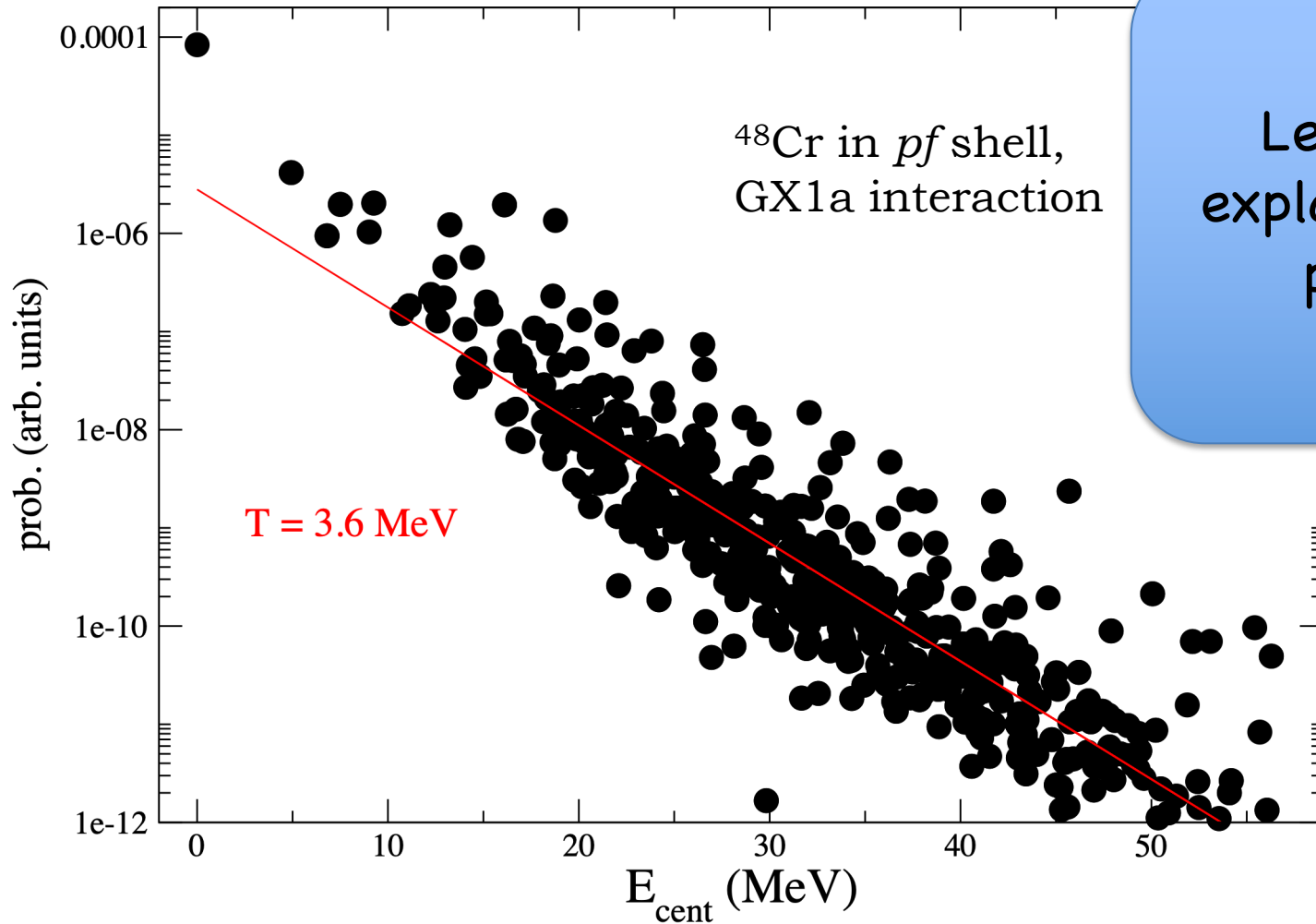
Part 2: Proton-neutron temperature

Part 3: Assumption-free evidence for clusters



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Boltzmann distributions everywhere!



Let me
explain this
plot





Imagine a shell model space. We expand a wave function as a vector:

$$|\Psi\rangle = \sum_i c_i |i\rangle$$

We can divide the model space into subspaces defined by single-particle orbital **configurations**, e.g. $(0f_{7/2})^4(1p_{3/2})^2$, etc

$$|\Psi\rangle = \left(\begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \right)$$

Each of these subspaces
is called a **configuration partition**



We can divide the model space into subspaces defined by single-particle orbital **configurations**, e.g. $(0f_{7/2})^4(1p_{3/2})^2$, etc

The Hamiltonian can then also be divided up

$$H = \left(\begin{array}{ccc} & & \\ & & \\ & & \\ & & \\ & & \end{array} \right)$$

The average diagonal element of the Hamiltonian in each subspace (which is just the trace divided by the subspace dimension) can be easily computed using the **monopole part of the Hamiltonian**, see arXiv:2511.03161 also github.com/cwjsdsu/tracer

These are the **configuration centroids**



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The Hamiltonian can then also be divided up

The monopole part of the
Hamiltonian looks like

$$n_a (n_b - \delta_{ab})$$

and contributes to shell
structure



The average diagonal element of the Hamiltonian in each subspace (which is just the trace divided by the subspace dimension) can be easily computed using the monopole part of the Hamiltonian, see arXiv:2511.03161 also github.com/cwjsdsu/tracer

These are the **configuration centroids**



In other words, $E_{cent} = \frac{\text{tr } \hat{P}_\alpha \hat{H}}{\text{tr } \hat{P}_\alpha}$



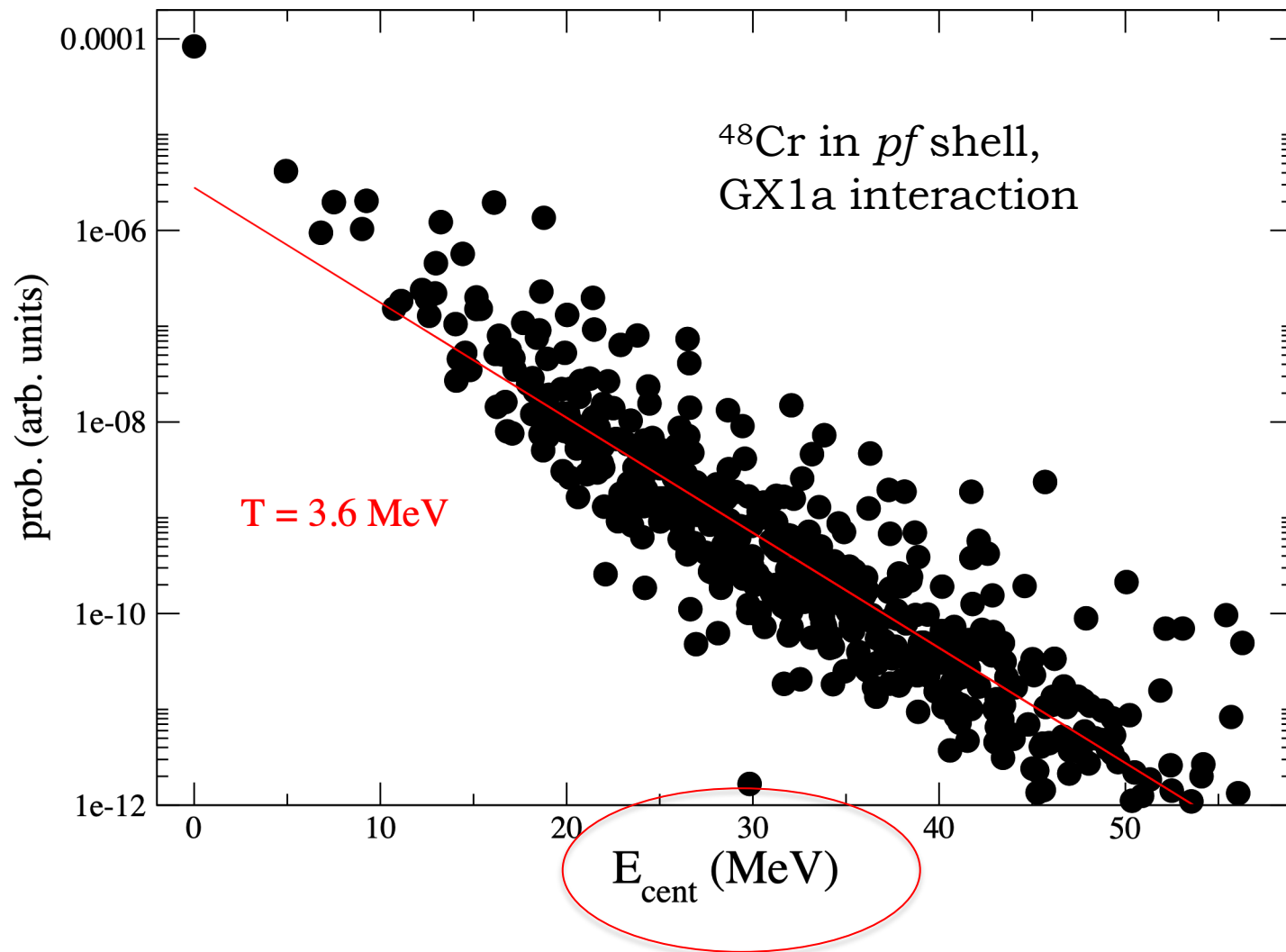
Projection operator for a
configuration partition
(subspace)

$$\hat{P}_\alpha = \sum_{i \in \alpha} |i\rangle\langle i|$$

$$H = \left(\begin{array}{ccc} & & \\ & & \\ & & \end{array} \right)$$



Boltzmann distributions everywhere!



UQ for
'temperature'
still to be done



I also compute the *average* probability
of the wave function in the configuration subspace:

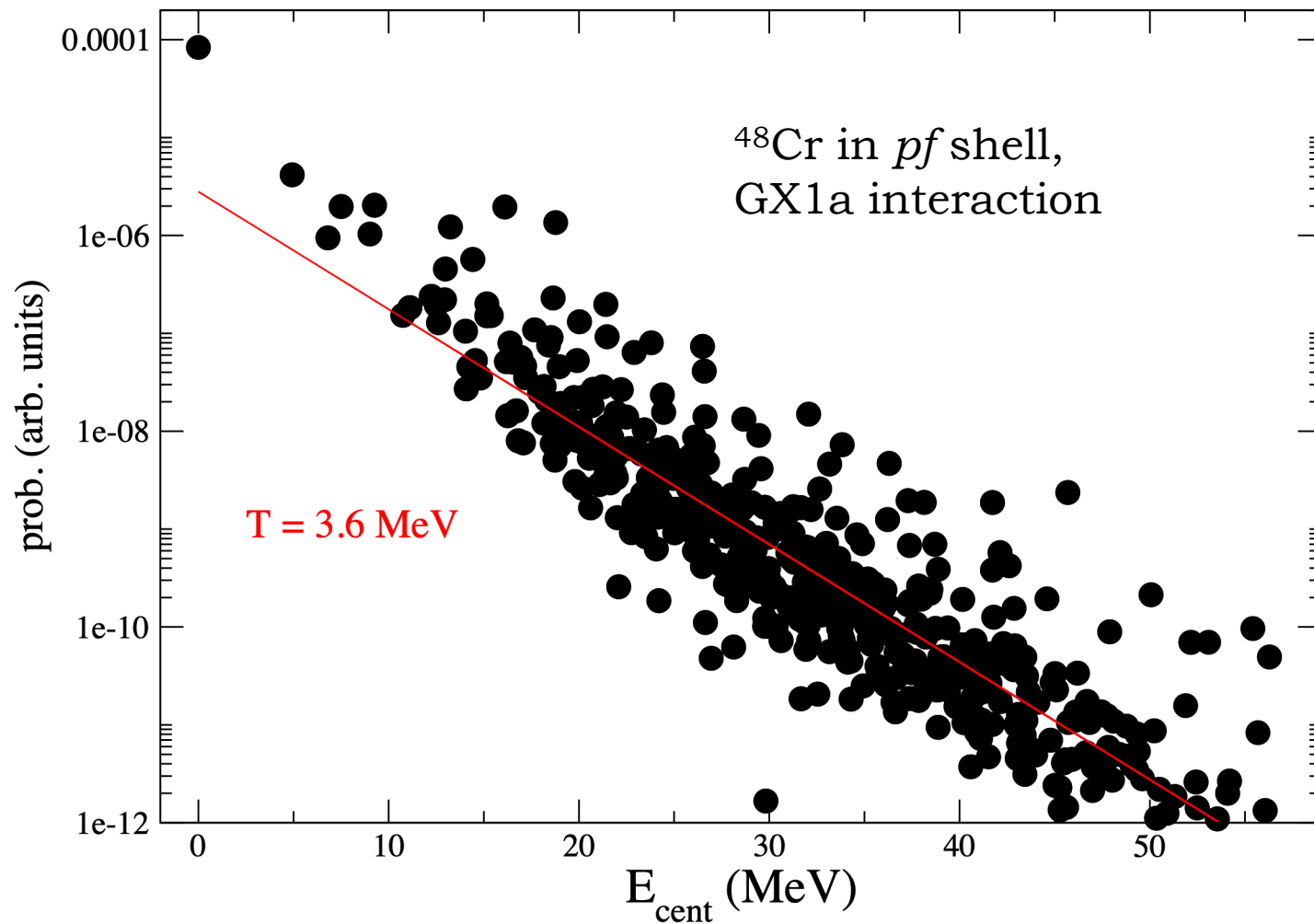
$$|\Psi\rangle = \sum_i c_i |i\rangle$$

$$\text{Avg prob}(\alpha) = \frac{\sum_{i \in \alpha} |c_i|^2}{\text{tr } \hat{P}_\alpha}$$



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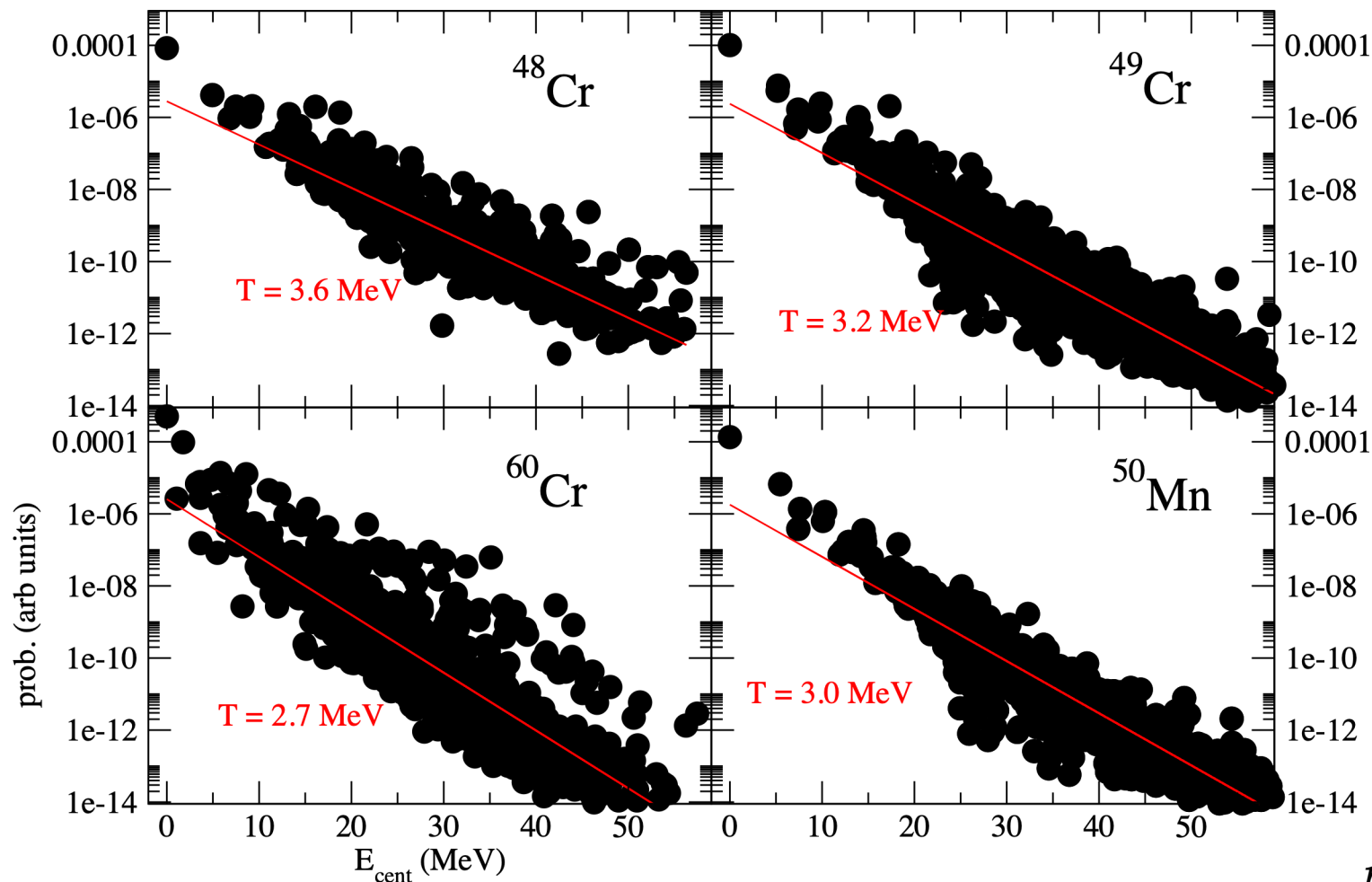
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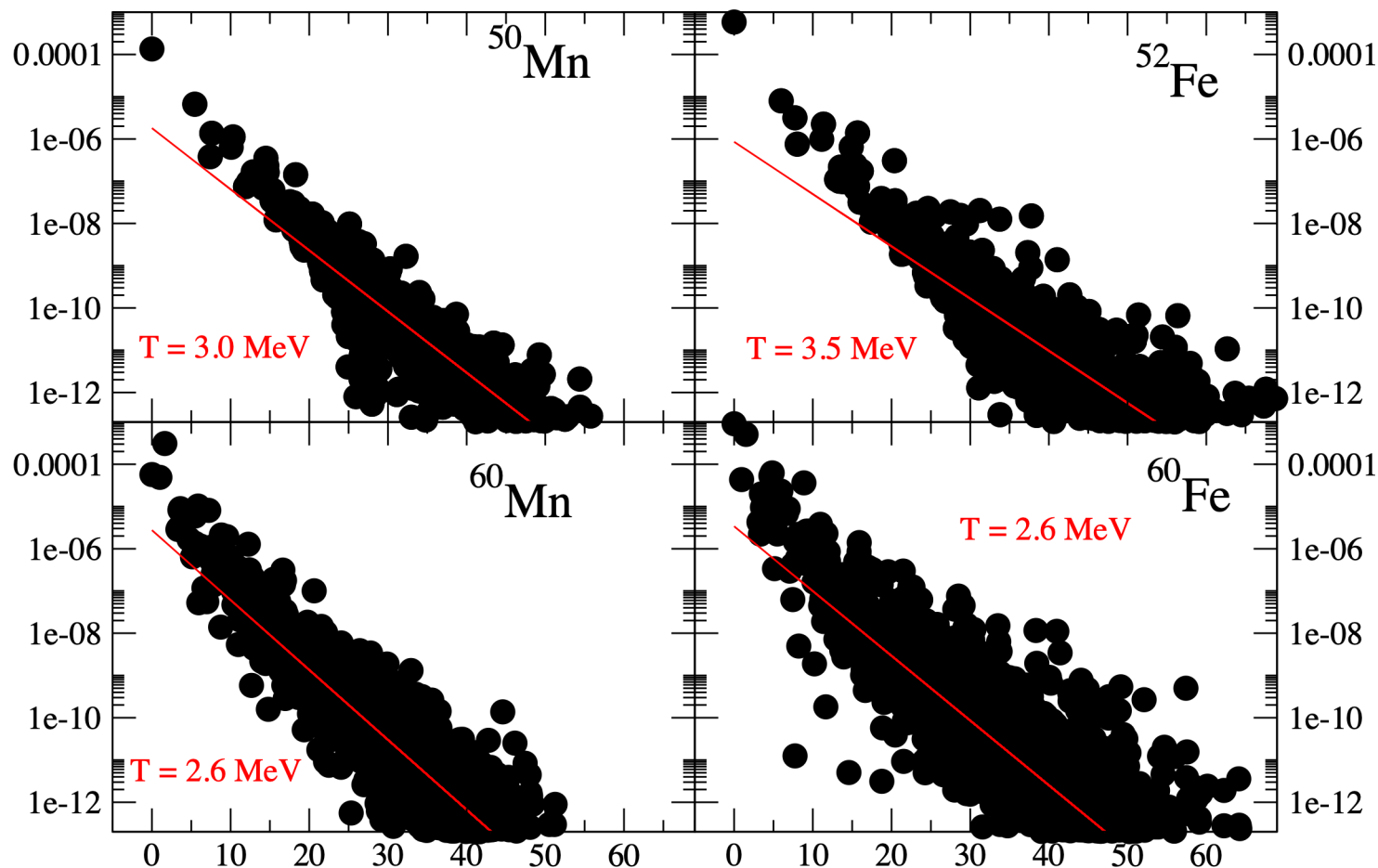


