# Microscopic shell-model calculations for neutron-rich carbon isotopes in the *spsdpf* space

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1. Recent studies of $^{16}$C
2. Derivation of effective interaction
3. Large-scale shell-model calculation
4. Results (energy levels, $B(E2)$)
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International Workshop, Joint JUSTIPEN-LACM Meeting
March 5-8, 2007, ORNL

VOLUME 92, NUMBER 6 PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2004

# Anomalously Hindered $E2$ Strength $B(E2; 2_1^+ \rightarrow 0^+)$ in $^{16}$C

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(Received 17 August 2003; published 12 February 2004)

The electric quadrupole transition from the first $2^+$ state to the ground $0^+$ state in $^{16}$C is studied through measurement of the lifetime by a recoil shadow method applied to inelastically scattered radioactive $^{16}$C nuclei. The measured mean lifetime is $77 \pm 14(\mathrm{stat}) \pm 19(\mathrm{syst})$ ps. The central value of mean lifetime corresponds to a $B(E2; 2_1^+ \rightarrow 0^+)$ value of $0.63e^2$ fm$^4$, or 0.26 Weisskopf units. The transition strength is found to be anomalously small compared to the empirically predicted value.

DOI: 10.1103/PhysRevLett.92.062501 PACS numbers: 23.20.Js, 21.10.Tg, 27.20.+n, 29.30.Kv

**Experiment**

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Physics Letters B 586 (2004) 34–40
PHYSICS LETTERS B
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# Decoupling of valence neutrons from the core in $^{16}$C

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Received 4 December 2003; received in revised form 10 February 2004; accepted 11 February 2004

Editor: J.P. Schiffer

**Abstract**

The neutron and proton excitations in $^{16}$C nucleus have been investigated by use of the Coulomb-nuclear interference method applied to the $^{208}$Pb + $^{16}$C inelastic scattering. Angular distribution of the $^{16}$C nuclei in the inelastic channel populating the first $2^+$ state has been measured. The neutron and proton transition matrix elements, $M_n$ and $M_p$, have been determined from the "Coulomb" and "matter" deformation-length parameters obtained by distorted wave calculations. The $M_p$ or its corresponding $B(E2; 2_1^+ \to 0^+)$ value was found to be extremely small: $0.28 \pm 0.06$ Weisskopf units consistent with a recent lifetime measurement. Furthermore, the extracted $M_n/M_p$ ratio has an unexpectedly large value of $7.6 \pm 1.7$. These results suggest that the $2_1^+$ state in $^{16}$C is a nearly pure valence neutron excitation.


*PACS:* 25.70.De; 24.10.Eq; 29.30.Kv; 21.10.Gv; 27.20.+n

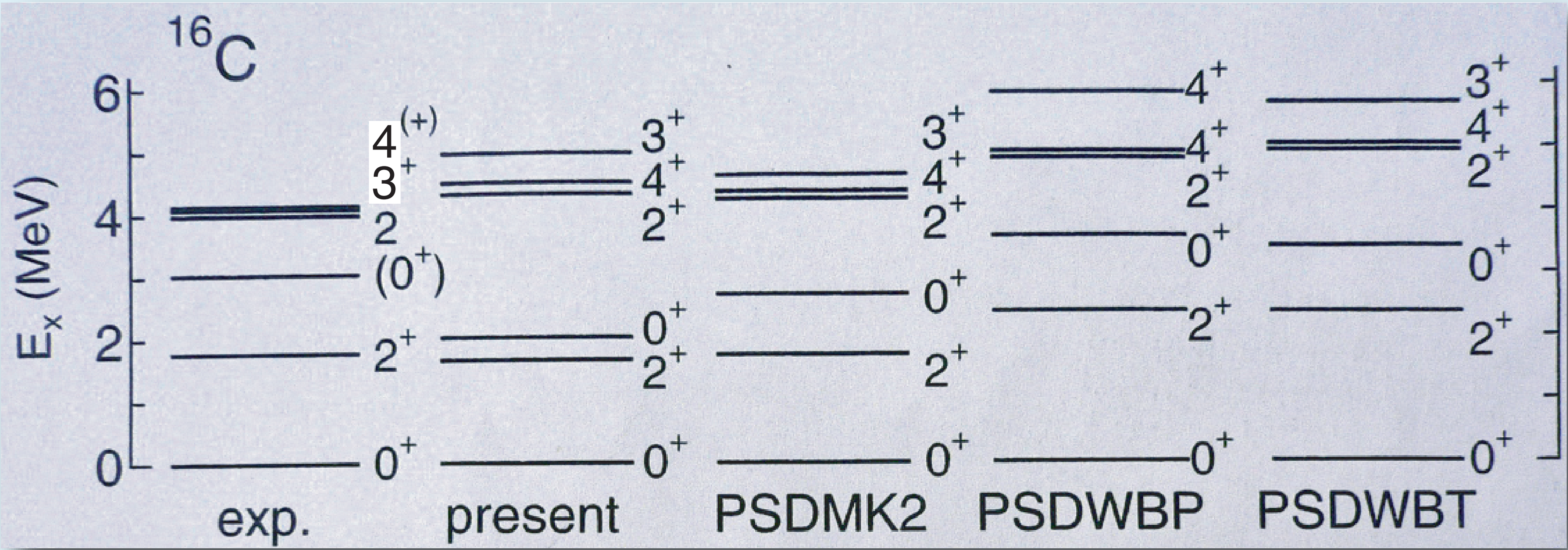
*Keywords:* Coulomb excitation of $^{16}$C; Angular distribution; Distorted wave calculation; Neutron and proton transition matrix elements

↑

**Experiment**

# Shell-model calc. in the *psd* ($2\hbar\omega$) space

(R. Fujimoto, Ph. D. Thesis, Univ. of Tokyo, 2003)




$B(E2; 2_1^+ \rightarrow 0_1^+)$ in $e^2 \mathrm{fm}^4$ ($e_p = 1.3e$, $e_n = 0.5e$)

| | present | PSDMK2 | PSDWBP | PSDWBT | Expt. |
|---|---|---|---|---|---|
| $^{12}$C | 11.78 | 12.06 | 11.41 | 11.36 | 8.2 ± 1.0 |
| $^{14}$C | 8.18 | 8.69 | 8.11 | 8.18 | 3.74 ± 0.50 |
| $^{16}$C | 8.05 | 8.37 | 8.70 | 8.05 | 0.63 ± 0.11(stat) ± 0.16(syst) |
| $^{18}$C | 10.26 | 13.18 | 12.81 | 12.33 | ? |

