OMEG 2017, International Symposium on Origin of Matter and Evolution of Galaxies, Daejeon, Korea, June 27-30, 2017

Unbound states in ^{17}C probed via single-neutron removal from ^{18}C at 245 MeV/u

Y.Satou

Institute for basic science

Rare Isotope Science Project

S.Kim, Thesis:
"Spectroscopy of ^{17}C via one-neutron knockout reaction"

c.f.) J.W.Hwang, S.Kim et al., PLB769(2017)503.
"Single-neutron knockout from ^{20}C and the structure of ^{19}C"

Issues:

A) The cross-shell states in light neutron-rich nuclei are known to be notoriously difficult to describe theoretically, because they involve transitions encompassing two major shells on a proton-neutron asymmetric system.

B) Obtaining a reliable relevant effective interaction in such cases remains of a special difficulty.

C) The cross-shell states might have implications to astrophysical radiative neutron captures processes, since they are strongly influenced by the presence of dipole resonances.

This presentation:

- An experimental attempt to enlarge the known realm of such dipole states in N-rich C isotopes.
- Capability of recently available shell-model calculations on dipole and other states examined.

RIKEN SAMURAI Day-1 collaborators

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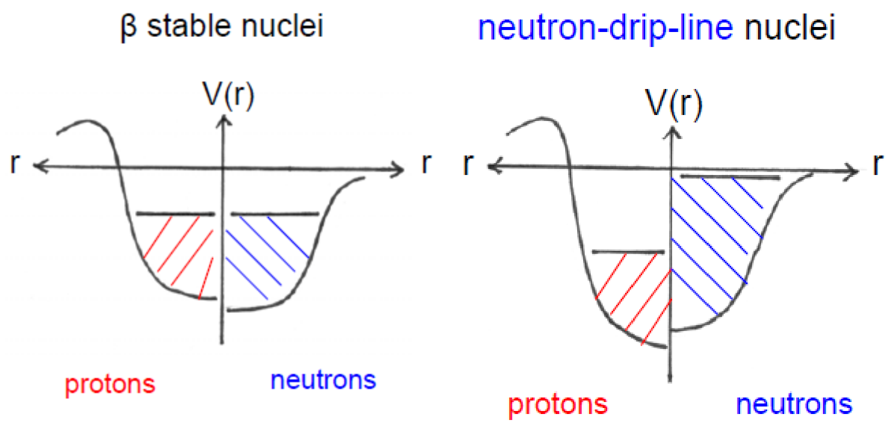
Nuclear structure of very-neutron-rich nuclei

- Exotic properties are anticipated due to the large excess of neutrons and weak binding of valence neutrons
  1. Nucleon density distribution may change drastically.
     ⇒ neutron halo, cluster
  2. Mean field can change accordingly.
     ⇒ modification of shell structure, melting of magicity
  3. Deformability of nuclei is modified accordingly.
  4. Large Fermi energy difference between neutrons and protons will modify the effects of Pauli blocking and enhance the coupling with continuum states.



Why study Carbon isotopes

1. In light elements (Z<10) the number of isotopes is the largest (14); suited for systematic study.

2. They offer a basis to study intricate effects of the nuclear forces.
   - Quenched N=14 shell gap
   - Proton core polarization effects

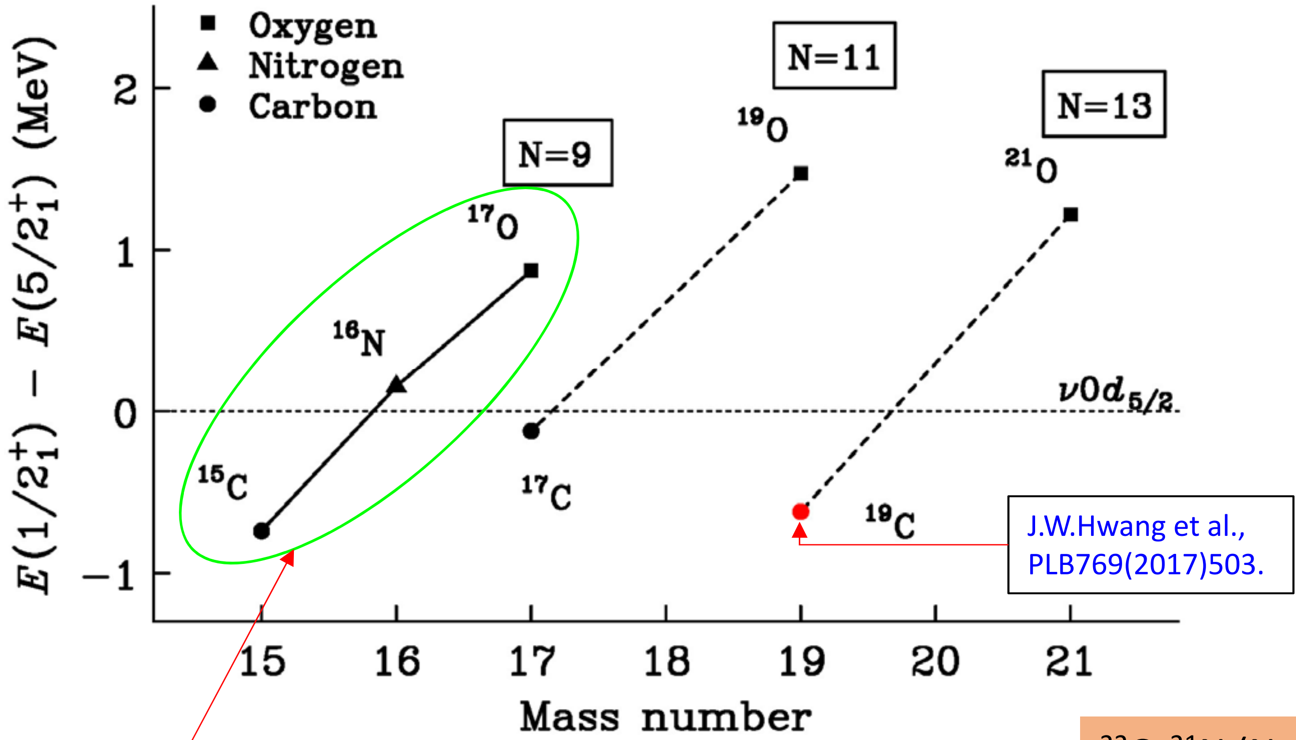
3. The region (A<~20) represents a frontier of current *ab initio* calculations including continuum and three-body forces. Advanced shell-model interactions also exist.

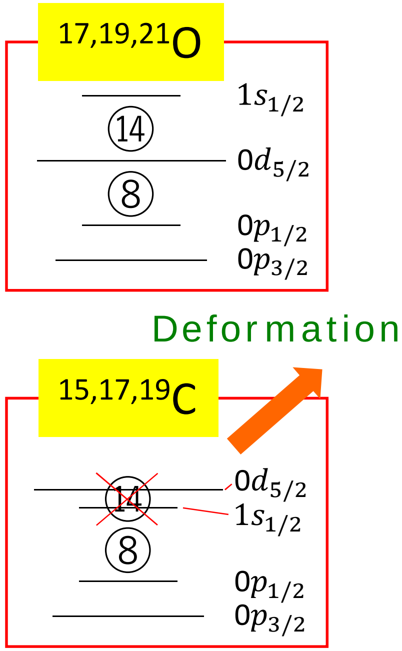
4. Possible implications of properties of light neutron-rich nuclei (including C) to r-process nucleosynthesis in neutrino-driven winds have been suggested. Dipole resonances (L=1) have impact on the neutron capture rates.

   M.Terasawa et al., ApJ562(2001)470. T.Sasaqui et al., ApJ634(2005)1173.
   S.Goriely, PLB436(1998)10.

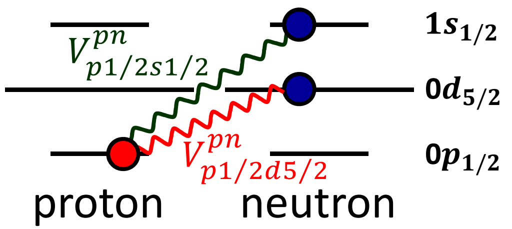
Quenched N=14 shell gap

M.Stanoiu et al., PRC78(2008)034315.





- I.Talmi, I.Unna, PR4(1960)469.

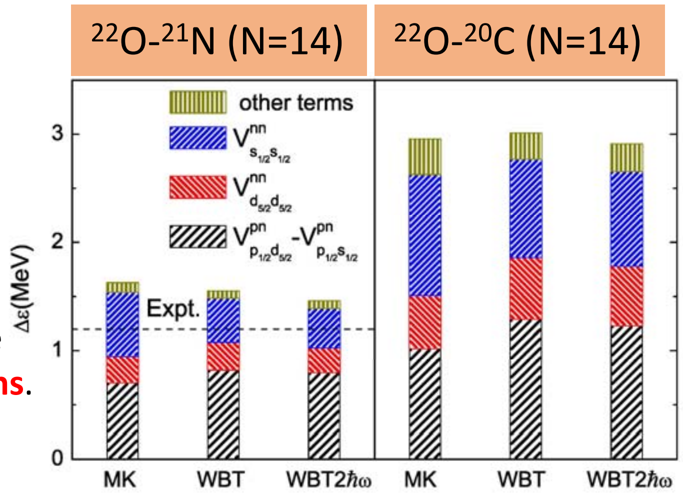


$$2\left(V^{pn}_{p1/2d5/2} - V^{pn}_{p1/2s1/2}\right)$$

- C.X.Yuan et al., Nucl. Phys. A 883 (2012) 25.

