PKU-CUSTIPEN Nuclear Reaction Workshop
"Reactions and Spectroscopy of Unstable Nuclei"
August 10-14, 2014, Peking University, Beijing

Inclusive one-neutron knockout reaction of ^{17,18,20}C and migration of lowest-lying negative parity states in neutron-rich C isotopes

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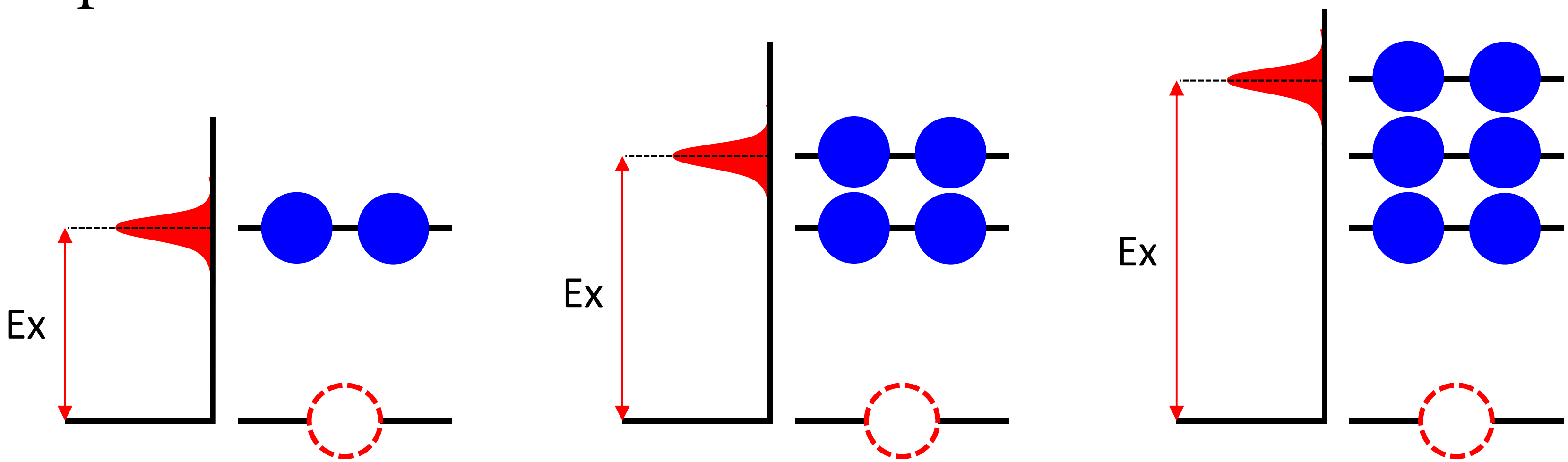
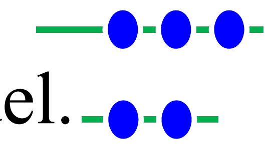
Motivation

- A high sensitivity of the nucleon knockout reaction processes in producing states with a hole in an orbit beneath the valence shell will provide a unique opportunity to study the evolution of valence orbits.
- We want to establish in-flight neutron decay spectroscopy followed by 1*n* knockout as a tool to probe the shell evolution and nuclear structure.

