Structure of neutron-rich carbon and oxygen isotopes in a restricted no-core shell-model space

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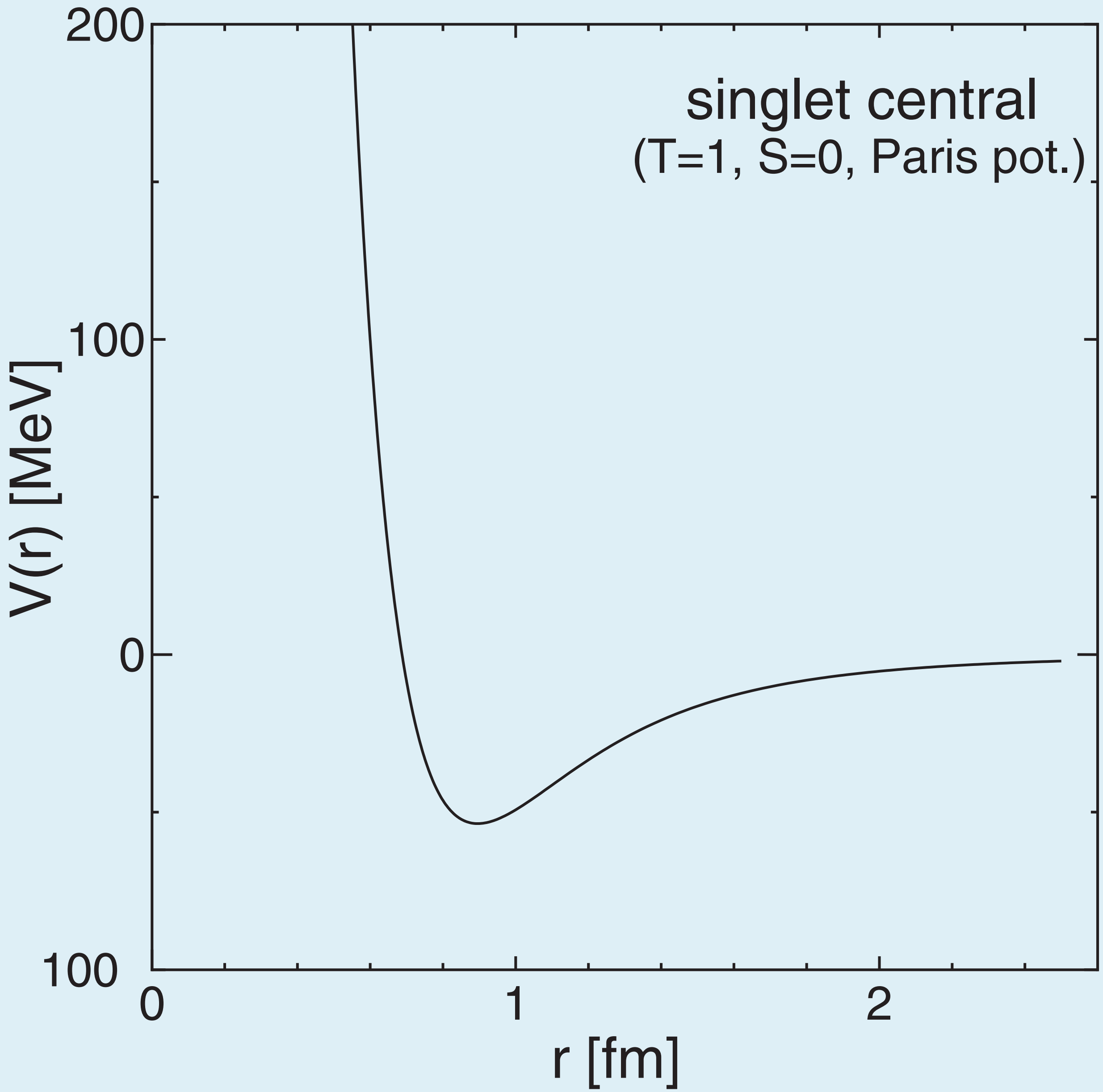


If we employ the bare NN force directly, extremely large-scale calculations are needed. (300$\hbar\Omega$ space with h.o. basis states for the deuteron!)

To perform a realistic calculation in a smaller model space, we need to derive an effective interaction microscopically.

Similarity / Unitary transformation

Derivation of effective interaction (Hamiltonian) by means of unitary transformation

Hamiltonian

$$H = H_0 + V$$

Unitary transformation of H

$$\tilde{H} = U^{-1}HU$$

$$U = e^S, \quad (S : \text{anti-Hermitian}, \ S^\dagger = -S)$$

Decoupling equation

$$Q(e^{-S}He^{S})P = 0$$

Solution

$$S = \operatorname{arctanh}(\omega - \omega^\dagger), \quad \omega = Q\omega P$$

(with the restrictive condition $PSP = QSQ = 0$)

K. Suzuki, Prog. Theor. Phys. **68** (1982), 246

Effective Hamiltonian

$$H_{\text{eff}} = P\tilde{H}P$$

Effective interaction

$$V_{\text{eff}} = P\tilde{H}P - PH_0P$$

Unitary transformation operator U in terms of ω

$$U = (1 + \omega - \omega^\dagger)(1 + \omega^\dagger\omega + \omega\omega^\dagger)^{-1/2}$$

$$= \begin{pmatrix} P(1+\omega^\dagger\omega)^{-1/2}P & -P\omega^\dagger(1+\omega\omega^\dagger)^{-1/2}Q \\ Q\omega(1+\omega^\dagger\omega)^{-1/2}P & Q(1+\omega\omega^\dagger)^{-1/2}Q \end{pmatrix}$$

S. Ōkubo, Prog. Theor. Phys. **12** (1954), 603

Our ongoing study

- **Unitary-model-operator approach (UMOA)**
  - Closed-shell nuclei, single-particle (-hole) states in nuclei up to the *pf*-shell region
  - Λ hypernuclei

