Exploring shell structure of nuclides in proximity of doubly-magic $^{132}\text{Sn}$

Angela Gargano, INFN Napoli
Why $^{132}$Sn region?

The only region around a heavy, neutron rich doubly-closed shell nucleus far-off stability experimentally accessible today

➢ gives important information, from the nuclear structure point of view, on the shell evolution and the underlying driving forces
➢ is of great relevance (especially nuclei with $Z<50$) for the description of the rapid neutron capture process of nucleosynthesis
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- is of great relevance (especially nuclei with $Z<50$) for the description of the rapid neutron capture process of nucleosynthesis

Experimental information $\rightarrow$ allows us to test nuclear models (for shell model: single-particle energies, two-body matrix elements of the residual interaction and effective electromagnetic operators) and to ascertain their capability to provide reliable predictions for nuclei

- which are still unaccessible for present experiments
- involved in $0\nu2\beta$ decay ($^{130}$Te, $^{136}$Xe)
The “realistic” Shell Model

\[ H_{\text{eff}} \psi_\alpha = H_0 + V_{\text{eff}} \psi_\alpha = E_\alpha \psi_\alpha \quad \text{with} \quad H_0 = T + U \]

in the model space for only valence nucleons
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Effective shell-model hamiltonian

The shell-model hamiltonian has to take into account in an effective way all the degrees of freedom not explicitly considered.

Two alternative approaches:
- Phenomenological
- Microscopic

\[ V_{\text{NN}} (+V_{\text{NNN}}) \Rightarrow \text{many-body theory} \Rightarrow H_{\text{eff}} \]

**Definition**

[for 2 valence-nucleon systems]

The eigenvalues of \( H_{\text{eff}} \) belong to the set of eigenvalues of the full nuclear hamiltonian in the full Hilbert space.
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**Definition** [for 2 valence-nucleon systems]

The eigenvalues of \( H_{\text{eff}} \) belong to the set of eigenvalues of the full nuclear hamiltonian in the full Hilbert space

\( H_{\text{eff}} \) takes into account in an effective way all the degrees of freedom not considered explicitly: namely core nucleons and excitations of valence nucleons into the shells above the model space
Flow chart of a RSMC

- Choice of the free NN potential

- Choice of the model space better tailored to study the system under investigation

- Derivation of the effective Hamiltonian making use of many-body theory

- Diagonalization of the Hamiltonian matrix & calculations of physical observables as energies, electromagnetic transition probabilities*, …

*Need to use microscopic effective operators consistent with the effective Hamiltonian
1st step: choice of the NN potential

Several realistic potentials $\chi^2/datum \approx 1$: CD-Bonn, Argonne V18, Nijmegen, ...

or derived by the chiral effective field theory

short-range repulsion

A. Gargano
1st step: choice of the NN potential

Several realistic potentials $\chi^2/\text{datum} \approx 1$: CD-Bonn, Argonne V18, Nijmegen, ...

or derived by the chiral effective field theory

- normalization procedure for $V_{\text{NN}}$

- low momentum potentials:
  
  ✓ $V_{\text{low-k}}$

  preserves the properties of the original NN potential up to a momentum-space cutoff $\Lambda$

  ✓ chiral potentials defined for momenta below a low cutoff
2nd step: choice of the model space

\[ \begin{array}{c}
\pi \\
133Sn \\
133Sb \\
50 \\
\pi^{-1} \\
131Sn \\
131In \\
132Sn \\
82 \\
\end{array} \]

- \[ i_{13/2} \]
- \[ f_{5/2} \]
- \[ p_{1/2} \]
- \[ h_{9/2} \]
- \[ p_{3/2} \]
- \[ f_{7/2} \]
- \[ h_{11/2} \]
- \[ s_{1/2} \]
- \[ d_{3/2} \]
- \[ d_{5/2} \]
- \[ g_{7/2} \]
- \[ g_{9/2} \]
- \[ f_{5/2} \]
- \[ p_{1/2} \]
- \[ p_{3/2} \]
3rd step: derivation of the effective interaction by the folded diagram method