Boltzmann distributions everywhere!



pf shell,
GX1a interaction

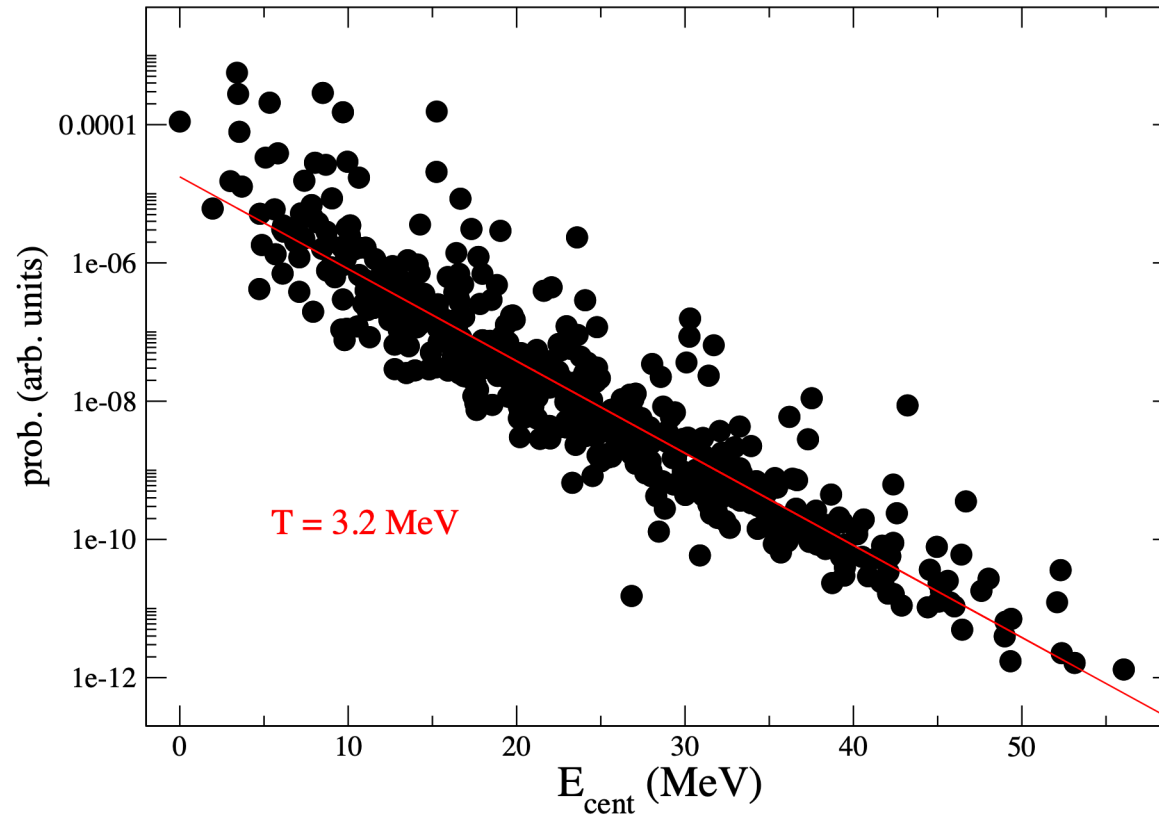
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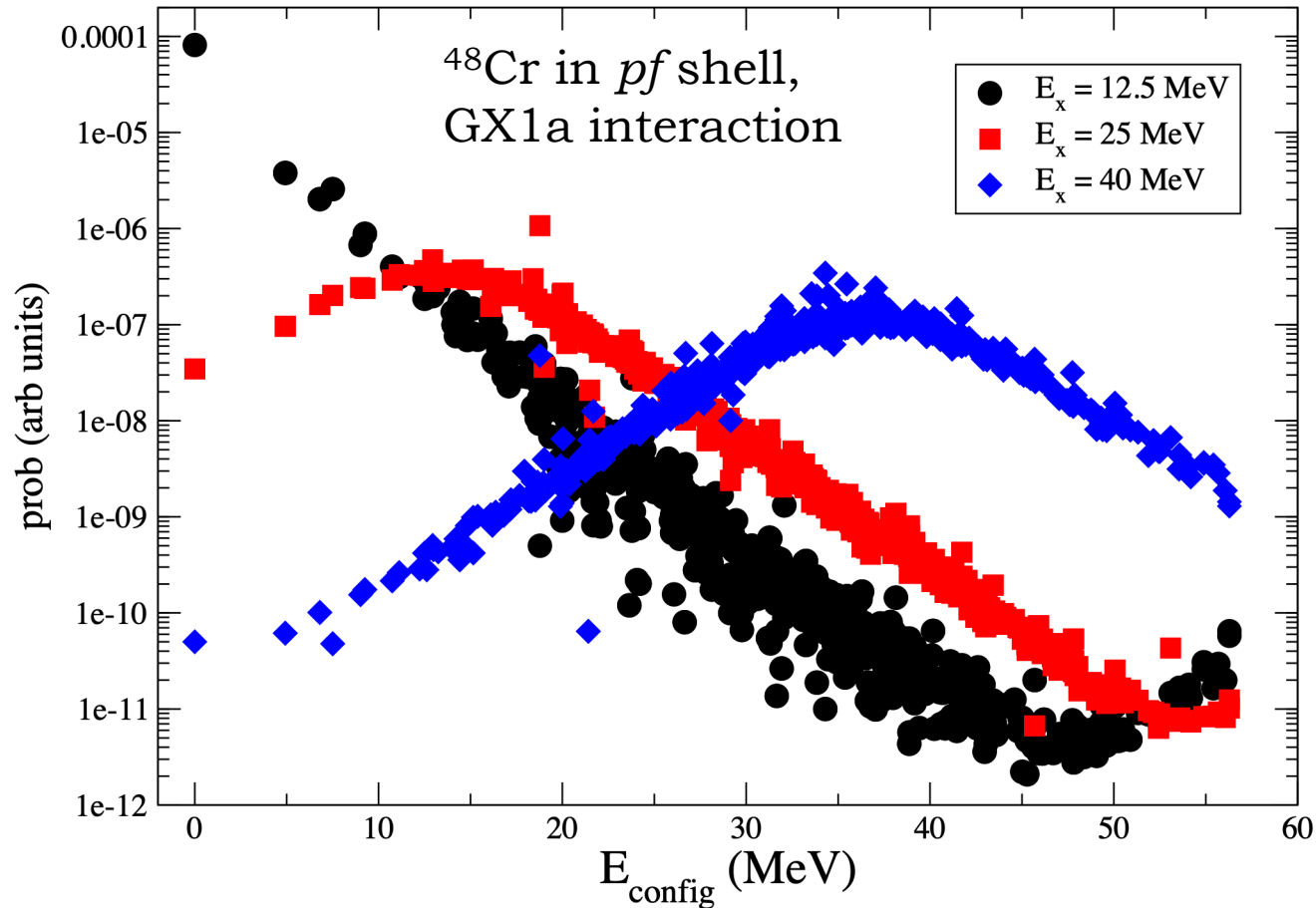
Boltzmann distributions everywhere!



^{72}Kr , pf shell,
GX1a interaction

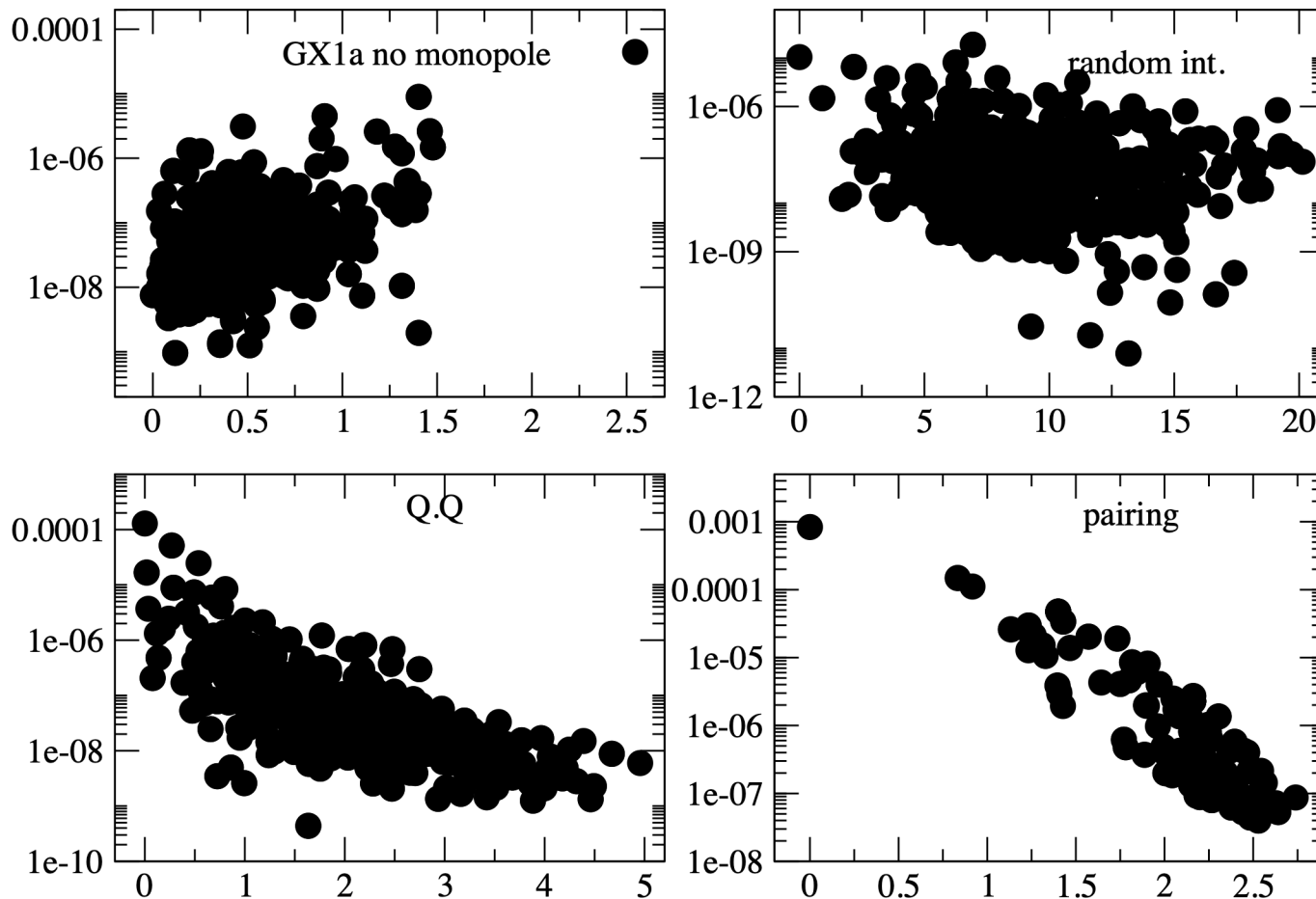


Boltzmann distributions everywhere!





Boltzmann distributions everywhere!



^{48}Cr in pf shell,



Attempts to develop a
random matrix model
(including very sparse
random matrices)
doesn't replicate the
results





Summary of Part 1

- Strong evidence for Boltzmann-like distributions of configurations, with ‘temperatures’ $\sim 2\text{-}3\text{ MeV}$
- T seems to decrease with isospin, but depends upon mass. (Probably depends upon shell structure.)
- Random interaction, **monopole-less realistic interaction** lacks Boltzmann-like distribution
- But schematic QQ, pairing does show Boltzmann-like behavior.



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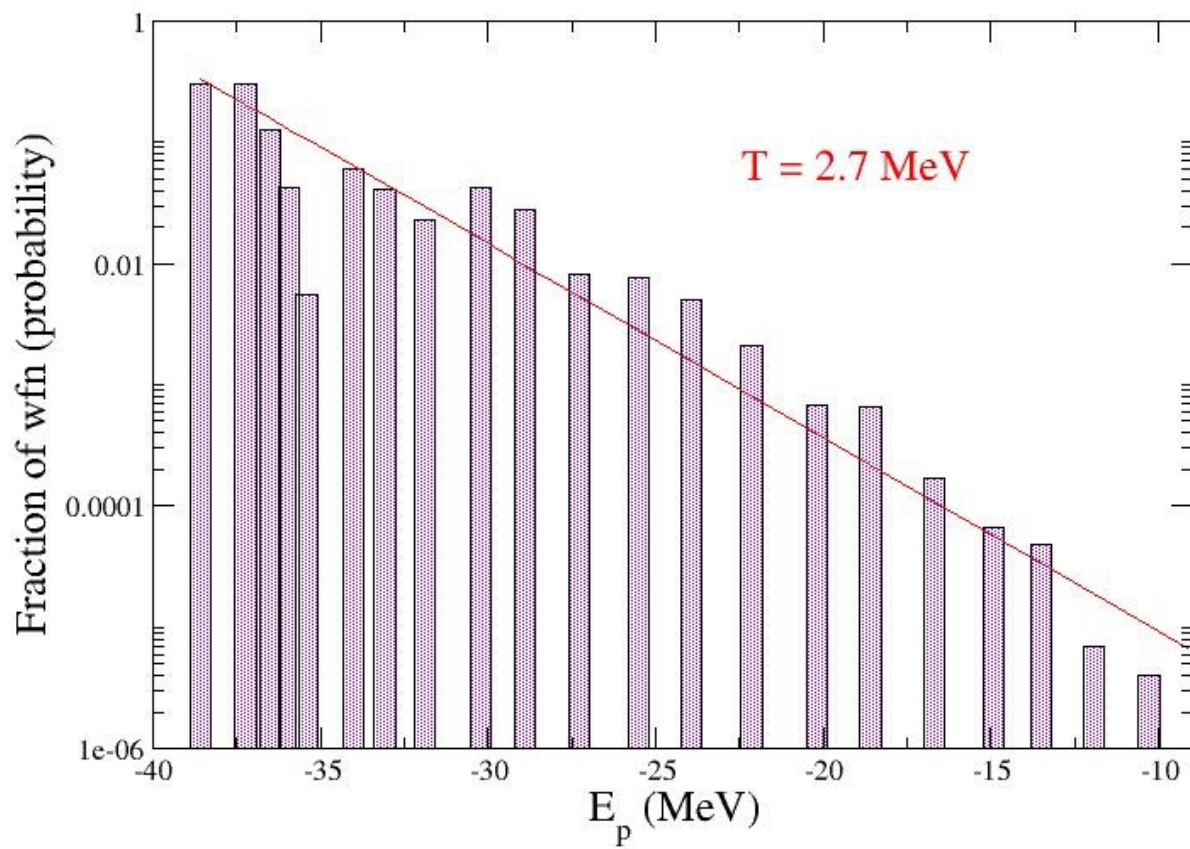
(even more)

Boltzmann distributions everywhere!



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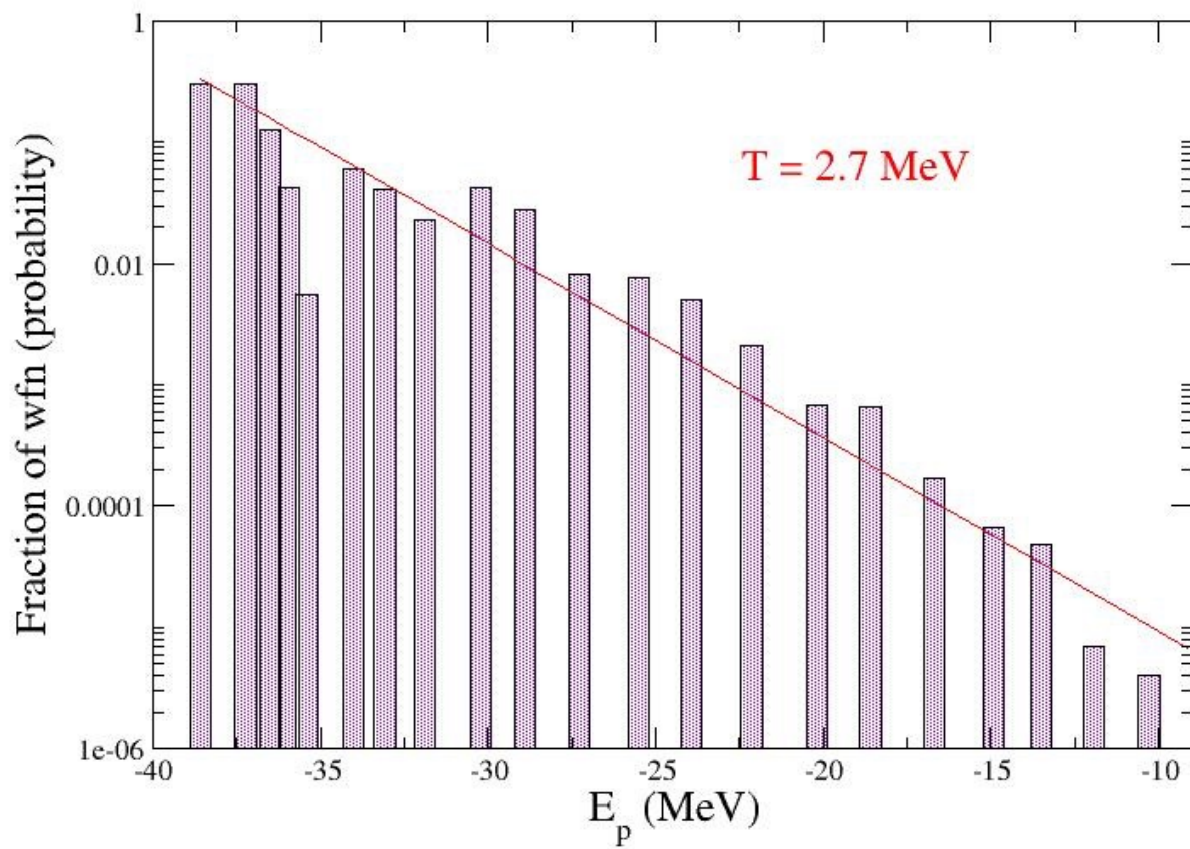
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Let me
explain **this**
plot





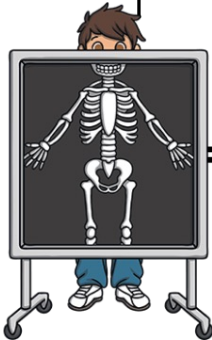
$$\hat{\mathbf{H}}|\Psi\rangle = E|\Psi\rangle$$

$$|\Psi\rangle = \sum_{\alpha} c_{\alpha} |\alpha\rangle$$

millions or even billions
of components (in M-scheme)





$$\hat{H}|\Psi\rangle = E|\Psi\rangle$$

$$= \sum_{\alpha} c_{\alpha} |\alpha\rangle$$

millions or even billions
of components (in M-scheme)

We can 'x-ray' the wave function



How most shell-model codes represent the basis:
Proton-neutron factorization

$$|\Psi\rangle = \sum_{\mu\nu} c_{\mu\nu} |p_{\mu}\rangle |n_{\nu}\rangle$$

the components are *often* simple Slater determinants.

... but they don't have to be. One can use more complicated proton and neutron components...