# New approach to neutron-rich C isotopes

- **Large-scale shell model**

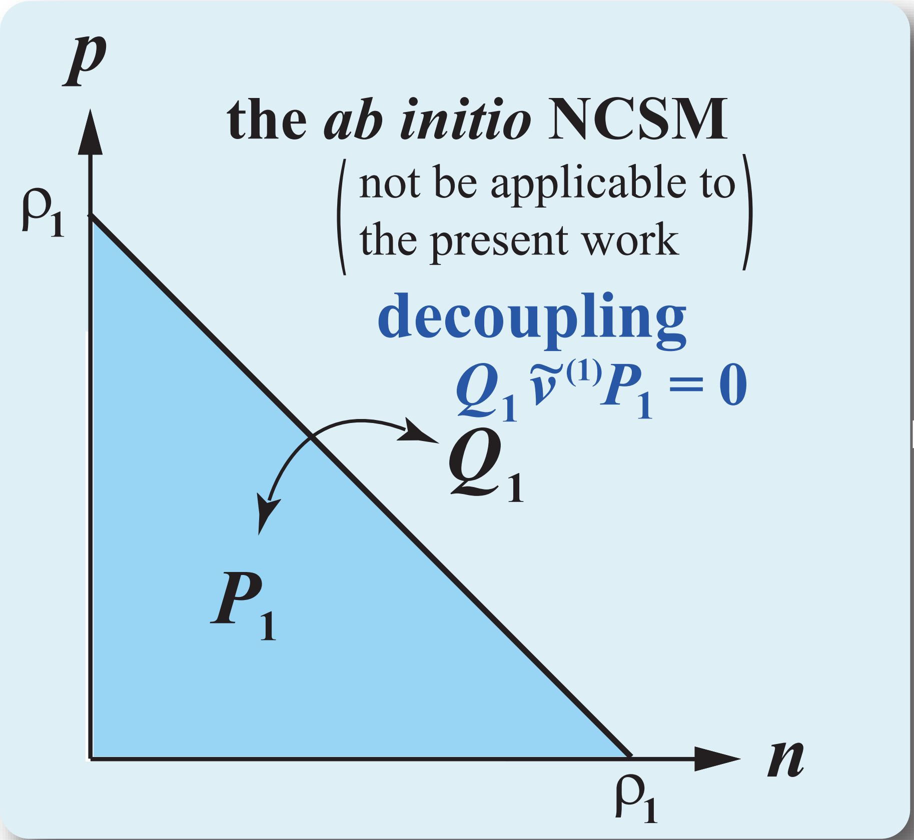
  - **Code: newly developed version of MSHELL**
  - **Model space: the 0*s*－1*p*0*f* shells**
  - **Nucleon excitation: up to 2 nucleons from the occupied shells for $^{14}$C**
    **up to 2 nucleons to the 1*p*0*f* shells**
  - **Bare transition operator**

- **Microscopic effective interaction**

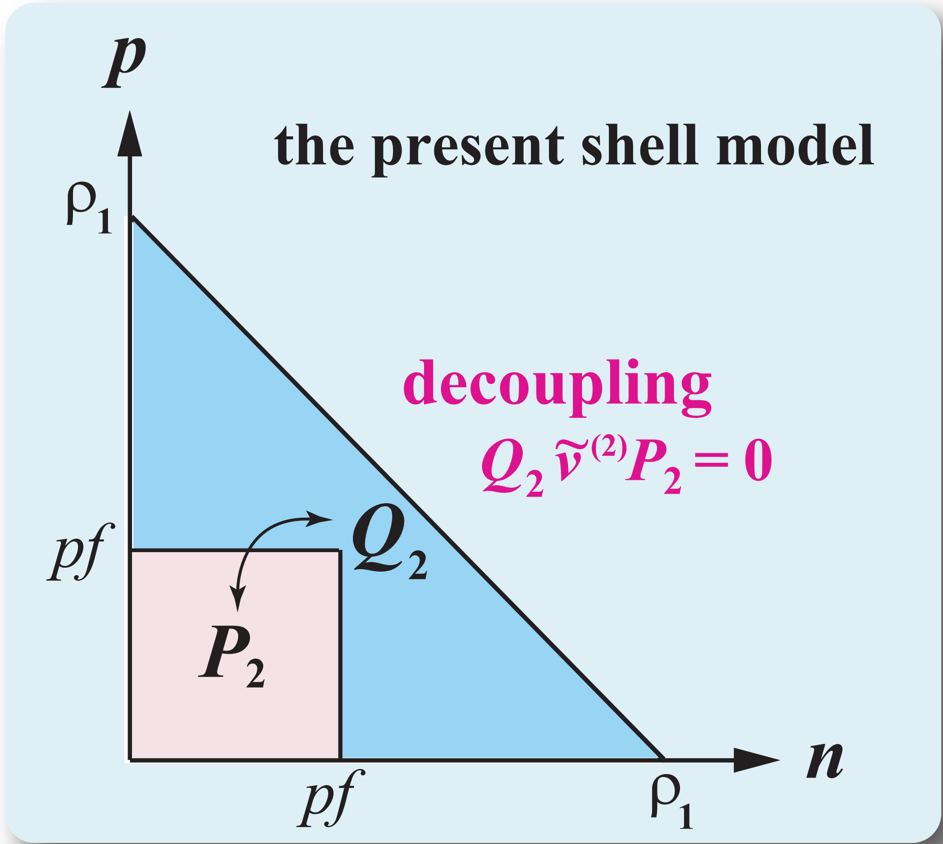
  **Derived from a high-precision NN interaction (CD Bonn, ⋯) and the Coulomb force in the neutron-proton formalism for the given model space through a unitary-transformation theory**