N=14 shell gap evolution

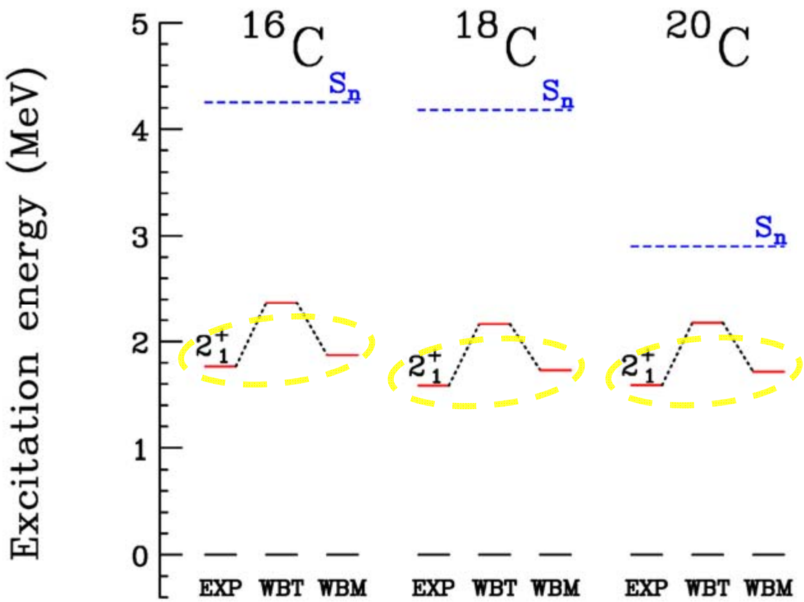
- Proton-neutron int.
- Attractive neutron-neutron int. due to the **many-body correlations**.

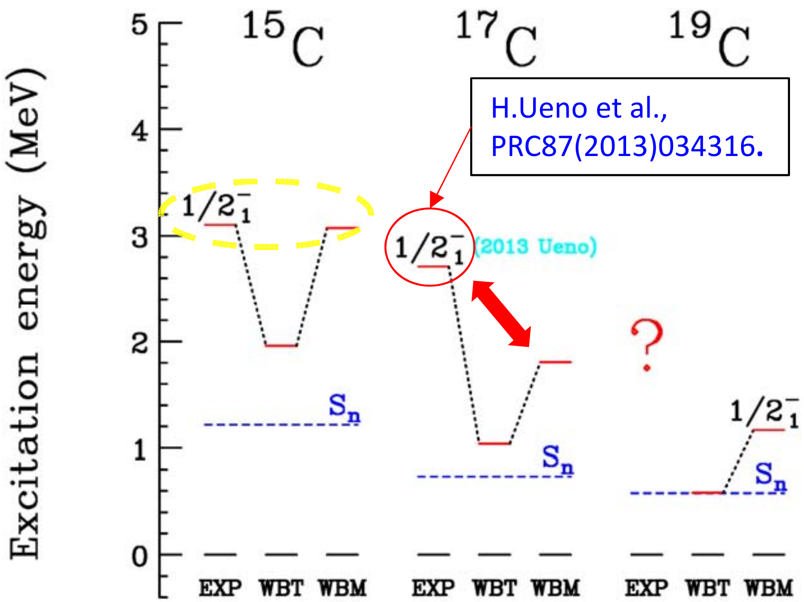


Proton core polarization effects

- Responsible for reduced neutron-neutron matrix elements in the sd shell in Carbon
- WBM provides a remedy for 2_1^+ in ^{16,18,20}C and $1/2_1^-$ in ^{15}C.
- To what extent WBM is applicable?

※ Only the lowest $\hbar\omega$ configurations are considered in SM calc.





Overprediction of E(2_1^+) with WBT.

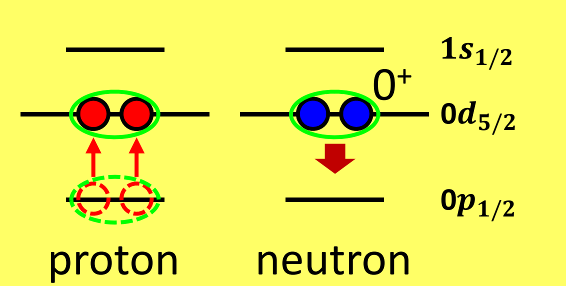
[1] **Core polarization effects** (should be mitigated in C).
K.Sieja, F.Nowacki, NPA857(2011)9.

[2] Extended radial wave function.
A.Signoracci et al., PRC83(2011)024315.

WBT: **E.K Warburton, B.A.Brown, PRC46(1992)923.**

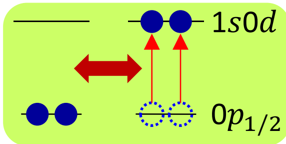
WBM: WBP with USD part reduced by 25%.

Proton core polarization effects



T.T.S.Kuo, G.E.Brown, NP85(1966)40.

Shell-model interactions examined

Code (Model space)	Interactions
NuShell@MSU (OXBASH) (*spsdpf*)	WBT: E.K Warburton, B.A.Brown, PRC46(1992)923. • $(0-1)\hbar\omega$ WBM: WBP with USD part reduced by 25%. M.Stanoiu et al., PRC78(2008)034315.
NuShellX@MSU (*psd*, $\hbar\omega$ unrestricted) B.A.Brown, W.D.M.Rae, Nucl. Data. Sheets 120 (2014) 115.	WBT_X: WBT as calculated with NuShellX. WBM_X: WBM as calculated with NuShellX. YSOX: C.Yuan et al., PRC85(2012)064324. • $(0-3)\hbar\omega$ • $\langle pp\|V\|pp\rangle$ SFO • $\langle sd\|V\|sd\rangle$ SDPF-M • $\langle psd\|V\|psd\rangle$ and $\langle pp\|V\|sdsd\rangle$ V_{MU} T.Otsuka et al., PRL104(2010)012501. • V_{MU} strengths adjusted to reproduce N-rich B,C,O masses. 2p2h excitations 

Ab Initio Coupled-Cluster Effective Interaction

CCEI: G.R.Jansen et al., PRL113(2014)142502.

- Nonperturbative calculation.
- Based on NN and NNN forces from chiral effective field theory.
- No account for the particle continuum.

$$\hat{H} = \sum_{i<j}\left(\frac{(p_i - p_j)^2}{2mA} + \hat{V}_{NN}^{(i,j)}\right) + \sum_{i<j<k}\hat{V}_{3NF}^{(i,j,k)}$$

Objectives

- To furnish spectroscopic information on ^{17}C, including cross-shell states.
  - **Confirm $1/2_1^-$ (and $3/2_1^-$) in ^{17}C reported in a βn study.**
  - **New information on other states in ^{17}C.**
  - **Test theories against new spectroscopy.**

  (1) enlarged $\hbar\omega$ model space, (2) reduced sd neutron-neutron matrix elements, (3) new SM interactions.

H.Ueno et al., PRC87(2013)034316.

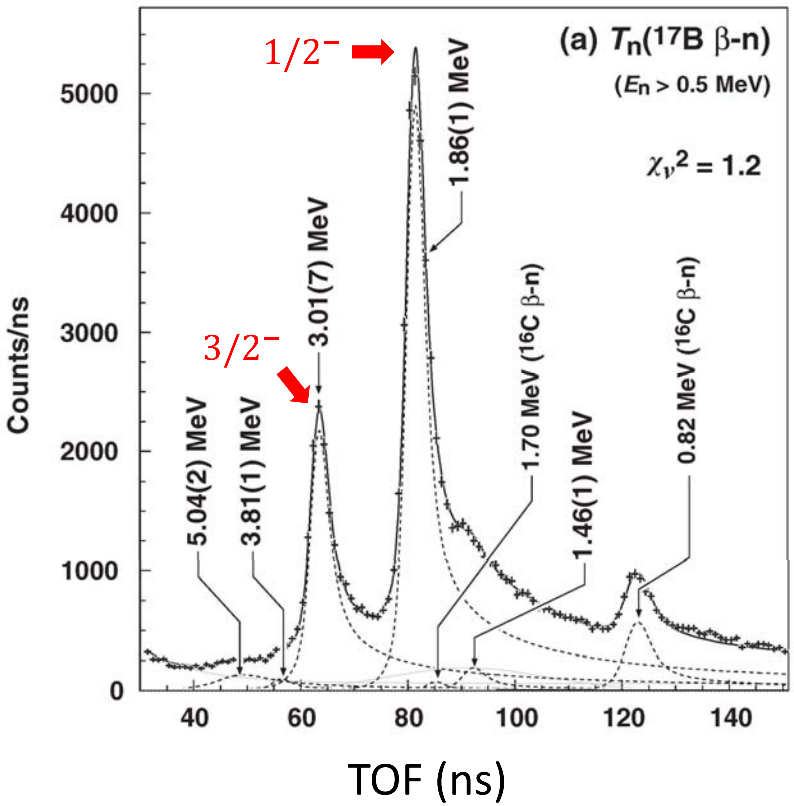
- To develop a new experimental technique involving neutron knockout which complements the βn spectroscopy.
  - **Newly commissioned SAMURAI spectrometer.**
  - **Reaction:** ^{12}C(^{18}C,^{17}C*→^{16}C+n) @ 245 MeV/nucleon
  - **Observables:** $\boldsymbol{\sigma_{-1n}}$, $\boldsymbol{d\sigma/dp_{\parallel}}$, $\boldsymbol{d\sigma/dp_T}$.

