Realistic Shell Model: Consistently Facing the Four Quadrants around ^{208}Pb

Nunzio Itaco

Seconda Università di Napoli
Istituto Nazionale di Fisica Nucleare - Sezione di Napoli

Joint LIA COLL-AGAIN, COPIGAL, and POLITA Workshop

Region around ^{208}Pb

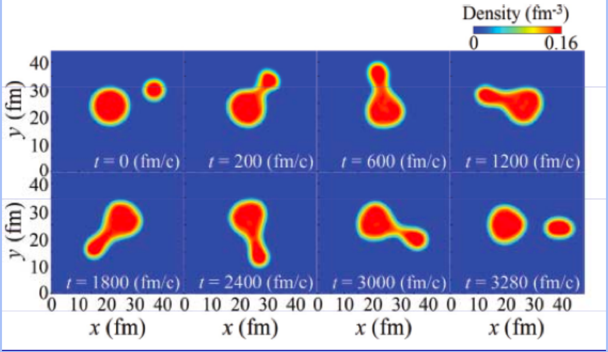
Nuclei around doubly magic nucleus ^{208}Pb are a very interesting laboratory to study nuclear forces

Z	204Rn	205Rn	206Rn	207Rn	208Rn	209Rn	210Rn	211Rn	212Rn	213Rn	214Rn	215Rn	216Rn	217Rn	218Rn	219Rn	220Rn
	203At	204At	205At	206At	207At	208At	209At	210At	211At	212At	213At	214At	215At	216At	217At	218At	219At
84	202Po	203Po	204Po	205Po	206Po	207Po	208Po	209Po	210Po	211Po	212Po	213Po	214Po	215Po	216Po	217Po	218Po
	201Bi	202Bi	203Bi	204Bi	205Bi	206Bi	207Bi	208Bi	209Bi	210Bi	211Bi	212Bi	213Bi	214Bi	215Bi	216Bi	217Bi
82	200Pb	201Pb	202Pb	203Pb	204Pb	205Pb	206Pb	207Pb	208Pb	209Pb	210Pb	211Pb	212Pb	213Pb	214Pb	215Pb	216Pb
	199Tl	200Tl	201Tl	202Tl	203Tl	204Tl	205Tl	206Tl	207Tl	208Tl	209Tl	210Tl	211Tl	212Tl	213Tl	214Tl	215Tl
80	198Hg	199Hg	200Hg	201Hg	202Hg	203Hg	204Hg	205Hg	206Hg	207Hg	208Hg	209Hg	210Hg	211Hg	212Hg	213Hg	214Hg
	197Au	198Au	199Au	200Au	201Au	202Au	203Au	204Au	205Au	206Au	207Au	208Au	209Au	210Au			
78	196Pt	197Pt	198Pt	199Pt	200Pt	201Pt	202Pt	203Pt	204Pt	205Pt							
	118		120		122		124		126		128		130		132		N

- Both “single-particle” & collective states are manifest

Region around ^{208}Pb

Multinucleon transfer reactions

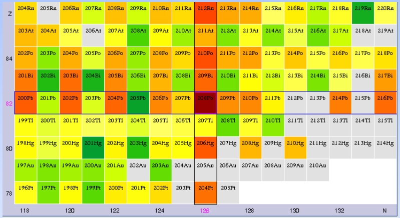


picture from L. Corradi talk at "Interplay of Structure and Dynamics of heavy ion collisions"

ECT* Trento May 14-15, 2015

- ISOLDE
- SPES-project

Shell model ⇒ well-established approach to obtain a microscopic description of both collective and single-particle properties of nuclei



Napoli group

- A. Covello
- A. Gargano (INFN)
- L. Coraggio (INFN)
- N. I. (SUN & INFN)

- HARMONIA-POLITA project

Shell-model effective Hamiltonian

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

Microscopic approach

$$V_{NN} \;\; (+V_{NNN}) \Rightarrow \text{many-body theory} \Rightarrow H_{\rm eff}$$