# Derivation of effective interaction

## Eff. int. in a huge model space




## Eff. int. in the 0s−1p0f shells

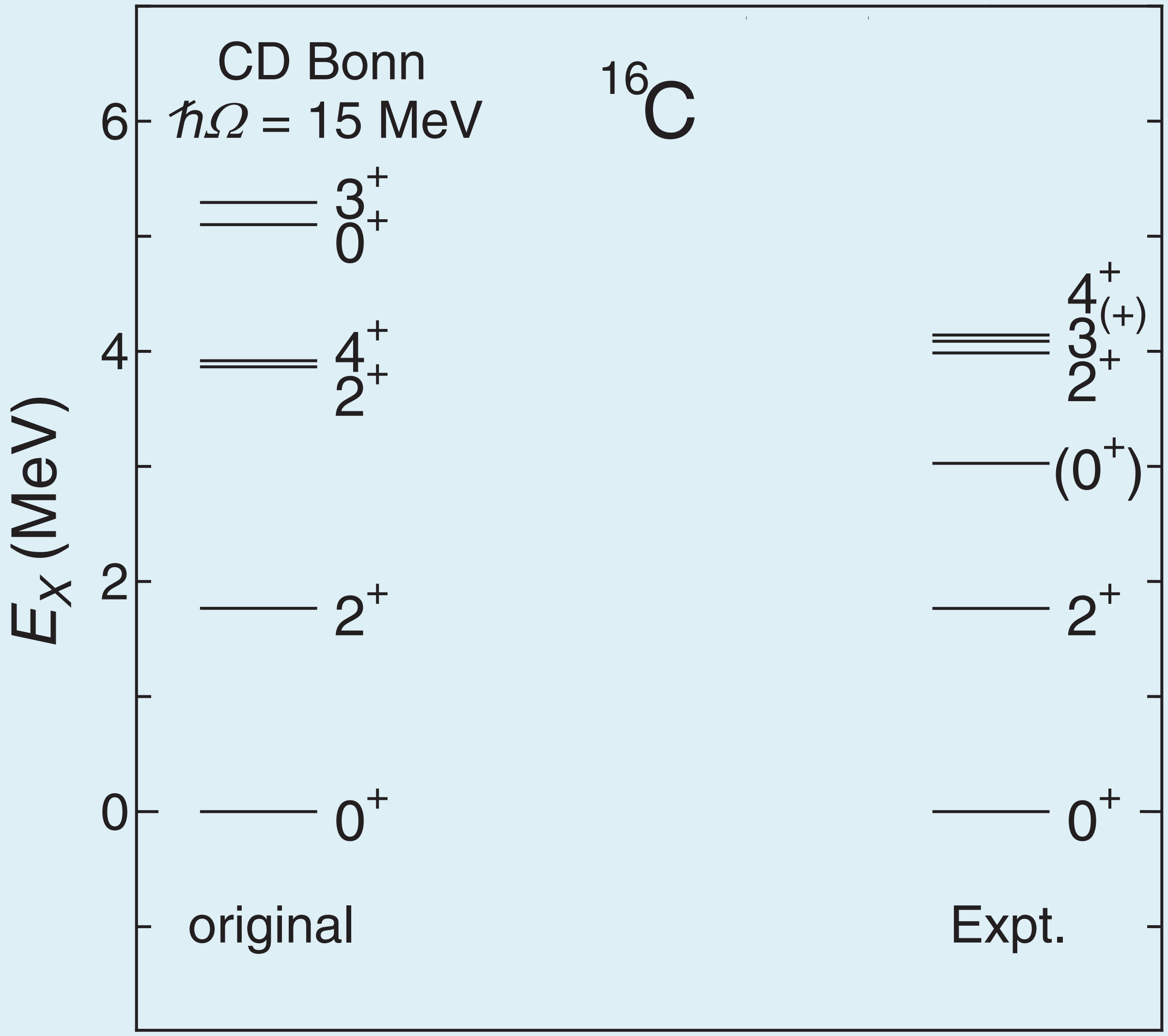



$\rho_1 = 2n_a + l_a + 2n_b + l_b$ ($\{n_a, l_a\}$ and $\{n_b, l_b\}$: sets of h.o. quantum numbers of two-body states)

(For details,

- S. F., T. Mizusaki, T. Otsuka, T. Sebe, and A. Arima, nucl-th/0602002.
- S. F., R. Okamoto, and K. Suzuki, Phys. Rev. C **69**, 034328 (2004).)