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$$\hat{H} = \hat{H}_{pp} + \hat{H}_{nn} + \hat{H}_{pn}$$

$$\hat{H}_{pp} | p_{\mu} \rangle = E_{\mu} | p_{\mu} \rangle$$

$$\hat{H}_{nn} | n_{\nu} \rangle = E_{\nu} | n_{\nu} \rangle$$



Decompose full wfn into proton, neutron components

$$|\Psi\rangle = \sum_{\mu\nu} c_{\mu\nu} |p_{\mu}\rangle |n_{\nu}\rangle$$

Eigenstate of proton part of H

Eigenstate of neutron part of H

$$frac_{\mu} = \sum_{\nu} |c_{\mu\nu}|^2 = \text{fraction of full wave function with}$$

proton (eigen)state μ and energy E_{μ}

or

$$Frac(E_p) = |\langle E_p | \Psi \rangle|^2 = |\langle p_{\mu} | \Psi \rangle|^2$$

This can be done efficiently using a variant of the Lanczos algorithm:
CWJ, PRC **91**, 034313 (2015)

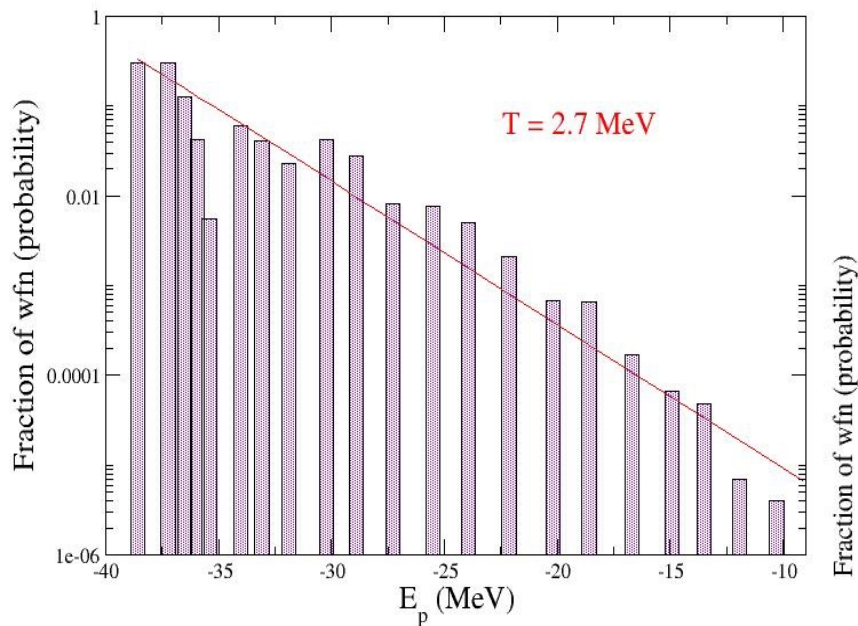
(even more)

Boltzmann distributions everywhere!

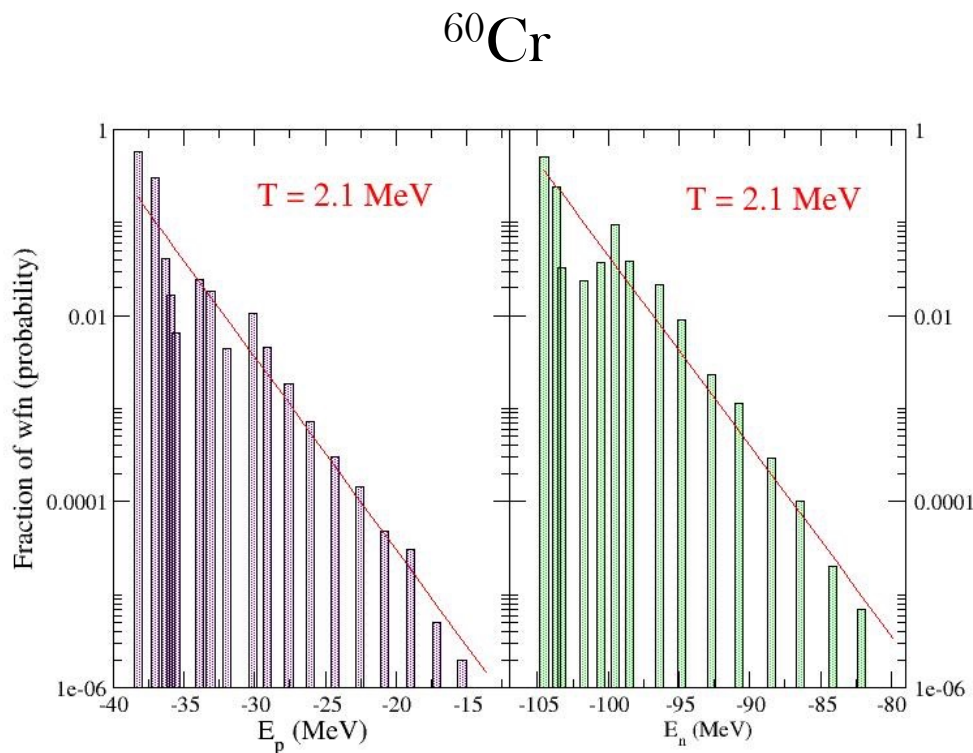


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pf shell,
GX1a interaction



^{48}Cr



proton decomp

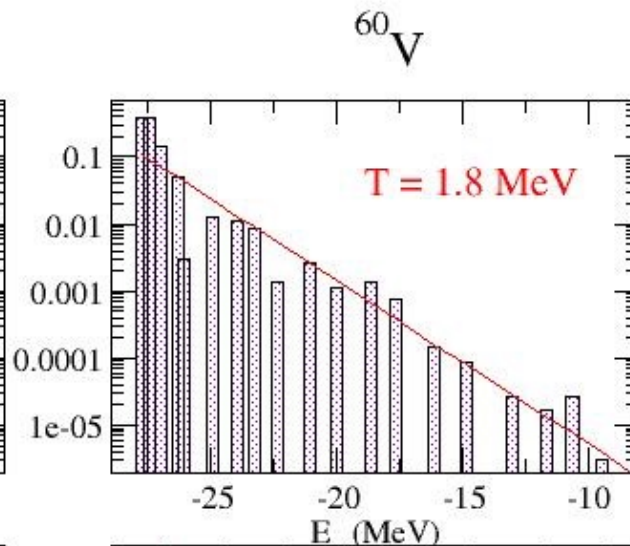
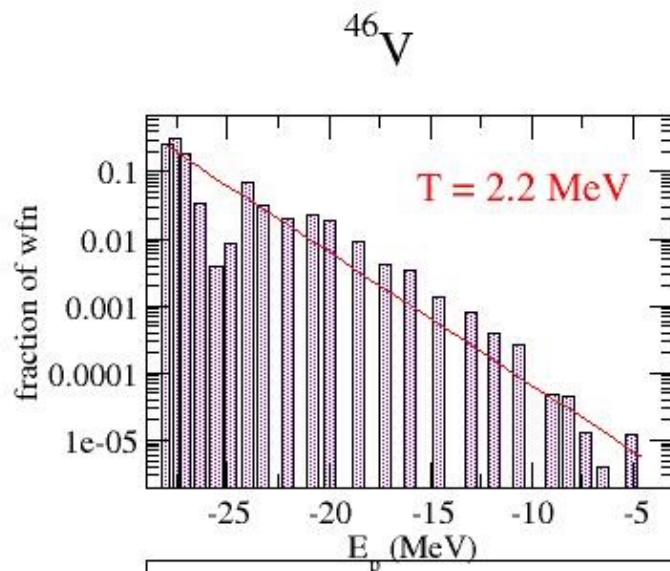
neutron decomp

(even more)

Boltzmann distributions everywhere!

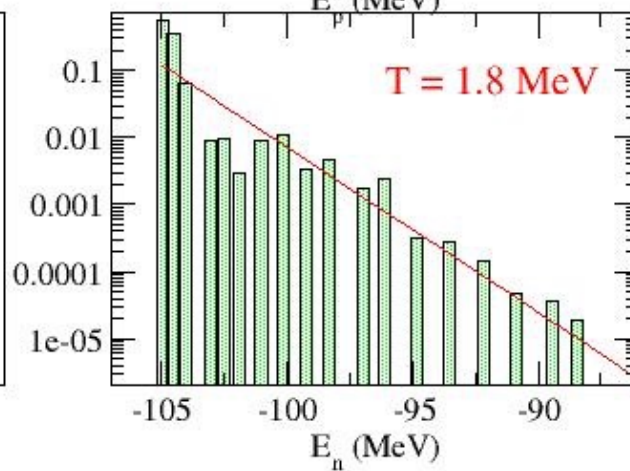


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proton decomp

pf shell,
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neutron decomp

(even more)

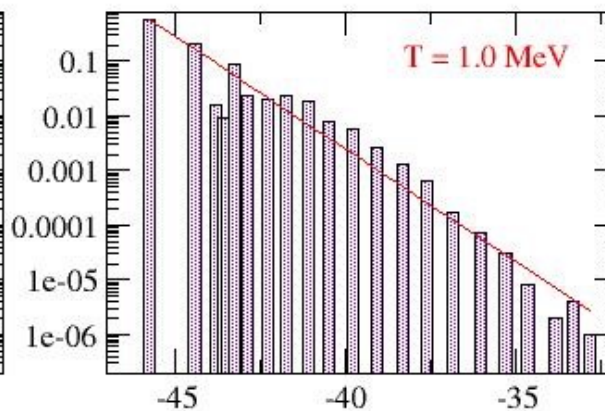
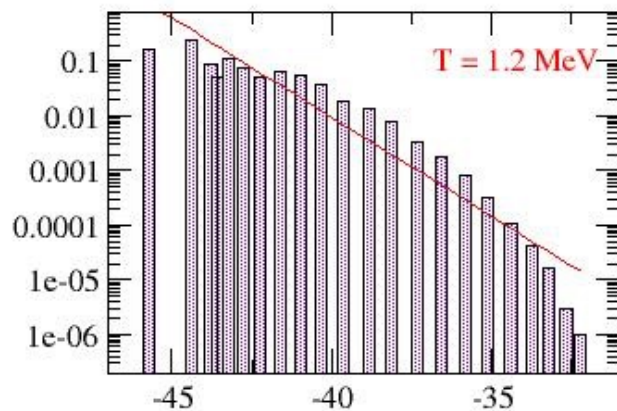
Boltzmann distributions everywhere!



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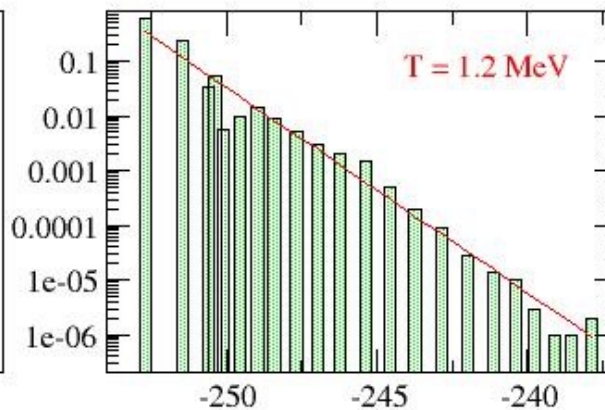
^{108}Xe

^{132}Xe



proton decomp

50-82 shell,
GCN5082 interaction



neutron decomp

(even more)

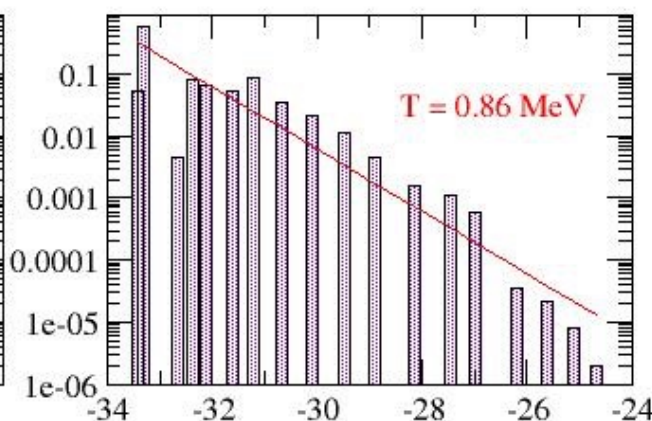
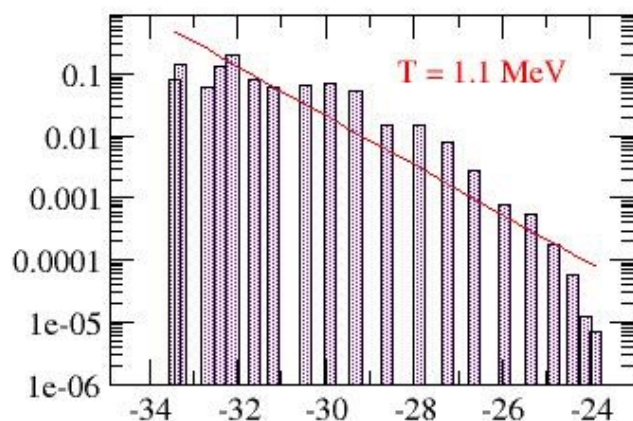
Boltzmann distributions everywhere!



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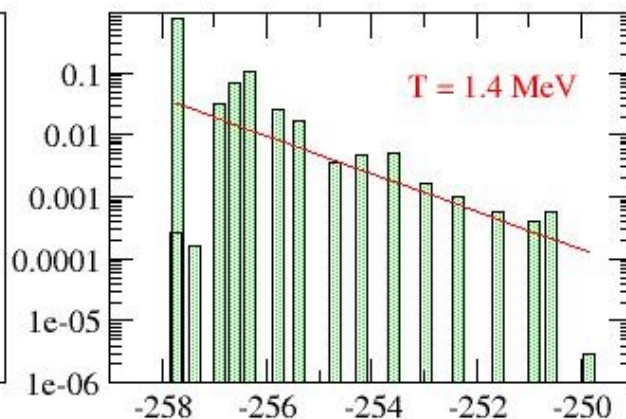
^{106}I