Definition

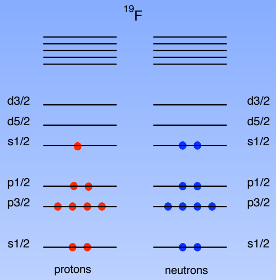
The eigenvalues of $H_{\rm eff}$ belong to the set of eigenvalues of the full nuclear hamiltonian

Shell-model effective Hamiltonian

A-nucleon system Schrödinger equation

$$H|\Psi_\nu\rangle = E_\nu|\Psi_\nu\rangle$$

$$H = H_0 + H_1 = \sum_{i=1}^{A}(T_i + U_i) + \sum_{i<j}(V_{ij}^{NN} - U_i)$$



Shell-model effective Hamiltonian

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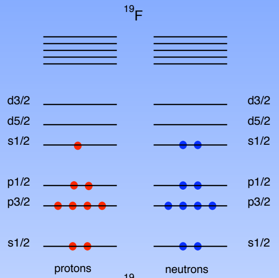
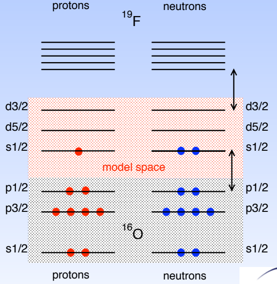
Model space

$$|\Phi_i\rangle = [a_1^\dagger a_2^\dagger \ldots a_n^\dagger]_i|c\rangle \Rightarrow P = \sum_{i=1}^{d}|\Phi_i\rangle\langle\Phi_i|$$

Model-space eigenvalue problem

$$H_{\rm eff} P|\Psi_\alpha\rangle = E_\alpha P|\Psi_\alpha\rangle$$



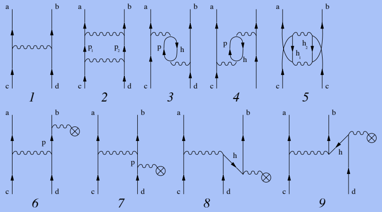


The shell-model effective hamiltonian

Perturbative approach

$$H_{\rm eff} = \hat{Q} - \hat{Q}' \int \hat{Q} + \hat{Q}' \int \hat{Q} \int \hat{Q} - \hat{Q}' \int \hat{Q} \int \hat{Q} \int \hat{Q} \cdots ,$$

$$\hat{Q} \ \text{box} \Rightarrow \hat{Q}(\epsilon) = PH_1P + PH_1Q \frac{1}{\epsilon - QHQ} QH_1P$$



Consistently Facing the Four Quadrants around ^{208}Pb

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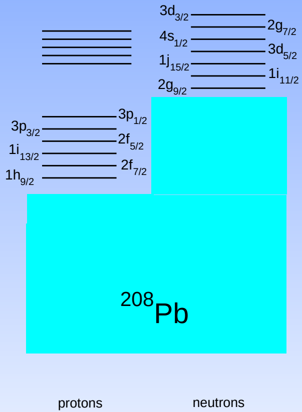

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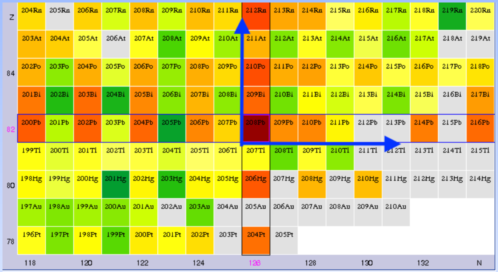
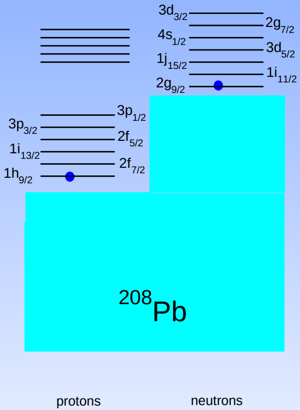
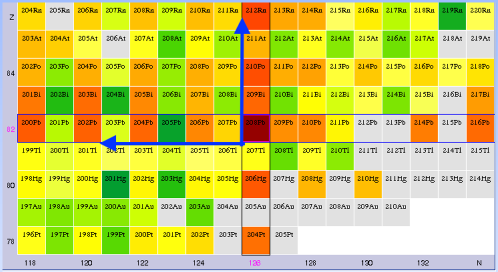
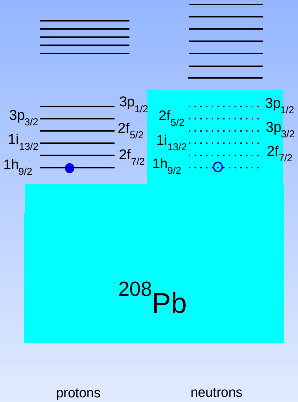