$H_{\text{eff}}$ is written as a series in terms of the $\hat{Q}$-box and its derivatives. For instance

$$H_{\text{eff}} = \sum_{i=0}^{\infty} F_i,$$

where

$$F_0 = \hat{Q}(\epsilon_0)$$
$$F_1 = \hat{Q}_1(\epsilon_0)\hat{Q}(\epsilon_0)$$
$$F_2 = \hat{Q}_2(\epsilon_0)\hat{Q}(\epsilon_0)\hat{Q}(\epsilon_0) + \hat{Q}_1(\epsilon_0)\hat{Q}_1(\epsilon_0)\hat{Q}(\epsilon_0)$$

$$\ldots$$

$$\hat{Q}(\epsilon) = PH_1P + PH_1Q \frac{1}{\epsilon - \hat{Q}\hat{H}\hat{Q}} QH_1P.$$

where $H_1 = V_{\text{low-k}} - U$; $P$ = model space; $Q = 1-P$; $\epsilon = PH_0P$;
3rd step: derivation of the effective interaction by the folded diagram method

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\ldots
\]

\[
\hat{Q}(\epsilon) = PH_1P + PH_1Q \frac{1}{\epsilon - QHQ} QH_1P.
\]

where \( H_1 = V_{\text{low-k}} - U; P = \text{model space}; Q = 1 - P; \epsilon = PH_0P \)

The series is summed by iterative techniques (Krenciglowa-Kuo, Lee-Suzuki)
Perturbative calculation

The diagrammatic expansion of the $\hat{Q}$-box

1-body diagrams up to 2nd order

2-body diagrams up to 2nd order:

$V$  $V_{1p1h}$  $V_{2p}$  $V_{2p2h}$
Perturbative calculation

The diagrammatic expansion of the $\hat{Q}$-box

1-body diagrams up to 2nd order

S-box

2-body diagrams up to 2nd order

1-4

2-1

2-2

2-3

2-4

A. Gargano

San Servolo, Venice

up-to-date calculations do not go beyond third order!
Results in $^{132}\text{Sn}$ region

- CD-Bonn
- $V_{\text{low-k}}$ ($\Lambda=2.2 \text{ fm}^{-1}$) + Coulomb interaction
- $V_{\text{eff}}$ @ second order
- Model space: one major shell for protons/neutrons
- with SP energies from experiment
Realistic shell-model studies around $^{132}$Sn


- Energy spectra and electromagnetic properties of nuclei below and above Z=50
- Behavior of odd-even mass staggering around $^{132}$Sn
- Evolution of single-particle states beyond $^{132}$Sn
- Mixed-symmetry states
- Predictions for exotic Sn isotopes with N>82
- Proton-neutron multiplets
- Similarity of nuclear structure in the $^{132}$Sn and $^{208}$Pb regions
- Role of three-nucleon forces in neutron-rich nuclei beyond $^{132}$Sn

Satisfactory description of nuclear structure properties, although some problems still remain to be solved.
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- Satisfactory description of nuclear structure properties, although some problems still remain to be solved

- $^{1/2^+ \rightarrow 3/2^+}$ M1 transition in $^{129}$Sn
- $(\pi g_{9/2}^{-1} \otimes v f_{7/2})$ multiplet in $^{132}$In

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- A. Jungclaus, A. Gargano et al, *First observation of $\gamma$ rays emitted from excited states south-east of $^{132}$Sn: The $\pi g_{9/2}^{-1} \otimes v f_{7/2}$ multiplet of $^{132}$In$_{83}$*, Phys. Rev. C 93, 041301(R) (2016)
Fast-timing study of the $I$-forbidden $1/2^+ \rightarrow 3/2^+ M1$ transition in $^{129}$Sn

$\beta^-$ decay of $^{129}$In isomers @ ISOLDE
Fast-timing study of the $l$-forbidden $1/2^+ \rightarrow 3/2^+ M1$ transition in $^{129}$Sn