^{132}I



proton decomp

50-82 shell,
GCN5082 interaction

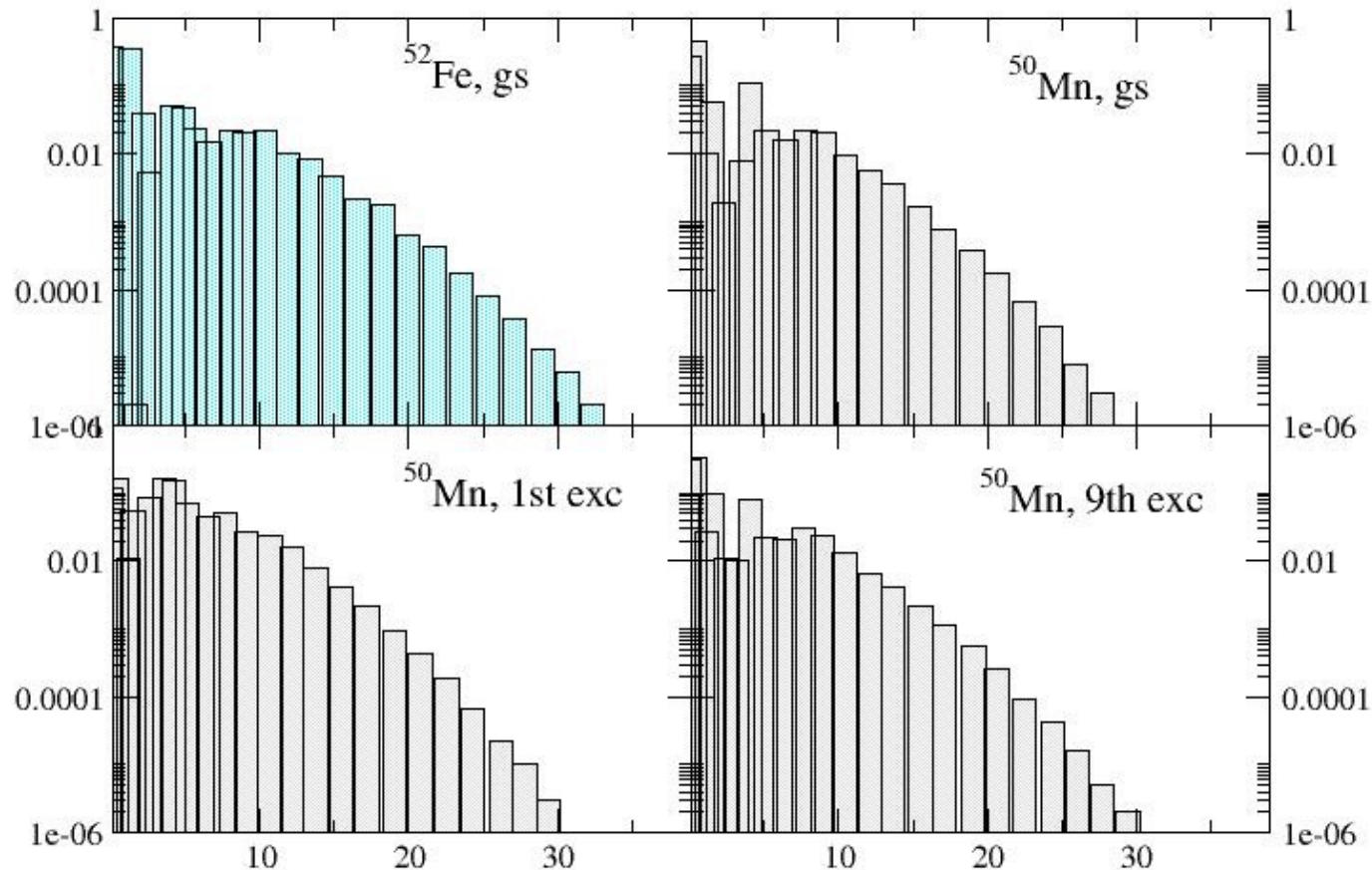


neutron decomp



pf-shell with GX1A interaction

decomposition into proton components



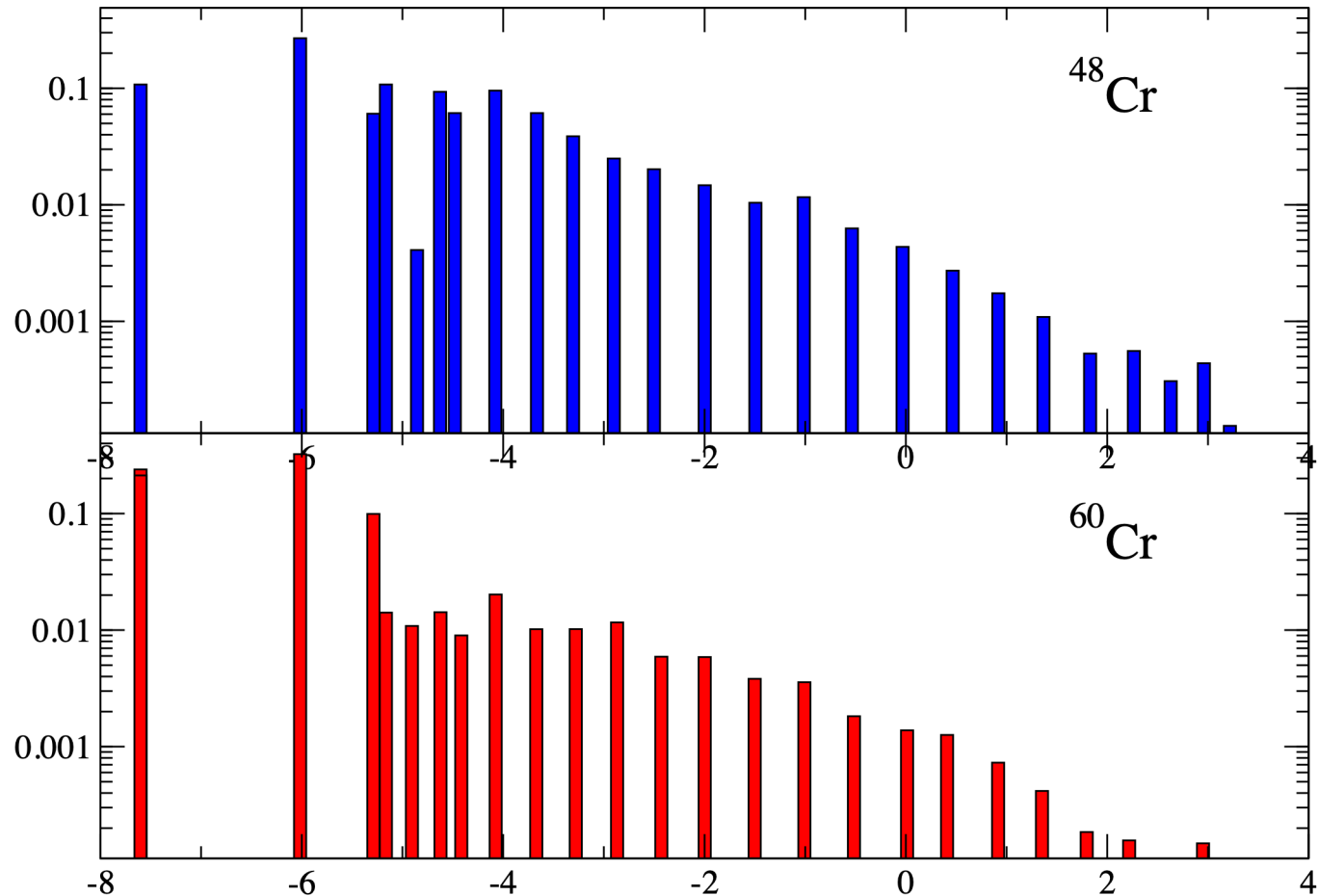
Note exponential
(Boltzmann) fall-off

Many-body correlations, phase transitions, and clustering, Saclay, Sept 2026



pf-shell with GX1A interaction, **with monopoles removed**

decomposition into proton components

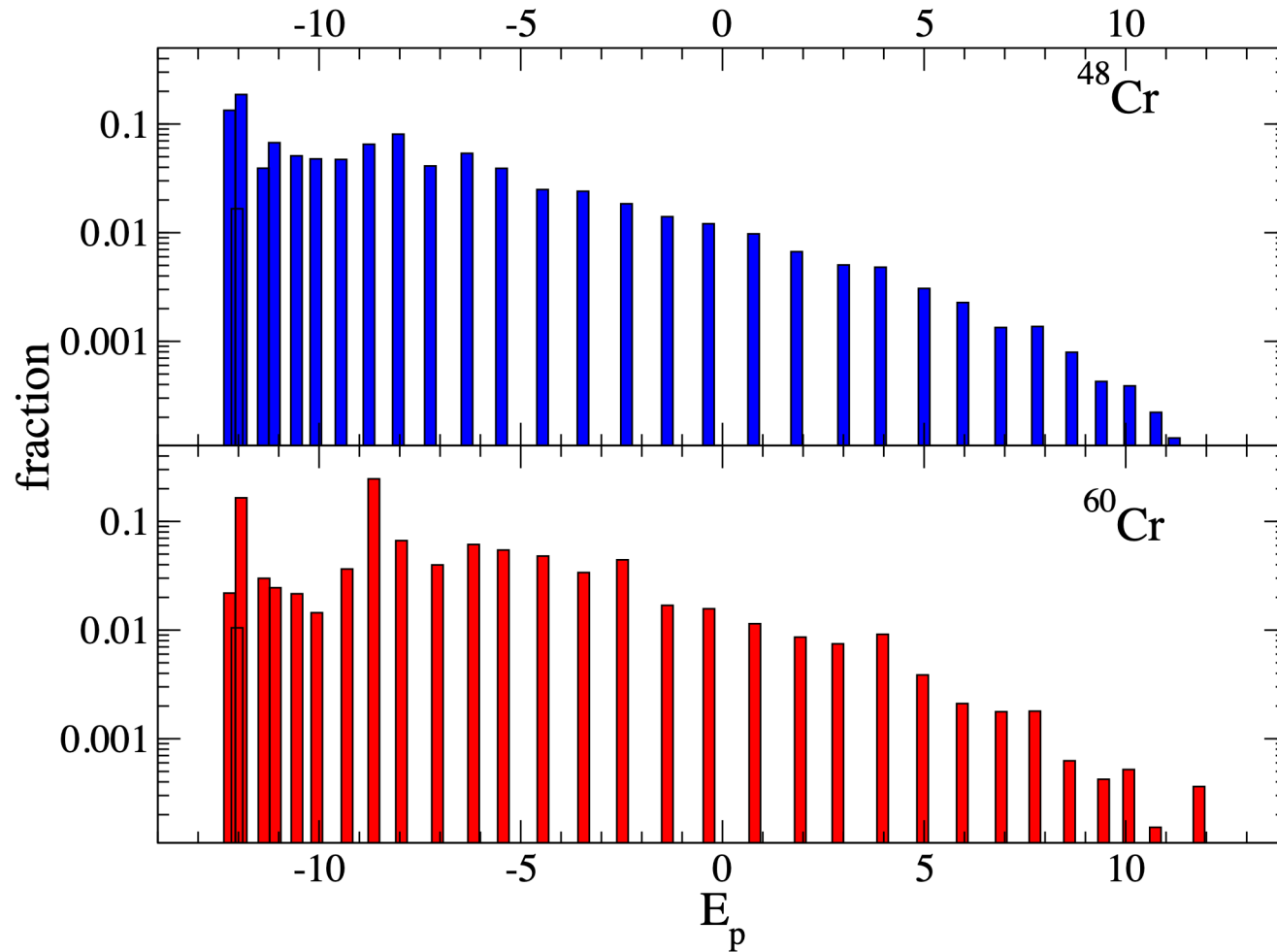




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pf-shell with random interaction

decomposition into proton components

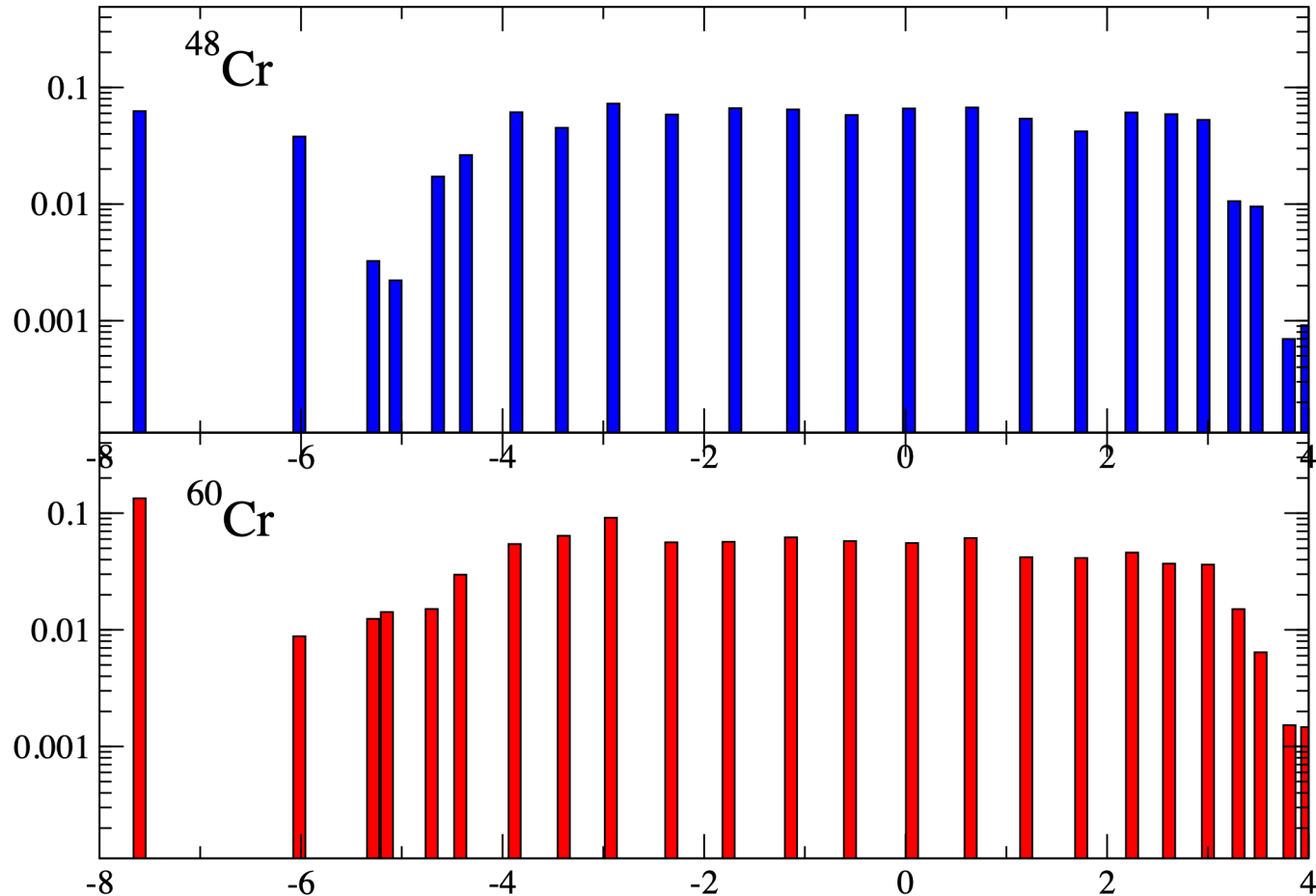




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pf -shell with random interaction **with monopoles removed**

decomposition into proton components

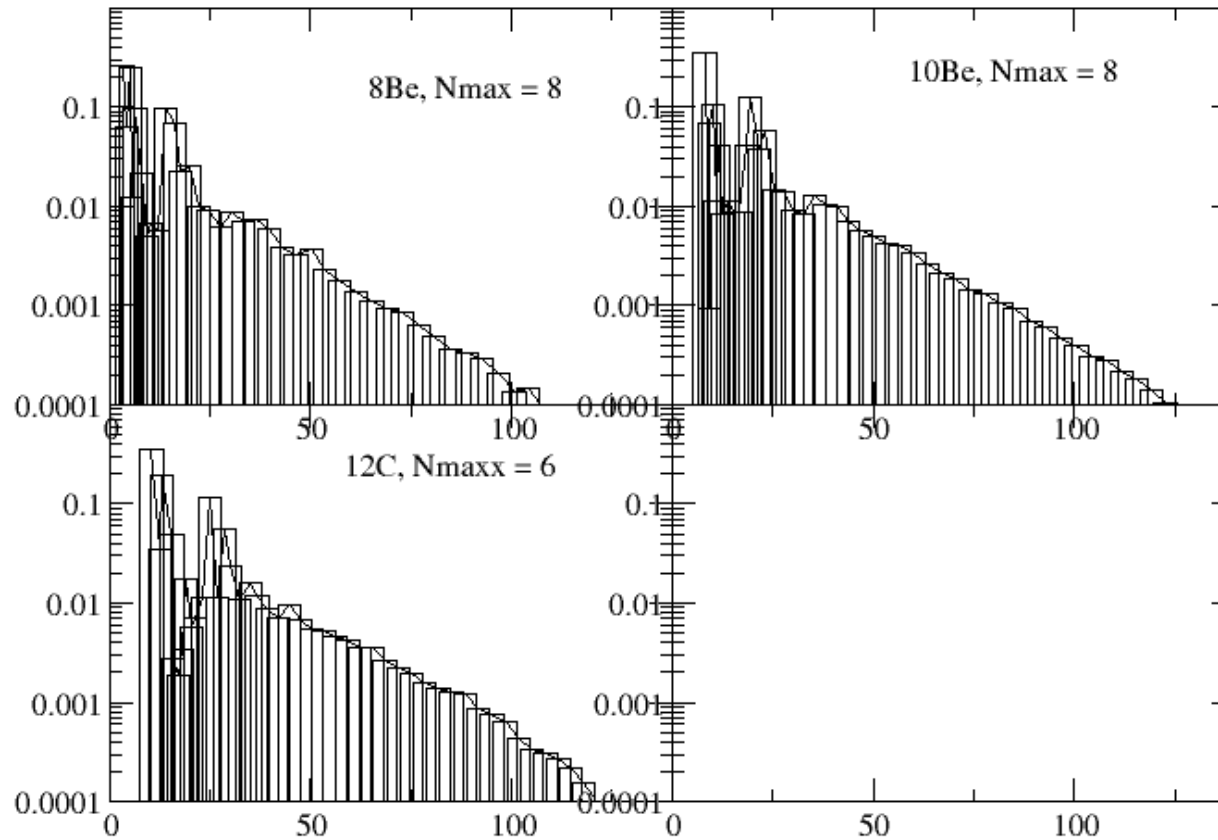


Moving forward



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Can we apply to the no-core shell model?





Summary of Part 2

- Strong evidence for Boltzmann-like distributions of proton/neutron components, with ‘temperatures’ $\sim 2\text{-}3\text{ MeV}$
 - T seems to (mostly) decrease with isospin, but depends upon mass. (Probably depends upon shell structure.)
 - Proton and neutron components (mostly) approximately equilibrated (same or similar temperature)
 - Random interaction, **monopole-less realistic interaction** still show evidence of Boltzmann-like distributions
- * Only random interactions with monopoles subtracted clearly violate Boltzmann-like behavior



Boltzmann-like
distributions
are ubiquitous!

But can we
explain these
results?





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Boltzmann-like
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But can we
explain these
results?

So far, no!





The Boltzmann distribution says the probability to find the system in a given state is proportional to

$$\exp(-E / T)$$

this in turn is related to

$$\frac{1}{T} = \frac{dS}{dE}$$

entropy



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entropy

density

$$S = -\text{tr } \rho \ln \rho$$

(even more)

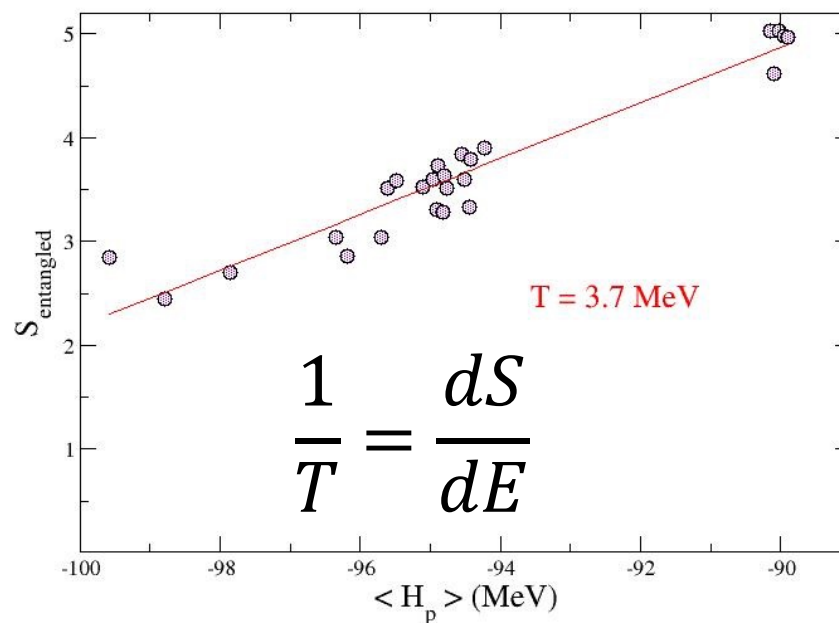
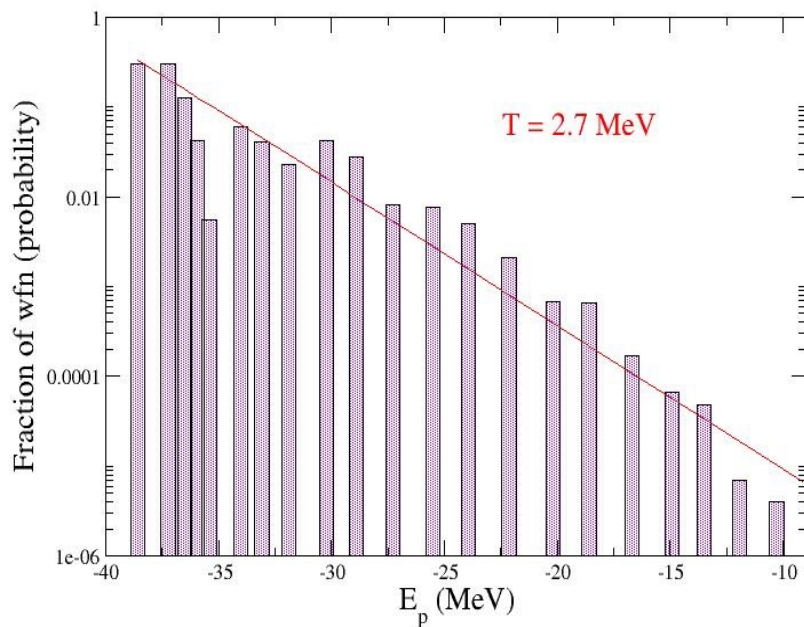
Boltzmann distributions everywhere!



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pf shell,
GX1a intera

^{48}Cr





The Boltzmann distribution says the probability
to find proportional to

Here I use the proton-
neutron entanglement
entropy

this in



$$\frac{1}{T} = \frac{dS}{dE}$$

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Entanglement has a formal definition,
typically in **bipartite** systems, that is,
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$$|\Psi\rangle = \sum_{i,a} c_{i,a} |i\rangle \otimes |a\rangle$$



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From this we define the *formal* density operator

$$\hat{\rho} = |\Psi\rangle\langle\Psi|$$

and the *formal* density matrix

$$\rho_{ia,jb} = c_{i,a} c_{j,b}^*$$



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The formal density matrix has $\text{tr } \rho = 1$, and is idempotent: $\rho^2 = \rho$,

which implies eigenvalues 0, 1



Next we define the *reduced* density matrix by tracing over one of the partitions:

$$|\Psi\rangle = \sum_{i,a} c_{i,a} |i\rangle \otimes |a\rangle \quad \hat{\rho} = |\Psi\rangle\langle\Psi| \quad \rho_{ia,jb} = c_{i,a} c_{j,b}^*$$

$$\rho_{i,j}^{red} = \text{tr}_a \rho = \sum_a c_{i,a} c_{j,a}^*$$

The reduced density matrix still has $\text{tr } \rho = 1$,
but is no longer necessarily idempotent: $\rho^2 \neq \rho$,
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back to 'formal' density matrices....

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If idempotent, the partitions are *not entangled*
but if *not* idempotent, the partitions are *entangled*



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Looking at the
eigenvalues of the
reduced density matrix
is related to **singular
value decomposition**
and is also called
Schmidt decomposition



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Often one characterizes the eigenvalues by the
entanglement entropy: $S = -\sum_n \lambda_n \ln \lambda_n$

(eigenvalues of ρ^{red} ,
 $0 \leq \lambda_n \leq 1$)

If the reduced density matrix has dimension N ,
then the maximum entropy is $S_{\text{max}} = \ln N$.



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Early calculation of entanglement
in nuclear systems:

O. Gorton MS thesis, 2018; CWJ and O. C. Gorton, J. Phys. G **50**, 045110 (2023)

The bipartite system was protons and neutrons, which works like a formal
density matrix.

$$|\Psi\rangle = \sum_{i,a} c_{i,a} |p_i\rangle \otimes |n_a\rangle$$

Application to nuclear calculations:

“*A weak entanglement approximation for nuclear structure*,” Gorton and CWJ,
Phys. Rev. C **110**, 034305 (2024)



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$$|\Psi\rangle = \sum_{i,a} c_{i,a} |p_i\rangle \otimes |n_a\rangle$$

can be extracted easily from
Bigstick shell model code

In most shell-model codes, such as Bigstick, the basis already
is bipartite in proton and neutron components, so carrying out such a
decomposition is easy.