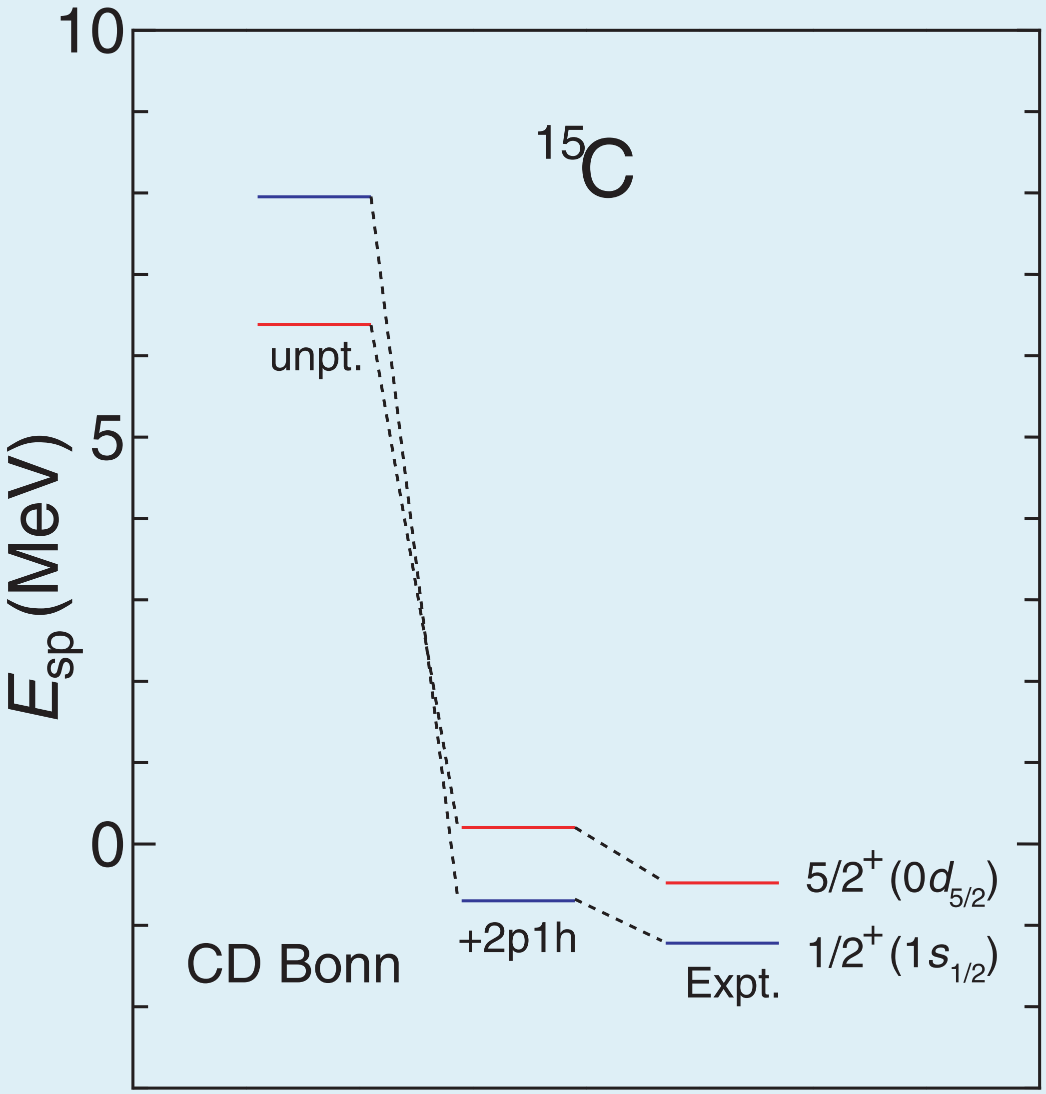
## Low-lying energy levels in $^{16}$C




$B(E2;\, 2_1^+ \rightarrow 0_1^+)$ in $e^2\mathrm{fm}^4$

1.30 $\quad$ $0.63^{\pm 0.11(\mathrm{stat})}_{\pm 0.16(\mathrm{syst})}$

## Single-particle energies in $^{15}$C




**Calculated results by the unitary-model-oparator approach (UMOA)**

**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**

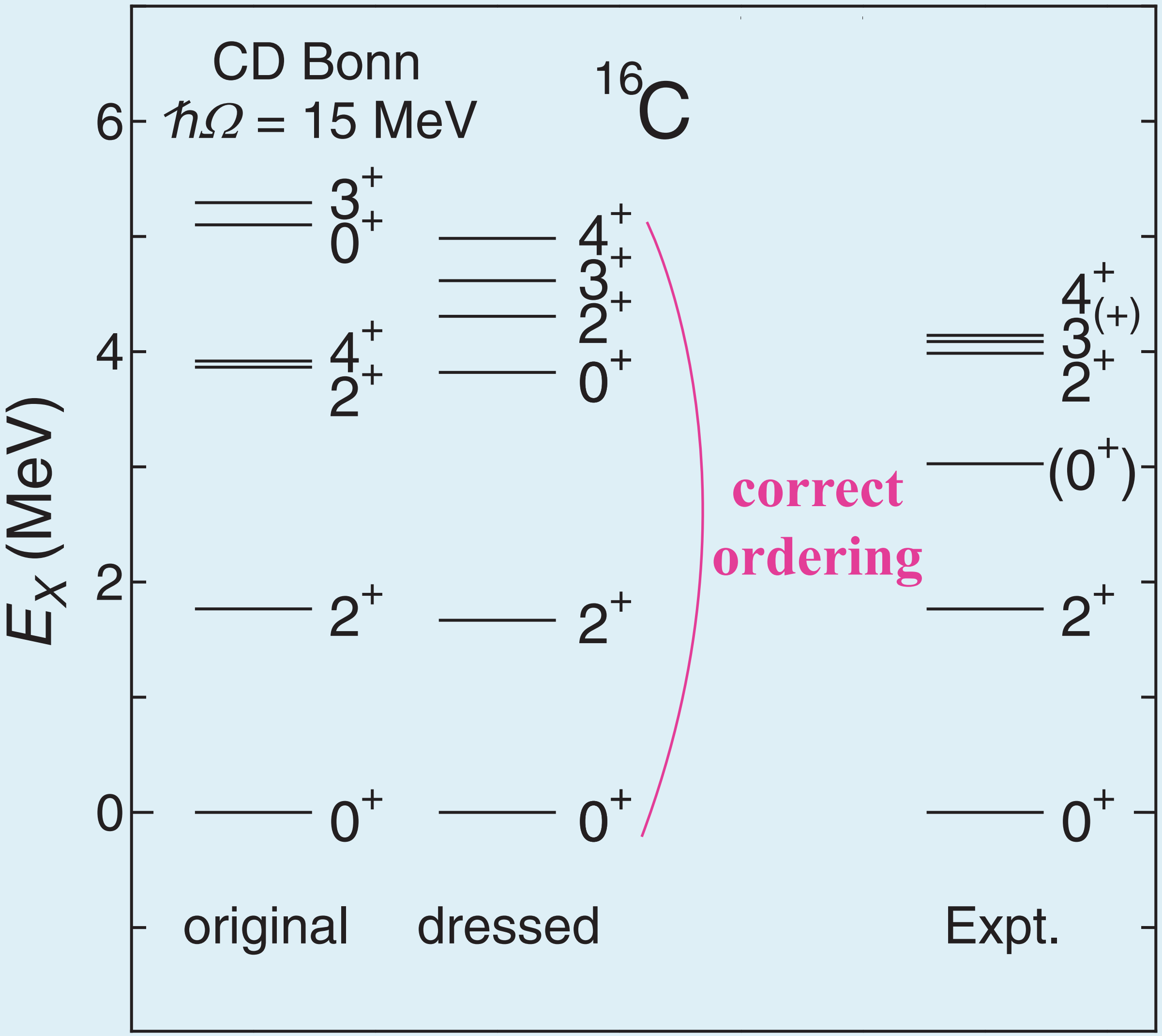
**To remedy the wrong ordering and reproduce the binding energies for the $1/2^+$ and $5/2^+$ states of the UMOA results**

**→ 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"**

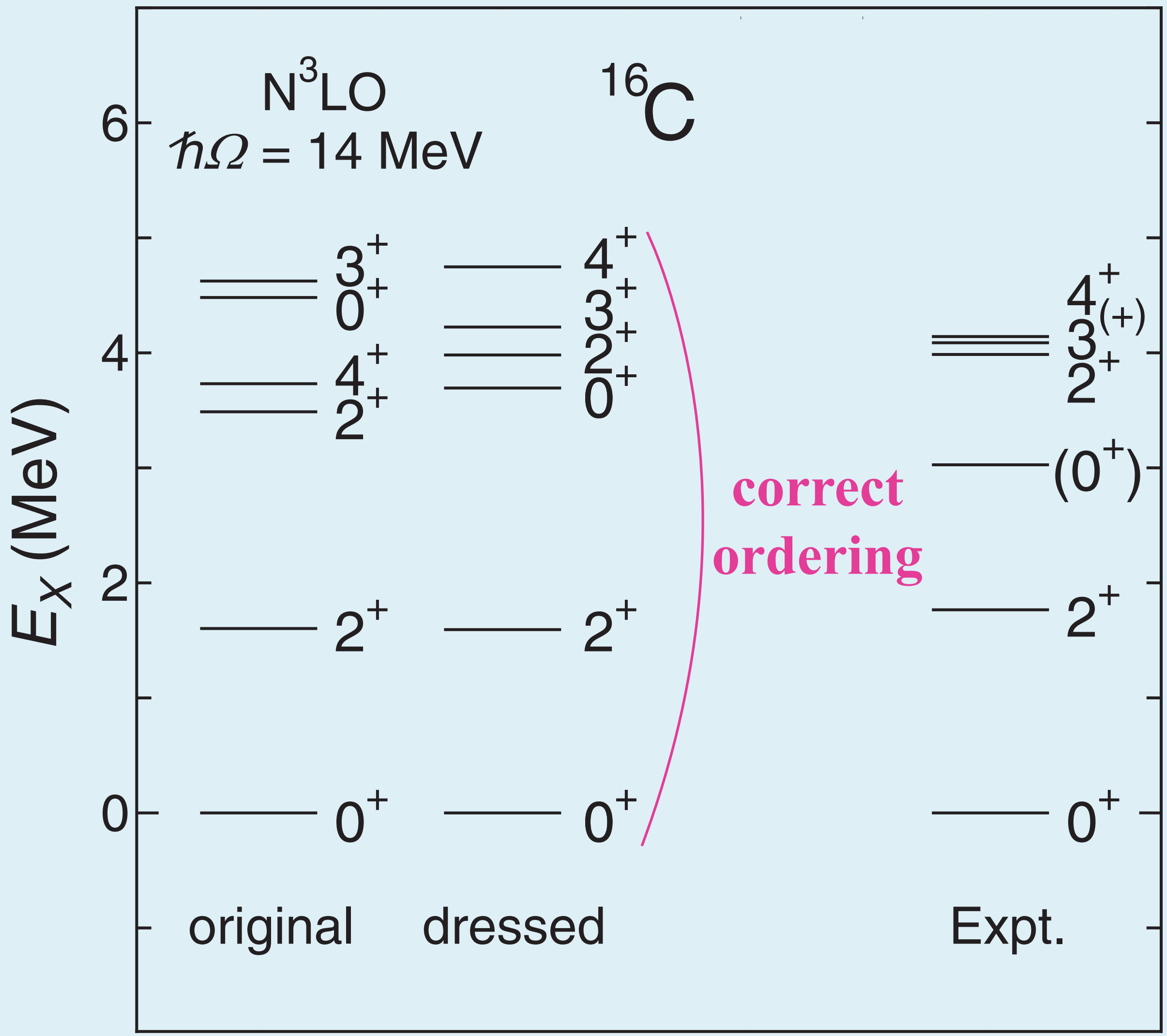
## Low-lying energy levels in $^{16}C$




$B(E2;\, 2_1^+ \rightarrow 0_1^+)$ in $e^2 fm^4$

| original | dressed | Expt. |
|---|---|---|
| 1.30 | 0.84 | $0.63^{\pm 0.11 (stat)}_{\pm 0.16 (syst)}$ |