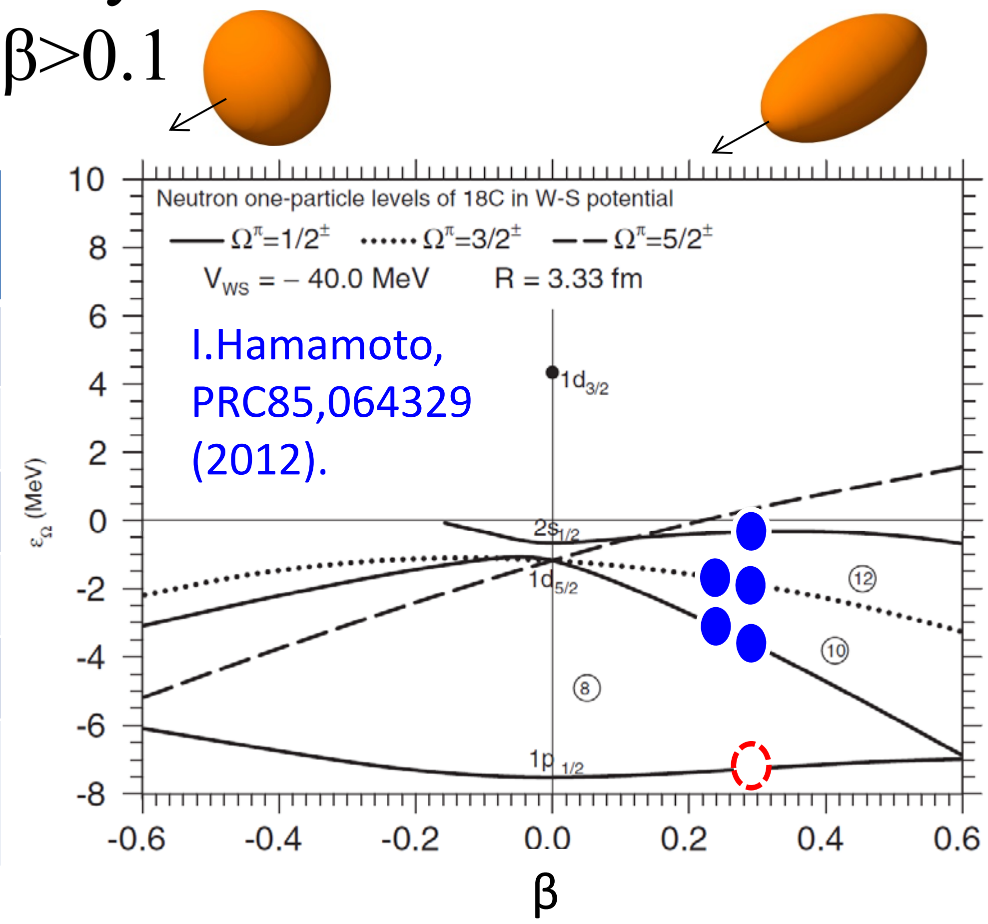


Properties of neutron-rich C isotopes



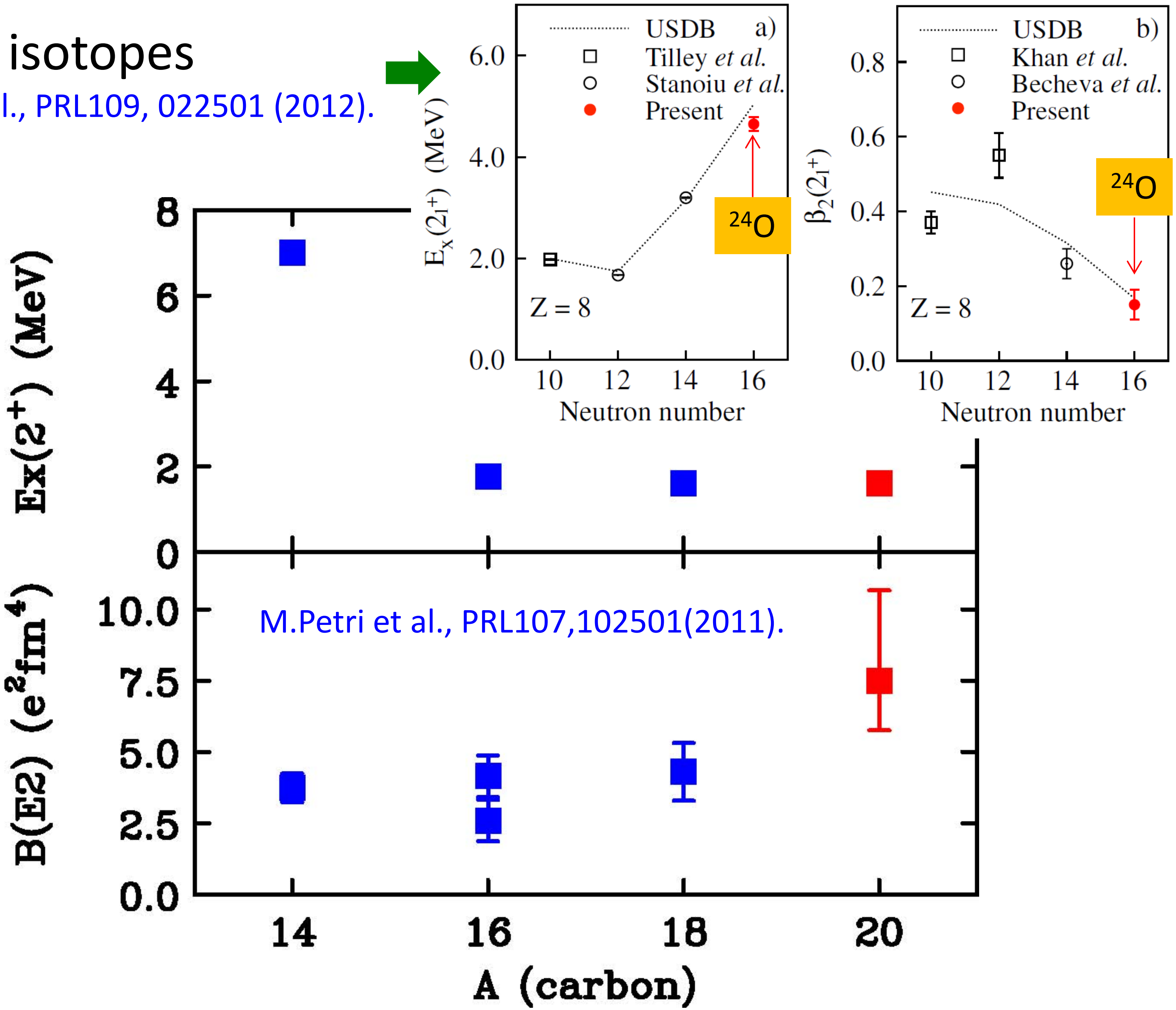
- $J^{\pi}_{g.s.}$ of ^{15,17,19}C do not follow naïve shell model.
- They are, however, naturally understood in terms of prolate deformation for β>0.1

Nucleus	$J^{\pi}_{g.s.}$	Ground state deformation
^{15}C	$1/2^+$	Prolate
^{16}C	0^+	Prolate
^{17}C	$3/2^+$	Prolate
^{18}C	0^+	Prolate
^{19}C	$1/2^+$	Prolate
^{20}C	0^+	?



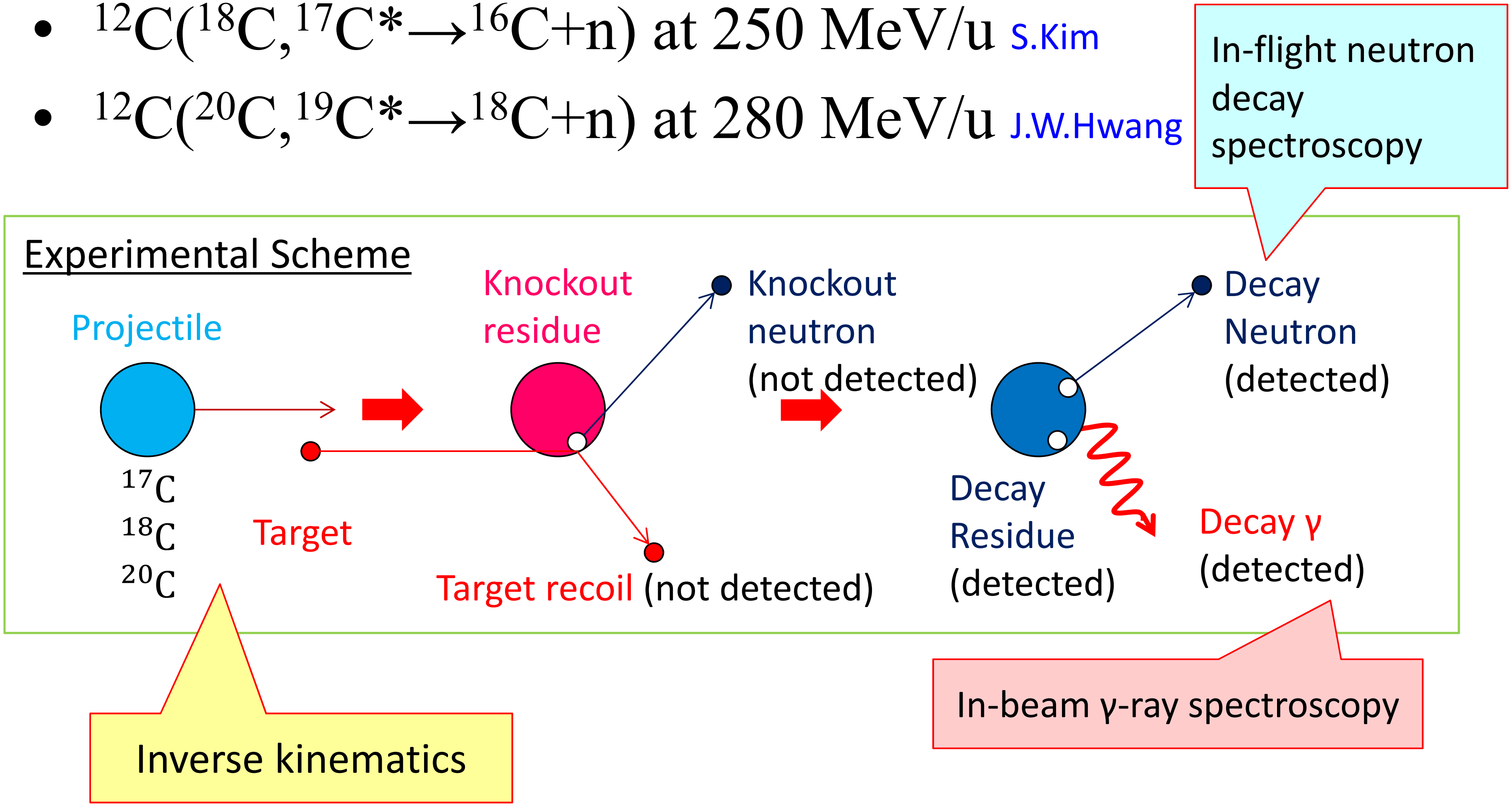
Oxygen isotopes

K.Tshoo et al., PRL109, 022501 (2012).