(even more)

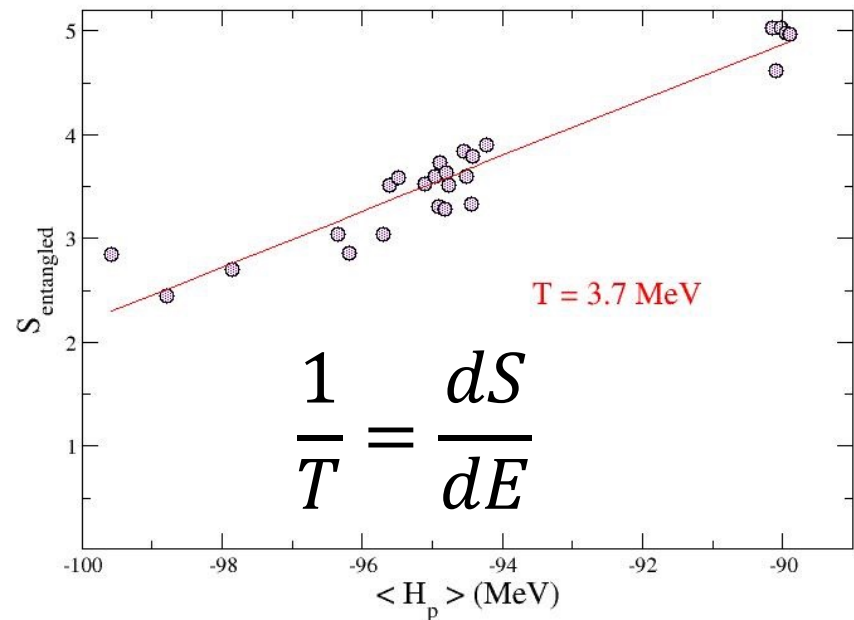
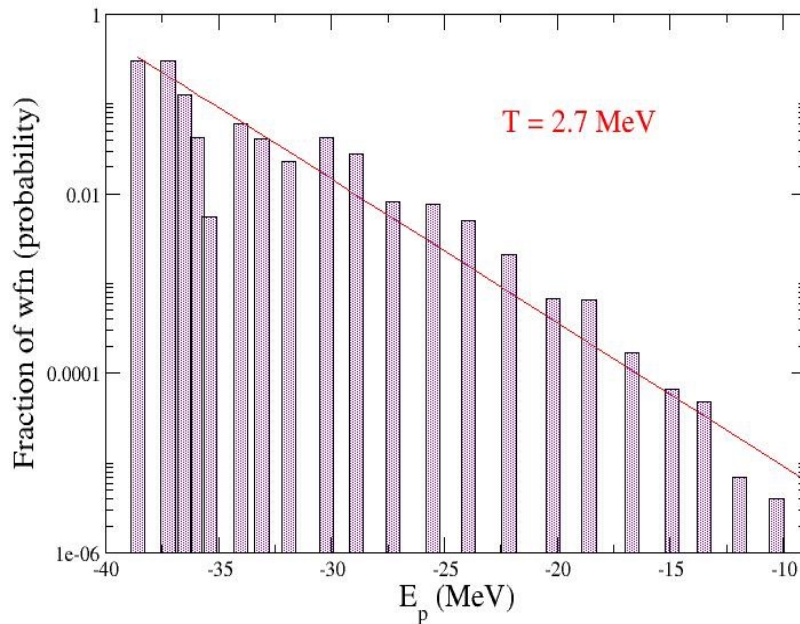
Boltzmann distributions everywhere!



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(even more)

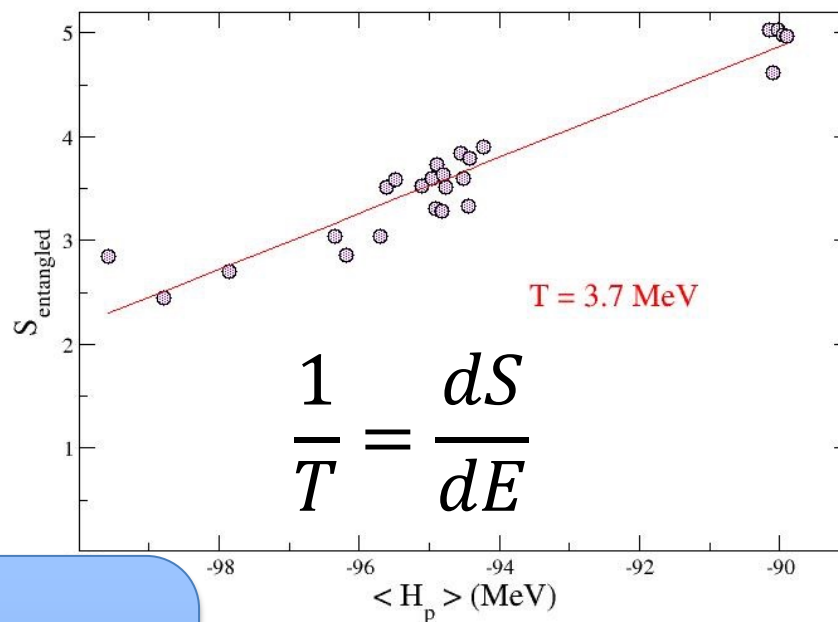
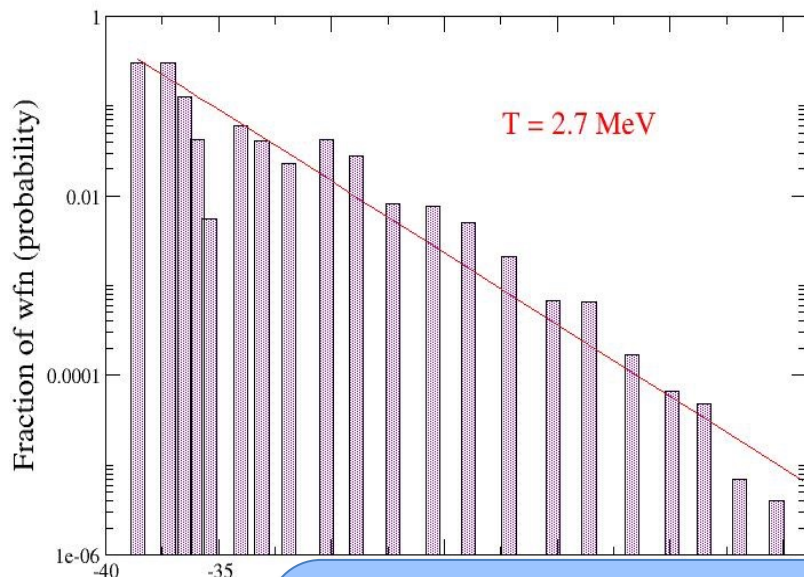
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$$\frac{1}{T} = \frac{dS}{dE}$$



Unfortunately, these
temperatures don't match!



OUTLINE

Prelude: What do we mean by ‘temperature’?

Part 1: Configuration temperature

Part 2: Proton-neutron temperature

Part 3: Assumption-free evidence for clusters



What do we need to describe atomic nuclei?

What are the crucial degrees of freedom? i.e.,

- Deformation (single particles/mean-field)
- Pairing ($S=0, T=1$ and $S=1, T=0$ or *neutron-proton pairing*)
- Quartets/ 'alpha clusters'
- Other clusters?

What do we need to describe atomic nuclei?

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- Other clusters?

In other words, how do we *know* that quartets are more important than triplets?





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In many-body theory we often
introduce various density operators,
such as the one-body density

$$\langle \hat{c}_i^\dagger \hat{c}_j \rangle$$

and the two-body density

$$\langle \hat{c}_i^\dagger \hat{c}_j^\dagger \hat{c}_l \hat{c}_k \rangle$$



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$$\text{tr} \langle \hat{c}_i^\dagger \hat{c}_j \rangle = A$$

and

$$\text{tr} \langle \hat{c}_i^\dagger \hat{c}_j^\dagger \hat{c}_l \hat{c}_k \rangle = A(A-1)/2$$

in general, the trace of an a -body density
is $\binom{A}{a} = \frac{A!}{a!(A-a)!}$.



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To look for important degrees of freedom,
we will use Yang's criterion for long-range
off-diagonal order $\rightarrow$

a large eigenvalue of a density matrix

Sometimes one plots the *entanglement spectrum**
which, traditionally, is $-\ln(\lambda_n)$ where λ_n is an eigenvalue
Li and Haldane, PRL **101**, 010504 (2008)

Small values (= large λ_n) and 'gaps' in the spectrum are meaningful

* because entanglement entropy $S = - \sum_n \lambda_n \ln \lambda_n$



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How to do this:

1. Solve $\hat{H}|\Psi\rangle = E|\Psi\rangle$ using shell model code
2. Compute $\rho_{abc\dots rst} = \langle\Psi|\hat{c}_a^\dagger\hat{c}_b^\dagger\hat{c}_c^\dagger\dots\hat{c}_t\hat{c}_s\hat{c}_r|\Psi\rangle$
3. Find eigenvalues λ_n of ρ (because density, $1 \geq \lambda_n \geq 0$)
4. Plot $-\ln(\lambda_n)$

(also see Sambataro & Sandulescu, Ann. Phys. 413, 168061 (2020)
and N. Sandulescu's talk from this workshop)

In many of my calculations, I remove the shell structure (single-particle energies and monopole interactions) and compare to a randomly generated two-body interaction; the latter acts as a control.



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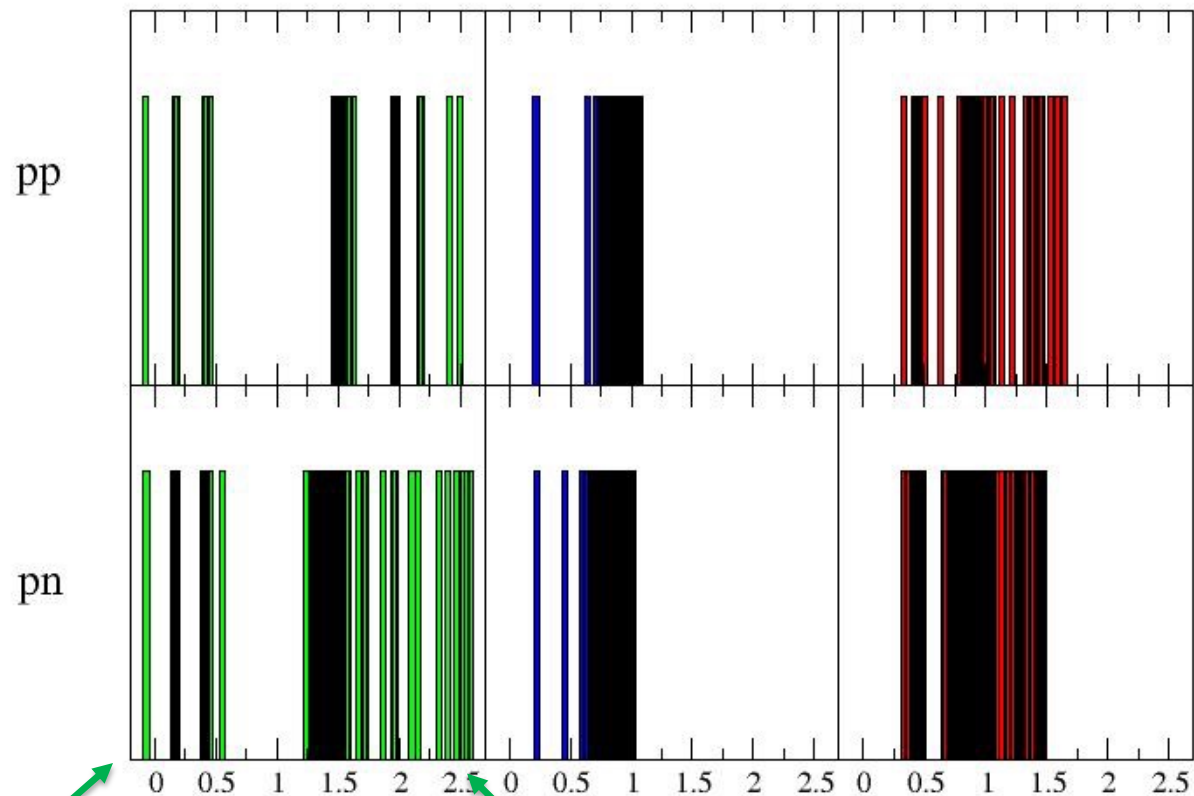
^{32}S (valence sd)

ground state $-\ln \lambda_n$

USDB

USDB (no mono)

random



high correlation

low correlation

Many-body correlations, phase transitions, and clustering, Saclay, Sept 2026



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^{32}S (valence sd)

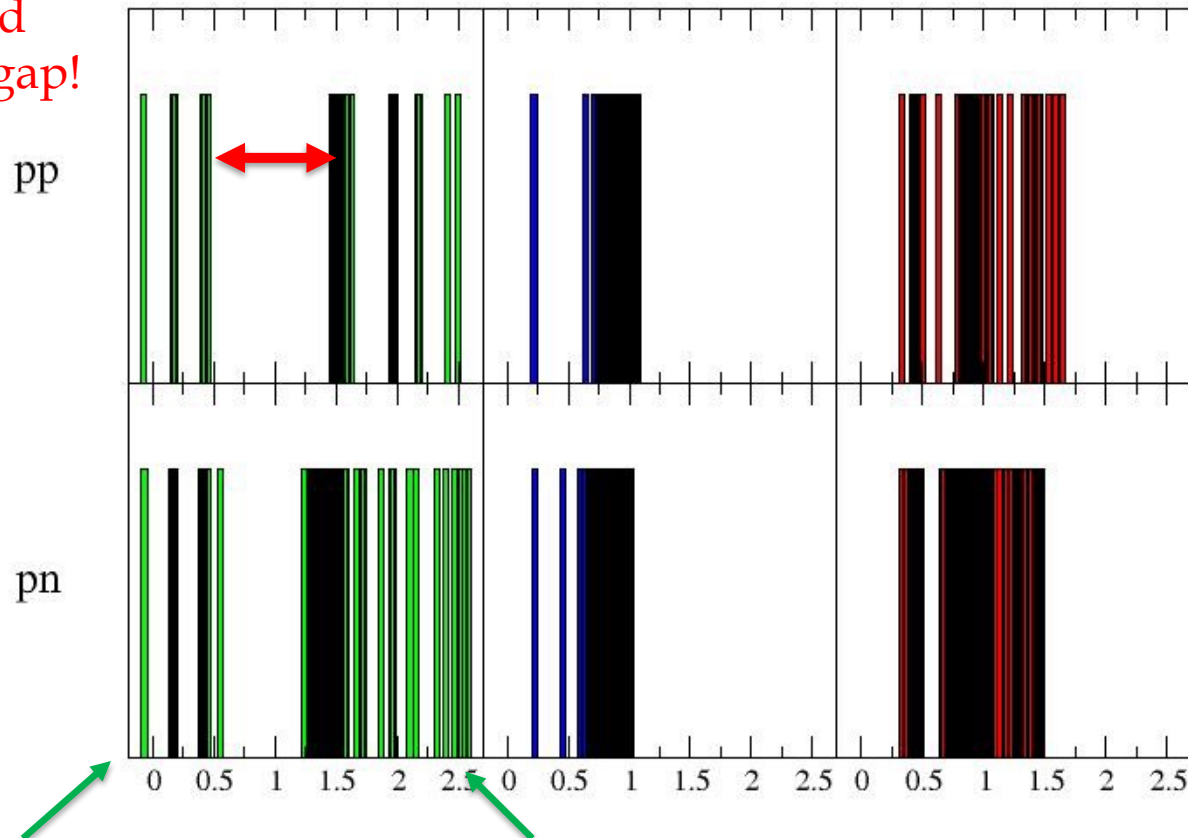
ground state $-\ln \lambda_n$

USDB

USDB (no mono)

random

Mind
the gap!



high correlation

low correlation

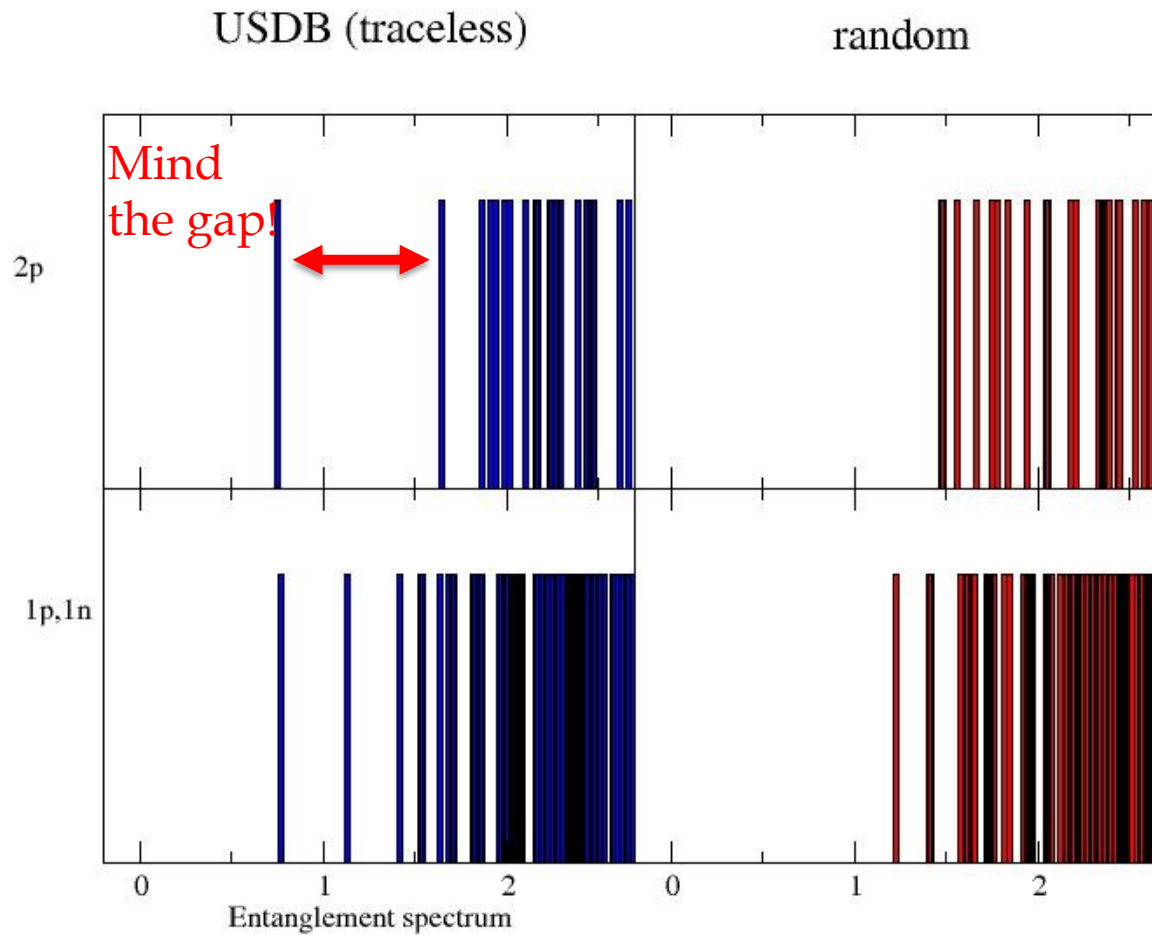
Many-body correlations, phase transitions, and clustering, Saclay, Sept 2026