S. Fujii, R. Okamoto, and K. Suzuki, Phys. Rev. C **69**, 034328 (2004)

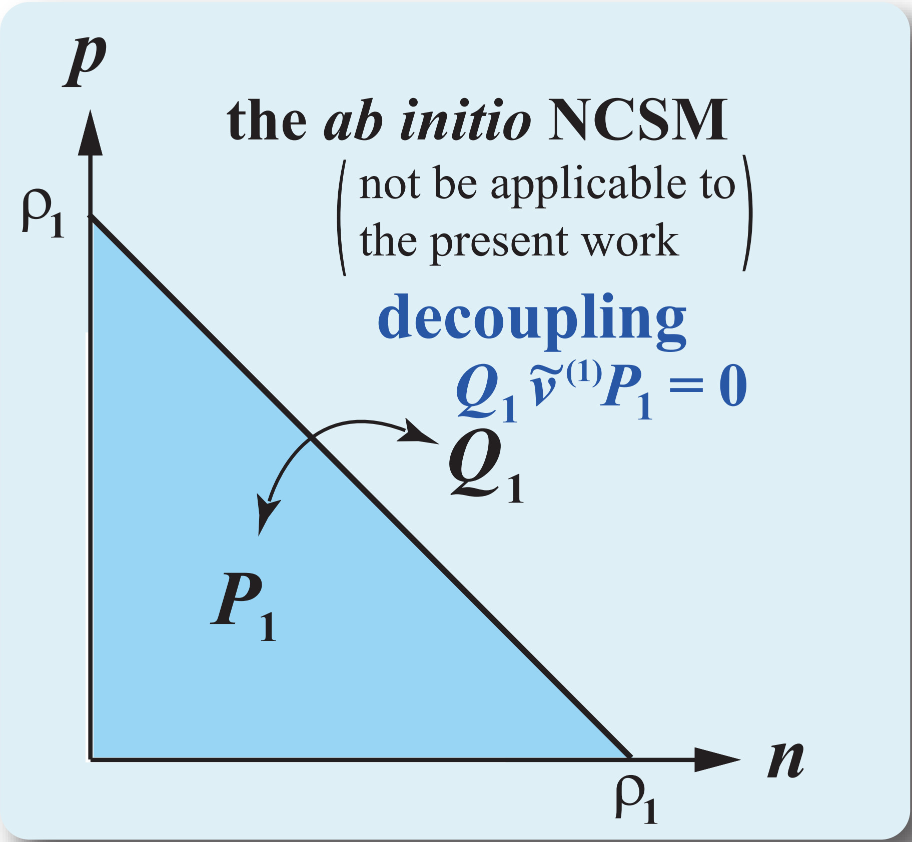
- **"No-core" shell model (in a restricted model space)**

  Hybrid method combining a no-core type of shell model with single-particle information obtained by the UMOA
  - Neutron-rich carbon isotopes, oxygen isotopes

S. Fujii, T. Mizusaki, T. Otsuka, T. Sebe, and A. Arima, Phys. Lett. **B650**, 9 (2007)

Derivation of effective interaction

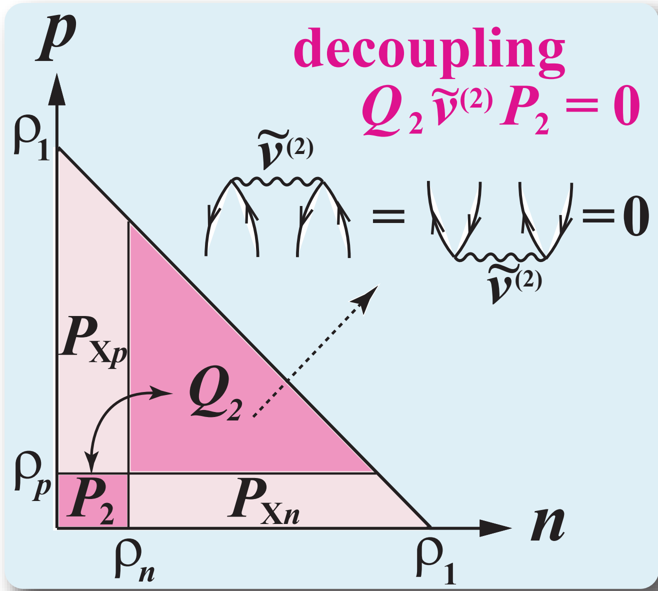
Eff. int. in a huge model space



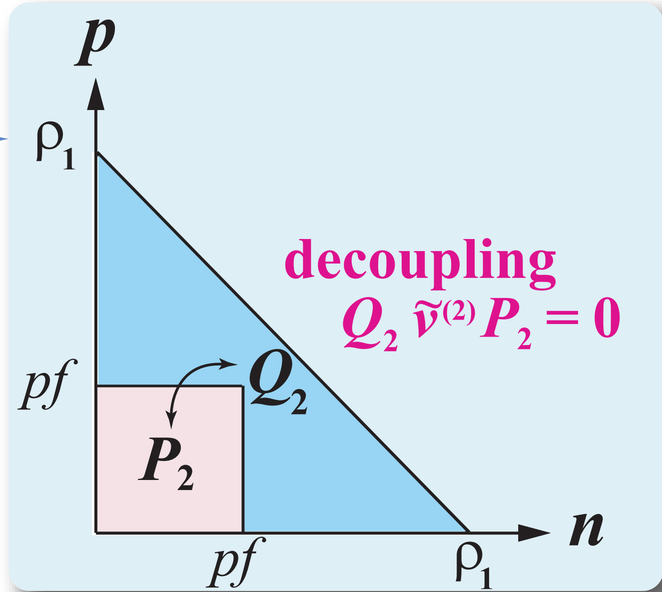
$\rho_1 = 2n_a + l_a + 2n_b + l_b$ ($\{n_a, l_a\}$ and $\{n_b, l_b\}$: sets of h.o. quantum numbers of the two-body states)

(For details,
- S. F., T. Mizusaki, T. Otsuka, T. Sebe, and A. Arima, Phys. Lett. **B650**, 9 (2007).
- S. F., R. Okamoto, and K. Suzuki, Phys. Rev. C **69**, 034328 (2004).)