1*n* knockout reactions studied

- $^{1}H(^{17}C,^{16}C^{*}\rightarrow^{15}C+n)$ at 70 MeV/u Y.Satou et al., PLB728,462(2014).
- $^{12}C(^{18}C,^{17}C^{*}\rightarrow^{16}C+n)$ at 250 MeV/u S.Kim
- $^{12}C(^{20}C,^{19}C^{*}\rightarrow^{18}C+n)$ at 280 MeV/u J.W.Hwang



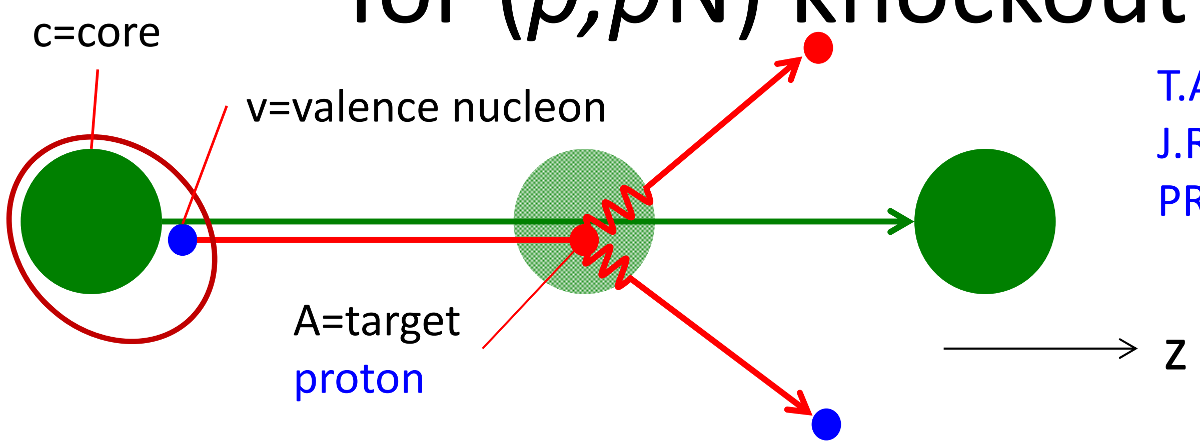
Nucleon knockout reactions

1. Exhibit large cross sections, 10~100 mb (spectroscopic factor).

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

2. Suited for populating both bound and unbound hole-like states of the residue.
3. Momentum distribution carries information on the wave function of the struck nucleon (orbital angular momentum ℓ)
4. Knockout of the minor nucleon species provides a good means to create more exotic nuclei, $^{25-28}\mathrm{O}$
5. Theoretical tools are readily available
   - B.Abu-Ibrahim, Y.Ogawa, Y.Suzuki, I.Tanihata, 2003 (CSC_GM)
   - C.A.Berturani and A.Gade, 2006 (MOMDIS)
   - T.Aumann, C.A.Bertulani, J.Ryckebusch, PRC88(2013)064610.

Momentum distributions within DWBA for (*p*,*p*N) knockout



T.Aumann, C.A.Bertulani, J.Ryckebusch, PRC88(2013)064610.

- DWIA quasifree cross section

$$\frac{d^3\sigma}{dT_N d\Omega_p' d\Omega_N} = K' \cdot \frac{d\sigma_{pN}}{d\Omega} \cdot |F(\boldsymbol{Q})|^2$$

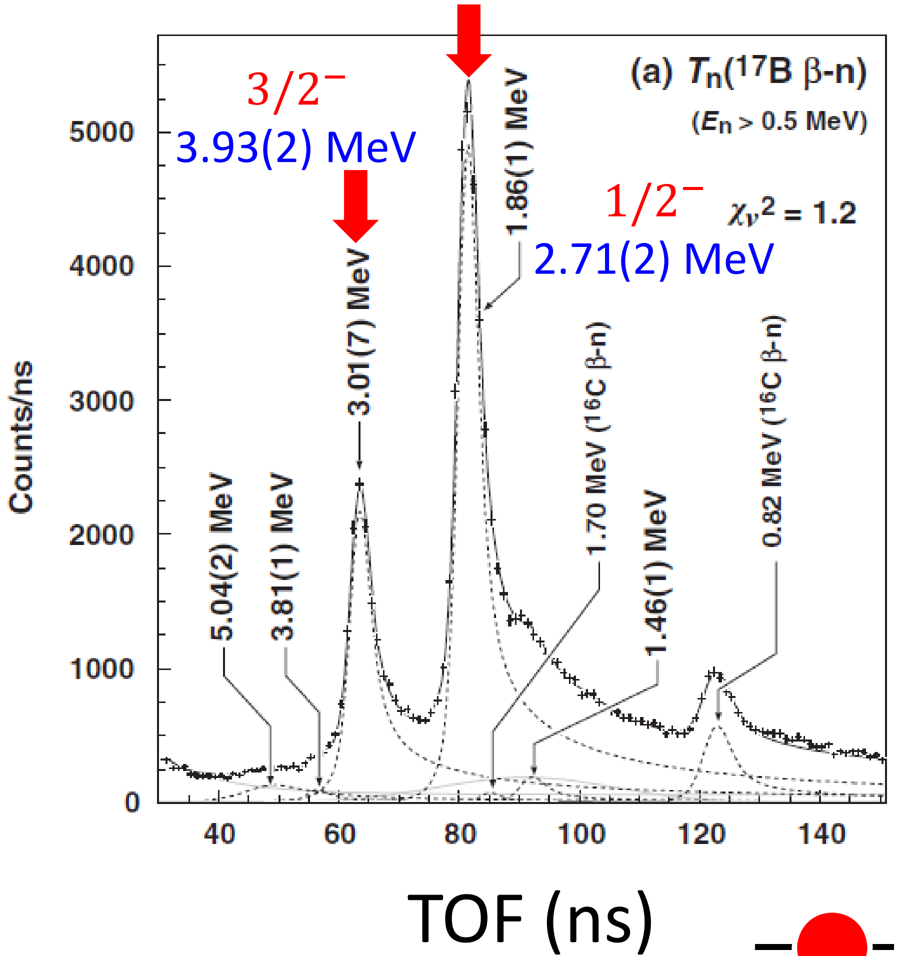
- Longitudinal momentum distribution $p_{\parallel}$

$$\frac{d\sigma}{dQ_z} = \frac{S(lj)}{2j+1} \sum_m \left\langle \frac{d\sigma_{pN}}{d\Omega} \right\rangle_{Q_z} |C_{lm}|^2 \int_0^\infty db\, b \left| \langle S(b) \rangle_{Q_z} \right|^2$$

$$\times \left| \int_{-\infty}^{\infty} dz e^{-iQ_z z} \frac{u_{lj}(r)}{r} P_{lm}(b,z) \right|^2$$