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^{24}Mg (valence sd)

ground state $-\ln \lambda_n$

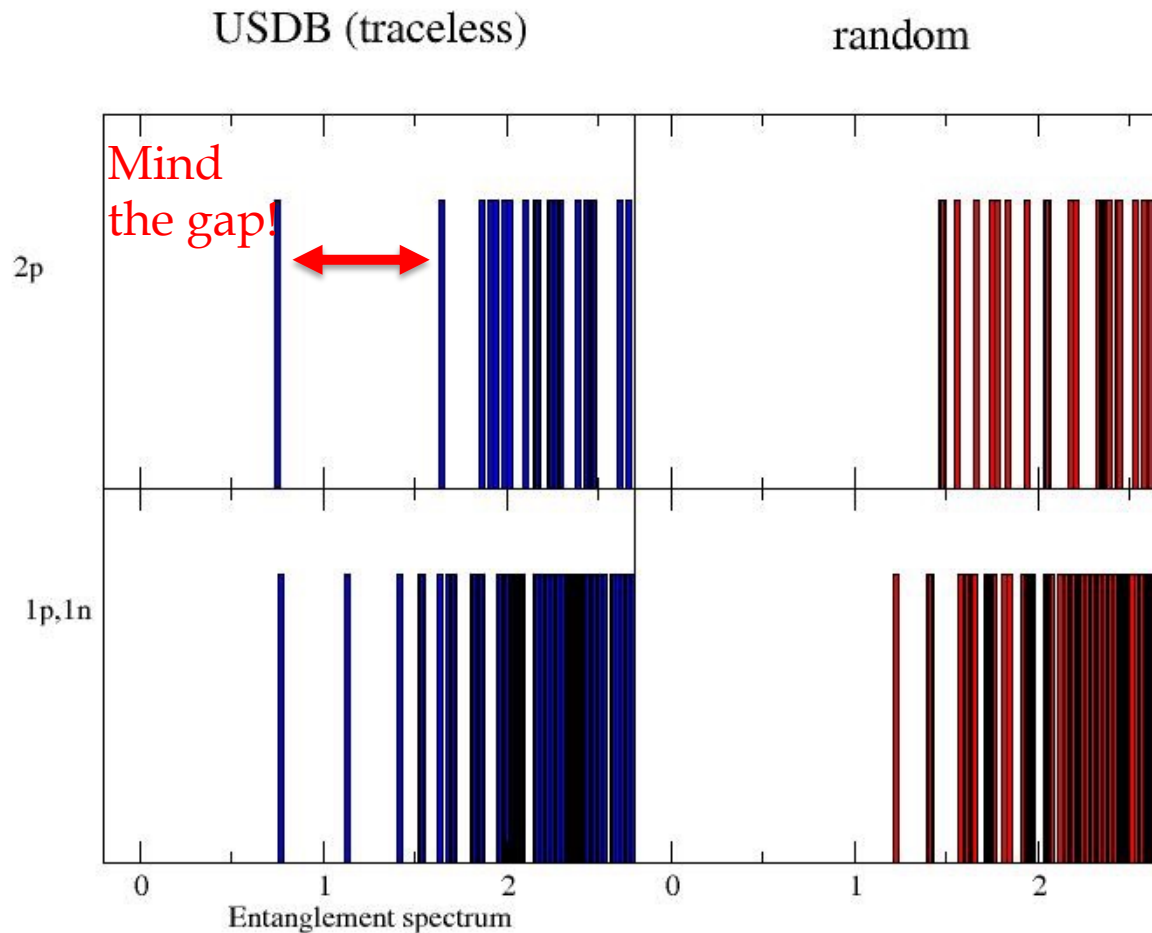




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^{24}Mg (valence sd)

ground state $-\ln \lambda_n$



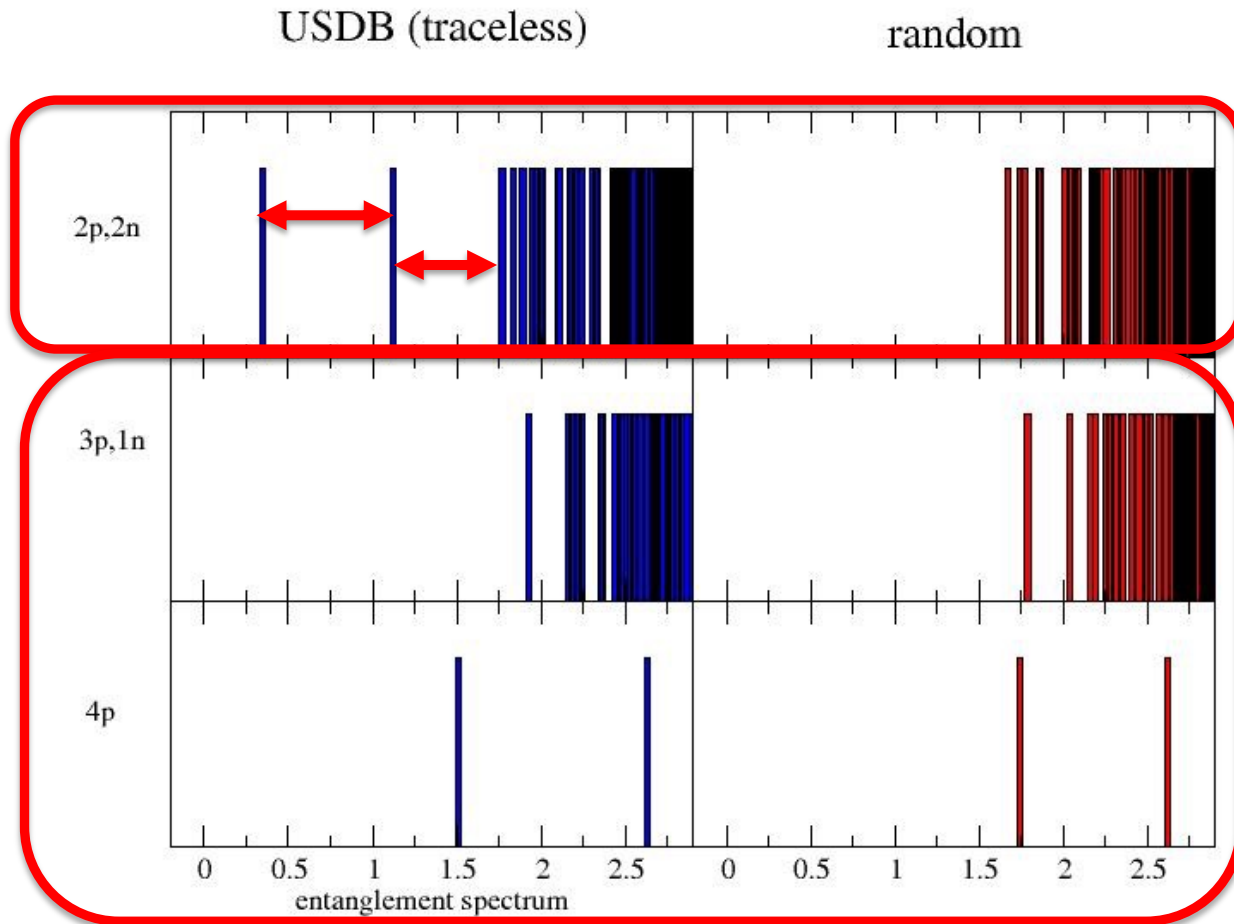
Note: these are
not necessarily
 $J = 0, 1$ pairs;
the results are
agnostic

^{24}Mg (valence sd)

ground state $-\ln \lambda_n$



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these spectra
differ

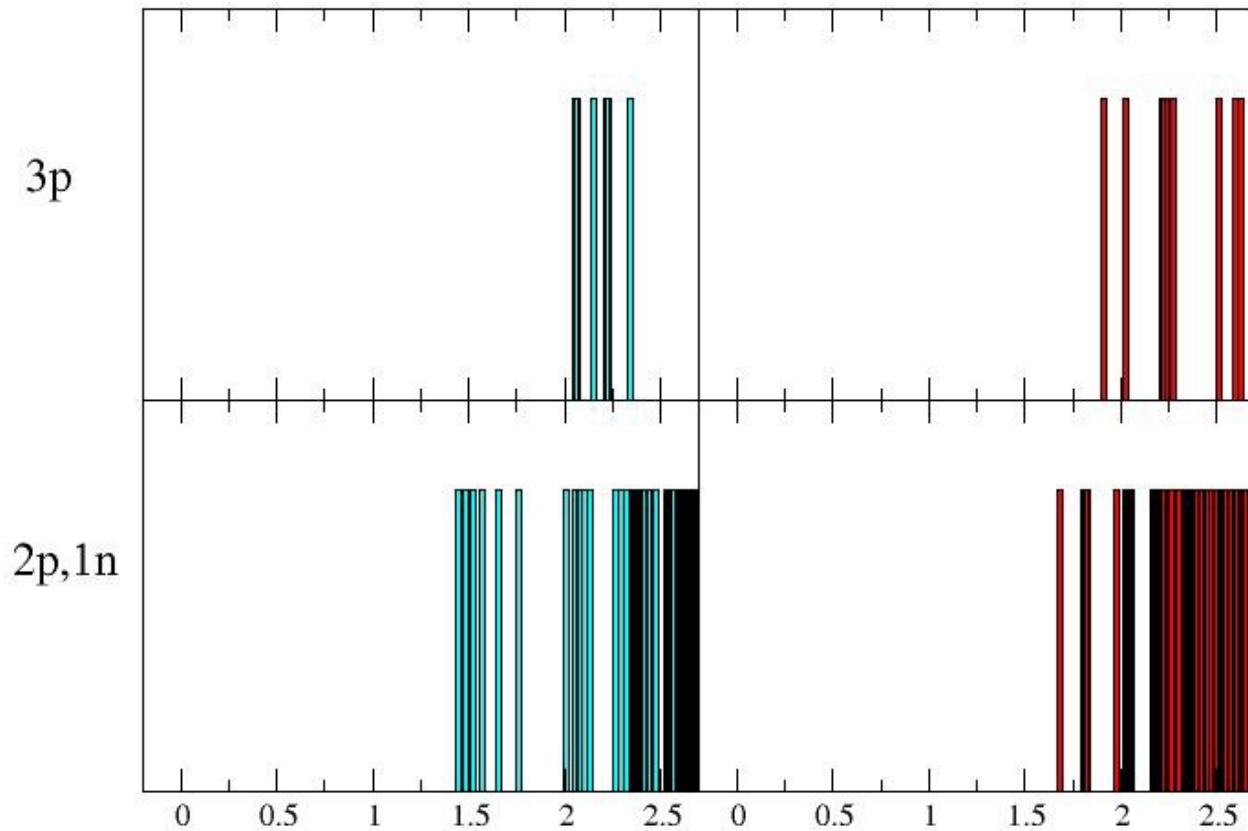
...while these
spectra are
not very
different



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^{24}Mg (valence sd)

ground state $-\ln \lambda_n$
USDB (no mono) random



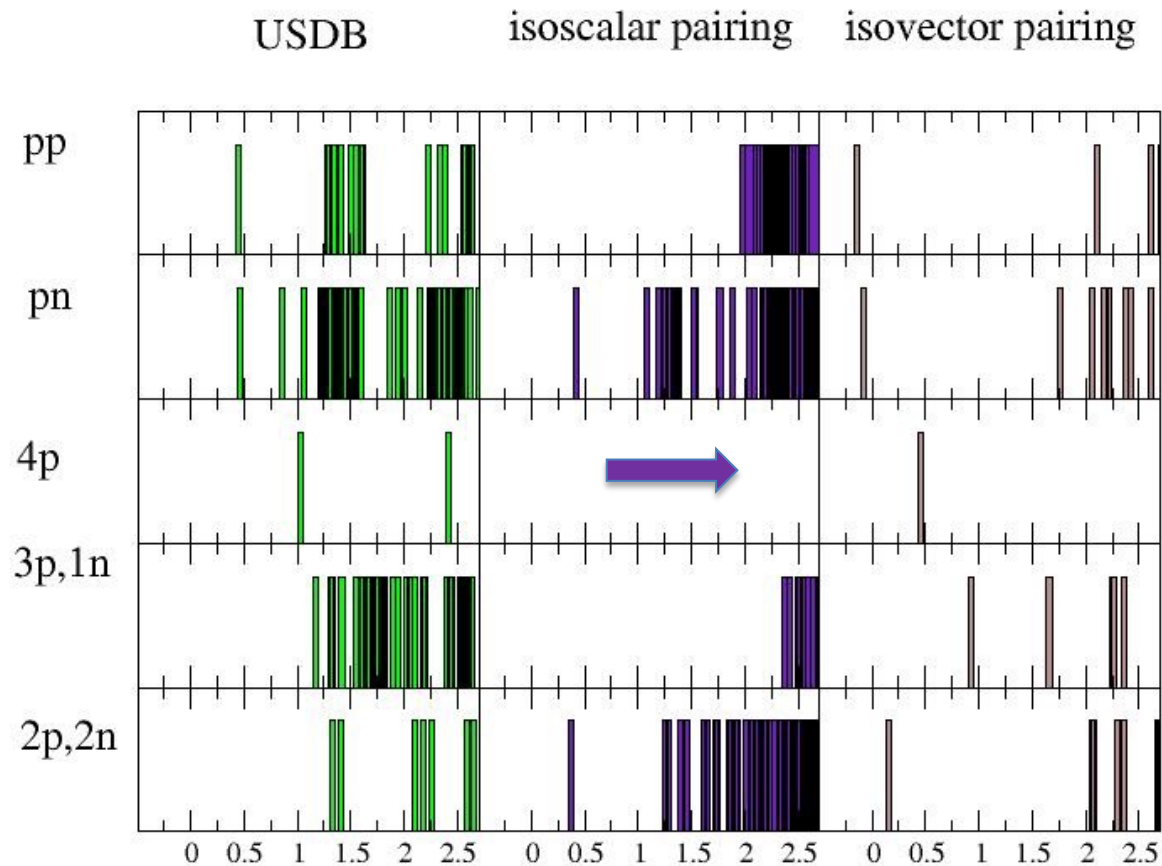
No evidence for
strong triplet
correlations

^{24}Mg (valence sd)

ground state $-\ln \lambda_n$



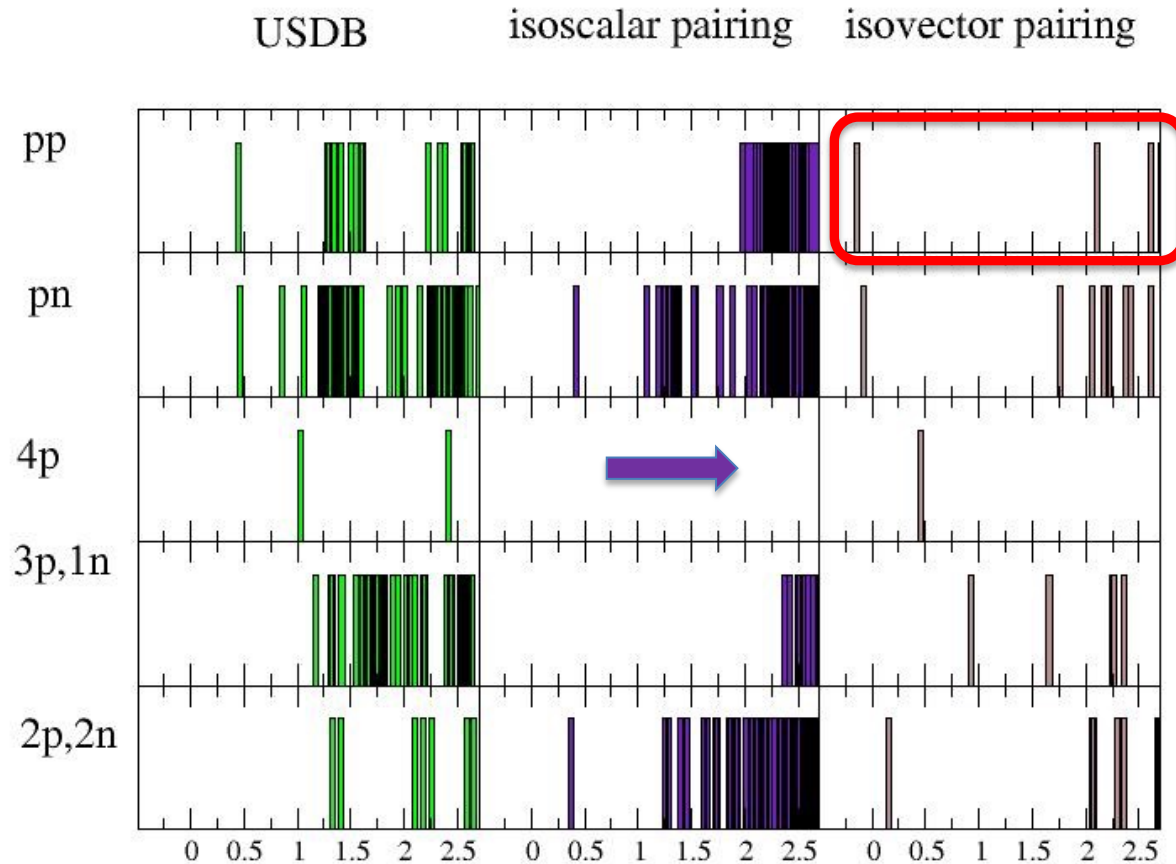
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^{24}Mg (valence sd)

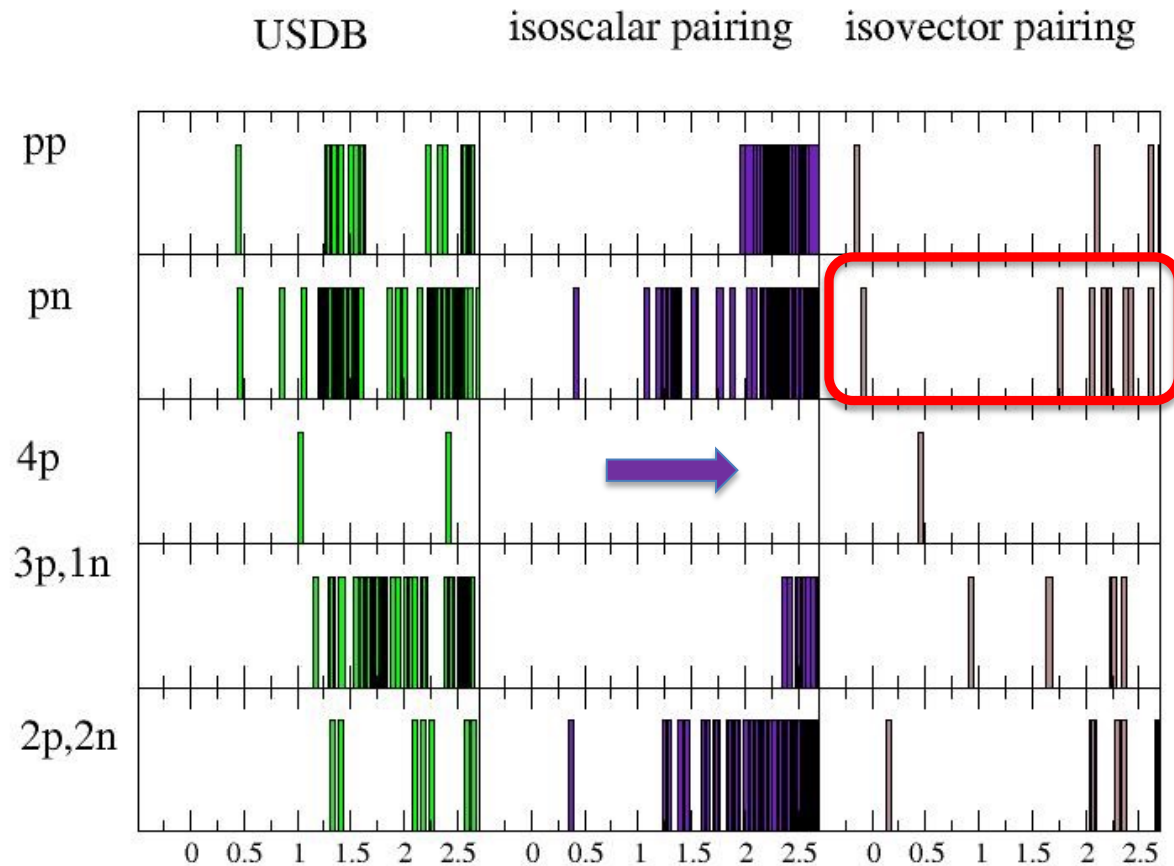
ground state $-\ln \lambda_n$





^{24}Mg (valence sd)

