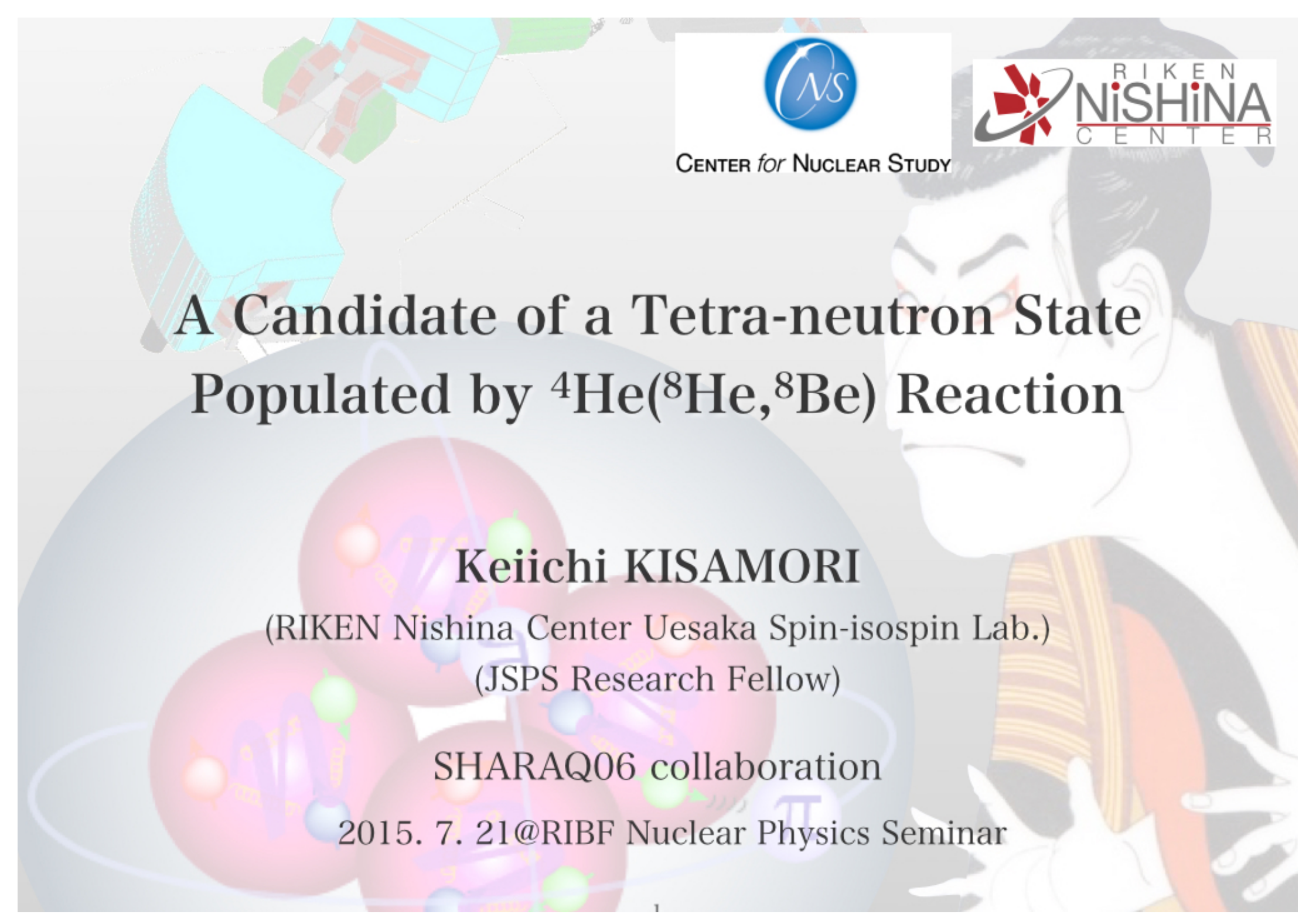

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RIKEN NiSHiNA CENTER

# A Candidate of a Tetra-neutron State Populated by $^{4}$He($^{8}$He,$^{8}$Be) Reaction


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(JSPS Research Fellow)