T.Kobayashi et al., NIMB317(2013)294.

PHYSICAL REVIEW C **87**, 034316 (2013)

β-delayed neutron and γ-ray spectroscopy of ^{17}C utilizing spin-polarized ^{17}B

H. Ueno,[1,*] H. Miyatake,[2] Y. Yamamoto,[3] S. Tanimoto,[3] T. Shimoda,[3] N. Aoi,[4] K. Asahi,[5] E. Ideguchi,[4] M. Ishihara,[1] H. Izumi,[3] T. Kishida,[1] T. Kubo,[1] S. Mitsuoka,[6] Y. Mizoi,[7] M. Notani,[8] H. Ogawa,[5,†] A. Ozawa,[9] M. Sasaki,[3] T. Shirakura,[3] N. Takahashi,[3] and K. Yoneda[1]



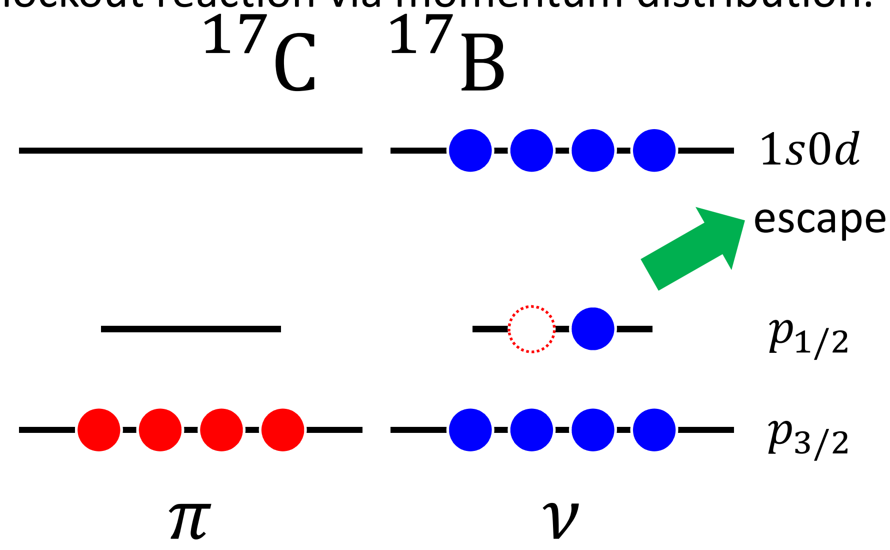
En (MeV)	Ex (MeV)	Width (MeV)	Log *ft*	J^π
1.86(1)	2.71(2)	0.04(1)	4.8(1)	$1/2^-$
3.01(1)	3.93(2)	0.16(4)	4.9(1)	$3/2^-$
1.86(1)	4.05(2)	0.06(6)	6.0(1)	$(5/2^-)$

- Allowed transitions do not involve parity change.

$$B(GT) = \frac{1}{2I_i + 1} \left| \left\langle f \left\| \sum_k \sigma_k \tau_\pm^k \right\| i \right\rangle \right|^2$$

- Resulting ν p-shell hole states can be populated by knockout reactions.

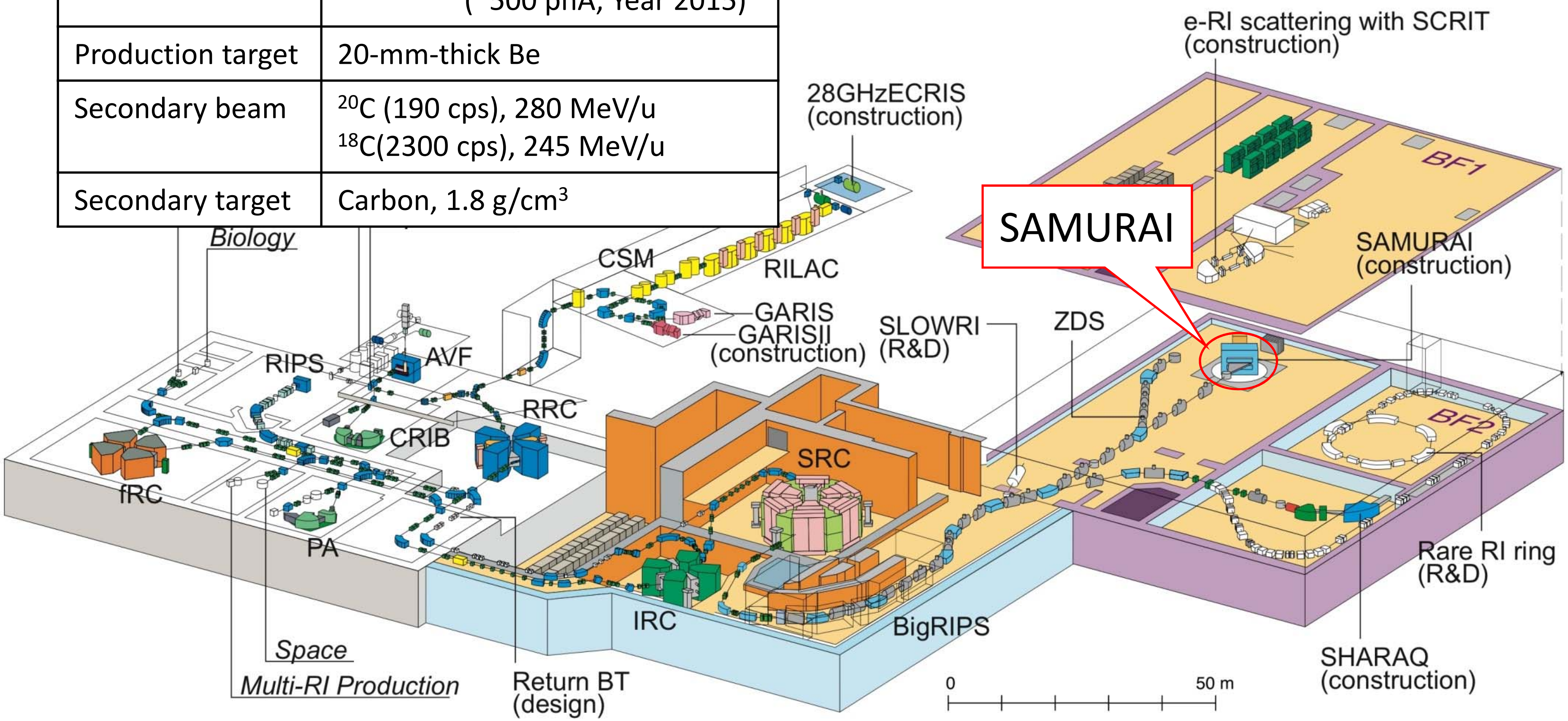
- The angular momentum, and thus parity, of the state can be determined experimentally in the knockout reaction via momentum distribution.



RIKEN RIBF : Radioactive Isotope Beam Factory

Primary beam	^{48}Ca, 345 MeV/u, 250 pnA MAX (~500 pnA, Year 2015)
Production target	20-mm-thick Be
Secondary beam	^{20}C (190 cps), 280 MeV/u ^{18}C(2300 cps), 245 MeV/u
Secondary target	Carbon, 1.8 g/cm^3

RIBF: Completed in 2007
New-Generation RI-Beam Facility



SAMURAI Day-1 campaign 2012

I. Coulomb Breakup of ^{19}B and ^{22}C, Nakamura et al.
II. Study of ^{18}B,^{21}C, and excited states of ^{19}B, ^{22}C, Orr et al.
III. Structure of Unbound Oxygen Isotopes ^{25}O,^{26}O, Kondo et al.

Y.Kondo et al., PRL116(2016)102503.
Y.Togano et al., PLB761(2016)412.
J.W.Hwang et al., PLB769(2017)503.

SAMURAI spectrometer

Superconducting Analyzer for MUlti-particles from RAdioIsotope beams   T.Kobayashi et al, NIMB317,294(2013).