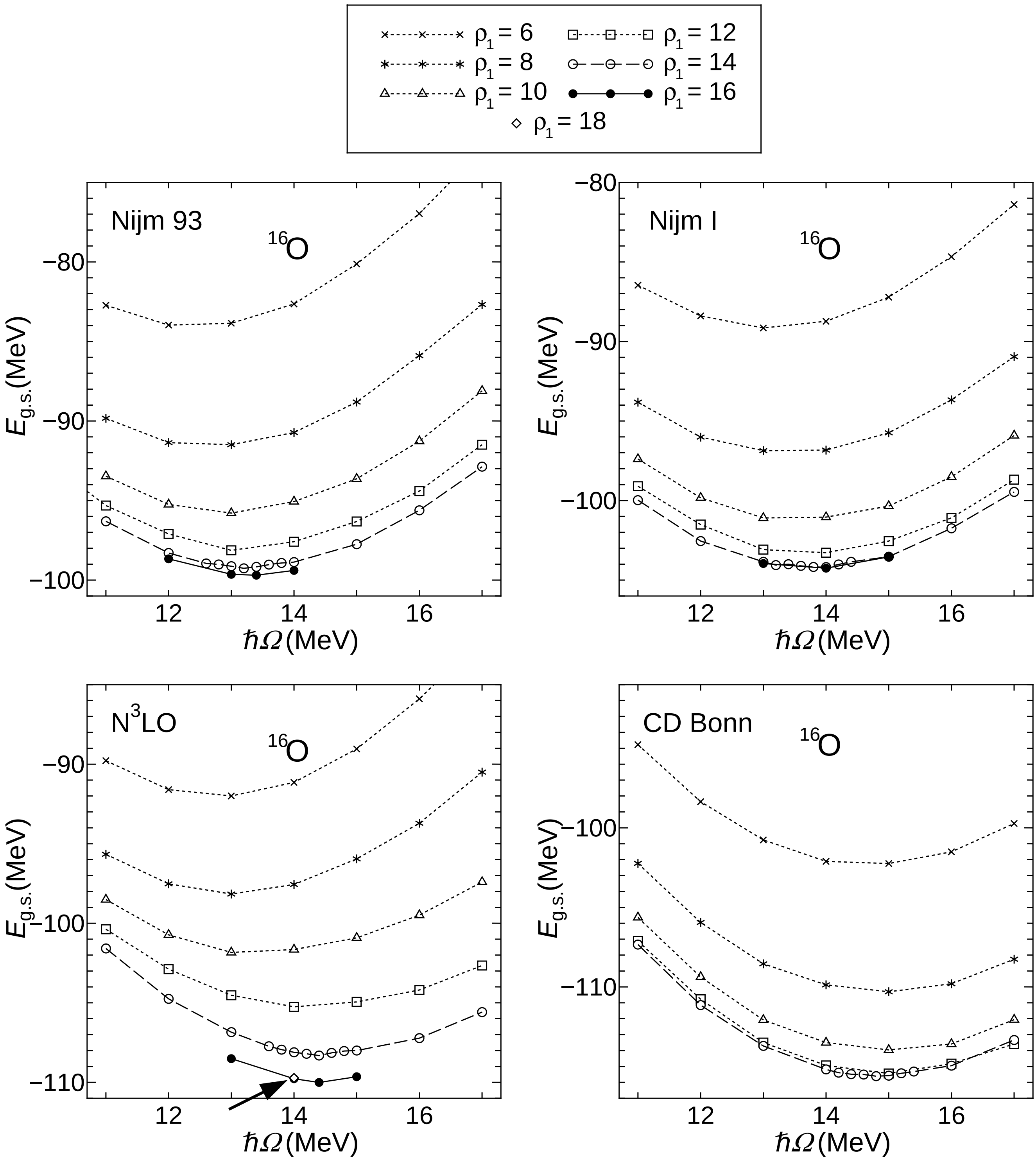
Eff. int. for the UMOA



Eff. int. for the 0*s*−1*p*0*f* shell model

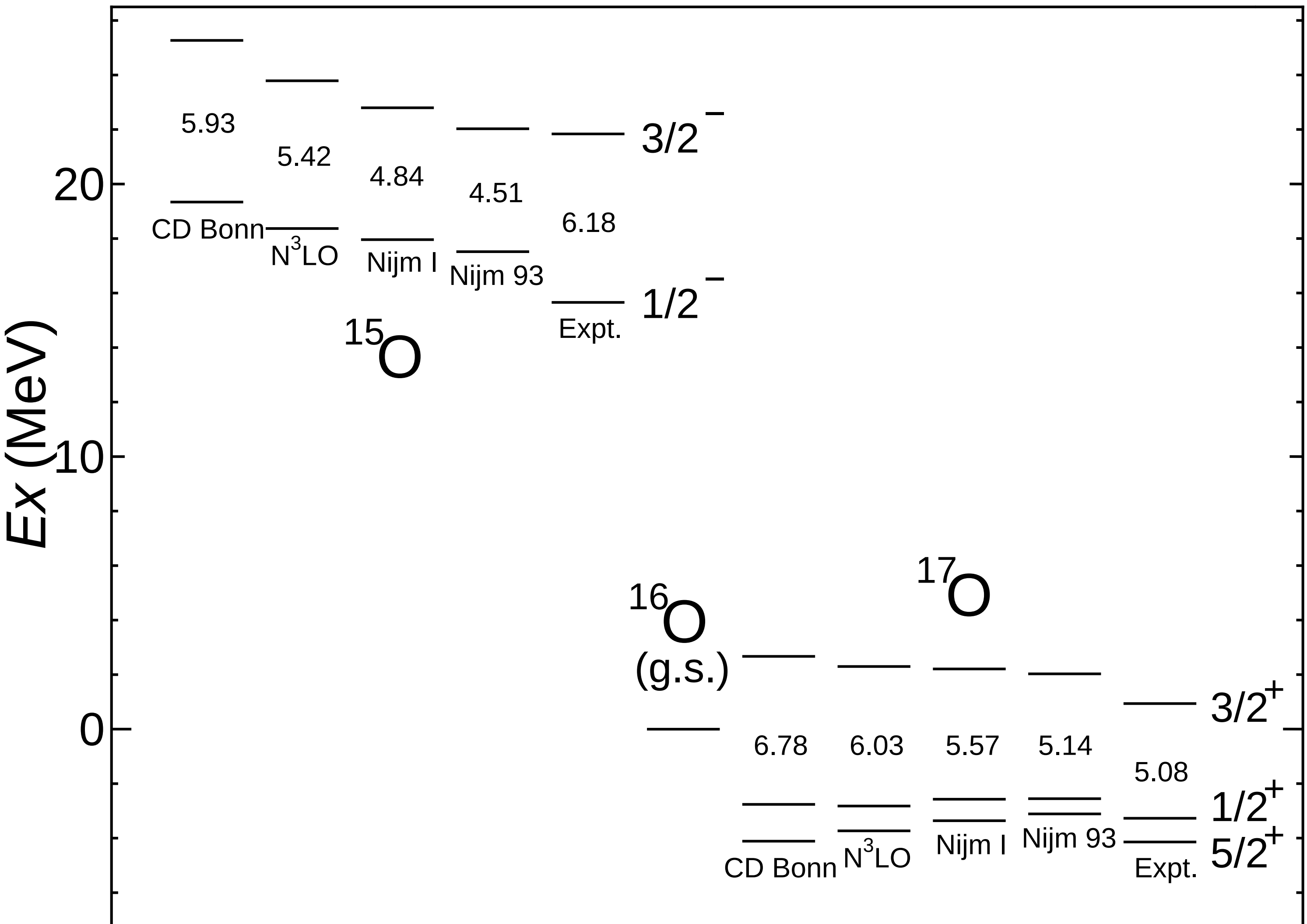


Ground−state energies of ^{16}O

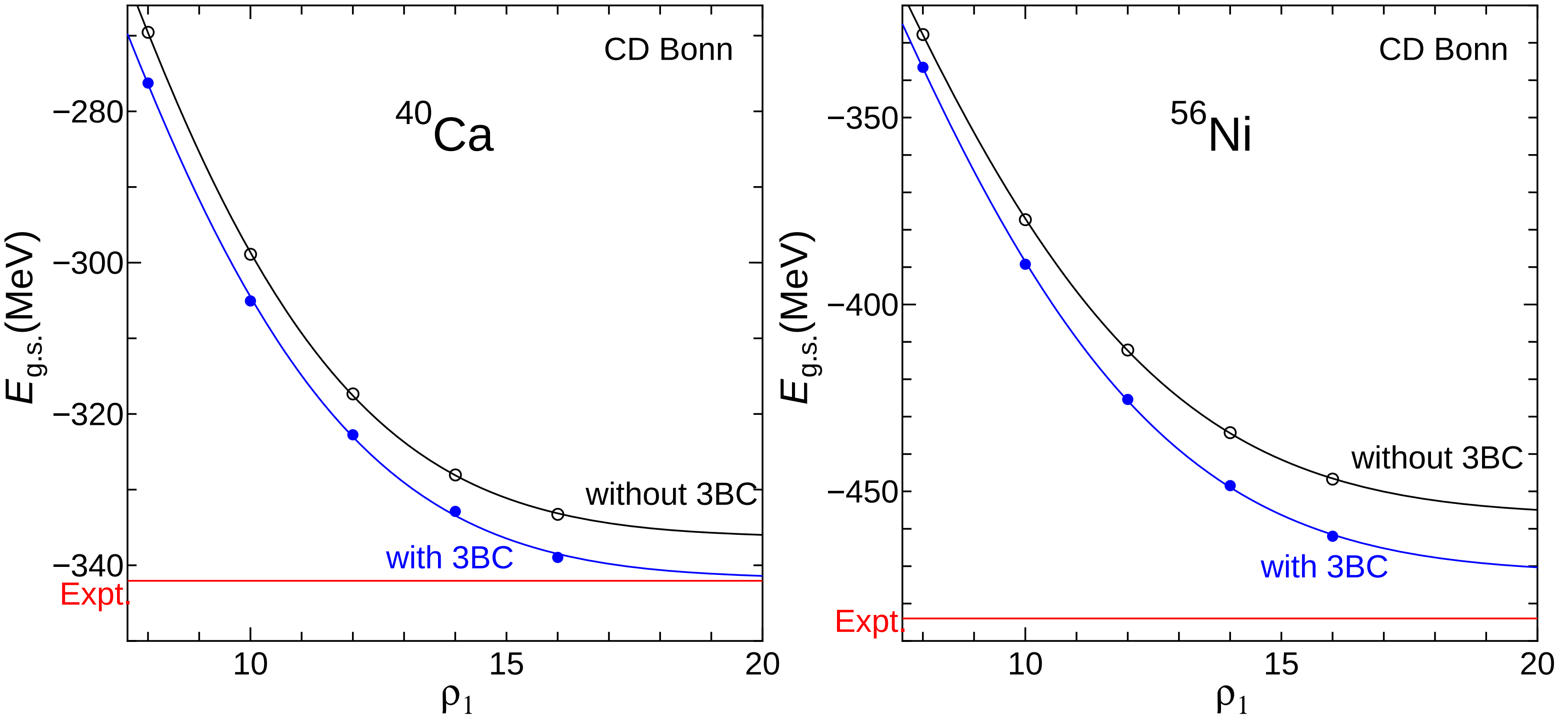


	Nijm 93	Nijm I	N^3LO	CD Bonn	Expt.	
$E_{g.s.}$	−99.69	−104.25	−110.00	−115.62	−127.62	
BE/A	6.23	6.52	6.88	7.23	7.98	(in MeV)

Comparison of Expt. and UMOA results from modern NN interactions