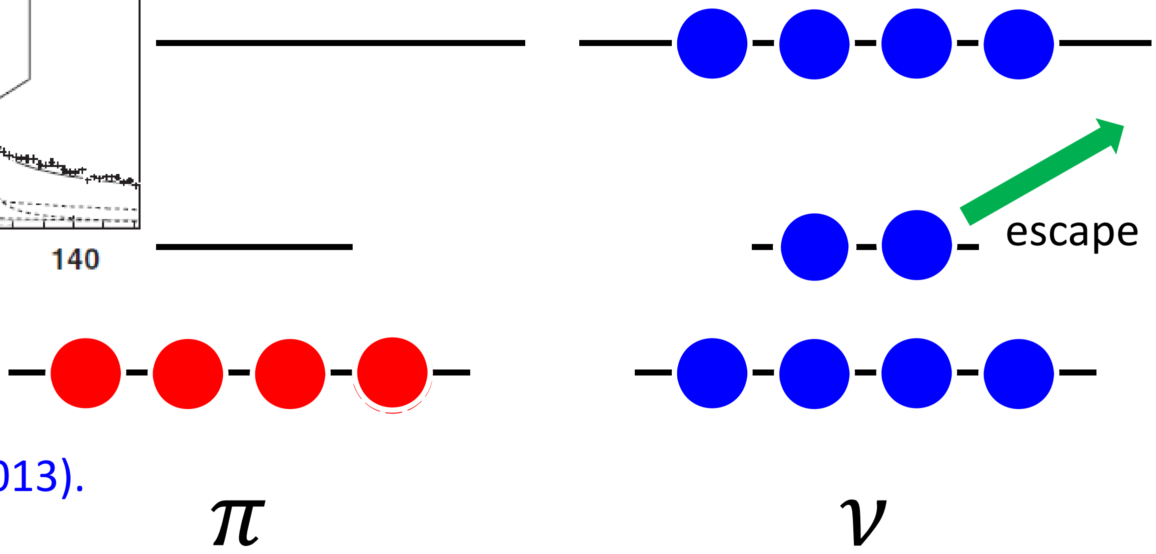
Fourier transform of the single particle w.f.

β^- delayed *n* emission of N-rich nuclei and 1*n* knockout

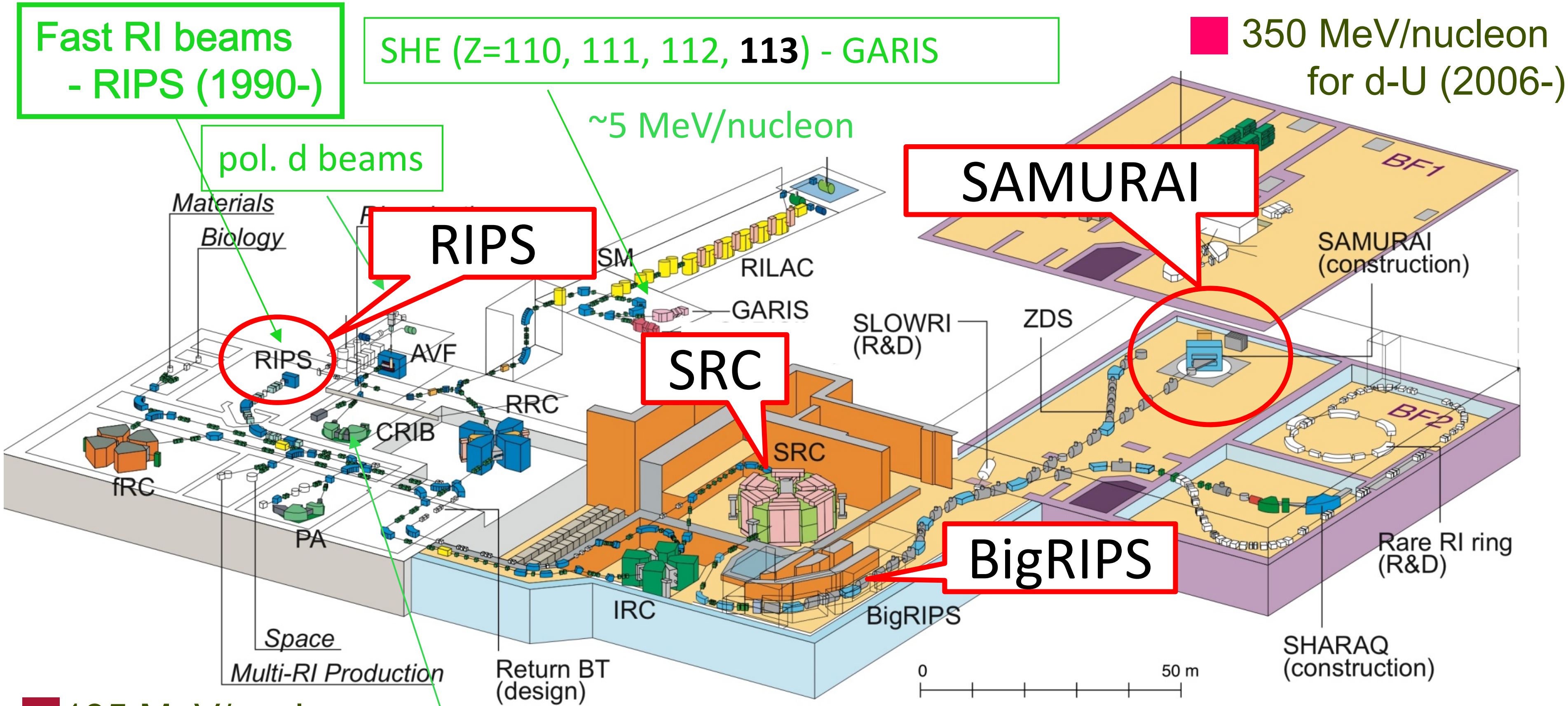


H.Ueno et al., PRC87,034316(2013).

^{17}C



RIKEN RI Beam Factory (RIBF)



135 MeV/nucleon
for light nuclei (1986-)

RI beams @ CRIB
(<5 MeV/nucleon)