Consistently Facing the Four Quadrants around ^{208}Pb





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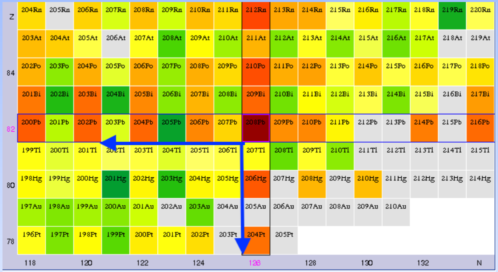

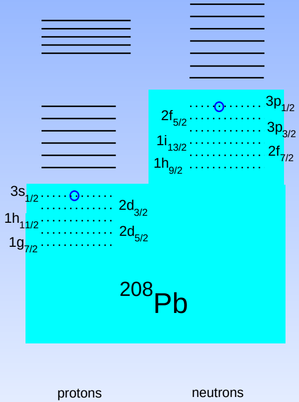

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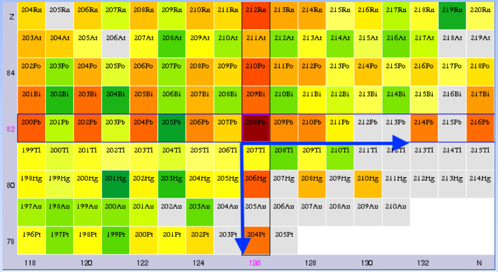
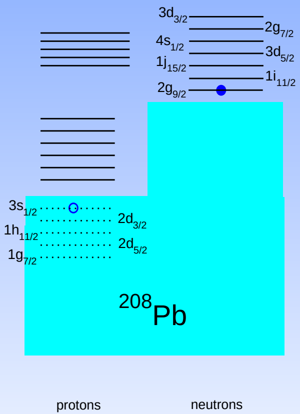
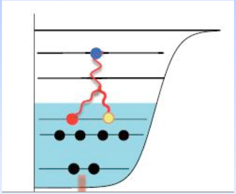
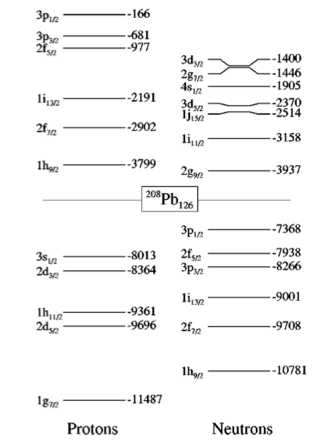




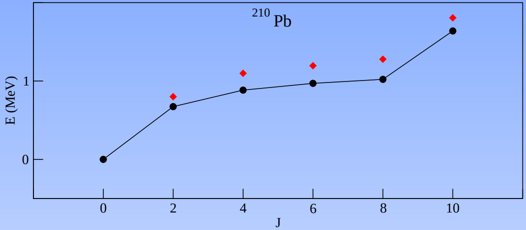
Results

- V_{low-k} from the high-precision *NN* CD-Bonn potential
- Single-particle energies from the experiment ⇒ reduced role of 3*N* force