The ρ_1 dependence of the calculated ground−state energies of ^{40}Ca and ^{56}Ni



New approach to neutron-rich C isotopes

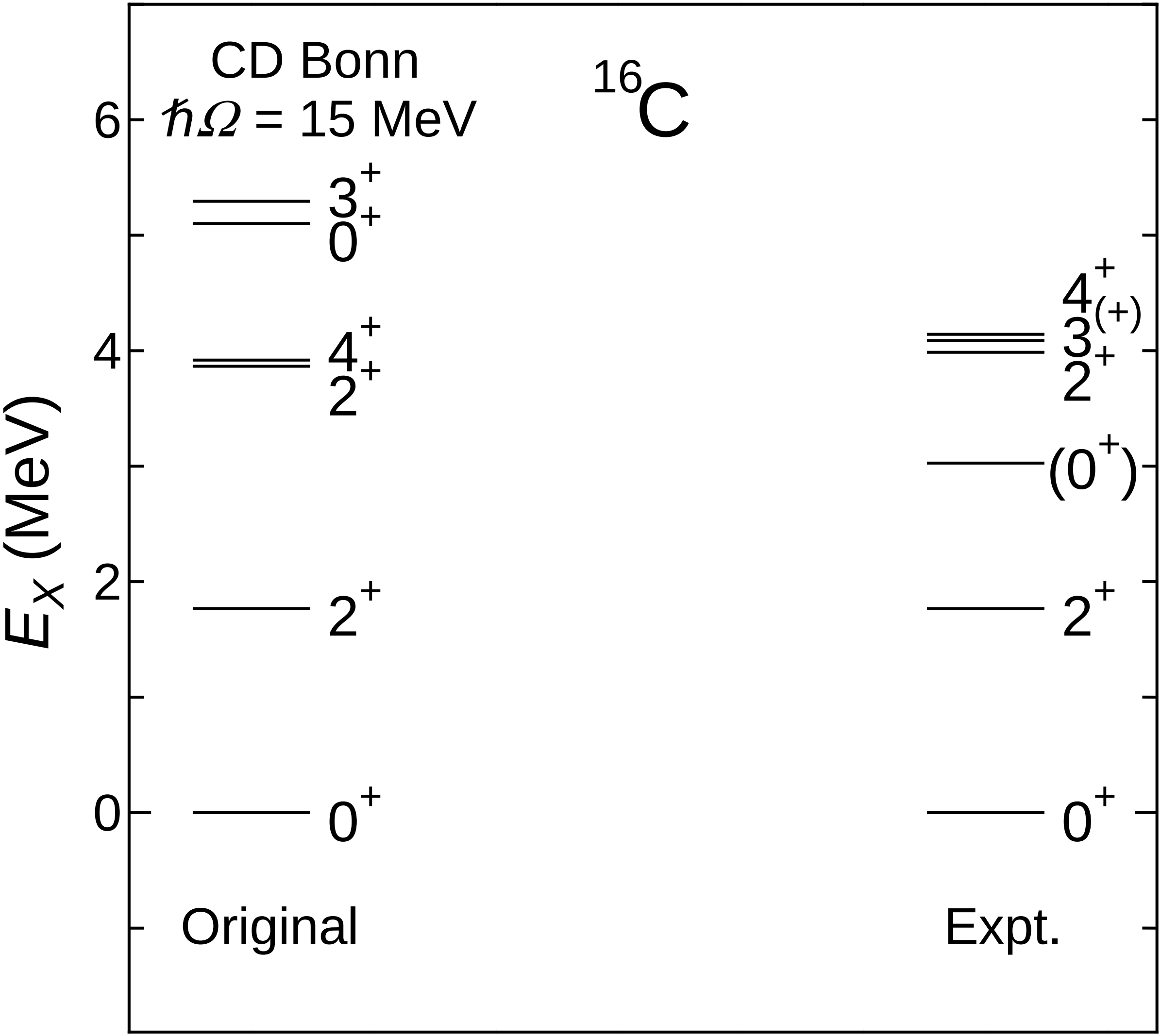
Large-scale shell model

- Code: newly developed version of MSHELL
- Model space: the 0*s*－1*p*0*f* shells
- Nucleon excitation: up to 2 nucleons from the occupied shells for ^{14}C
  up to 2 nucleons to the 1*p*0*f* shells
- Bare transition operator