SHARAQ06 collaboration

2015. 7. 21@RIBF Nuclear Physics Seminar

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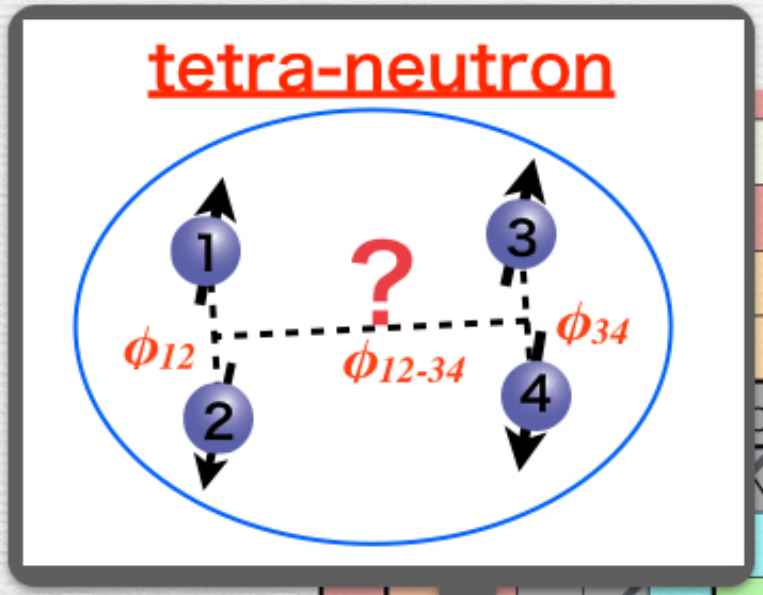
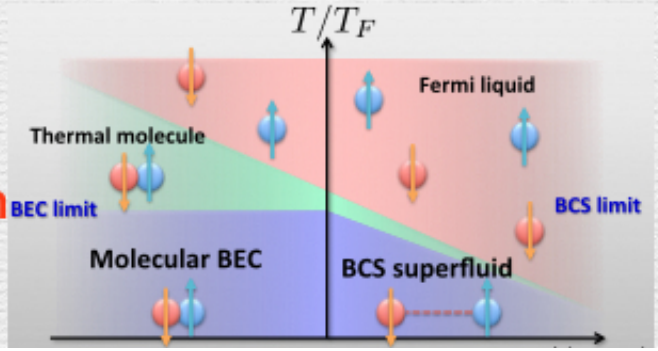
# Tetra-Neutron System










Universality of
few-body Fermion

# Historical Review

## ~ search for a bound state of 4n~

1960s

### fission of Uranium

- No evidence for particle stable state of tetra-neutron

J. P. Shiffer Phys. Lett. 5, 4, 292 (1963)

1980s

### $^4He(\pi^-,\pi^+)$ reaction

- Only upper limit of cross section was decided.

J. E. Unger, et al., Phys. Lett. B 144, 333 (1984)

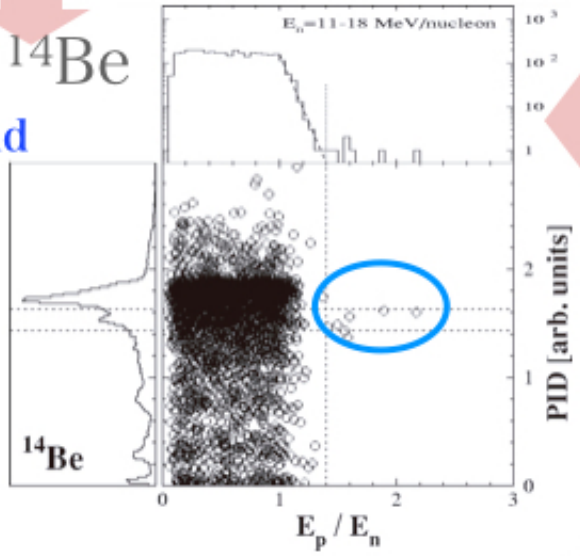
**No clear evidence of bound state**

2000s

### Breakup of $^{14}Be$

- Candidates of **bound tetra-neutron** were observed.

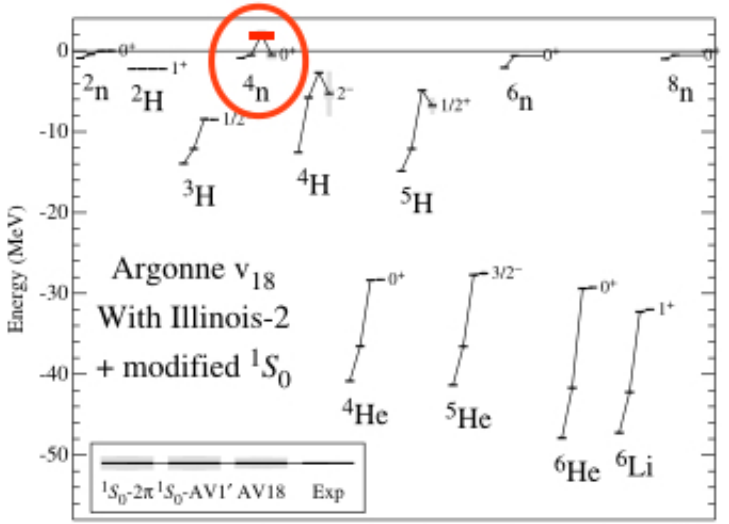
F. M. Marques, et al, Phys. Rev. C 65, 044006 (2002)