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$^{129}$Sn $\leftrightarrow$ 3 neutron holes in the 50-82 shell
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$^{129}$Sn $\leftrightarrow$ 3 neutron holes in the 50-82 shell

slow $l$ forbidden ($\Delta l=2$) M1 transition
E2 transition hindered

$^{129}$Sn

<table>
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<tr>
<th>State</th>
<th>Configuration</th>
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<tbody>
<tr>
<td>$3/2^+$</td>
<td>$(1d_{1/2})^{-1}$</td>
</tr>
<tr>
<td>$1/2^+$</td>
<td>$(2s_{1/2})^{-1}$</td>
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Fast-timing study of the $l$-forbidden $1/2^+ \rightarrow 3/2^+$ M1 transition in $^{129}\text{Sn}$

$\beta^-$ decay of $^{129}\text{In}$ isomers @ ISOLDE

$^{129}\text{Sn} \leftrightarrow 3$ neutron holes in the 50-82 shell

$1/2^+ \rightarrow 315$ keV $3/2^+$

slow $l$ forbidden ($\Delta l=2$) M1 transition

E2 transition hindered

$1/2^+$ $T_{1/2}=19(10)$ ps $\rightarrow$ (assuming a pure M1 transition)

$B(M1; 1/2^+ \rightarrow 3/2^+)=6.4(30) \times 10^{-2} \mu_N^2$

Relatively fast M1 transition
Fast-timing study of the $l$-forbidden $1/2^+ \rightarrow 3/2^+$ $M1$ transition in $^{129}$Sn

<table>
<thead>
<tr>
<th>$E_{\text{exc}}$ (in keV)</th>
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<th>Expt</th>
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<tr>
<td>$1/2^+$</td>
<td>294</td>
<td>315</td>
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<tr>
<th>$J^\pi$</th>
<th>$(n\ell_j)^{-2}$</th>
<th>$(0\ell_{1/2})^{-2}$</th>
<th>$(1\ell_{3/2})^{-2}$</th>
<th>$(2\ell_{1/2})^{-2}$</th>
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<th>$(0\ell_{7/2})^{-2}$</th>
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<td>$3/2^+$</td>
<td>69%</td>
<td>12%</td>
<td>8%</td>
<td>6%</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>$1/2^+$</td>
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<td>27%</td>
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Percentage of the wf configurations $3/2^+ \rightarrow (1d_{3/2})^{-1} (n\ell_j)^{-2}$ & $1/2^+ \rightarrow (2s_{1/2})^{-1} (n\ell_j)^{-2}$
Fast-timing study of the \( l \)-forbidden 1/2\(^+ \) → 3/2\(^+ \) M1 transition in \(^{129}\)Sn

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### Percentage of the wave-function configurations

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<th>( J^\pi )</th>
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\( e_{\text{eff}} = 0.7 \) \( e \)

\( g_{l}^{\text{free}} = 0, \ g_{s} = 0.7g_{s}^{\text{free}} = -2.68 \)

\( B(E2; \ 1/2^+ \rightarrow 3/2^+) \)

32.89 \( e^2 \) fm\(^4\)

\( B(M1; \ 1/2^+ \rightarrow 3/2^+) \)

0.58 \( \times 10^{-4} \) \( \mu_N^2 \)
**Fast-timing study of the $l$-forbidden $1/2^+ \rightarrow 3/2^+$ M1 transition in $^{129}$Sn**

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**Percentage of the wave function configurations**

\[
\begin{array}{cccccc}
J^\pi & (nl_j)^{-2} & (0h_{11/2})^{-2} & (1d_{3/2})^{-2} & (2s_{1/2})^{-2} & (1d_{5/2})^{-2} & (0g_{7/2})^{-2} \\
3/2^+ & 69\% & 12\% & 8\% & 6\% & 5\% & 5\% \\
1/2^+ & 60\% & 27\% & 7\% & 6\% & 5\% & 5\% \\
\end{array}
\]

**Electromagnetic Transition Probabilities**

- $e_{\text{eff}} = 0.7e$
- $g_l^{\text{free}} = 0$, $g_s = 0.7g_s^{\text{free}} = -2.68$

- $B(E2; 1/2^+ \rightarrow 3/2^+) = 32.89 \text{ e}^2 \text{ fm}^4$
- $B(M1; 1/2^+ \rightarrow 3/2^+) = 0.58 \times 10^{-4} \mu_N^2$