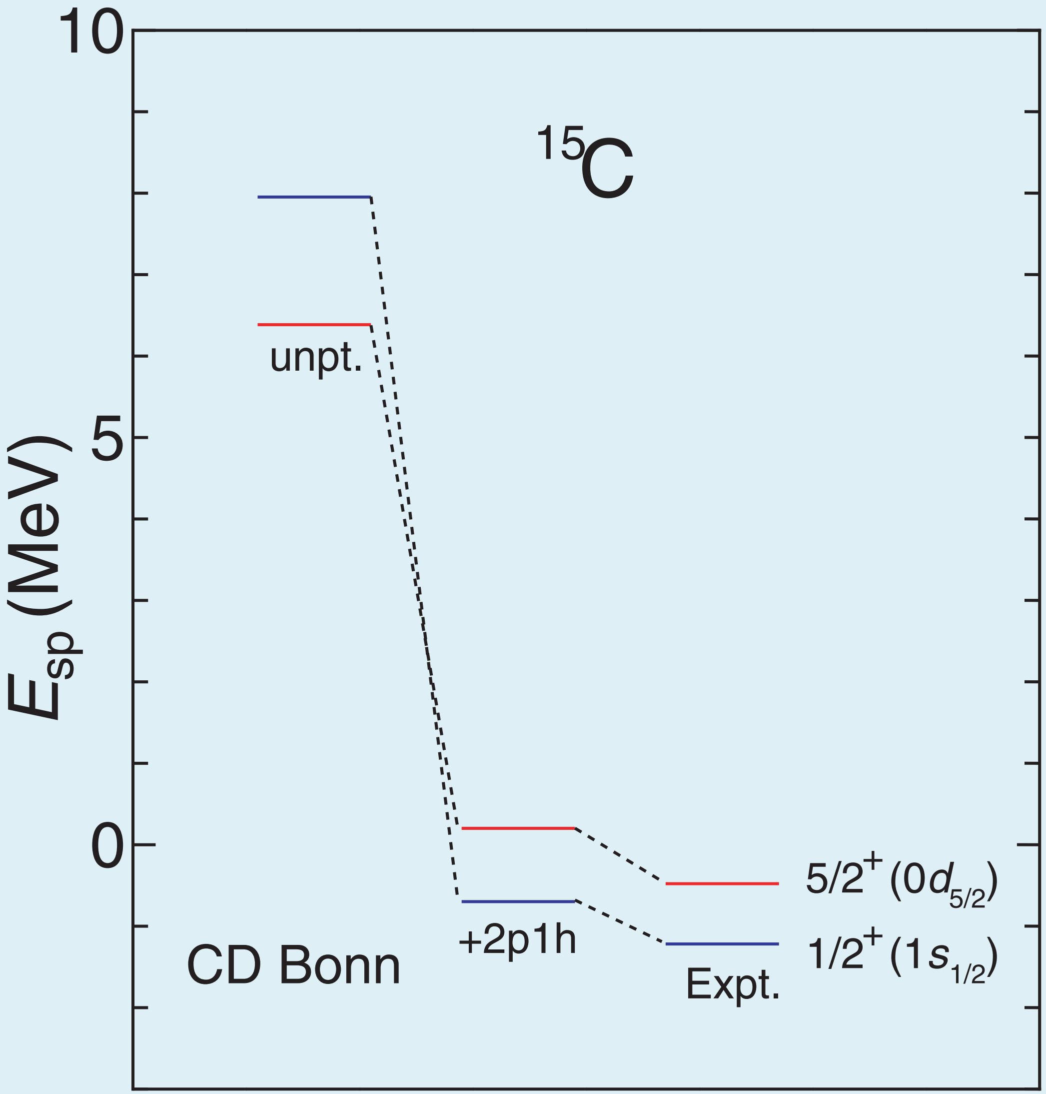
Microscopic effective interaction

Derived from a high-precision NN interaction (CD Bonn, ···) and the Coulomb force in the neutron-proton formalism for the given model space through a unitary-transformation theory