Results: 2 valence-particles nuclei



- $(g_{9/2})^2$ $\nu\nu$ multiplet ($J^\pi = 0^+, ..., 8^+$)
-

$E_{exp}(3^-)$ MeV	$E_{th}(3^-)$ MeV
1.870	1.993
2.828	2.915

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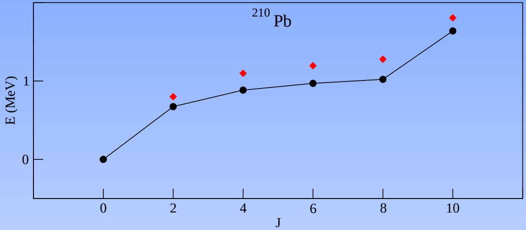

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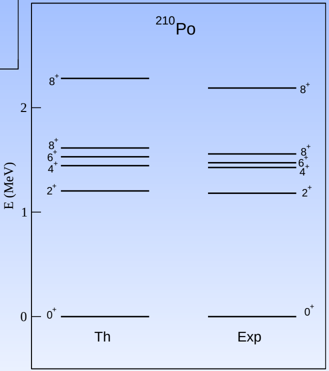
-

$E_{exp}(3^-)$ MeV	$E_{th}(3^-)$ MeV
1.870	1.993
2.828	2.915

- low-energy spectrum up to 2.3 MeV
- $(h_{9/2})^2$ $\pi\pi$ multiplet ($J^\pi = 0^+, ..., 8^+$)



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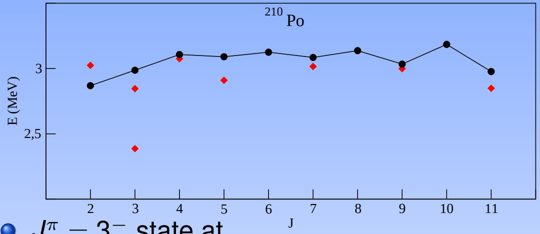
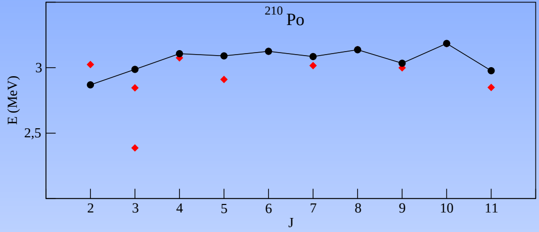
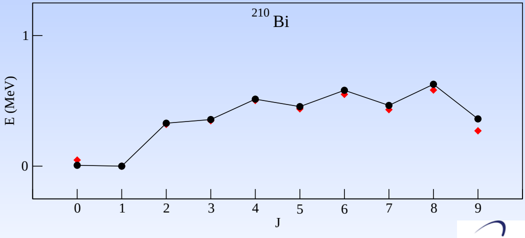


- $J^{\pi} = 3^{-}$ state at 2.4 MeV $\Rightarrow$ collective excitation
- other negative parity states arising from core excitations in the range 3.5-4.5 MeV