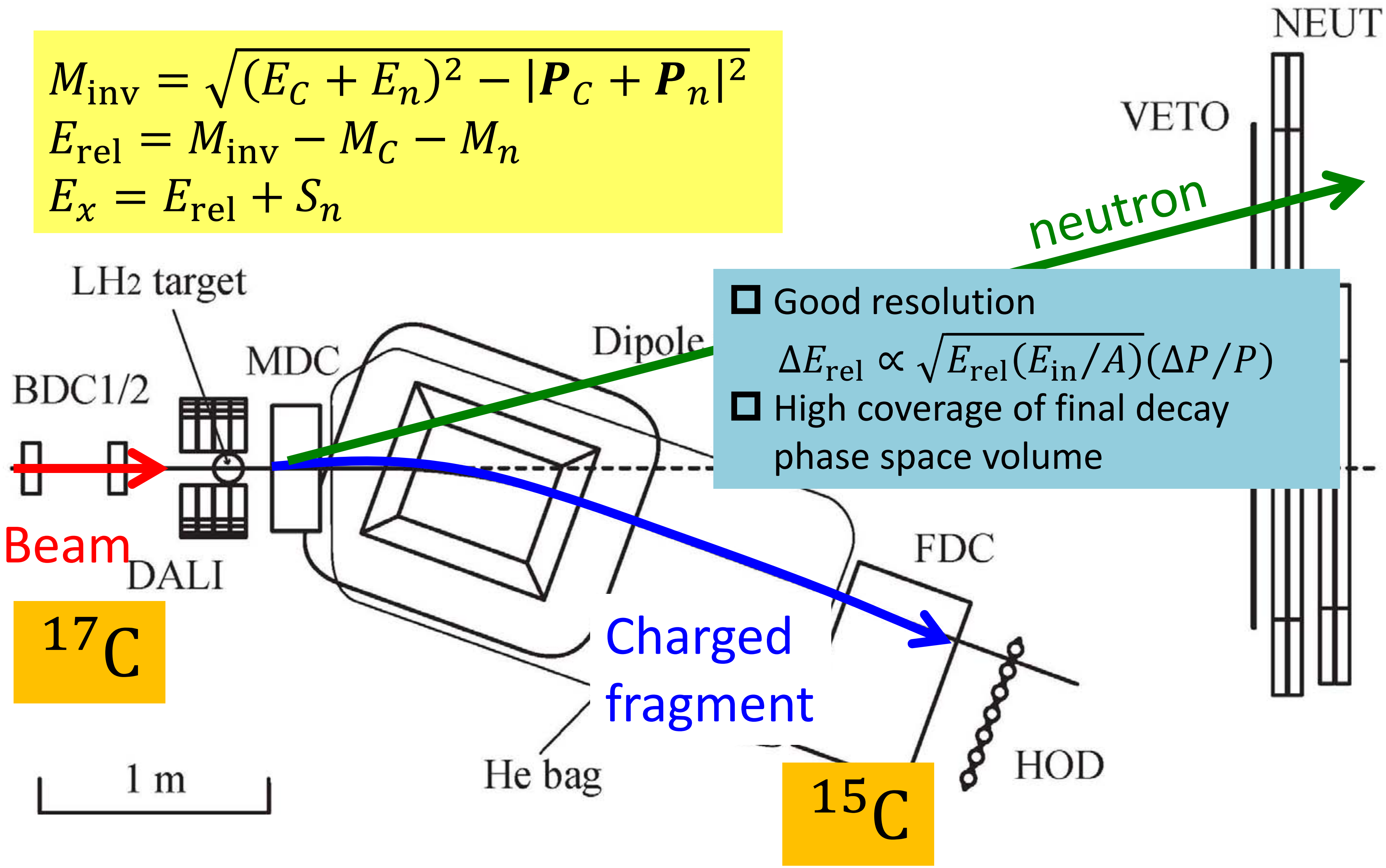
- 1st beam: in Dec. 2006
- U beam/RI beams with U-fission: in Mar. 2007
- RI beams with ^{48}Ca- fragmentation: in Dec. 2008

Intense RI beams

1. **In-flight methods (PF, fission)**
2. **Whole range of atomic masses**
3. **A few 100 MeV/nucleon**

Invariant mass method

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



- Good resolution
  $\Delta E_{\mathrm{rel}} \propto \sqrt{E_{\mathrm{rel}}(E_{\mathrm{in}}/A)}(\Delta P/P)$
- High coverage of final decay phase space volume

RIKEN Fragment separator RIPS

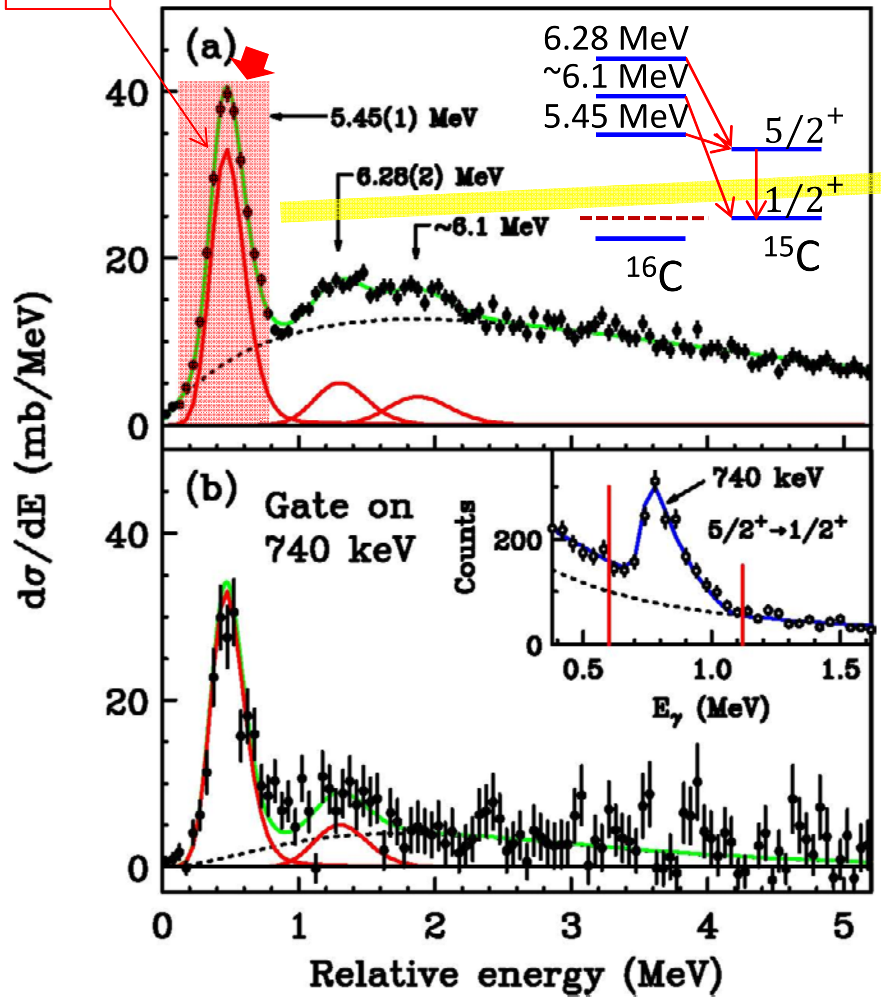
Y.Satou et al., PLB728,462(2014).
T.Fortune Y.Satou submitted.