Low−lying energy levels in ^{16}C



Single-particle energies in ^{15}C



Calculated results by
<u>the unitary-model-oparator approach</u>
<u>(UMOA)</u>

In the present shell model without any adjustable parameters

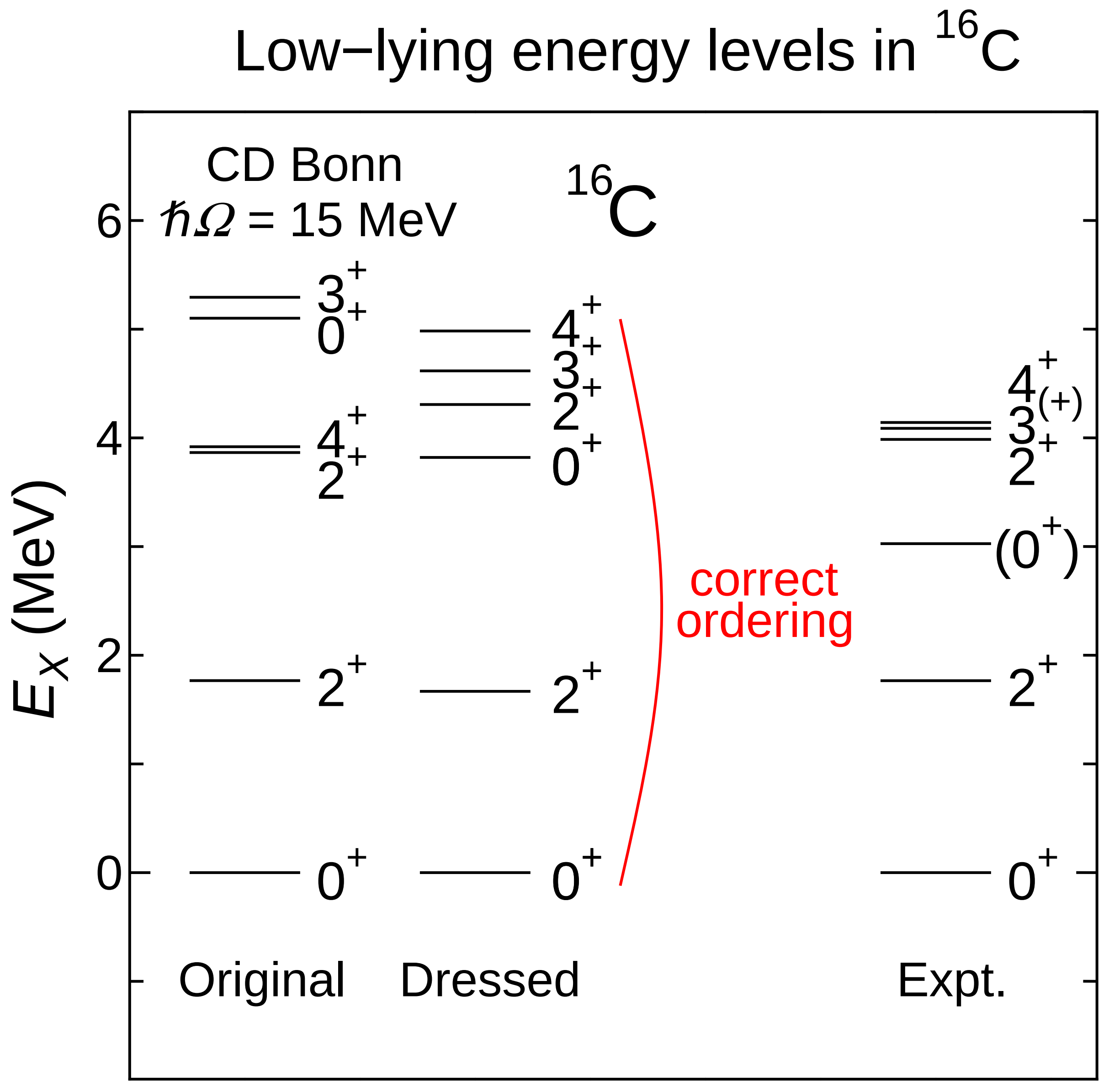
→ wrong ordering for the $1/2^+$ and $5/2^+$ states in ^{15}C due to the *small* model-space size

To remedy the wrong ordering and reproduce the binding energies for the $1/2^+$ and $5/2^+$ states of the UMOA results

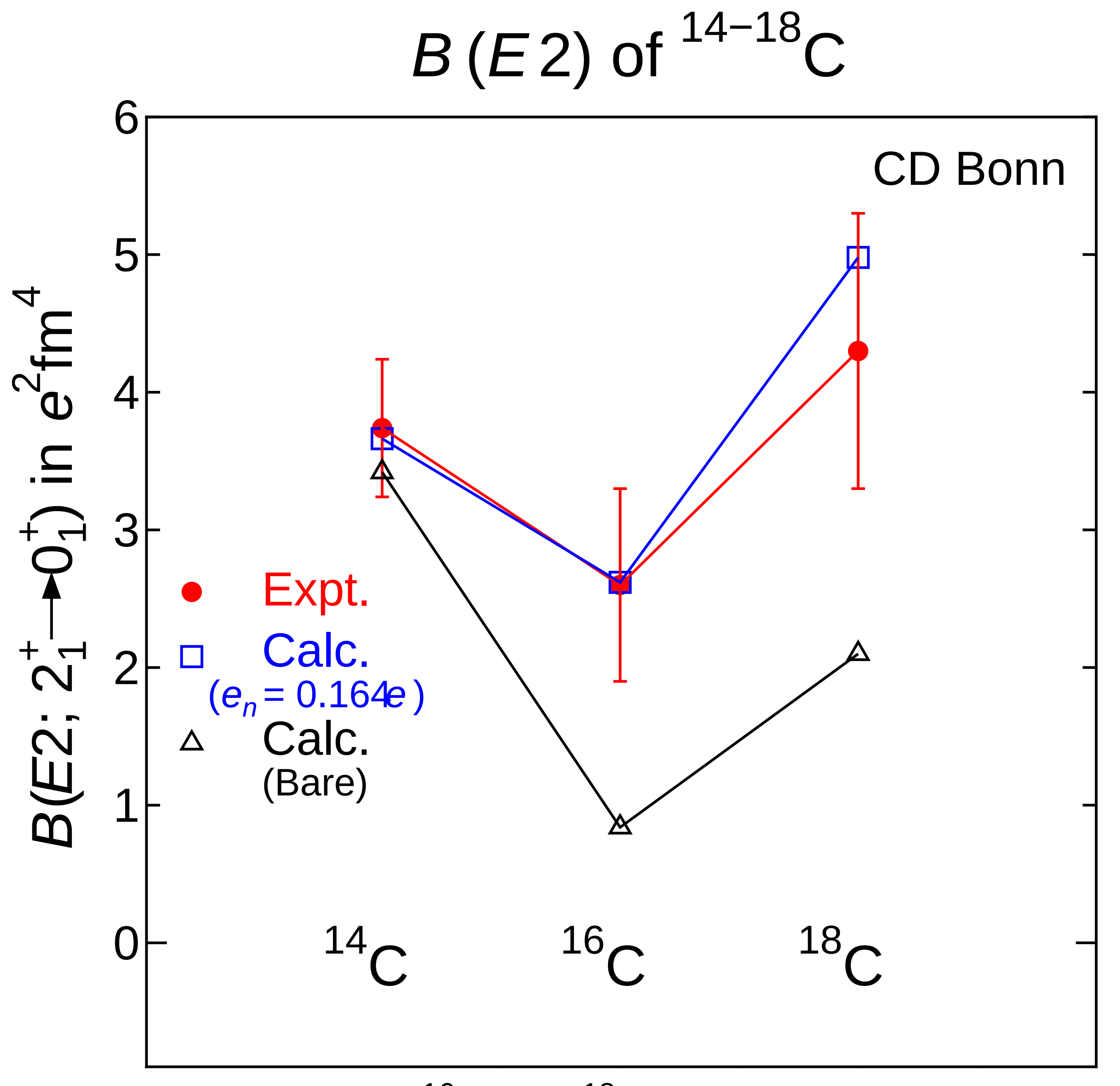
→ introduce a minimal refinement of the one-body energies for the $0d_{5/2}$ and $1s_{1/2}$ orbits of the neutron

The calculated results are denoted by

"dressed"