ground state $-\ln \lambda_n$

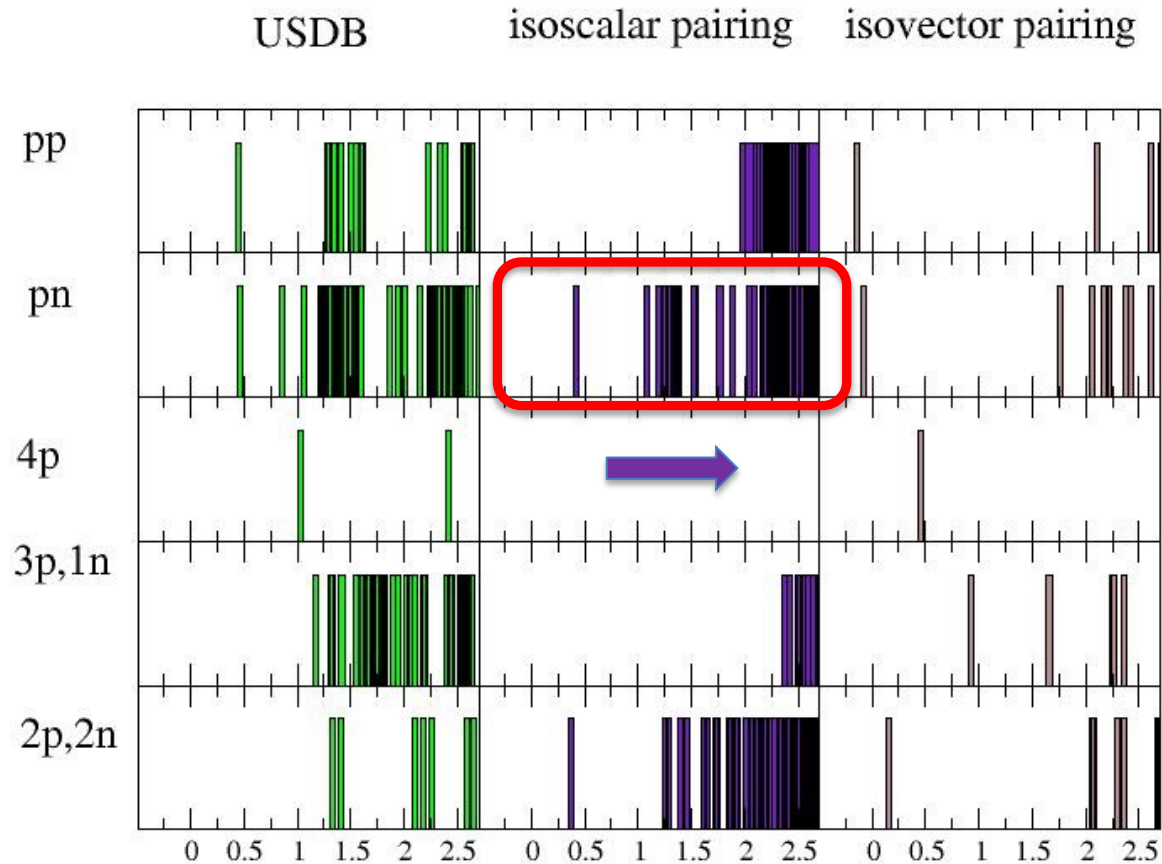




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^{24}Mg (valence sd)

ground state $-\ln \lambda_n$

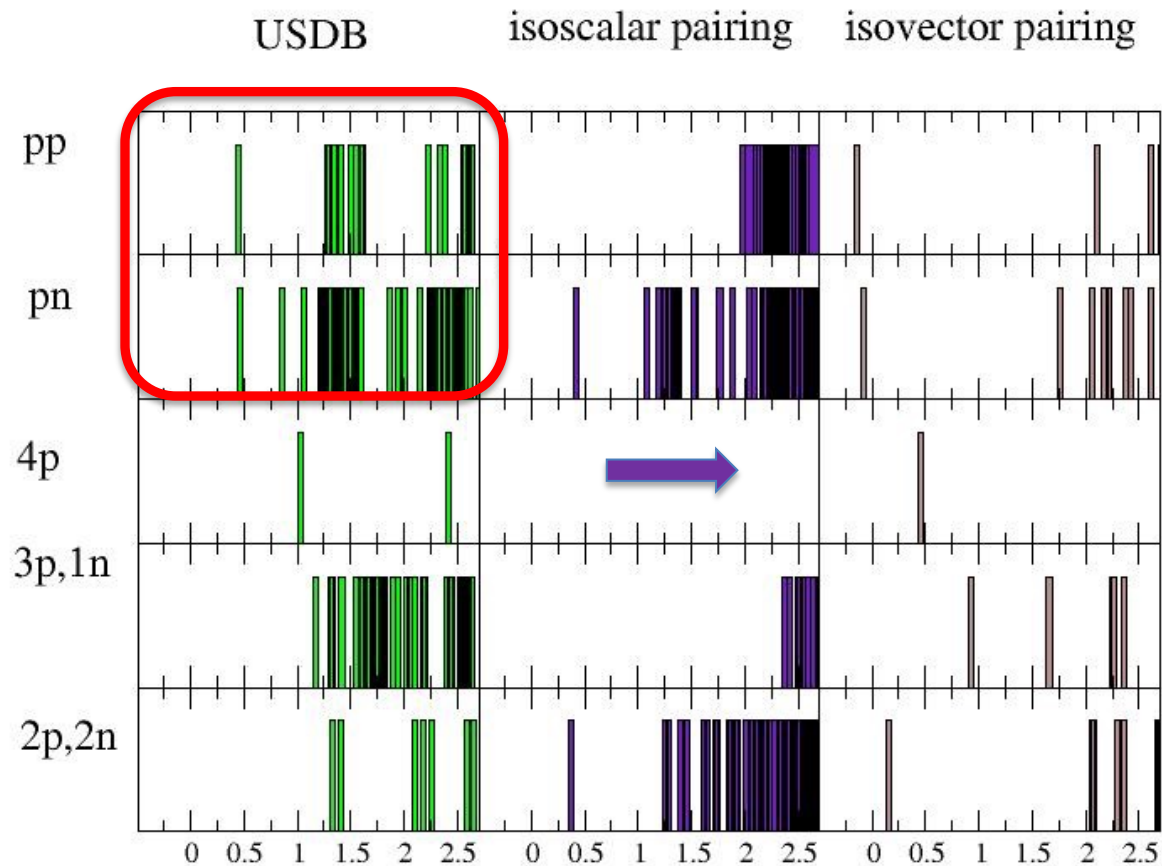




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^{24}Mg (valence sd)

ground state $-\ln \lambda_n$

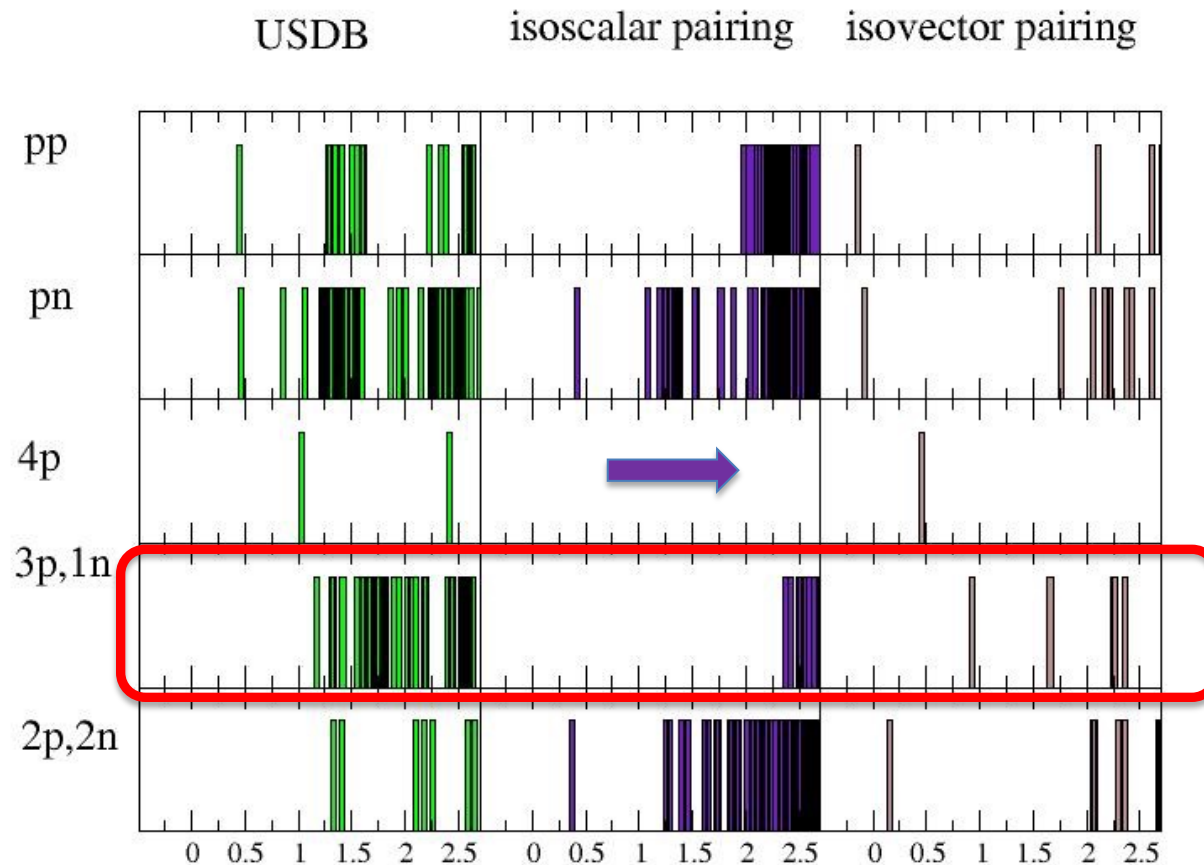


^{24}Mg (valence sd)

ground state $-\ln \lambda_n$



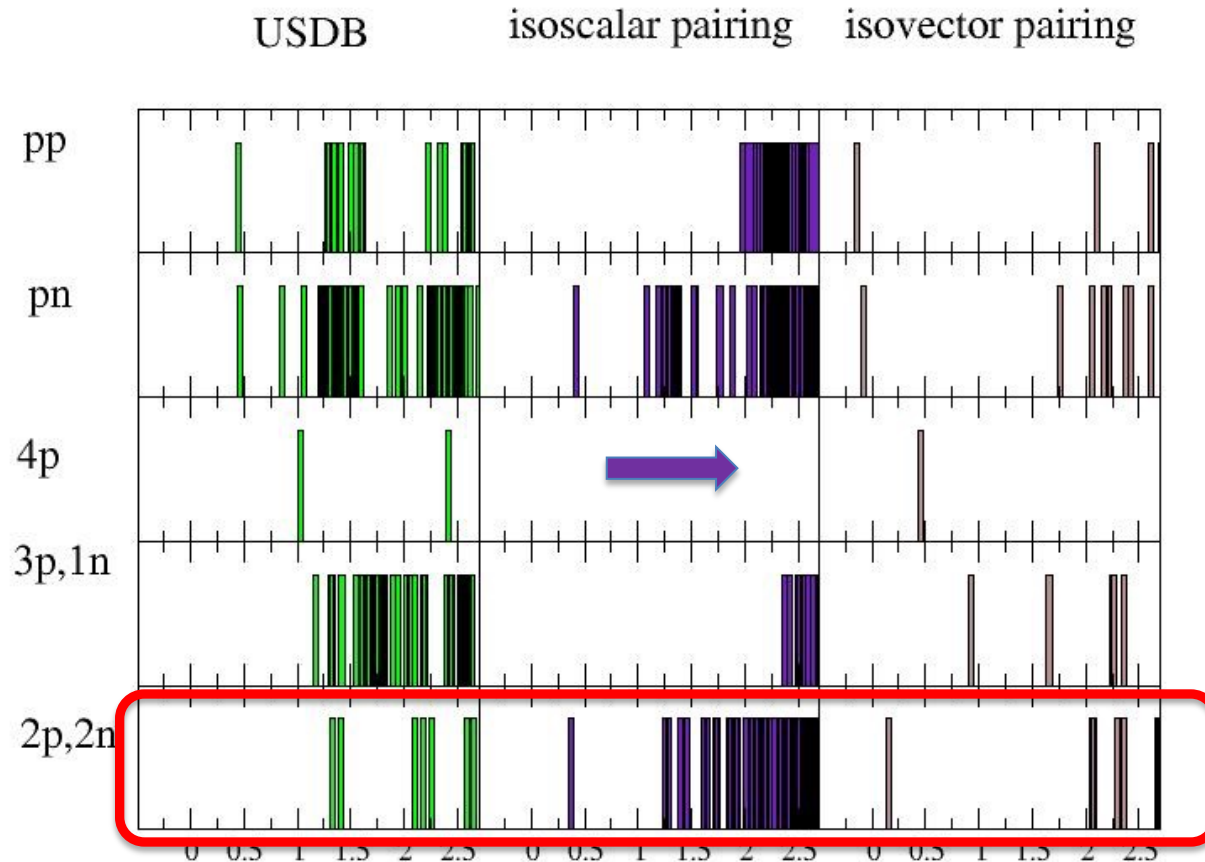
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^{24}Mg (valence sd)

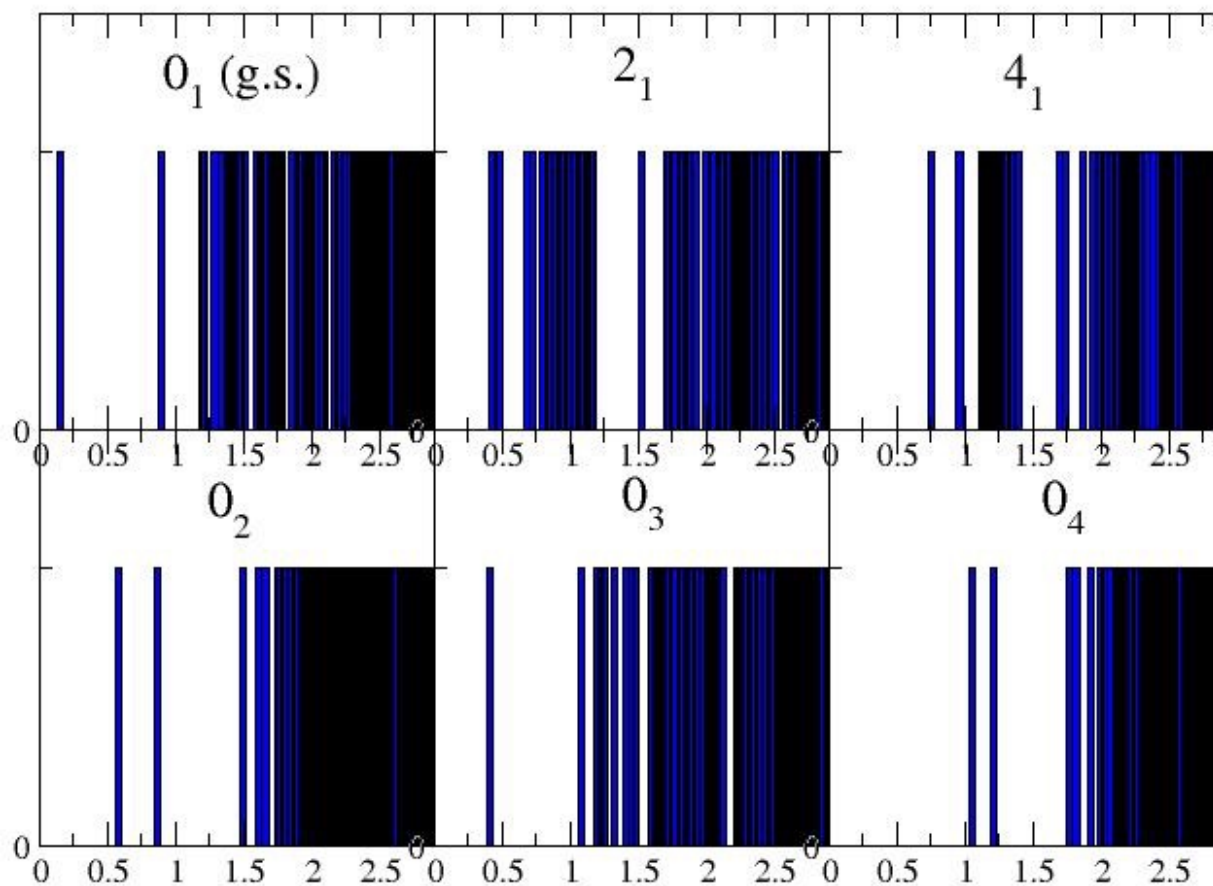
ground state $-\ln \lambda_n$





^{24}Mg (valence sd)

2p, 2n



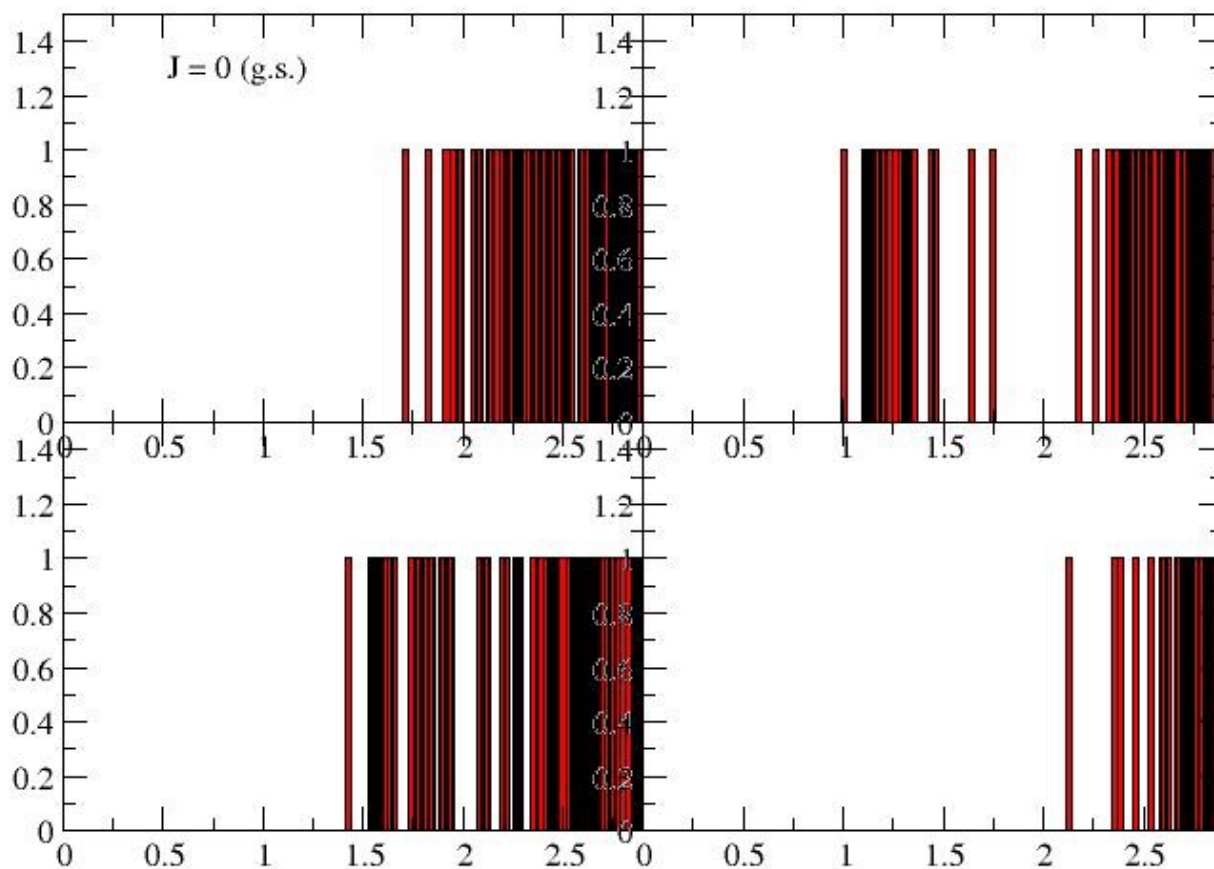
USDB
interaction



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^{24}Mg (valence sd)