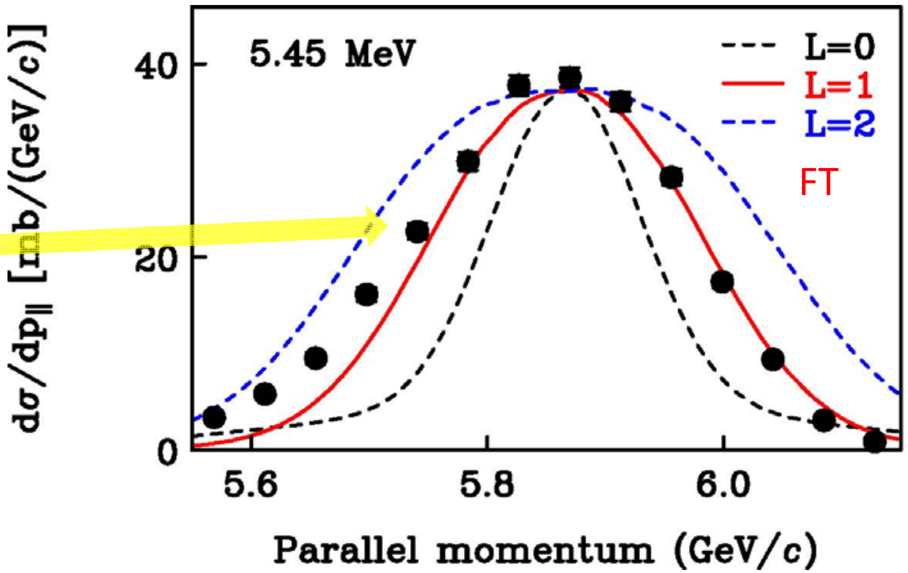
^{1}H(^{17}C,^{16}C*) at 70 MeV/u

↳ ^{15}C+n+γ

$\Delta P_{||} = 43$ MeV/c (in σ)

2⁻ This work



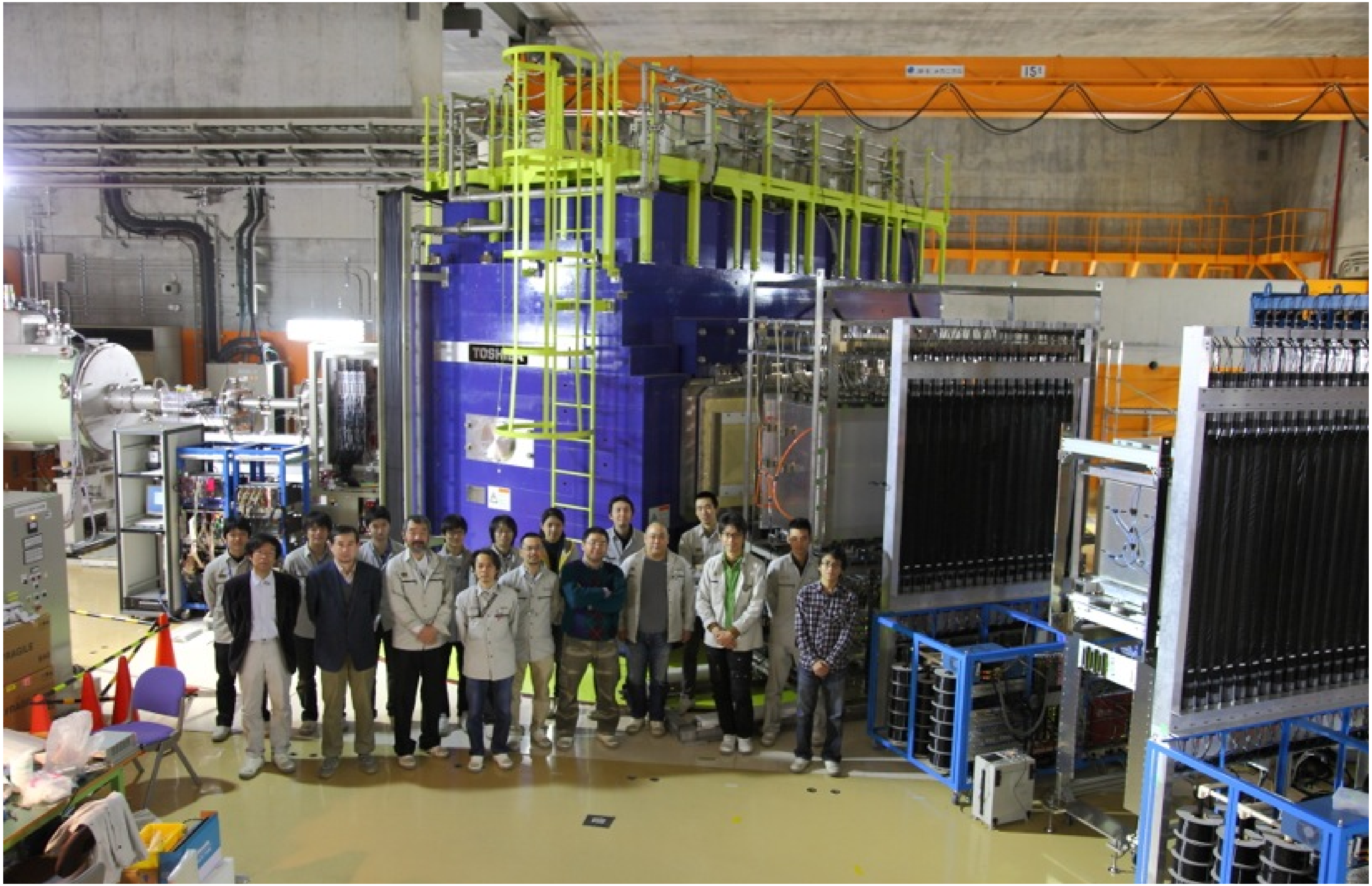


Ex (MeV)	L ($\hbar$)	σ_{-1n} (mb)	J^{π}	$b_{g.s.}$(b)
5.45	1	10.6(6)	2^-	0.000
~6.1	---	$2.0^{+0.4}_{-0.8}$	$\begin{pmatrix}1^-_1,\\0^-,\\1^-_2\end{pmatrix}$(a)	(0.997, 1.000, 0.991)
6.28	---	$2.5^{+0.2}_{-1.9}$	(2^-)	0.000

(a) From the weak-coupling model, T.Fortune.
(b) YS et al., ARIS2014 proceedings.

SAMURAI Day-One, 2012 May

One-neutron knockout reactions of $^{18,20}C$



Kim Sunji

$^{12}C(^{18}C, \underline{^{17}C^*})$ at 250 MeV/u

$\Delta P_{||} < 20$ MeV/c
(in σ)