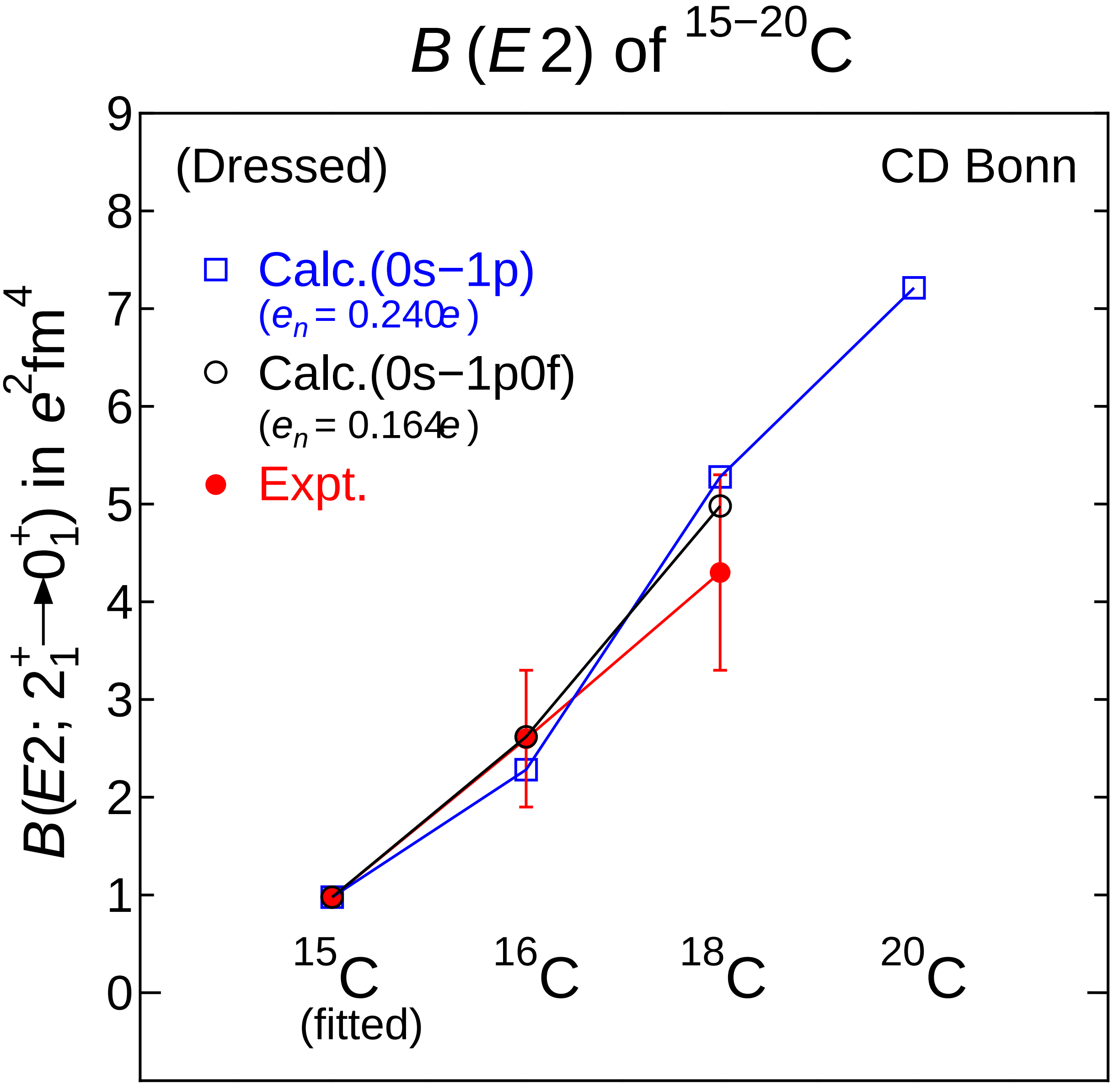


Low−lying energy levels in 16C
CD Bonn
ħΩ = 15 MeV
16C
Ex (MeV)
6
4
2
0
3+
0+
4+
2+
2+
0+
4+
3+
2+
0+
2+
0+
correct
ordering
4+
3(+)
2+
(0+)
2+
0+
Original
Dressed
Expt.



Expt. data for ^{16}C and ^{18}C:

H. J. Ong *et al.*, Phys. Rev. C**78**, 014308 (2008)



Expt. data for ^{16}C and ^{18}C:

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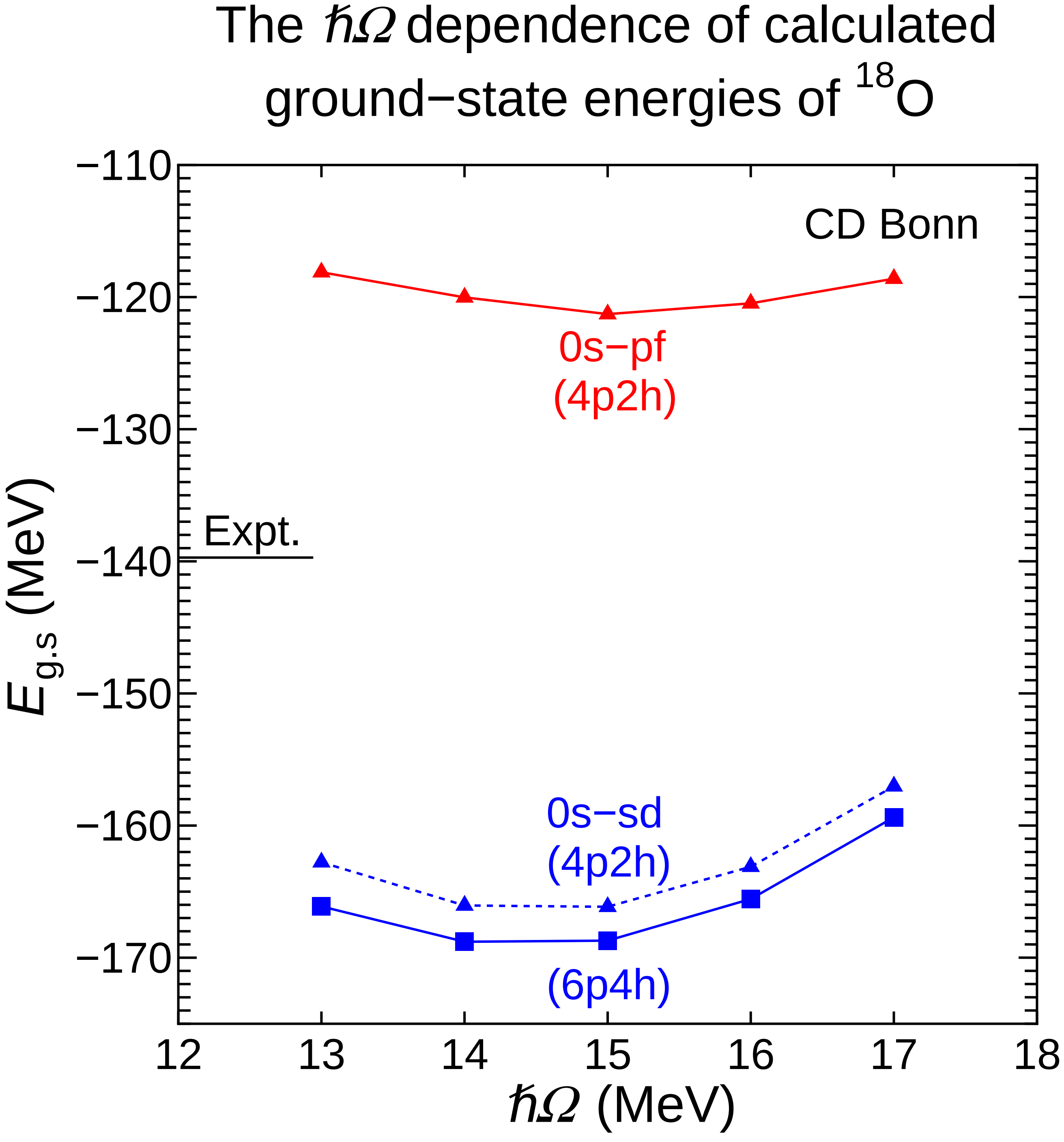
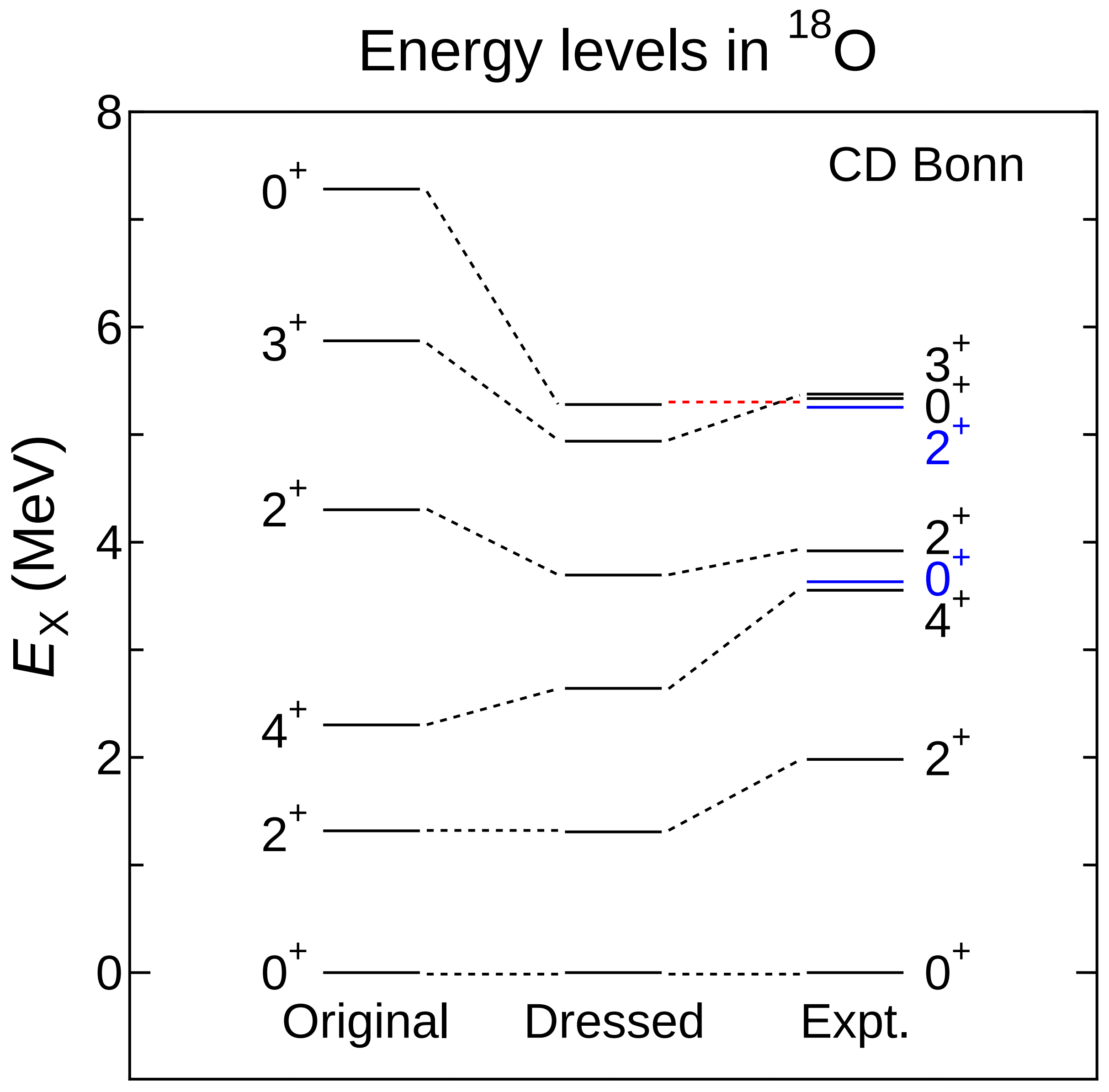

The ħΩ dependence of calculated
ground−state energies of ¹⁸O
CD Bonn
0s−pf
(4p2h)
Expt.
0s−sd
(4p2h)
(6p4h)
−110
−120
−130
−140
−150
−160
−170
12
13
14
15
16
17
18
ħΩ (MeV)
E g.s (MeV)



Energy levels in ^{18}O
CD Bonn
E_X (MeV)
0
2
4
6
8
0^+
3^+
2^+
4^+
2^+
0^+
3^+
0^+
2^+
2^+
0^+
4^+
2^+
0^+
Original
Dressed
Expt.

Excitation energies and probabilities of the 4p2h configuration for the lowest 4p2h dominant 0^+ state in ^{18}O

Configuration (*spsd*)	4p2h	6p4h	8p6h
Ex (MeV)	41.75	31.50	30.29
P_{4p2h}	0.996	0.855	0.816

Summary

- We have developed two methods for the microscopic description of nuclei beyond *p* shell with a realistic NN force in free space.
    - Unitary-model-operator approach (UMOA)
    - "No-core" shell model in a restricted model space
- In both methods, the microscopic effective interaction derived through a unitary transformation is the key ingredient.
- The "no-core" shell model has been applied to neutron-rich carbon isotopes and ^{18}O.
- The structures of low-lying states are well described, except for the experimental 0_2^+ and 2_3^+ states in ^{18}O.
- For those intruder states, we need a larger model space to reveal the real structure.

Collaborators

UMOA

- Ryoji Okamoto (Kyushu Inst. of Tech.)
- Kenji Suzuki (Kyushu Inst. of Tech.)

"No-core" shell model

- Takahiro Mizusaki (Senshu Univ.)
- Takaharu Otsuka (Univ. of Tokyo)
- Takashi Sebe (Hosei Univ.)
- Akito Arima (Japan Science Foundation)

Application of the "No-core" shell model to ^{18}O

- Bruce R. Barrett (Univ. of Arizona)