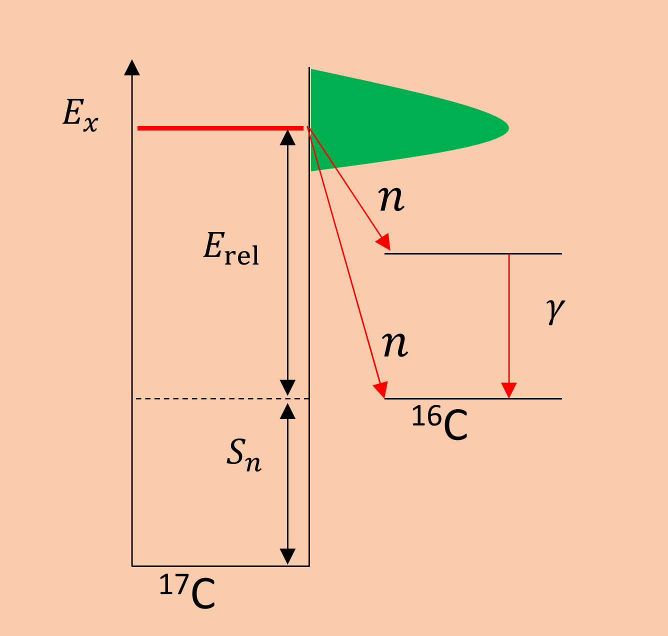
- Invariant mass method

$^{12}C(^{18}C, ^{17}C^* \rightarrow ^{16}C+n)$

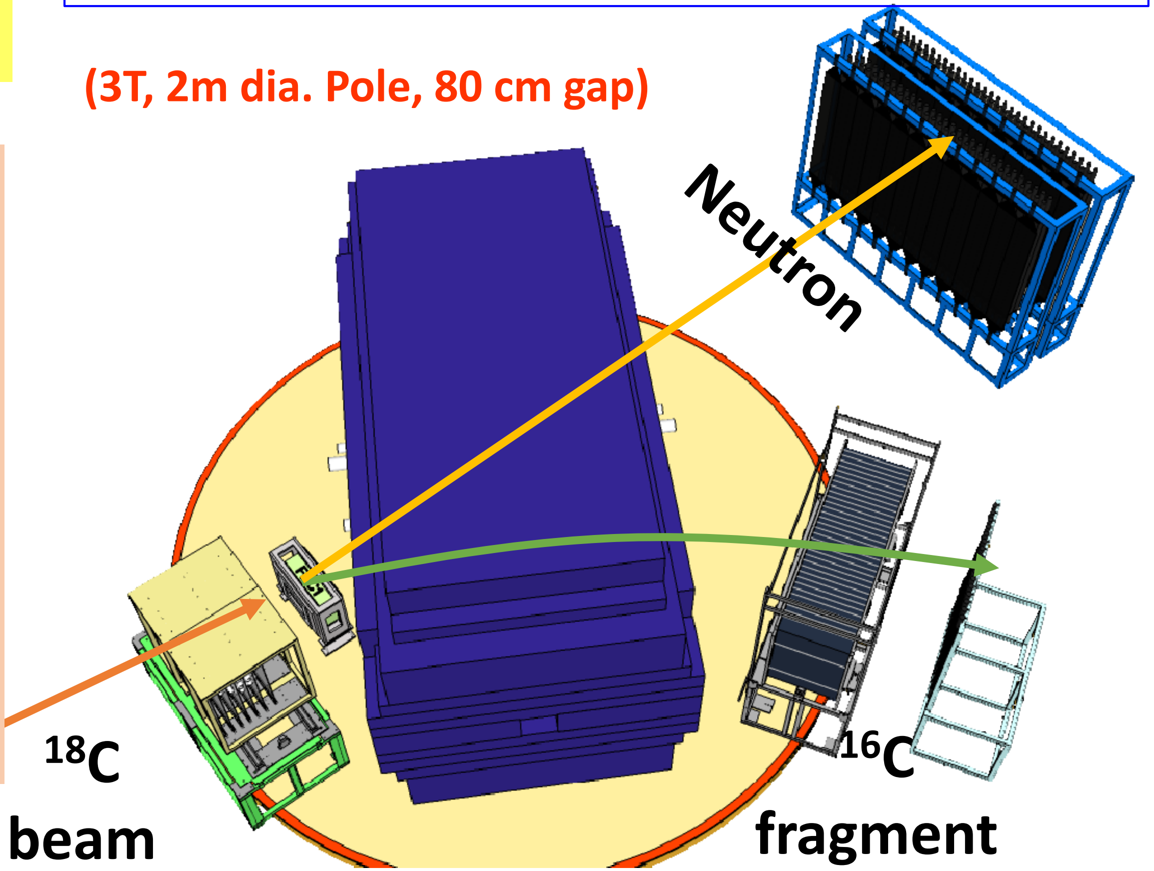
$$M_{\mathrm{inv}} = \sqrt{(E_C + E_n)^2 - |\boldsymbol{P}_C + \boldsymbol{P}_n|^2}$$
$$E_{\mathrm{rel}} = M_{\mathrm{inv}} - M_C - M_n$$
$$E_x = E_{\mathrm{rel}} + S_n$$

(1) High detection efficiency for decay neutrons. Large ε_n
(2) High coverage of decay phase space due to kinematical focusing.
(3) Large acceptance near E_{rel}~0 MeV due to magnetic separation of neutrons and charged particles.
(4) Good E_{rel} resolution suited for spectroscopy.

$$\Delta E_{\mathrm{rel}} \propto \sqrt{E_{\mathrm{rel}}(E_{\mathrm{in}}/A)}(\Delta P/P)$$



(3T, 2m dia. Pole, 80 cm gap)



SAMURAI Day-One, 2012 May

SAMURAI Day-1 campaign 2012

I. Coulomb Breakup of ^{19}B and ^{22}C, Nakamura et al.

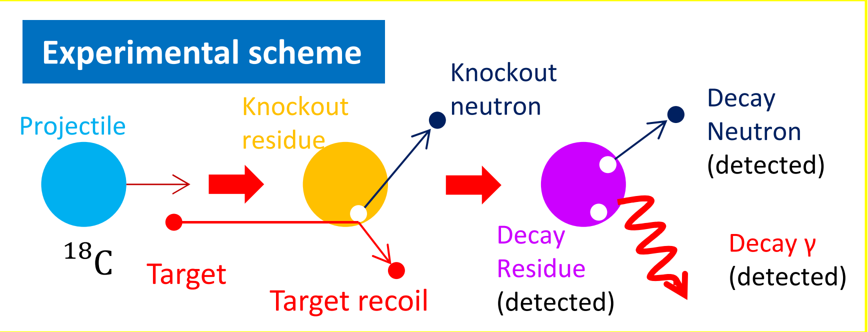
II. Study of ^{18}B, ^{21}C, and excited states of ^{19}B, ^{22}C, Orr et al.

III. Structure of Unbound Oxygen Isotopes ^{25}O, ^{26}O, Kondo et al.

One-neutron knockout reaction

P.G.Hansen and J.A.Tostevin, Annu. Rev. Nucl. Part. Sci. 53, 219 (2003).

- Exhibit large cross sections ~100 mb.
- Knocked-out nucleon is democratically selected from valence orbits.
- Momentum distributions of the residue carry information on L, within the approximation the nucleon is suddenly removed.



Stripping cross section :

$$\frac{d\sigma_{\rm str}}{d^3k_c} = \frac{1}{(2\pi)^3}\frac{1}{2l+1}\sum_m \int d^2b_v\left[1-|S_v(b_v)|^2\right] \times \left|\int d^3r e^{-i\boldsymbol{k}_c\cdot\boldsymbol{r}} S_c(b_c)\psi_{lm}(\boldsymbol{r})\right|^2$$

Inclusive -1n cross section:

$$\sigma_{-1n} = \sum_{nlj}\left(\frac{A}{A-1}\right)^N \cdot C^2\, S(J^\pi, nlj)\cdot \sigma_{sp}\left(nlj, S_n^{\rm eff}\right)$$

Longitudinal momentum $p_\parallel$ distribution:

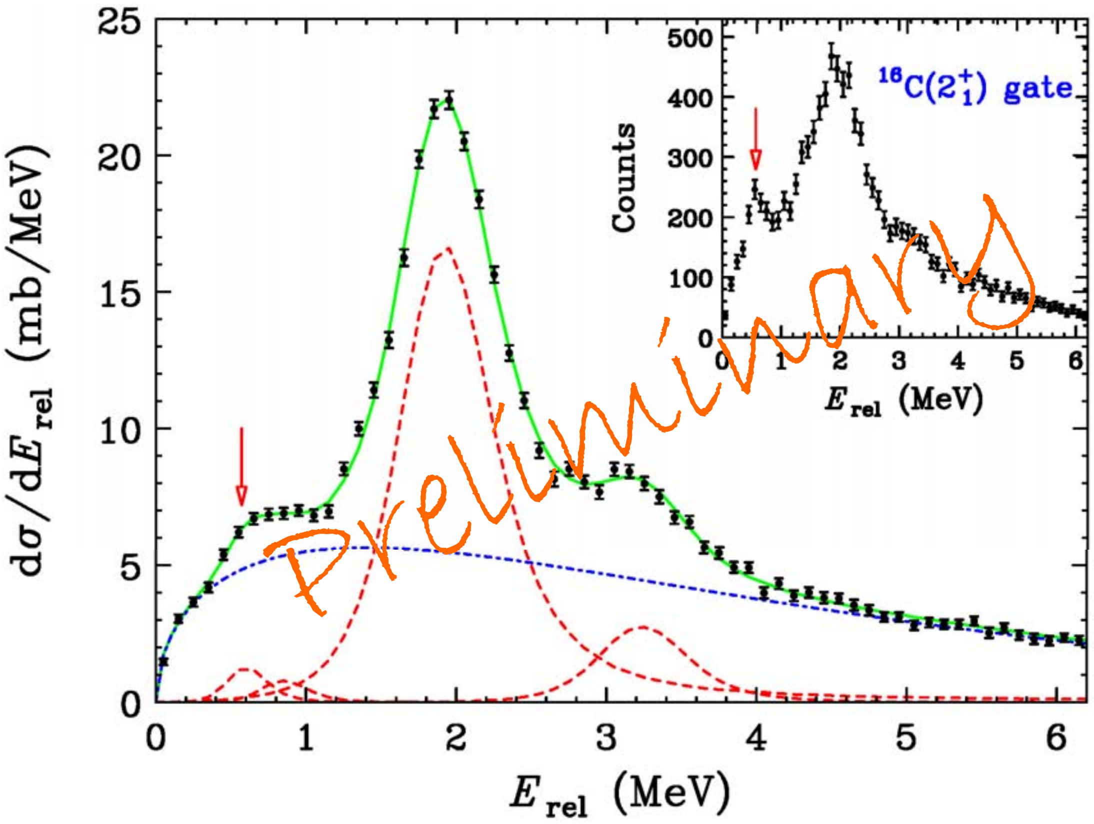
$$\frac{d\sigma_{\rm str}}{dk_z} = \frac{1}{(2\pi)^3}\frac{1}{2l+1}\sum_m \int d^2b_v\left[1-|S_v(b_v)|^2\right]\int_0^\infty d^2\rho |S_c(b_c)|^2 \left|\int_{-\infty}^{\infty} dz e^{-ik_z z}\psi_{lm}(\boldsymbol{r})\right|^2$$

Transverse momentum $p_\perp$ distribution:

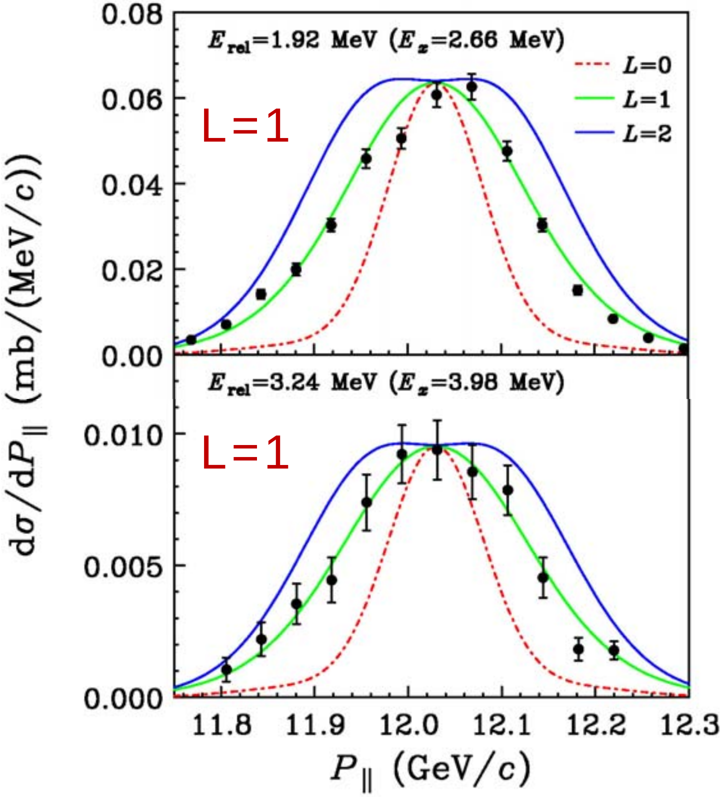
$$\frac{d\sigma_{\rm str}}{d^2k_\perp} = \frac{1}{2\pi}\frac{1}{2l+1}\int_0^\infty d^2b_v\left[1-|S_v(b_v)|^2\right]\sum_{m,p}\int_{-\infty}^{\infty} dz \left|\int d^2\rho \exp(-i\boldsymbol{k}_c^\perp\cdot\boldsymbol{\rho}) S_c(b_c)\psi_{lm}(\boldsymbol{r})\right|^2$$

Single-particle wave function

Results: $^{12}C(^{18}C,^{17}C^{*}\rightarrow^{16}C+n)$@245 MeV/u



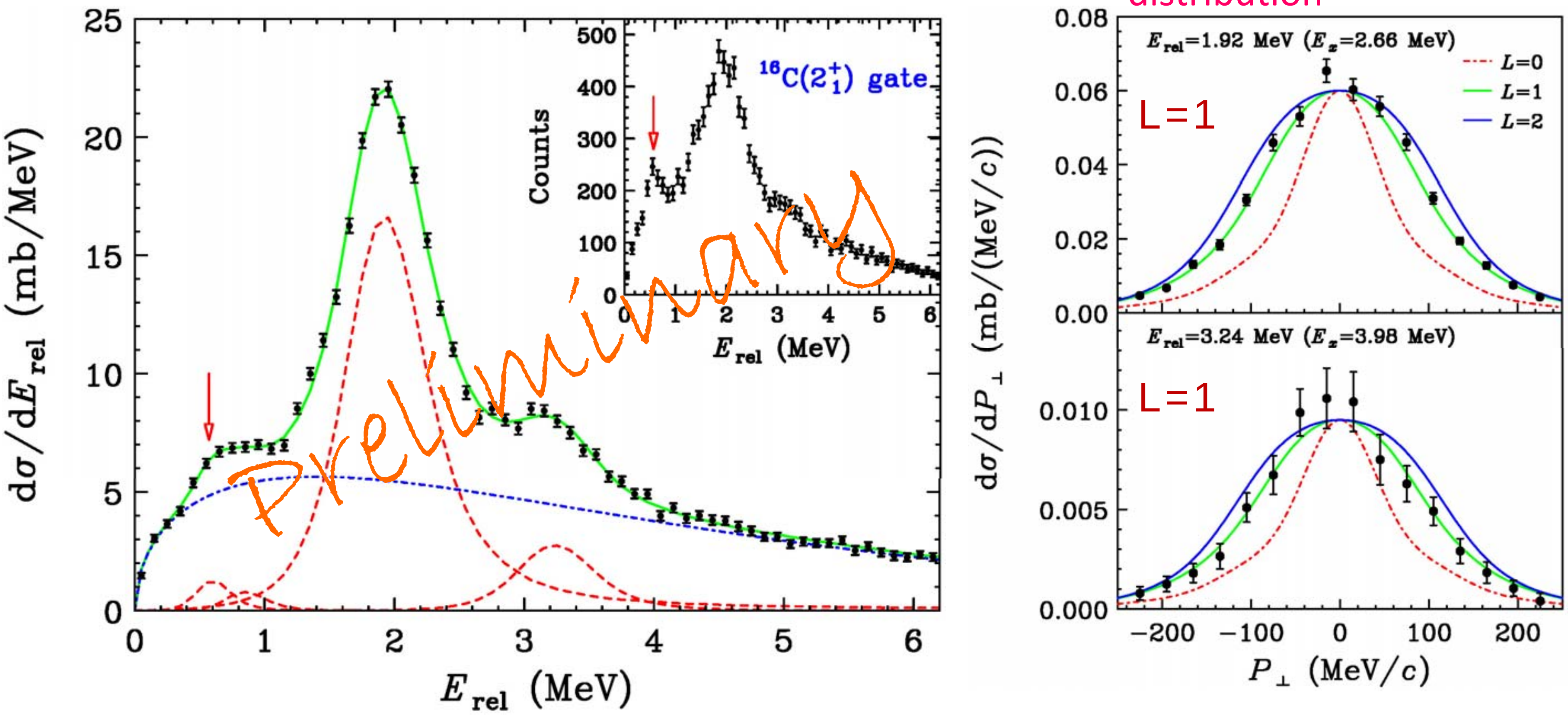
Longitudinal momentum distribution



Momentum distributions were calculated by MOMDIS: **C.A.Bertulani, A.Gade, Comput. Phys. Commun. 175(2006)372.**