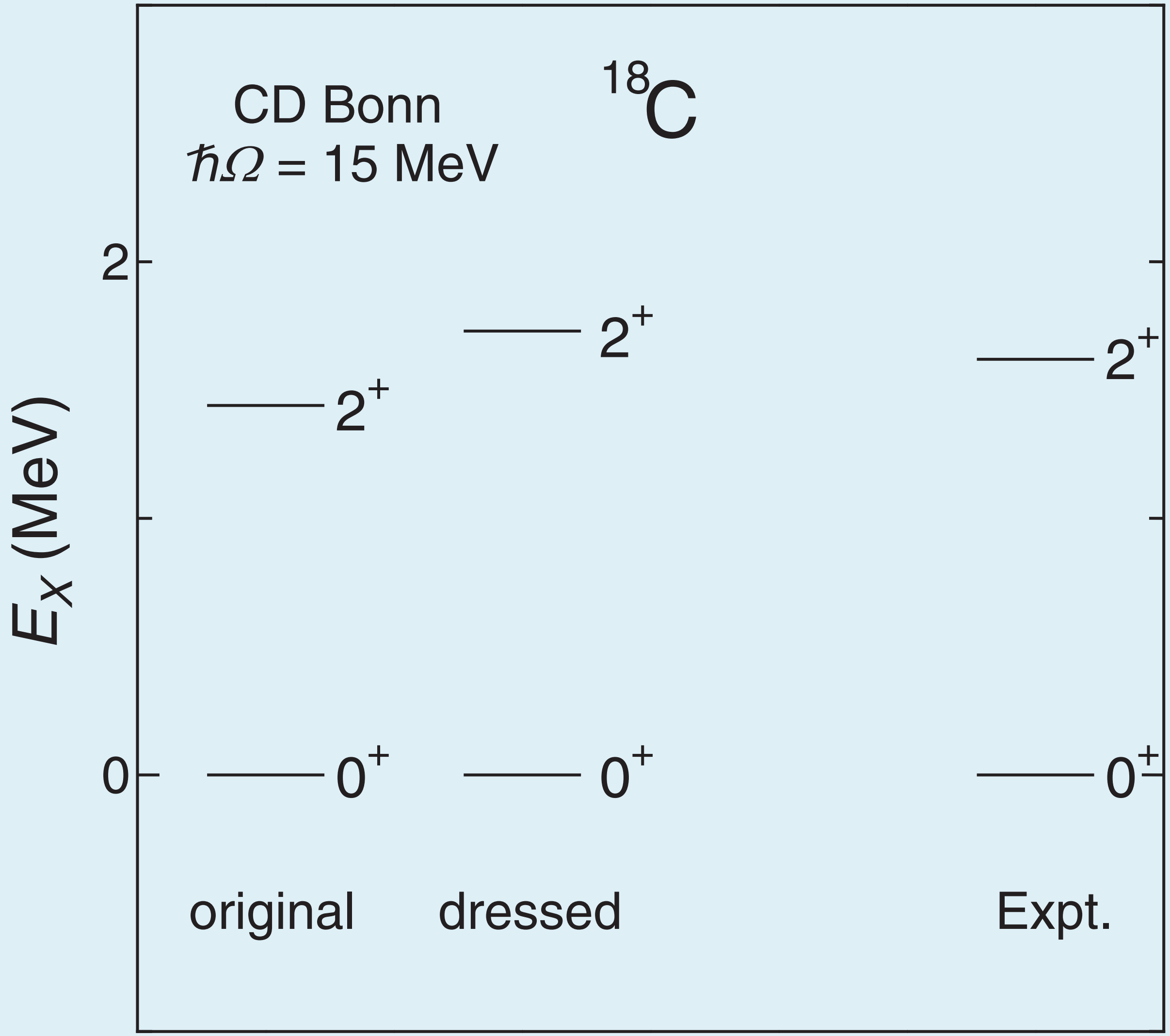
## Low-lying energy levels in $^{16}C$




$B(E2; 2_1^+ \rightarrow 0_1^+)$ in $e^2\text{fm}^4$

1.38 0.91 $0.63^{\pm 0.11(\text{stat})}_{\pm 0.16(\text{syst})}$

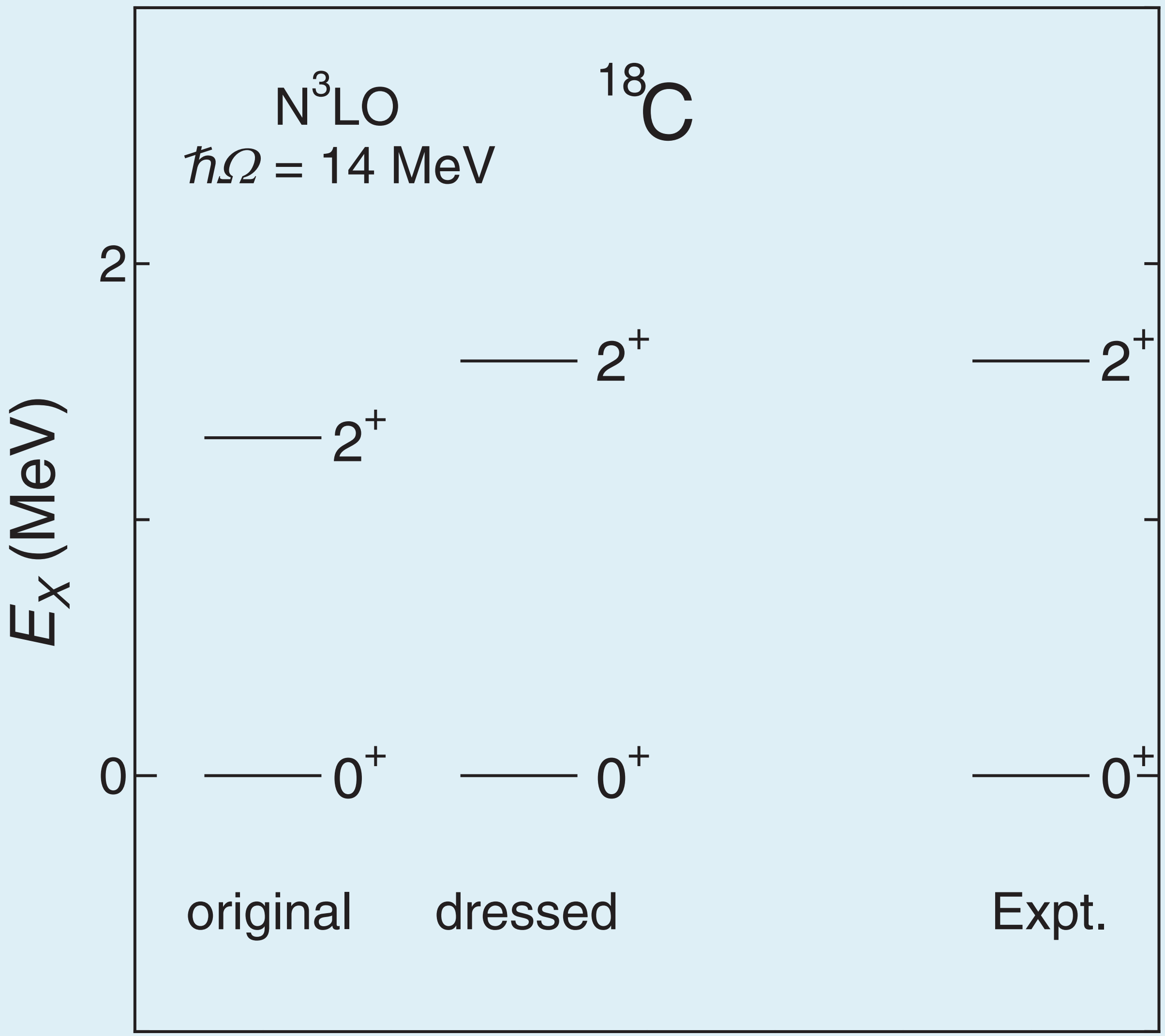
# Energy differences between the $2_1^+$ and $0_1^+$ states in $^{18}C$