↳ ^{17}C & $^{16}C+n$

Hwang Jongwon

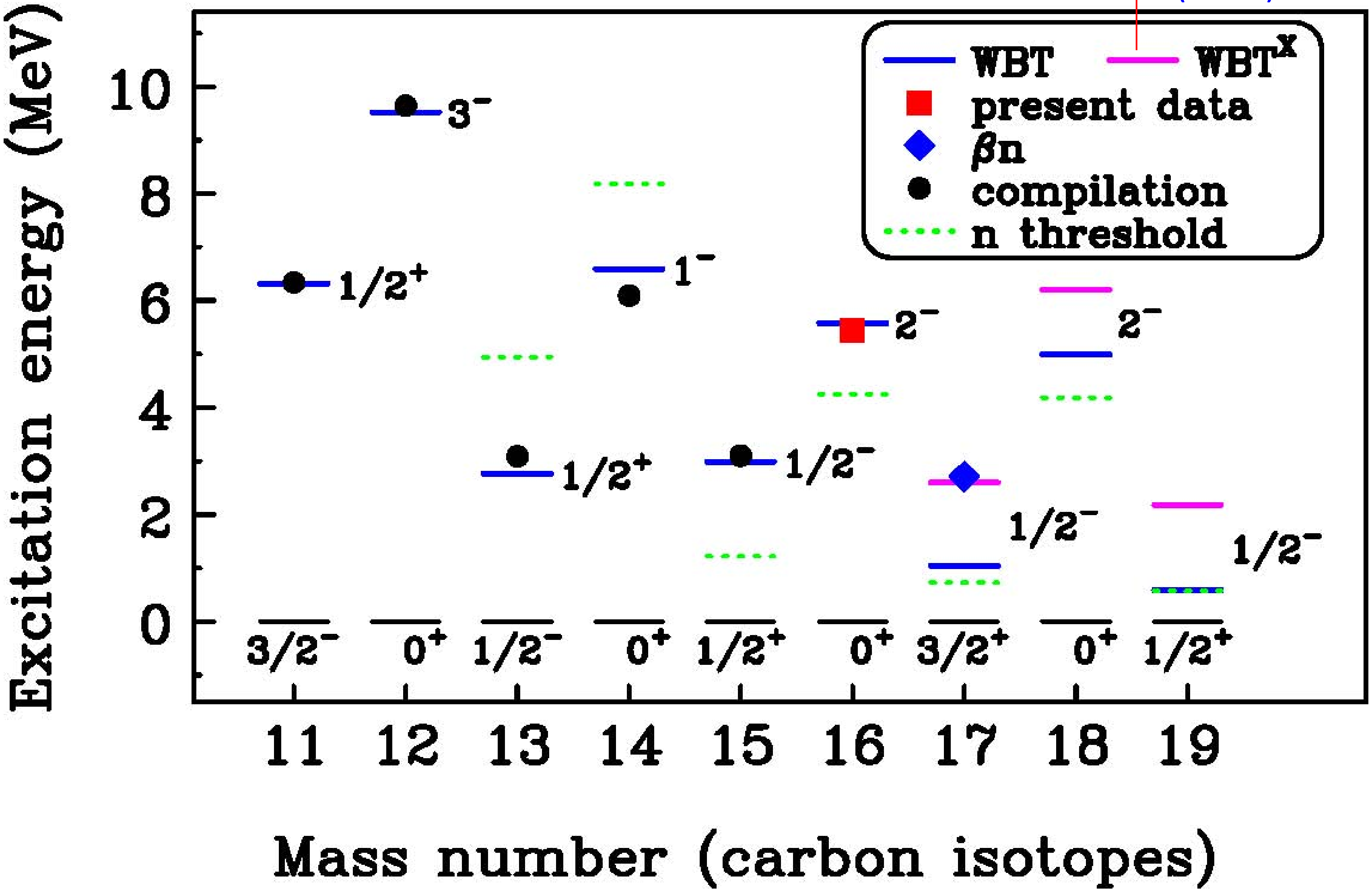
$^{12}C(^{20}C,^{19}C^*)$ at 280 MeV/u

$\Delta P_{||} < 20$ MeV/c (in σ)

$^{19}C^* \rightarrow {}^{18}C+n$

Migration of lowest-lying cross-shell states in C isotopic chain

NuShellX: Nucl. Data Sheet, 230 (2014) 115.



How the $1/2^{-}$ energies are interpreted in terms of nuclear deformation?

- The $1/2^{-}$ energy measures the interval between $p_{1/2}$ and one of sd Nilsson orbits.
- If $\beta \approx 0.4$ for both ^{18,20}C,

$$E_{\frac{1}{2}^-}(^{19}\mathrm{C}) = E_{\frac{1}{2}^-}(^{17}\mathrm{C}) + \Delta E$$

$$\Delta E \sim 1.8\ \mathrm{MeV}$$

- But, experimentally, $\Delta E \sim$ MeV:

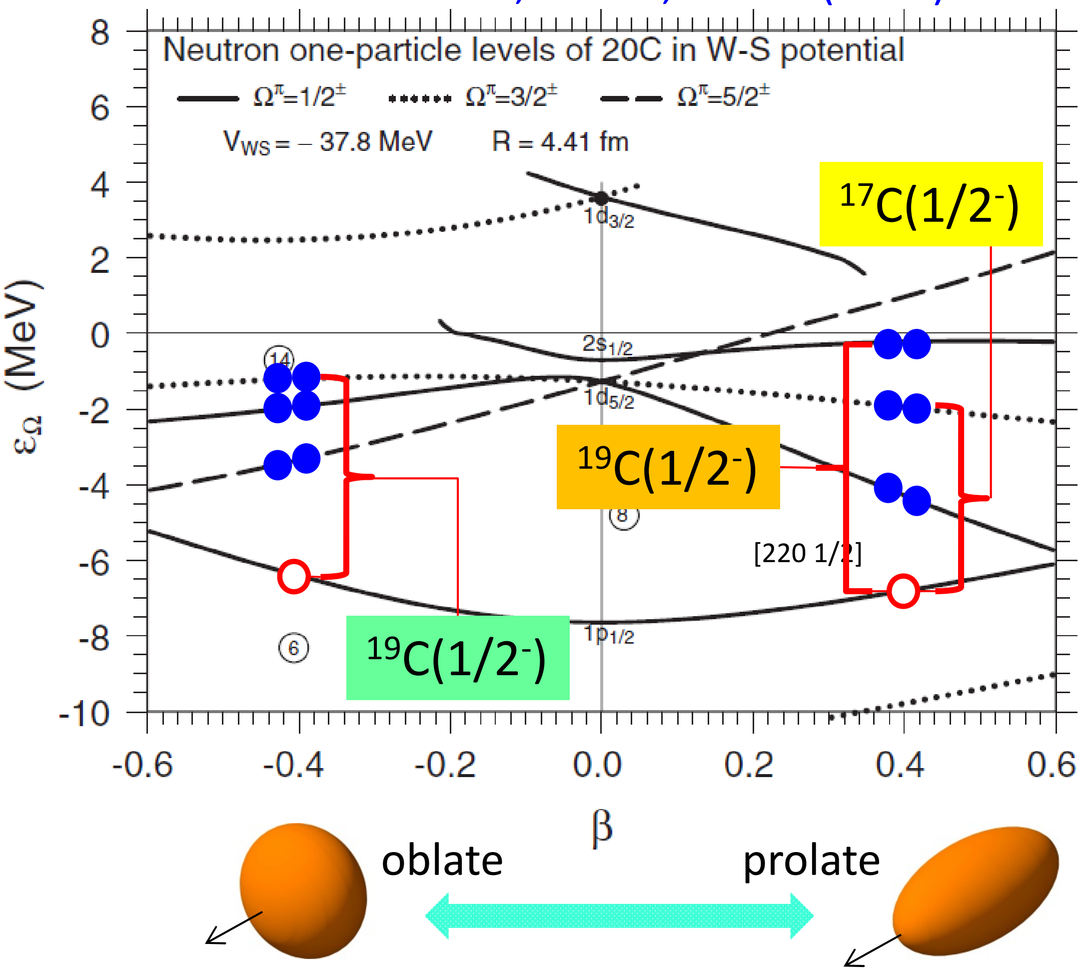
$$E_{\frac{1}{2}^-}(^{17}\mathrm{C}) = \ \mathrm{MeV},$$

$$E_{\frac{1}{2}^-}(^{19}\mathrm{C}) = \ \mathrm{MeV}.$$

<u>How can we reconcile this?</u>

➡ Oblate deformation for ^{20}C at $\beta \sim -0.4$.