Results: $^{12}C(^{18}C,^{17}C^*\rightarrow^{16}C+n)$@245 MeV/u

Transverse momentum distribution



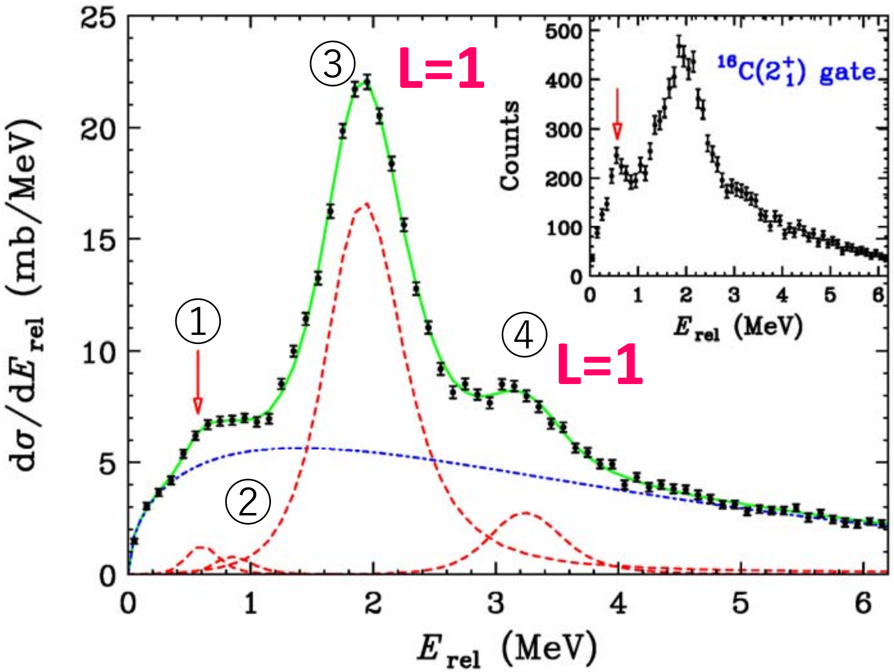
Momentum distributions were calculated by MOMDIS: **C.A.Bertulani, A.Gade, Comput. Phys. Commun. 175(2006)372.**

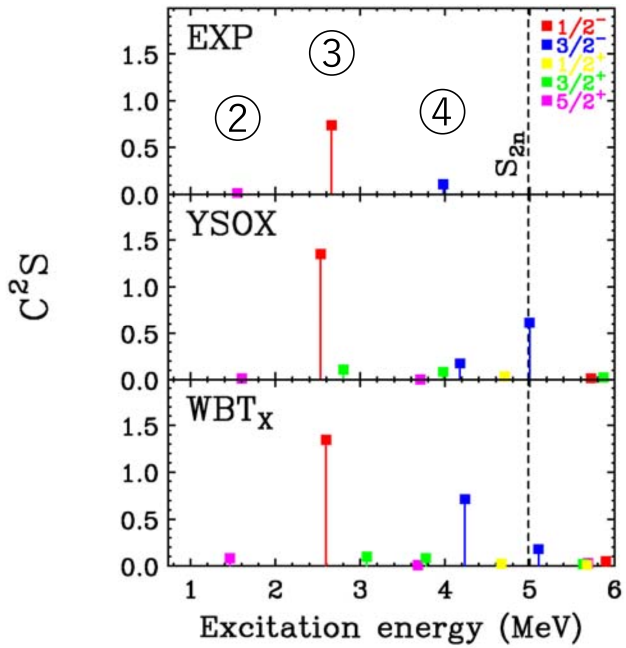
Summary of parameters of observed resonances in ^{17}C*

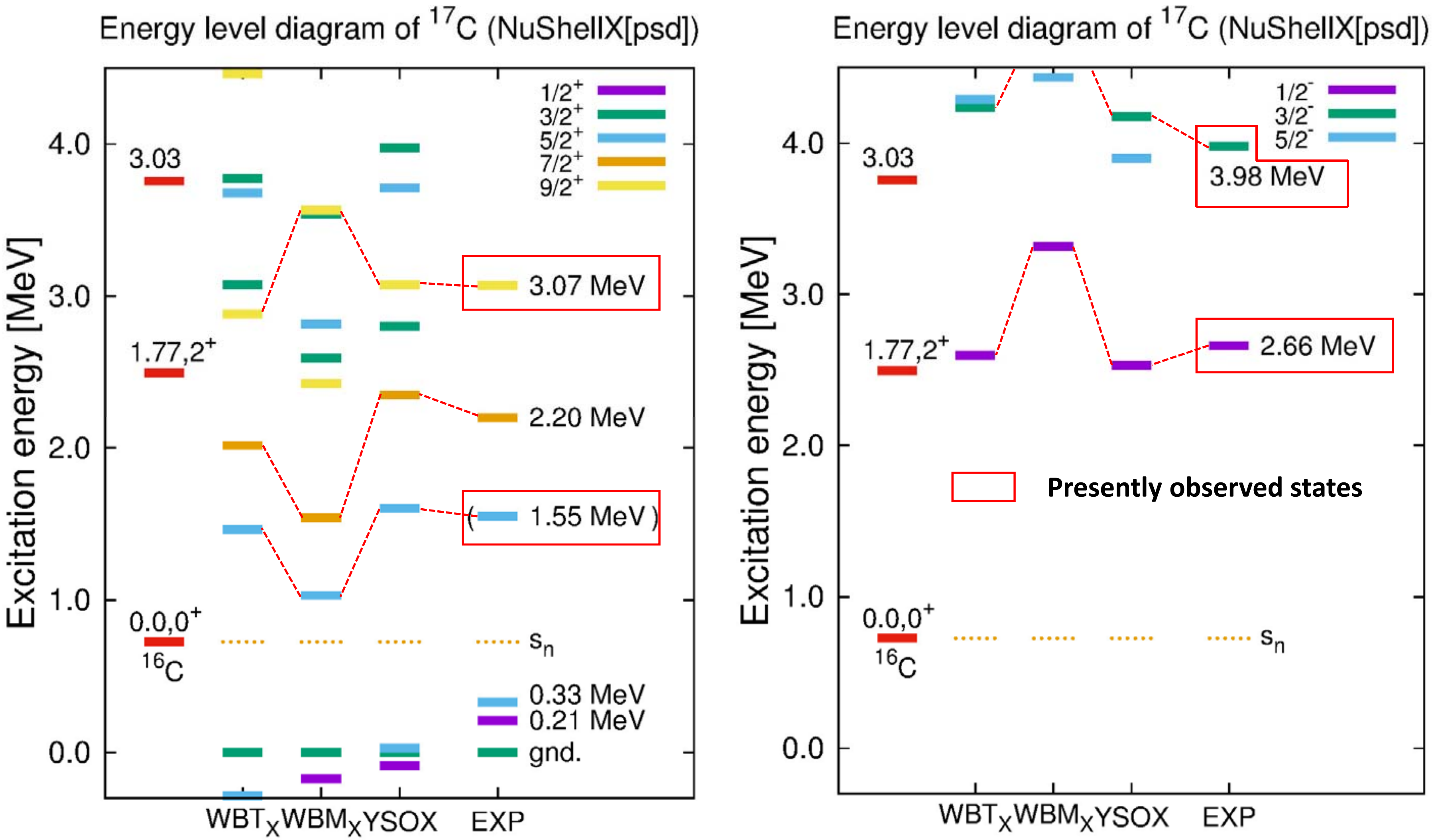
No.	Erel (MeV)	Ex (MeV)	Γ (MeV)	L	σ_{-1n}^{exp} (mb)	σ_{-1n}^{th} (mb)	C^2S^{exp}	C^2S^{th} [b]	E_x^{th} [b] (MeV)	J^π
①	0.57(4)[a]	3.07(5)	0 (fixed)	---	0.38(7)	---	---	---	3.07	$9/2_1^+$[c]
②	0.81(5)	1.55(6)	0 (fixed)	---	0.37(8)	0.36	0.015	0.015	1.60	$(5/2_2^+)$
③	1.92(1)	2.66(2)	0.32(1)	1	15.8(10)	29.0	0.736	1.350	2.53	$1/2_1^-$[d]
④	3.24(2)	3.98(2)	0.03(6)	1	2.20(16)	3.58	0.107	0.174	4.18	$3/2_1^-$[d]

Preliminary

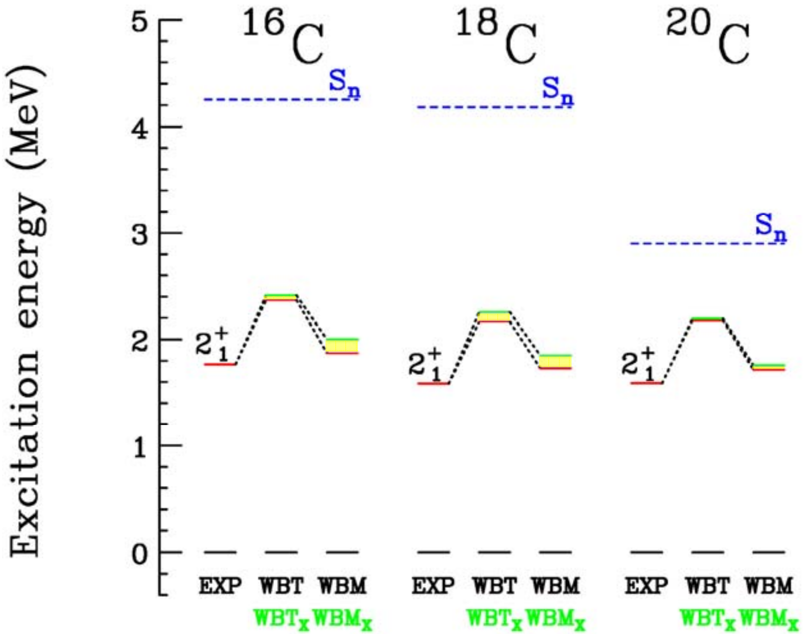
[a] γ-ray coincidence is observed.
[b] From YSOX.
[c] H.G.Bohlen et al., EPJA31(2007)279. Y.Satou et al., PLB660(2008)320.
[d] H.Ueno et al., PRC87(2013)034316. Ex=2.71(2) MeV for $1/2_1^-$ and 3.93(2) MeV for $3/2_1^-$.