$B(E2;\, 2_1^+ \rightarrow 0_1^+)$ in $e^2\mathrm{fm}^4$

| original | dressed | Expt. |
|---|---|---|
| 1.19 | 2.10 | ? |

Energy differences between the $2_1^+$ and $0_1^+$ states in $^{18}$C




$B(E2;\, 2_1^+ \rightarrow 0_1^+)$ in $e^2$fm$^4$

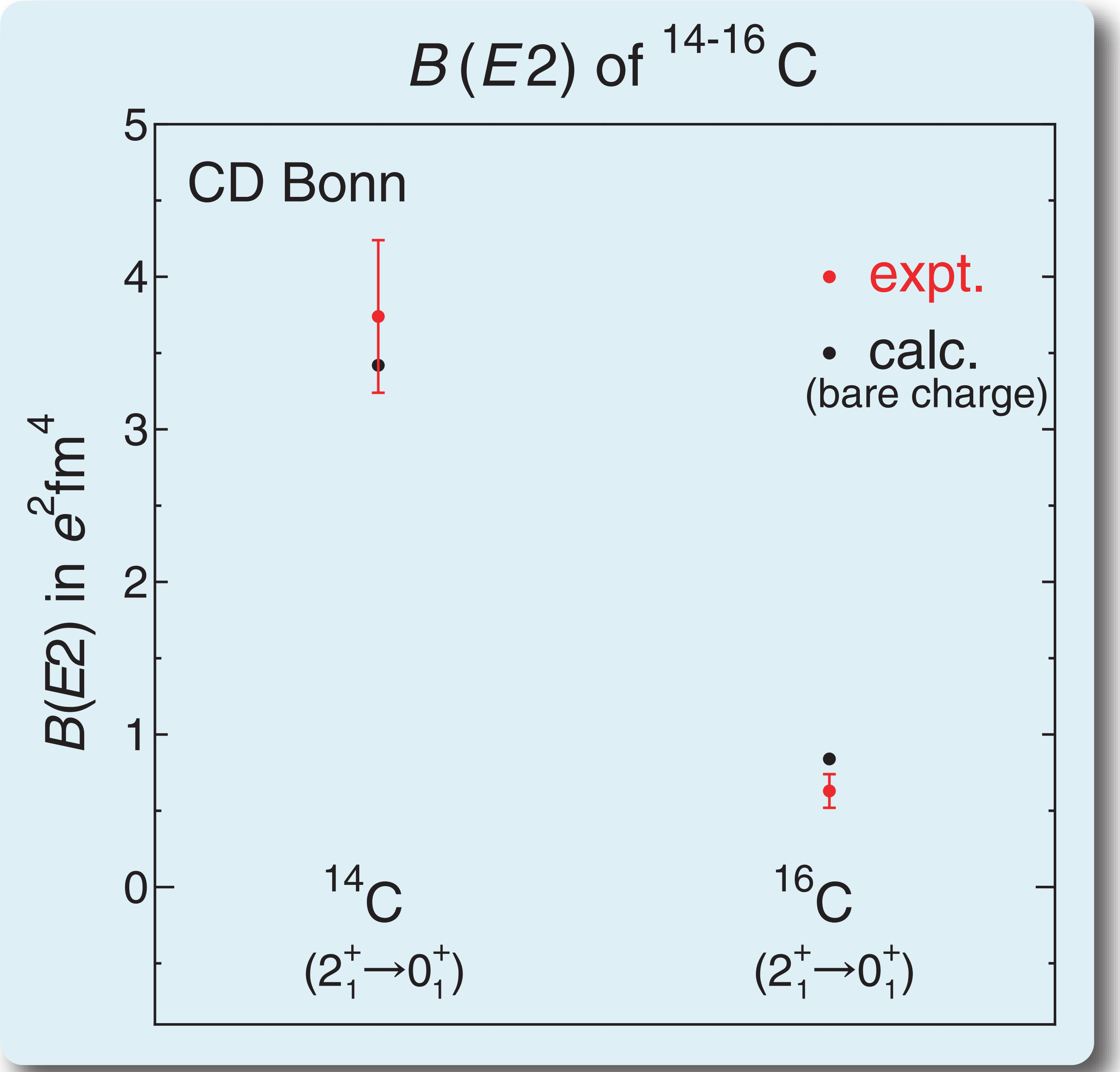
| original | dressed | Expt. |
|---|---|---|
| 1.38 | 2.47 | ? |