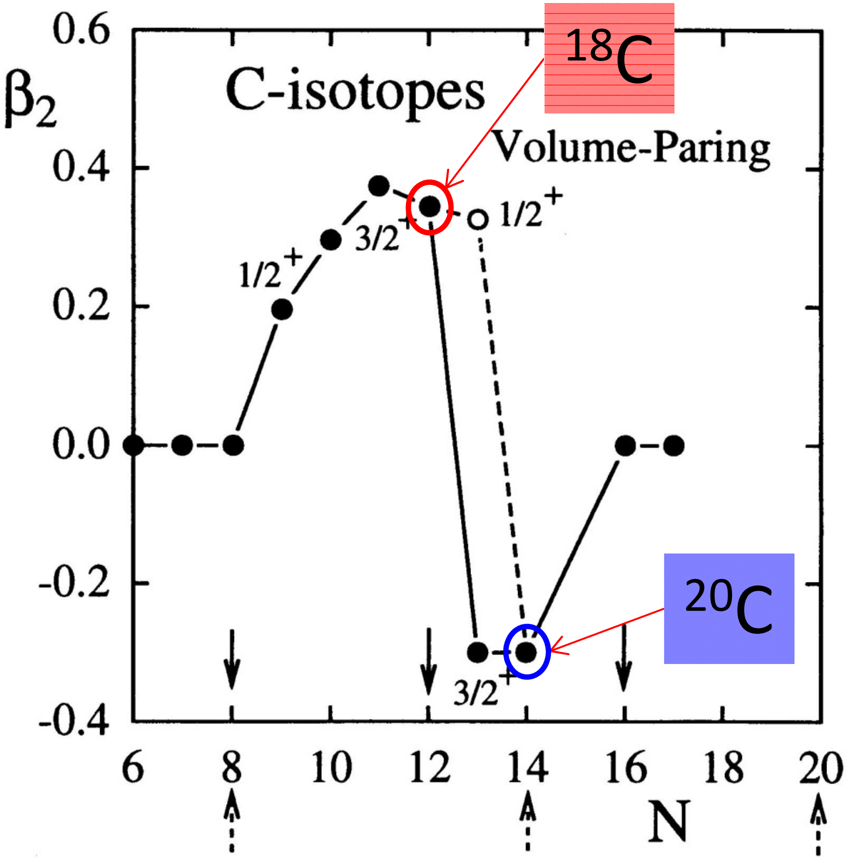
I.Hamamoto, PRC89,057301(2014).



Model predictions

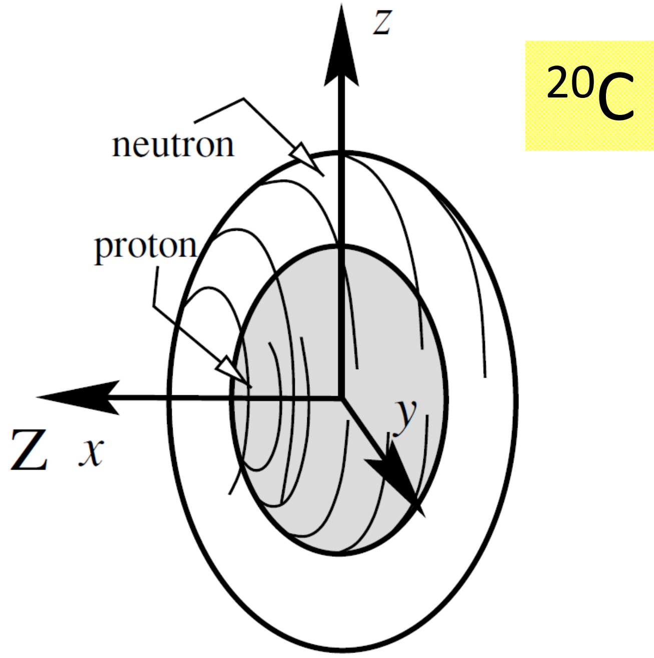
Deformed HF+BCS model

H.Sagawa et al., PRC70(2004)054316.



AMD model

Y.Kanada-En'yo, PRC71(2005)014310.



(b) ^{20}C

Maximum overlap between ρ_n and ρ_p.

Summary

- New (deep) hole states in $^{16,17,19}C$ have been successfully populate by 1*n*-knockout of $^{17,18,20}C$.

^{16}C	^{17}C	^{19}C
5.45(1) MeV, 2^-	MeV, $1/2^-$ MeV, $3/2^-$ cf) 2.71(2) MeV 3.93(2) MeV β*n*	MeV, $1/2^-$

- **^{16}C:** $p_{\parallel}$ distribution width is a good measure of *L* (angular momentum), for knockout involving unbound residue, as well.
- **^{17}C:** Reproducing the position of reported states, we have shown that a new spectrometer system SAMURAI started successful operation.
- **^{19}C:** Relative positions of $1/2^-$ states in $^{17,19}C$ infers an oblate shape for the ground state of ^{20}C.

Collaborators: — RIKEN, R364n —

^{16}C

- Seoul National University
  - Y.Satou, J.W.Hwang, S.Kim, K.Tshoo, S.Choi
- Tokyo Institute of Technology
  - T.Nakamura, T.Sugimoto, Y.Kondo, N.Matsui, Y.Hashimoto, T.Nakabayashi, T.Okumura,M.Shinohara
- RIKEN
  - N.Fukuda, T.Motobayashi, Y.Yanagisawa, N.Aoi, S.Takeuchi, T.Gomi, H.Sakurai, H.Otsu, M.Ishihara
- Rikkyo University
  - Y.Togano, S.Kawai
- Tokyo University
  - H.J.Ong, T.K.Onishi
- Center of Study (CNS) Tokyo University
  - S.Shimoura, M.Tamaki
- Tohoku University
  - T.Kobayashi, Y.Matsuda, N.Endo, M.Kitayama

Collaborators: — RIKEN SAMURAI Day-One —

$^{17,19}C$

- LPC-Caen, ENSICAEN, University de Caen, CNRS/IN2P3
  - N.L.Achouri, F.Delaunay, J.Gibelin, S.Leblond, M.Marques, N.Orr
- Tokyo Institute of Technology
  - Y.Kondo, T.Nakamura, N.Kobayashi, R.Tanaka, R.Minakata, S.Ogoshi, S.Nishi, D.Kanno, T.Nakashima
- RIKEN
  - H.Baba, P.Doornenbal, N.Fukuda, N.Inabe, T.Isobe, D.Kameda, T.Kubo, J.Lee, H.Otsu, T.Motobayashi, H.Sato, Y.Shimizu, H.Suzuki, H.Takeda, S.Takeuchi, K.Yoneda
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  - T.Aumann
- Seoul National University
  - Y.Satou, J.W.Hwang, S.Kim
- Tohoku University
  - T.Kobayashi, K.Muto, K.Takahashi
- Rikkyo University
  - D.Murai
- Kyoto University
  - N.Nakatsuka, T.Murakami
- University of York
  - A.Navin, A.G.Tuff
- Extreme Matter Institute and Research Division, GSI
  - Y.Togano
- Institute de Physique Nucleaire
  - M.Vanderbrouck