Energy level diagram of 17C (NuShellX[psd])
Excitation energy [MeV]
4.0
3.0
2.0
1.0
0.0
3.03
1.77,2+
0.0,0+
16C
1/2+
3/2+
5/2+
7/2+
9/2+
3.07 MeV
2.20 MeV
(1.55 MeV)
sn
0.33 MeV
0.21 MeV
gnd.
WBTX WBMX YSOX EXP
Energy level diagram of 17C (NuShellX[psd])
Excitation energy [MeV]
1/2-
3/2-
5/2-
3.98 MeV
2.66 MeV
Presently observed states



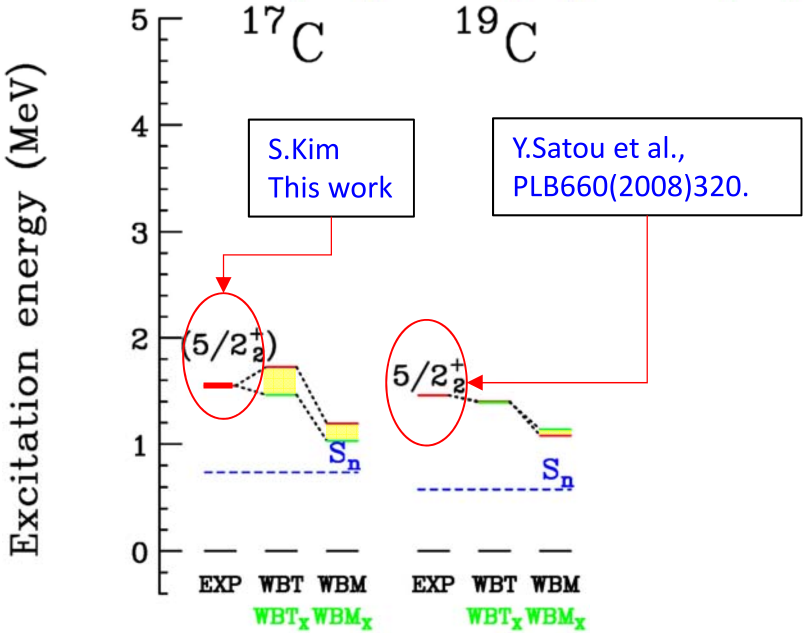
Discussion-1:

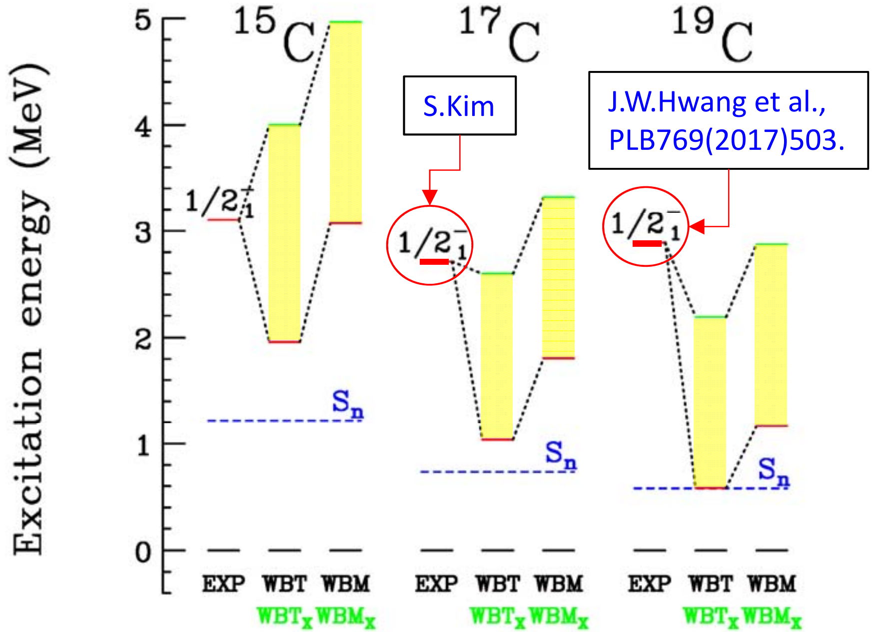
Spectroscopy of lowest-lying states,

- ➢ **2_1^+ in even C** and
- ➢ **$5/2_2^+$ and $1/2_1^-$ in odd C**,

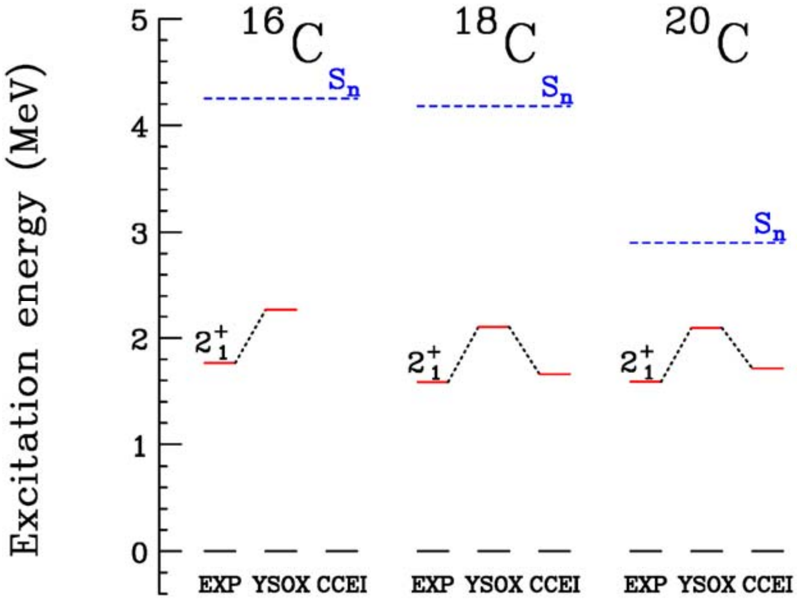
in comparison to **WBT$_{(X)}$**, **WBM$_{(X)}$** SM.

- The effects of enlarged $\hbar\omega$ model space by using **NuShellX** are small (large) for positive (negative) parity states.
- **WBM** gives a deteriorated description of $5/2_2^+$.





※ Excitation energy is from $E(3/2_1^+)$ and $E(1/2_1^+)$ for ^{17}C and ^{19}C, respectively.



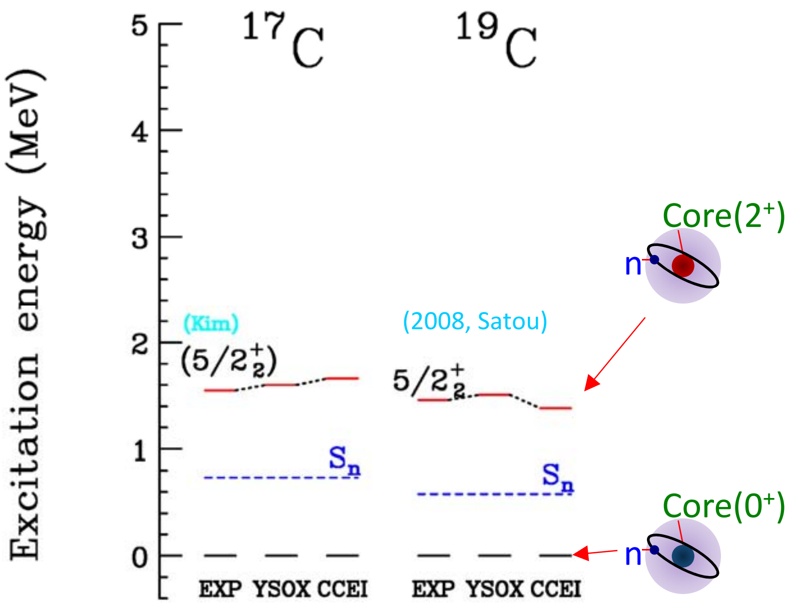
Discussion-2:

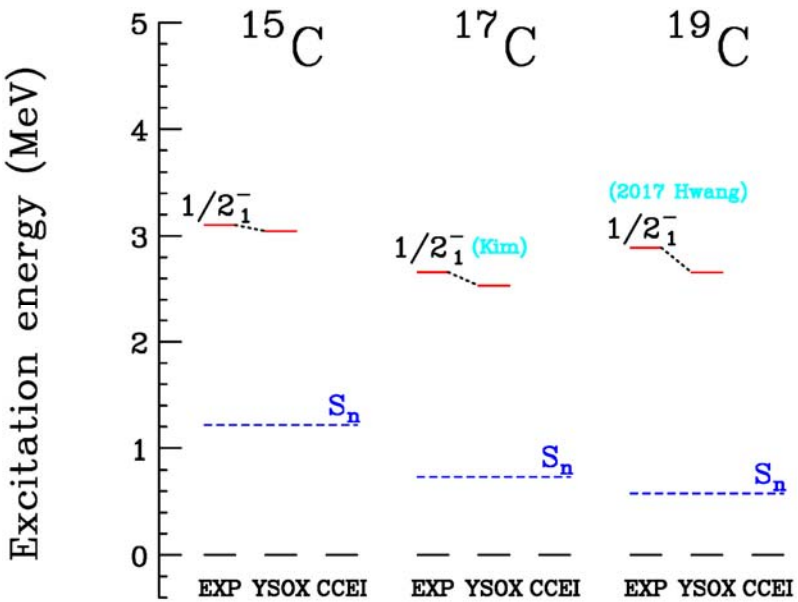
Spectroscopy of lowest-lying states,

- **2_1^+ in even C** and
- **$5/2_2^+$ and $1/2_1^-$ in odd C**,

in comparison to **YSOX**, **CCEI** SM.

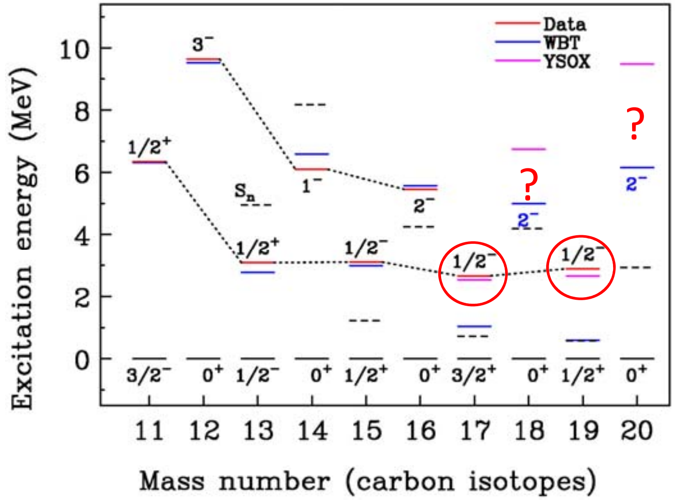
- **YSOX** does not solve the overprediction problem of 2_1^+, while it provides a good description of $5/2_2^+$ and $1/2_1^-$.
- **CCEI** works well for both positive parity states, 2_1^+ and $5/2_2^+$.





※ Excitation energy is from $E(3/2_1^+)$ and $E(1/2_1^+)$ for ^{17}C and ^{19}C, respectively.

Summary



- Knockout reaction can give information which complements the βn study.

- First $1/2_1^-$ cross-shell states in C now extend to ^{19}C.

- New spectroscopy is used to test SM interactions.
  - **YSOX describes cross shell states well.**
  - **YSOX overpredicts 2_1^+ in ^{16,18,20}C, but CCEI not.**
  - **YSOX and CCEI describe the $5/2_2^+$ location in ^{17,19}C well.**

- Light nuclear systems, as C isotopes, continues to pose challenges to our attempt to understand nuclear structures.

PHYSICAL REVIEW C **70**, 054316 (2004)

Deformations and electromagnetic moments in carbon and neon isotopes

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Electromagnetic observables will provide useful information to study the structure of nuclei, not only ground states but also excited states. Namely, these observables are expected to pin down precise information of deformations and unknown spin parities of both stable and unstable nuclei since the deformation is intimately related to observables such as Q moments and $E2$ transitions. The magnetic moments will also give empirical information of deformation in comparison with the single-particle value (Schmidt value) in the spherical limit. The isotope dependence of the deformation is an interesting subject to study in relation to a manifestation of the spontaneous symmetry breaking effect from the beginning of one closed shell to the next closed shell. To this end, carbon and neon might be promising in future experiments within the next few years. The effect of spontaneous symmetry breaking effect is a general phenomenon known in many fields of physics. In molecular physics, spontaneous symmetry breaking was discovered by Jahn and Teller in 1937 [6]. There is a very similar fundamental mechanism in nuclear physics and molecular physics, which is responsible for causing deformations in the ground state. The coupling to the quadrupole vibration is the main origin of the static deformation in atomic nuclei [7]. On the other

N.Imai et al., PRL92(2004)062501. “Anomalously hindered E2 strength B(E2;2+->0+) in 16C”
Z.Elekes et al., PLB586(2004)34. “Decoupling of valence neutrons from the core in 16C”
Z.Elekes et al., PLB614(2005)174. “Low-lying excited states in 17,19C”
H.J.Ong et al., PRC73(2006)024610. “Neutron-dominant quadrupole collective motion in 16C”
J.G.Bohlen et al., EPJA31(2007)279. “Spectroscopy of 17C and (sd)3 structures in heavy carbon isotopes”
H.J.Ong et al., PRC78(2008)014308. “Lifetime measurements of first excited states in 16,18C”
M.Stanoiu et al., PRC78(2008)034315. “Disappearance of the N=14 shell gap in the carbon isotopic chain”
Y.Satou et al., PLB660(2008)320. “Unbound excited states in 19,17C”
D.Suzuki et al., PLB666(2008)222. “Lifetime measurements of excited states in 17C: Possible interplay between collectivity and halo effects”
Z.Elekes et al., PRC79(2009)011392(R). “Persistent decoupling of valence neutrons toward the dripline: Study of 20C by γ spectroscopy”
T.Nakamura et al., PRC79(2009)035805. “Neutron capture cross section of 14C of astrophysical interest studied by Coulomb breackup of 15C”
Y.Kondo et al, PRC79(2009)014602. “One-neutron removal reactions of 18C and 19C on a proton target”
K.Tanaka et al., PRL104(2010)062701. “Observation of a large reaction cross section in the drip-line nucleus 22C”
A.H.Wuosmaa et al., PRL105(2010)132501. “15C(d,p)16C reaction end exotic behavior in 16C”
A.Ozawa et al., PRC84(2011)064315. “One- and two-neutron removal reactions from 19,20C with a proton target”
M.Petri et al., PRL107(2011)102501. “Lifetime measurement of the 2_1+ state in 20C”
N.Kobayashi et al., PRC86(2012)054604. “One- and two-neutron removal reactions from the most neutron-rich carbon isotopes”
M.Petri et al., PRC86(2012)044329. “Structure of 16C: Testing shell model and *ab initio* approaches”
P.Voss et al., PRC86(2012)011303(R). “Excited-state transition-rate measurements in 18C”
Y.Matsuda et al., PRC87(2013)034614. “Elastic scattering of protons from 9C with a 290 MeV/nucleon 9C beam”
H.Ueno et al., PRC87(2013)034316. “β-delayed neutron and γ-ray spectroscopy of 17C utilizing spin-polarized 17B”
M.Thoennessen et al., NPA912(2013)1. “Observation of a low-lying neutron-unbound state in 19C”
Y.Satou et al., PLB728(2014)462. “One-neutron knockout reaction of 17C on a hydrogen target at 70 MeV/nucleon”
F.Cappuzzello et al., Nature Communications 6(2015)6743. “Signatures of the giant paring vibration in the 14C and 15C atomic nuclei”
K.Whitmore et al., PRC91(2015)041303(R). “Magnetic response of the halo nucleus 19C studied via lifetime measurement”
Zs.Vajta et al., PRC91(2015)064315. “γ-ray spectroscopy of 19C via the single-neutron knockout reaction”
D.Smalley et al., PRC92(2015)064314. “Lifetime measurements of 17C excited states and three-body and continuum effects”
M.Cavallaro et al., PRC93(2016)064323. “Neutron decay of 15C resonances by measurements of neutron time-of-flight”
Y.Togano et al., PLB761(2016)412. “Interaction cross section study of the two-neutron halo nucleus 22C”
D.T.Tran et al., PRC94(2016)064604. “Charge-changing cross-section measurements of 12-16C at around 45A MeV and development of a Glauber model for incident energies 10A-2100A MeV”
H.Yamaguchi et al., PLB766(2017)11. “Experimental investigation of a linear-chain structure in the nucleus 14C”
J.W.Hwang et al., PLB769(2017)503. “Single-neutron knockout from 20C and the structure of 19C”
S.Kim et al., in preparation. “Spectroscopy of 17C via one-neutron knockout reaction”