# $B(E2;\, 2_1^+ \rightarrow 0_1^+)$ in $^{14,16,18}C$

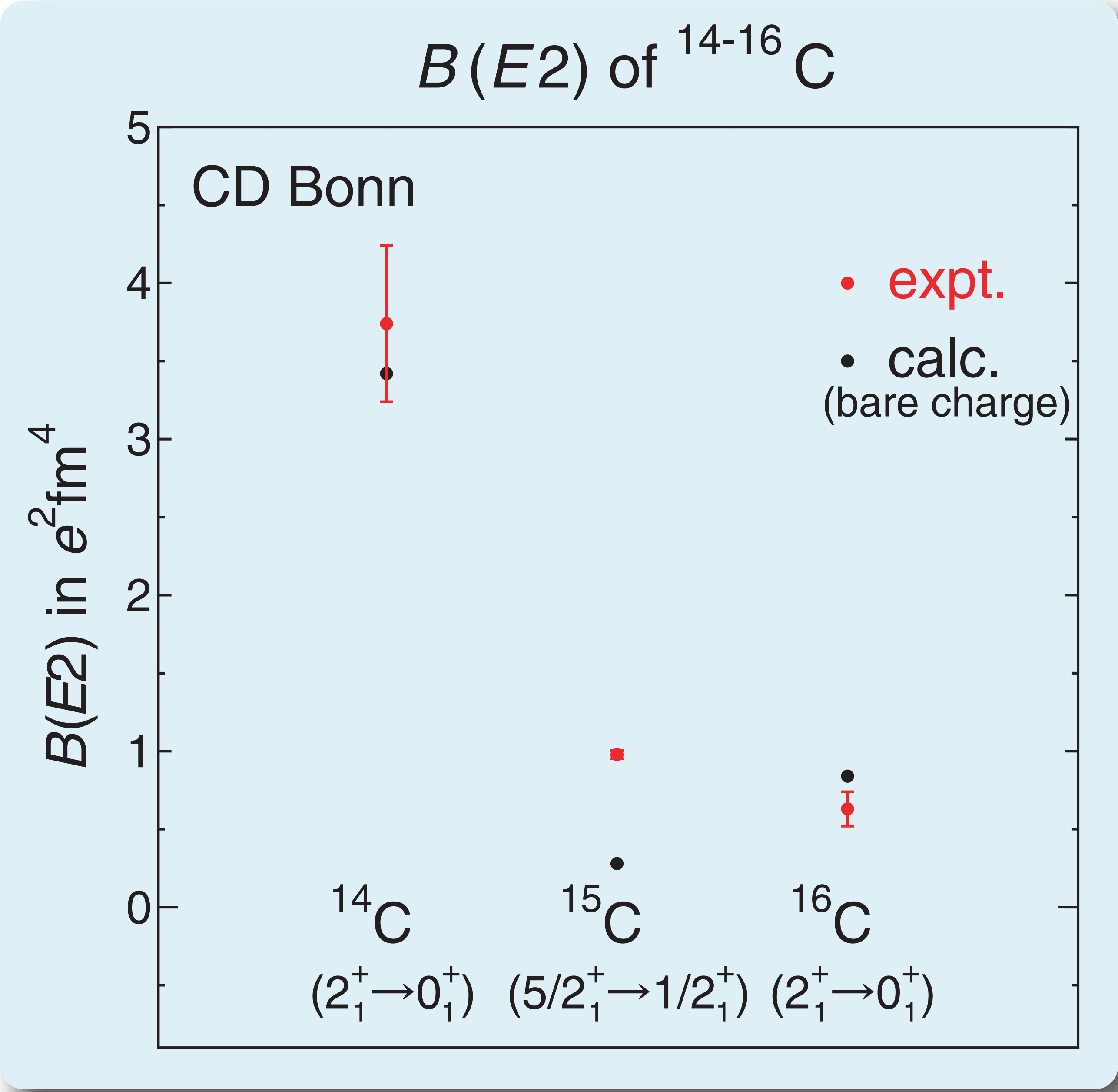
for "dressed"

| | CD Bonn | $N^3LO$ | Expt. |
|---|---|---|---|
| $^{14}C$ | 3.42 | 4.11 | 3.74±0.50 |
| $^{16}C$ | 0.84 | 0.91 | 0.63 ± 0.11(stat) ± 0.16(syst) |
| $^{18}C$ | 2.10 | 2.47 | ? |