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<tr>
<th>Transition</th>
<th>$T(E2)$</th>
<th>$T(M1)$</th>
<th>$T_{1/2}$</th>
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<tr>
<td>$T(E2)$</td>
<td>$0.13 \times 10^9 \text{ s}^{-1}$</td>
<td></td>
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</tr>
<tr>
<td>$T(M1)$</td>
<td>$0.03 \times 10^9 \text{ s}^{-1}$</td>
<td></td>
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<tr>
<td>$T_{1/2}$</td>
<td></td>
<td></td>
<td>$4 \text{ ns}$</td>
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**Two order of magnitude larger than the experimental value**

$T_{1/2} = 19(10) \text{ ps}$
Fast-timing study of the $l$-forbidden $1/2^+ \rightarrow 3/2^+$ $M1$ transition in $^{129}$Sn

M1 effective operator

with core excitations microscopically taken into account by means of many-body perturbation theory, consistently with the derivation of the effective two-body interaction
Fast-timing study of the $l$-forbidden $1/2^+ \rightarrow 3/2^+$ $M1$ transition in $^{129}\text{Sn}$

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with core excitations microscopically taken into account by means of many-body perturbation theory, consistently with the derivation of the effective two-body interaction

| $a$     | $b$     | $\langle a || M1 || b \rangle_{(I)}$ | $\langle a || M1 || b \rangle_{(II)}$ |
|---------|---------|-------------------------------------|-------------------------------------|
| $0g_{7/2}$ | $0g_{7/2}$ | 1.65                                | 1.36                                |
| $0g_{7/2}$ | $1d_{5/2}$ | 0                                   | 0.15                                |
| $1d_{5/2}$ | $1d_{5/2}$ | -1.92                               | -1.89                               |
| $1d_{5/2}$ | $1d_{3/2}$ | 2.05                                | 1.88                                |
| $1d_{3/2}$ | $1d_{3/2}$ | 1.02                                | 1.05                                |
| $1d_{3/2}$ | $2s_{1/2}$ | 0                                   | 0.10                                |
| $2s_{1/2}$ | $2s_{1/2}$ | -1.62                               | -1.61                               |
| $0h_{11/2}$ | $0h_{11/2}$ | -2.49                               | -2.48                               |

**TABLE III.** Comparison between the single-hole neutron $M1$ matrix elements (in $\mu_N$) obtained using $g$ factors $g_{l}^{\text{free}} = 0$, $g_s = -2.68$ (I), and those of the effective $M1$ operator (II) (see text for details).
Fast-timing study of the $l$-forbidden $1/2^+ \rightarrow 3/2^+$ M1 transition in $^{129}$Sn

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| $1d_{3/2}$ | $1d_{3/2}$ | 1.02                             | 1.05                              |
| $1d_{3/2}$ | $2s_{1/2}$ | 0                                | 0.10                              |
| $2s_{1/2}$ | $2s_{1/2}$ | −1.62                            | −1.61                             |
| $0h_{11/2}$ | $0h_{11/2}$ | −2.49                            | −2.48                             |

Perturbation expansion: some diagrams

OBTD:

$(3)^{-1/2} <3/2^+ | [a_{d3/2}^+ \otimes a_{s1/2}]^1 | 1/2^+ > \sim 0.9$
**Fast-timing study of the $l$-forbidden $1/2^+ \rightarrow 3/2^+$ $M1$ transition in $^{129}\text{Sn}$**

### M1 effective operator

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<th>$B(M1; 1/2^+ \rightarrow 3/2^+)$</th>
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<td>$0.55 \times 10^{-2} \mu_N^2$</td>
<td>$3.42 \times 10^9$ s$^{-1}$</td>
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$T_{1/2} = 200$ ps

20 times shorter than the $T_{1/2}$ obtained with empirical $g$ factors and closer to the experimental value [19(10)ps]
**Fast-timing study of the $l$-forbidden $1/2^+ \rightarrow 3/2^+$ M1 transition in $^{129}$Sn**

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**E2?**

No substantial change is produced by using a microscopic effective E2 operator!