Results: 2 valence-particles nuclei

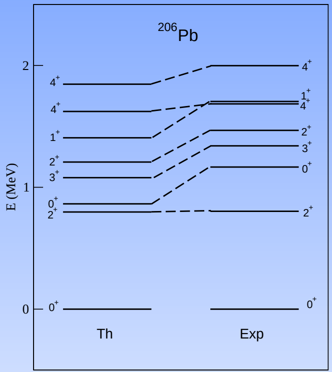


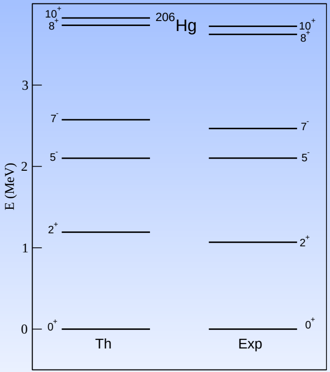
$\pi h_{9/2}\ \nu g_{9/2}$ multiplet



- violation of Nordheim strong coupling rule

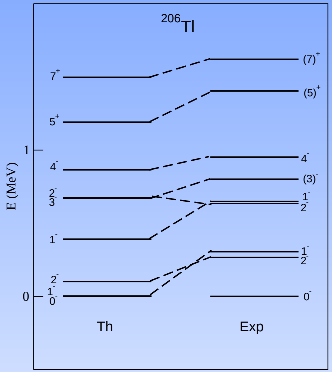
Results: 2 valence-holes nuclei



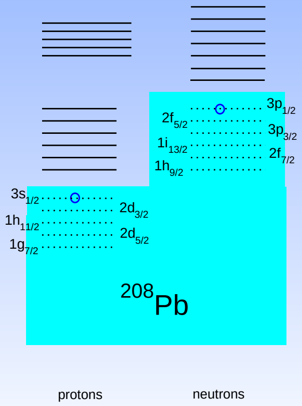


- ^{206}Pb energy spectrum up to 2.0 MeV
- scanty experimental information on ^{206}Hg

Results: 2 valence-holes nuclei



- no multiplets
- apart from 1^- states, max discrepancy $\simeq$ 200 keV



Takeaway points

- consistent approach to the four quadrants around ^{208}Pb
- good reproduction of low-energy spectra
- no adjustable parameters
- core excitations

Perspectives

Explicit inclusion of $N = 126$ and $Z = 82$ cross-shell excitations

- computational complexity grows very fast
- Example: ^{210}Po
  2 protons in (82-126) shell

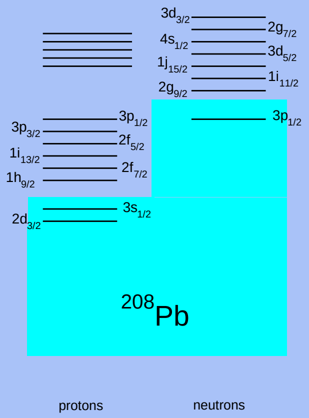
  $\Downarrow$

  10^3

  8 protons in (82-126) shell + $d_{3/2}, s_{1/2}$

  $\Downarrow$

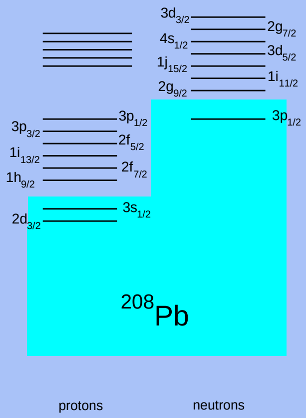
  500×10^6



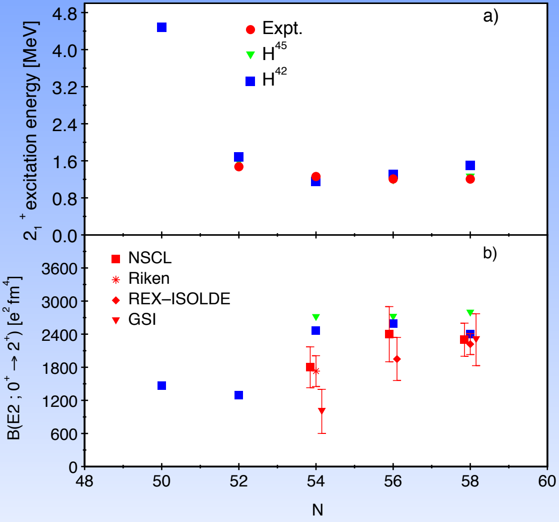
Perspectives

Double step approach

- shell-model effective hamiltonian defined in a large model space ("mother hamiltonian")
- relevant degrees of freedom that characterize the physical system
- unitary transformation of the "mother hamiltonian" into a reduced model space



Quadrupole collectivity in light tin isotopes



L. Coraggio, A. Covello, A. Gargano, N. I., and T. T. S. Kuo, Phys. Rev. C **91**, 041301 (2015).

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