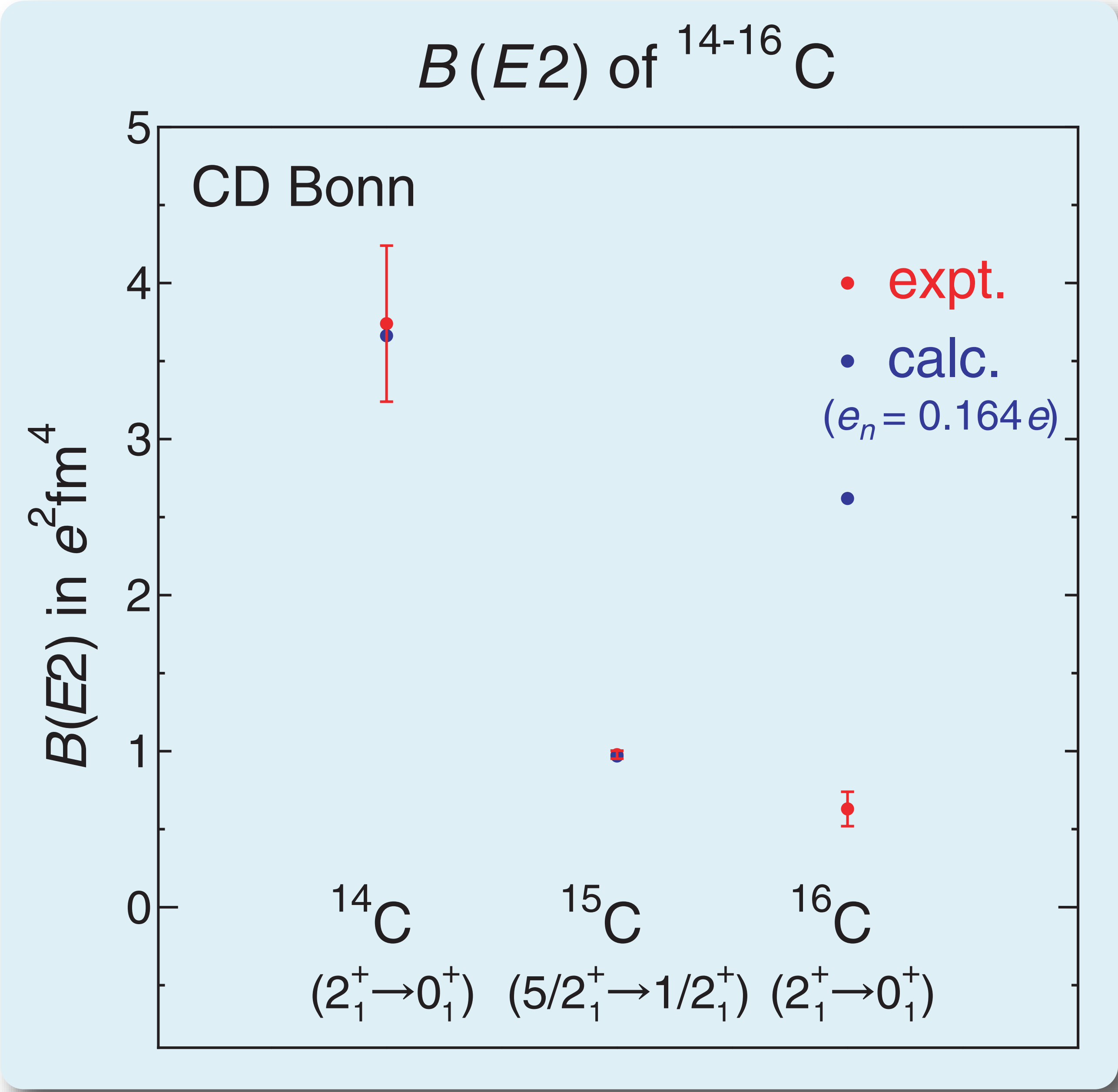
in $e^2fm^4$



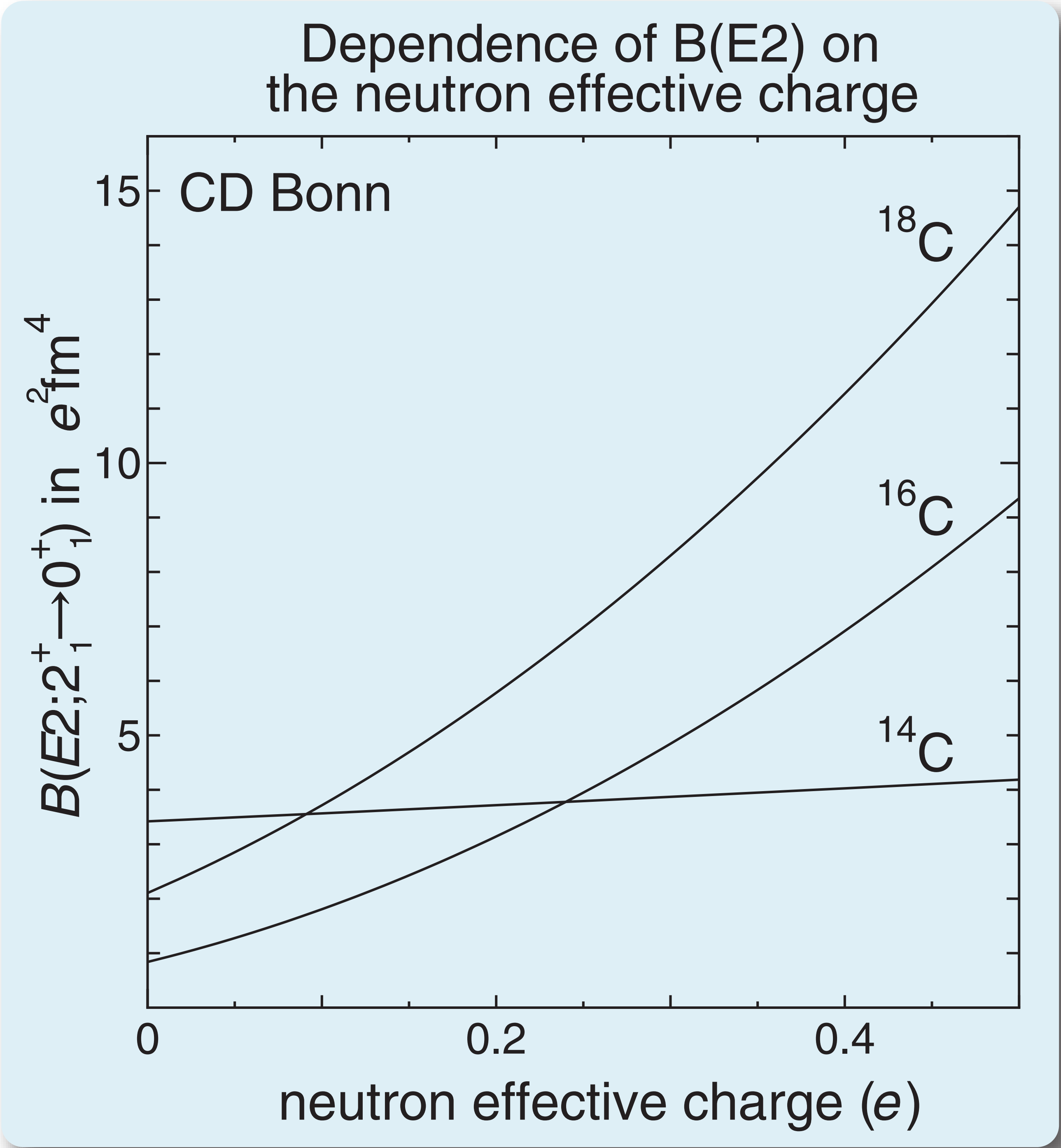
B(E2) of 14-16 C
CD Bonn
expt.
calc.
(bare charge)
B(E2) in e²fm⁴
0
1
2
3
4
5
14C
(2+1→0+1)
16C
(2+1→0+1)



B(E2) of 14-16C
CD Bonn
expt.
calc.
(bare charge)
B(E2) in e2fm4
5
4
3
2
1
0
14C
(2+1→0+1)
15C
(5/2+1→1/2+1)
16C
(2+1→0+1)



B(E2) of 14-16 C
CD Bonn
expt.
calc.
(e_n = 0.164 e)
B(E2) in e2fm4
0
1
2
3
4
5
14C
(2+1→0+1)
15C
(5/2+1→1/2+1)
16C
(2+1→0+1)



Dependence of B(E2) on
the neutron effective charge
CD Bonn
$^{18}C$
$^{16}C$
$^{14}C$
15
10
5
0
0.2
0.4
$B(E2;2_1^+\rightarrow0_1^+)$ in $e^2fm^4$
neutron effective charge ($e$)

## $B(E2; 2_1^+ \rightarrow 0_1^+)$ in $^{14,16,18}C$

CD Bonn

for "dressed"

| | $e_n = 0$ | $e_n = 0.164e$ | Expt. |
|---|---|---|---|
| $^{14}C$ | 3.42 | 3.66 | 3.74±0.50 |
| $^{16}C$ | 0.84 | 2.62 | 0.63 ± 0.11(stat) ± 0.16(syst) |
| $^{18}C$ | 2.10 | 4.98 | ? |

in $e^2 fm^4$

# Occupation numbers in $^{14}$C and $^{16}$C

**CD Bonn** **for "dressed"**

| | $J^\pi$ | $p$ or $n$ | $0p_{3/2}$ | $0p_{1/2}$ | $1s_{1/2}$ | $0d_{5/2}$ |
|---|---|---|---|---|---|---|
| $^{14}$C | $0_1^+$ | $p$ | 3.59 | 0.27 | 0.09 | 0.02 |
| | | $n$ | 3.88 | 1.94 | 0.08 | 0.02 |
| | $2_1^+$ | $p$ | 2.83 | 1.03 | 0.09 | 0.02 |
| | | $n$ | 3.87 | 1.95 | 0.07 | 0.03 |
| $^{16}$C | $0_1^+$ | $p$ | 3.41 | 0.42 | 0.12 | 0.03 |
| | | $n$ | 3.88 | 1.95 | 0.97 | 1.01 |
| | $2_1^+$ | $p$ | 3.39 | 0.44 | 0.11 | 0.03 |
| | | $n$ | 3.88 | 1.94 | 0.81 | 1.17 |

# Summary

- Developed a new shell-model framework to microscopically investigate neutron- or proton-rich exotic nuclei
  - Large-scale shell-model code
    new MSHELL
  - Microscopic effective interaction
    derived from modern NN interactions through a unitary-transformation theory
- Low-lying energy levels of $^{16}$C and $^{18}$C
  → well reproduced by the calculation
  $B(E2)$s of $^{15}$C and $^{16}$C
  → *not* well described with the *same* effective charge
- Including the genuine three-body force and diminishing the approximations in the calculation

# Nucleon configurations in neutron-rich C isotopes