Effective charge for $\langle 1d_{3/2} || E2 || 2s_{1/2} \rangle \sim 0.8 \Rightarrow$ an increase in $T(E2)$ slightly $>1$
Fast-timing study of the $l$-forbidden $1/2^+ \to 3/2^+$ $M1$ transition in $^{129}$Sn

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$T_{1/2} = 200 \text{ ps}$

20 times shorter than the $T_{1/2}$ obtained with empirical $g$ factors and closer to the experimental value [19(10)ps]

No substantial change is produced by using a microscopic effective $E2$ operator!

Effective charge for $\langle 1d_{3/2} | E2 | 2s_{1/2} \rangle \sim 0.8$ ➔ an increase in $T(E2)$ slightly $>1$

An enhancement of the $T$ ($E2$) similar to the one obtained for the $M1$ transition would require a neutron effective charge equal to 10, a value without any physical meaning!!

➔ the $T_{1/2}(1/2^+)$ arises essentially from the $M1$ transition

➔ the still existing difference between the experimental and calculated half-life may be from higher-order diagrams not included in the calculation of the $M1$ effective operator.
First observation of $\gamma$ rays emitted from excited states south-east of $^{132}$Sn:  
The $\pi g_{9/2}^{-1} \otimes \nu f_{7/2}$ multiplet of $^{132}$In$_{83}$

$^{132}$In $\leftrightarrow$ 1 proton hole in the 28-50 shell +  
1 neutron particle in the 50-82 shell

Identification of the first-excited states in $^{132}$In SE of $^{132}$Sn

$[(\pi g_{9/2})^{-1} \otimes \nu f_{7/2}] J^\pi = 1^- \ldots 8^-$
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Unique study case in the table of isotopes:

- the corresponding multiplets south-east of $^{78}$Ni and $^{42}$Si are currently not accessible for experimental studies

- the $(\pi 0 h_{11/2})^{-1} \otimes \nu 1 g_{9/2}$ multiplet in $^{208}$Tl is distorted by
the presence of the $2s_{1/2}$ and $1d_{3/2}$ proton orbitals
First observation of $\gamma$ rays emitted from excited states south-east of $^{132}\text{Sn}$: The $\pi g_{9/2}^{-1} \otimes \nu f_{7/2}$ multiplet of $^{132}\text{In}_{83}$

$\beta$-delayed neutron emission from $^{133}\text{Cd}$ @ RIBF of RIKEN
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γ-ray spectra in prompt coincidence with decay events during the first 200 ms after the implantation of a $^{133}$Cd ion

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Counts/2 keV

Energy (keV)

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First observation of $\gamma$ rays emitted from excited states south-east of $^{132}$Sn: The $\pi g_{9/2}^{-1} \otimes \nu f_{7/2}$ multiplet of $^{132}$In$_{83}$

$\beta$-delayed neutron emission from $^{133}$Cd @ RIBF of RIKEN

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{graph.png}
\end{figure}

$\gamma$ -ray spectra in prompt coincidence with decay events during the first 200 ms after the implantation of a $^{133}$Cd ion

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Six lines at energies of 50, 86, 103, 227, 357, 602 keV
First observation of $\gamma$ rays emitted from excited states south-east of $^{132}$Sn:
The $\pi g^{-1}_{9/2} \otimes v f_{7/2}$ multiplet of $^{132}$In$_{83}$

$\beta$-delayed neutron emission from $^{133}$Cd @ RIBF of RIKEN

$\gamma$-ray spectra in prompt coincidence with decay events during the first 200 ms after the implantation of a $^{133}$Cd ion

<table>
<thead>
<tr>
<th>Condition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Without further condition</td>
</tr>
<tr>
<td>b</td>
<td>requiring multiplicity one in the $\gamma$-ray detector</td>
</tr>
<tr>
<td>c</td>
<td>b + strict spatial correlation, decay took place either in the Si detector in which the ion was implanted or in the one in front or behind</td>
</tr>
</tbody>
</table>

Six lines at energies of 50, 86, 103, 227, 357, 602 keV

The statistics accumulated are very limited so that no conclusive $\gamma\gamma$ coincidence information could be obtained

A. Gargano
First observation of γ rays emitted from excited states south-east of $^{132}\text{Sn}$:

The $\pi g_{9/2}^{-1} \otimes \nu f_{7/2}$ multiplet of $^{132}\text{In}_{83}$

Assuming that the six observed γ rays correspond to the expected cascade of M1 transitions from the $1^-$ to the $7^-$ member of the $(\pi g_{9/2})^{-1} \otimes \nu f_{7/2}$ multiplet.