2p, 2n



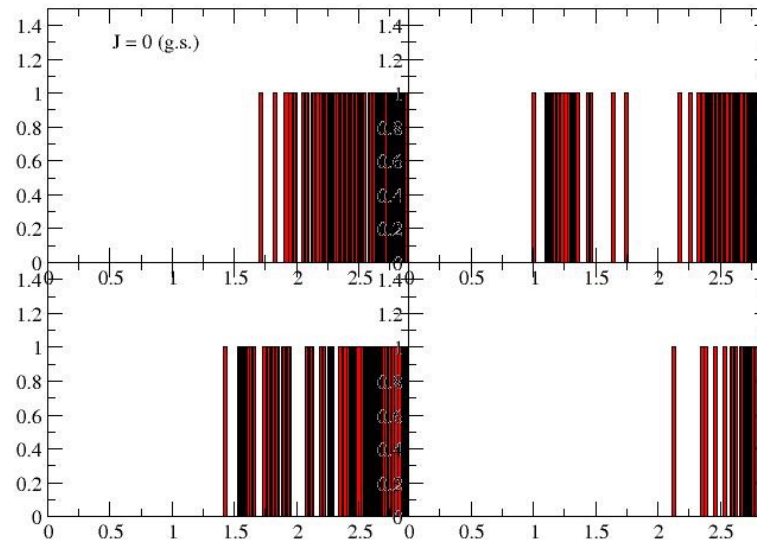
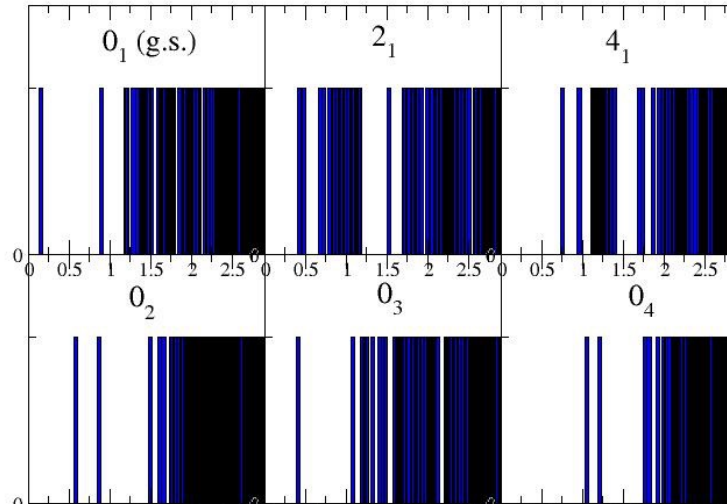
random
interaction



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USDB
interaction

2p, 2n
 ^{24}Mg (valence sd)



random
interaction



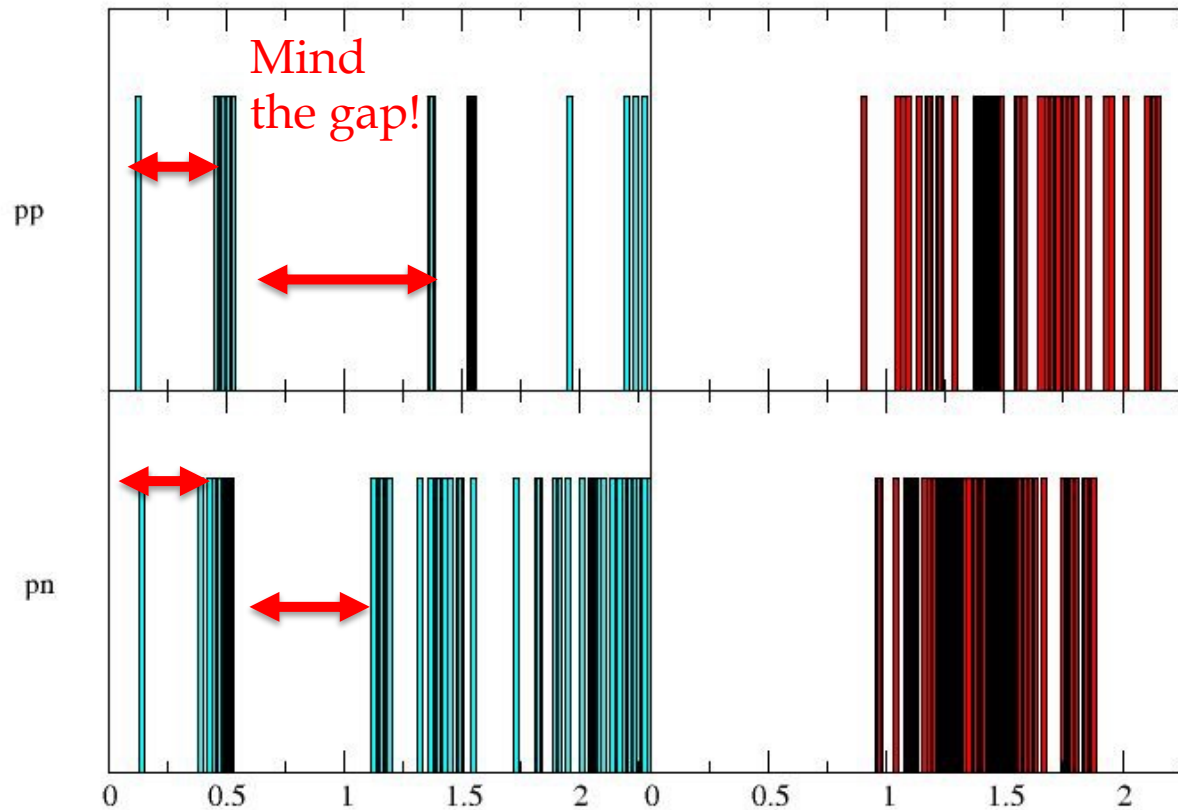
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^{28}Si (valence sd)

ground state $-\ln \lambda_n$

USDB (no mono)

random





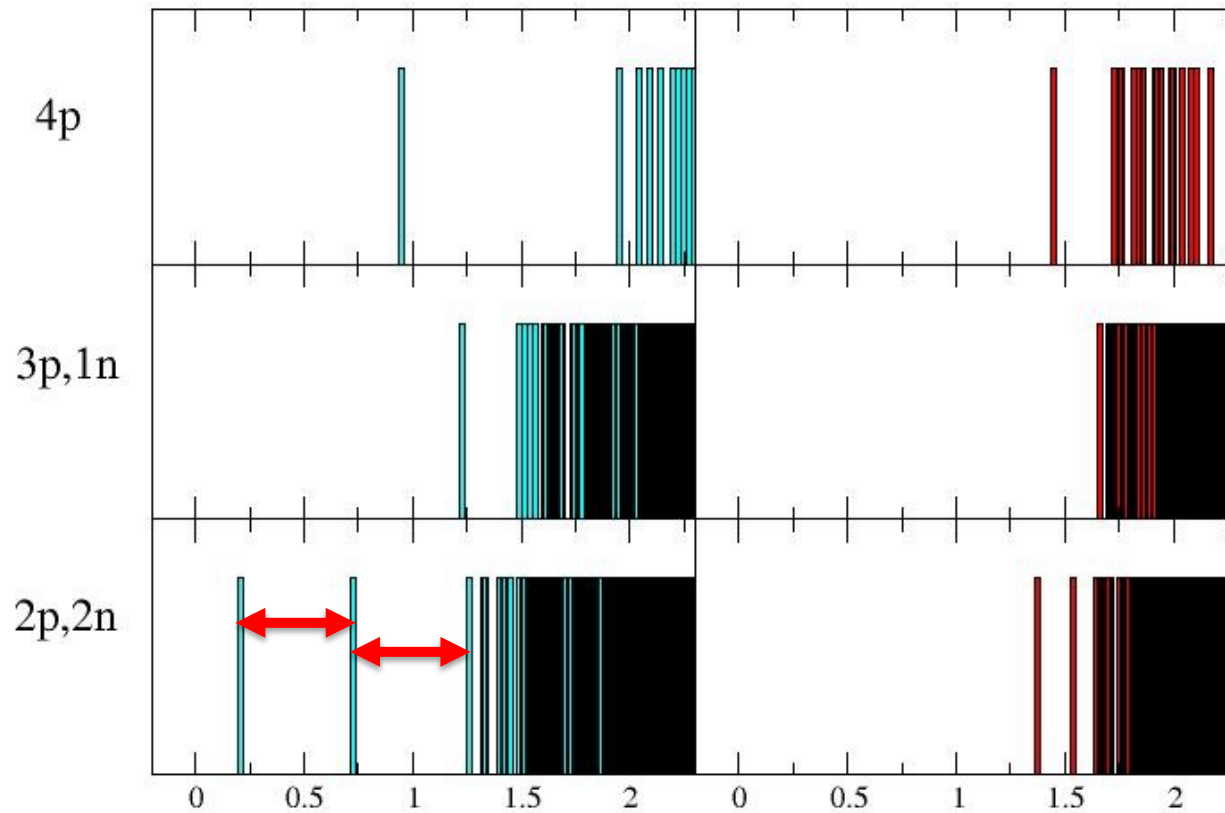
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^{28}Si (valence sd)

ground state $-\ln \lambda_n$

USDB (no mono)

random

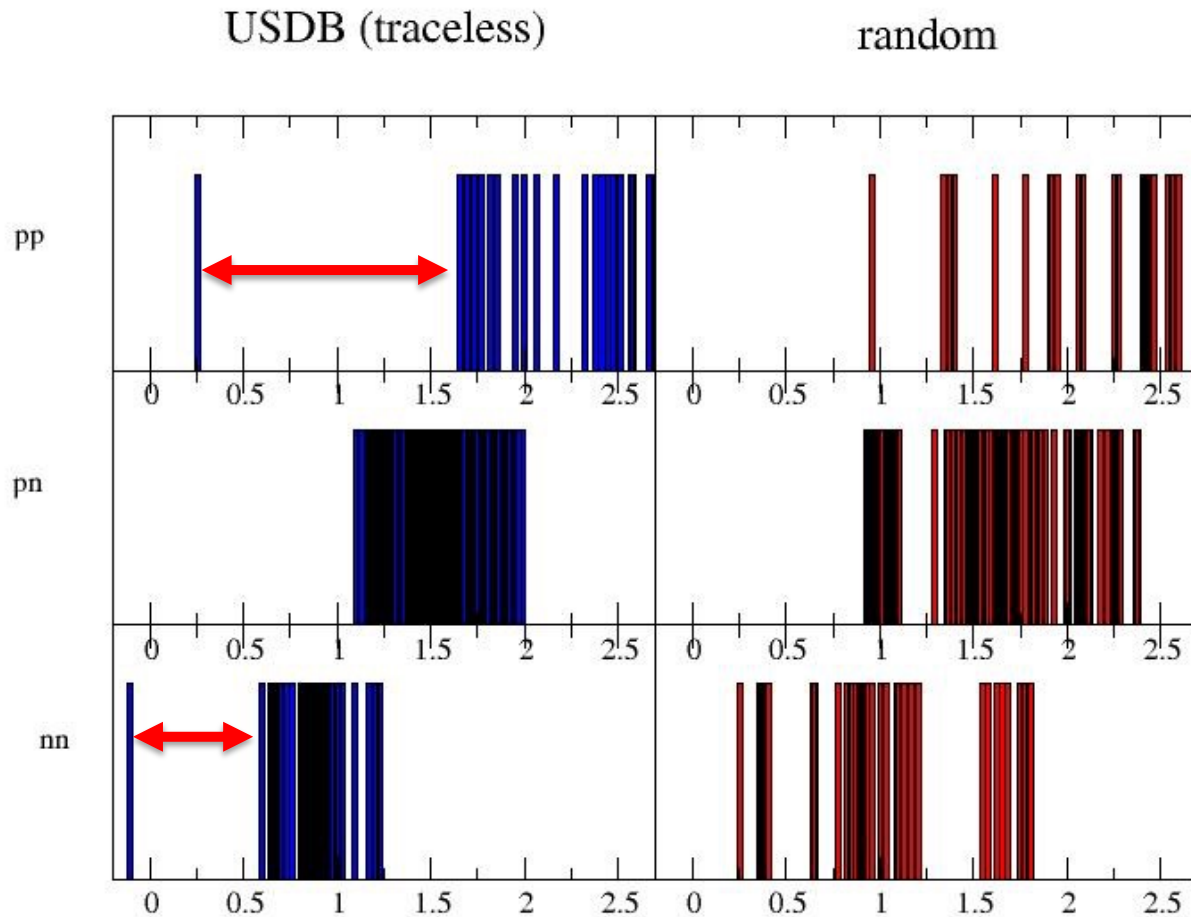




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^{28}Mg (valence sd)

ground state $-\ln \lambda_n$





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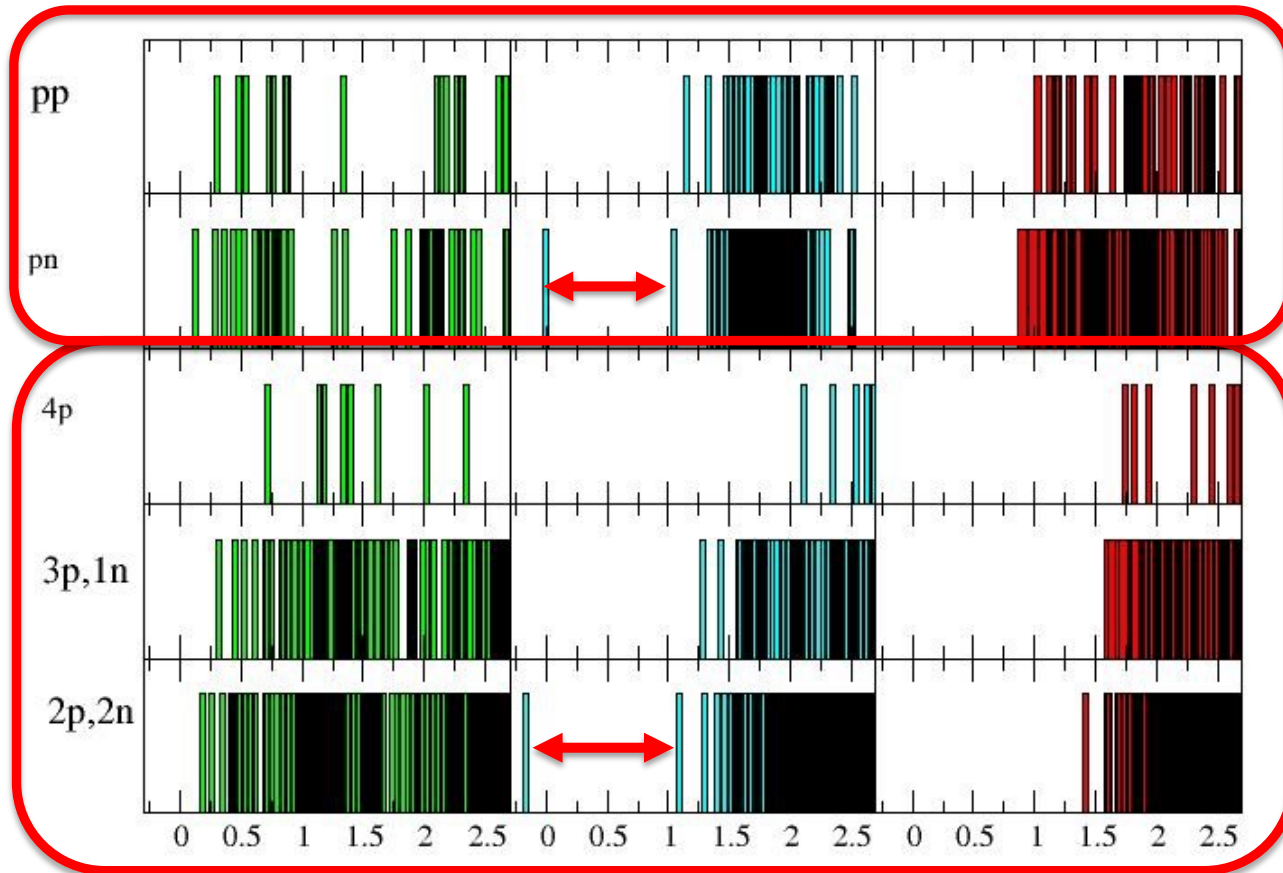
^{26}Al (valence sd)

ground state $-\ln \lambda_n$

USDB

USDB (no mono)

random





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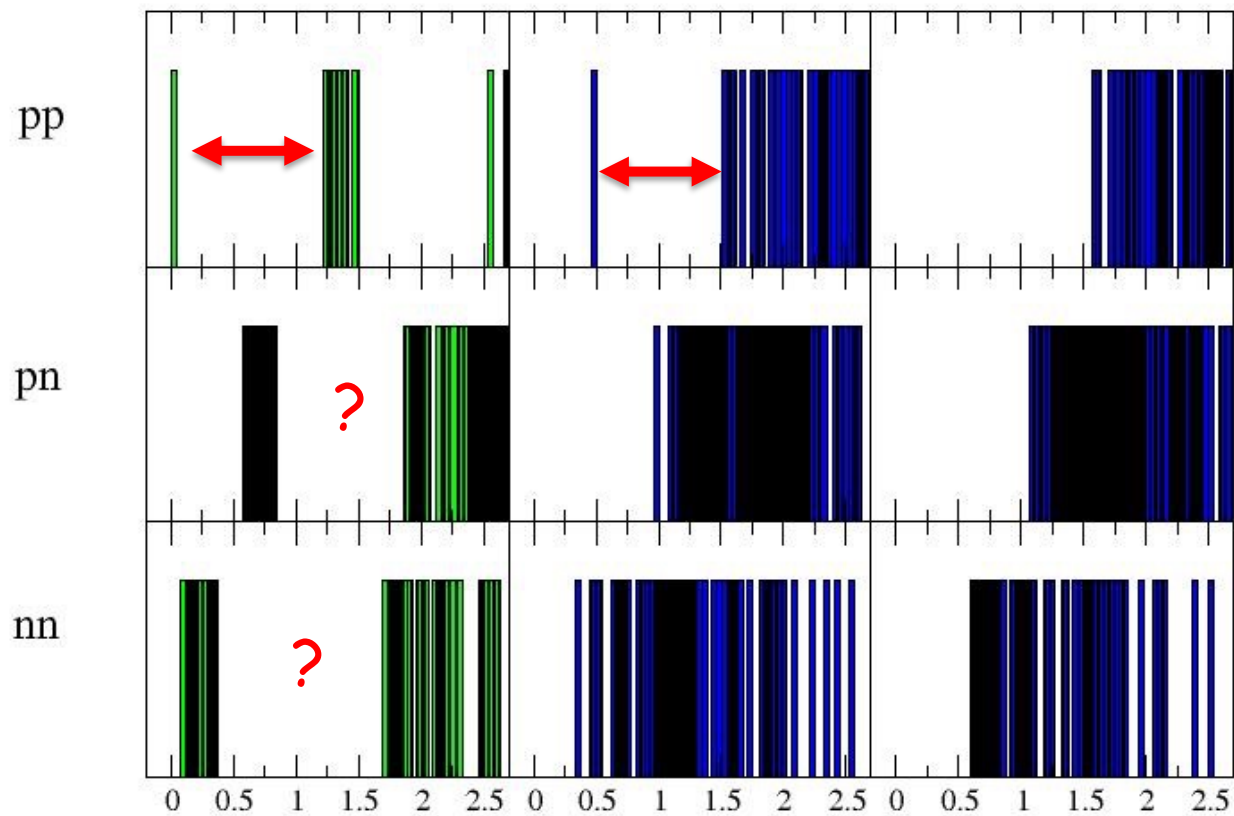
^{27}Mg (valence sd)

ground state $-\ln \lambda_n$

USDB

USDB (no mono)

random





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Next steps

More $N > Z$, odd-odd, odd- A cases

fp shell cases

no-core shell model (*need to make code more efficient*)

**Go up in energy, at what energy do the gaps disappear?
When does the max correlation (lowest eigenvalue)
approach the random interaction avg. value?**

Do the trends hold?



Summary of part 3

The *entanglement spectrum* for a given a -body ‘cluster’, can give clues to which correlations are relevant in many-body systems (especially when contrasted against a ‘null case’ calculated with a randomly generated interaction).

We clearly see that like-particle pairs and 2 proton, 2 neutron correlations are important, while triplets are not.

The evidence on 1-proton, 1-neutron pairs is less strong.

and finally....



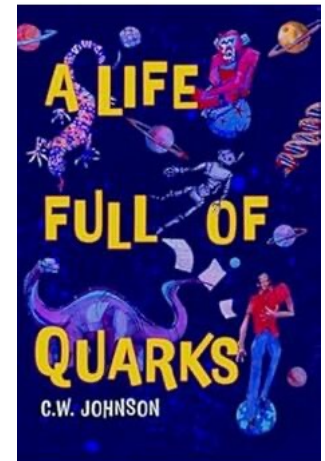
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Summary

Much work remains to be done!



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