The experimental energies are systematically higher than the calculated ones, leading to a total energy spread which is twice as large as theoretically predicted.

average difference between experimental and calculated excitation energies is $\sim 300$ keV
First observation of $\gamma$ rays emitted from excited states south-east of $^{132}$Sn: The $\pi g_{9/2}^{-1} \otimes \nu f_{7/2}$ multiplet of $^{132}$In$_{83}$

In $^{134}$Sb, average difference between experimental and calculated level energies amounts to less than 10% of the SM energy spread
First observation of $\gamma$ rays emitted from excited states south-east of $^{132}$Sn:
The $\pi g_{9/2}^{-1} \otimes \nu f_{7/2}$ multiplet of $^{132}$In$_{83}$

Assuming that one of the lowest transitions within the multiplet is unobserved and adopting an energy of 25 ± 25 keV for this transition.
First observation of $\gamma$ rays emitted from excited states south-east of $^{132}$Sn:
The $\pi g_{9/2}^{-1} \otimes \nu f_{7/2}$ multiplet of $^{132}$In$_{83}$

Assuming that one of the lowest transitions within the multiplet is unobserved and adopting an energy of 25 ± 25 keV for this transition

- The resulting excitation energies are much closer to the SM predictions and the average difference drops to 80 keV, i.e., 12% of the SM energy spread

The region of the chart of nuclides south-east of doubly magic $^{208}$Pb.

\begin{itemize}
  \item The $^{132}$Sn region with quantum numbers $(h/2, l/2) = (29/2, 1/2)$ and $(27/2, 3/2)$ receives at most 6% of the total feeding.
  \item The lowest transitions within the multiplet are unobserved.
  \item The average difference drops to 80 keV, i.e., 12% of the SM energy spread.
\end{itemize}

Expt
Calc

$\pi p_{3/2}^{-1} \nu f_{7/2}$
$\pi g_{9/2}^{-1} \nu p_{3/2}$
$\pi p_{1/2}^{-1} \nu f_{7/2}$

SM results with effective interaction based on a scaling of TBMEs from the $^{208}$Pb region
First observation of γ rays emitted from excited states south-east of $^{132}$Sn:
The $\pi g_{9/2}^{-1} \otimes v f_{7/2}$ multiplet of $^{132}$In$_{83}$

Assuming that one of the lowest transitions within the multiplet is unobserved and adopting an energy of $25 \pm 25$ keV for this transition

![Graph showing energy levels for different transitions.]

The resulting excitation energies are much closer to the SM predictions and the average difference drops to 80 keV, i.e., 12% of the SM energy spread

More experimental information is needed!!
Conclusions

• Substantial progress has been made toward a microscopic derivation of the shell-model effective interaction.

• RSMC have proved to lead to an accurate description of the structure of nuclei in $^{132}$Sn regions, which makes us confident in their predictive power for physical quantities not yet measured.
Conclusions

- Substantial progress has been made toward a microscopic derivation of the shell-model effective interaction.
- RSMC have proved to lead to an accurate description of the structure of nuclei in $^{132}$Sn regions, which makes us confident in their predictive power for physical quantities not yet measured.

For a better assessment of RSMC we certainly need:

- more comprehensive experimental information
- to improve and extend the range of applicability of RSMC by addressing some specific questions.
Contributors

L. Coraggio
A. Covello
A. G.
T. T. S. Kuo (SUNY, Stony Brook-USA)
N. Itaco

+ R. Liča, L. M. Fraile, A. Jungclaus, ....

Thanks for your attention!