2000s

### Theoretical work

- ab-initio calculation
  NN, NNN interaction




S. C. Piper, Phys. Rev. Lett. 90, 252501 (2003)

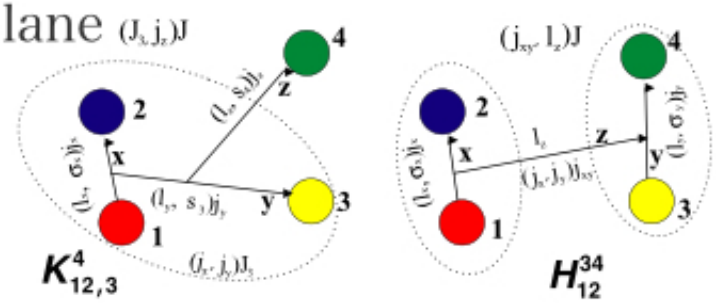
- **Bound $^4n$ cannot exist**
- **Possible resonance stete ~2 MeV**

**Possibility of the resonance state is still an open and fascinating question.**

# Theoretical Works for Resonance

- Solving Faddeev-Yakubovsky eq.
  - resonance pole trajectory on complex energy plane w/ realistic NN interaction

    → **physically unobservable**




R. Lazauskas, et al., Phys. Rev. C 72, 034003 (2005)

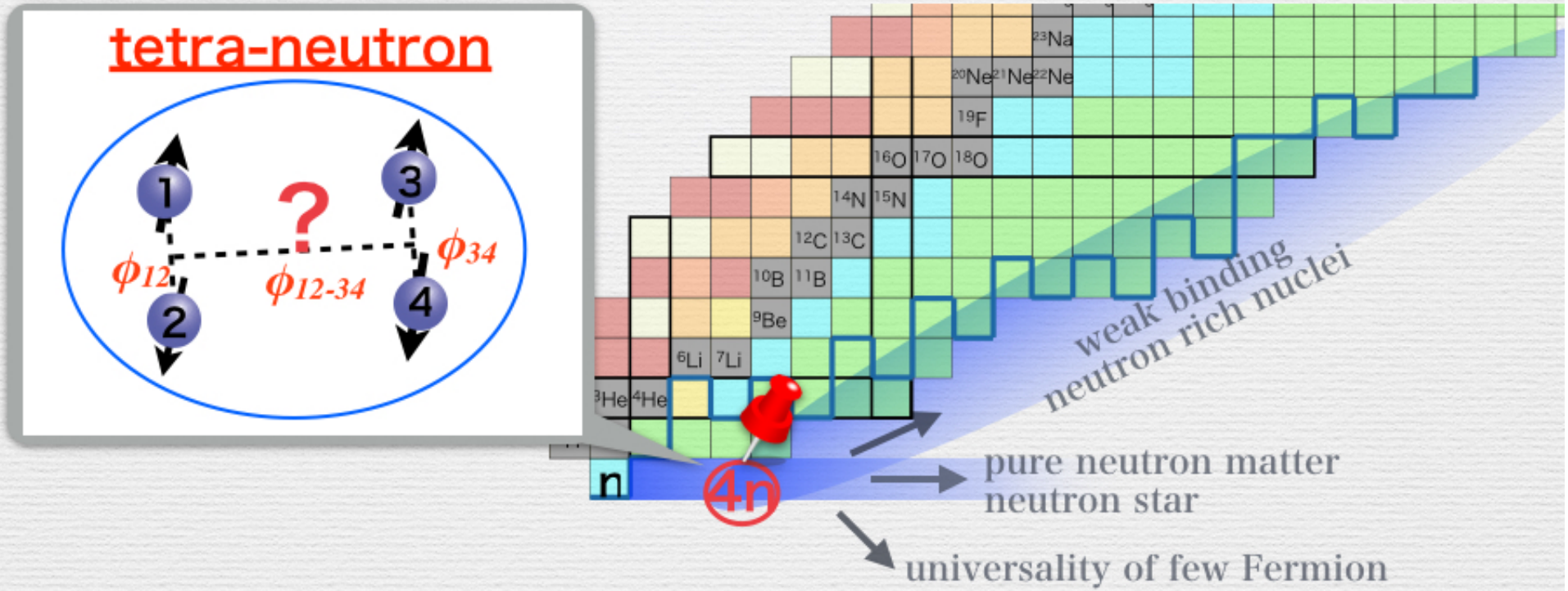
- Cluster configuration coexist
  - compound system, where $^3$n+n and $^2$n+$^2$n coupled cluster configurations

  → "The strength of attraction is high enough to ensure the existence of resonance, provided that the oscillator length is large enough."

Y. A. Lashko, et al., Phys. of Atomic Nucl., 71, 2 (2008)

**The observation of the resonant state can provide a significant impact of our understanding of the nuclear few-body systems and NN interaction.**

# Purpose of this Work



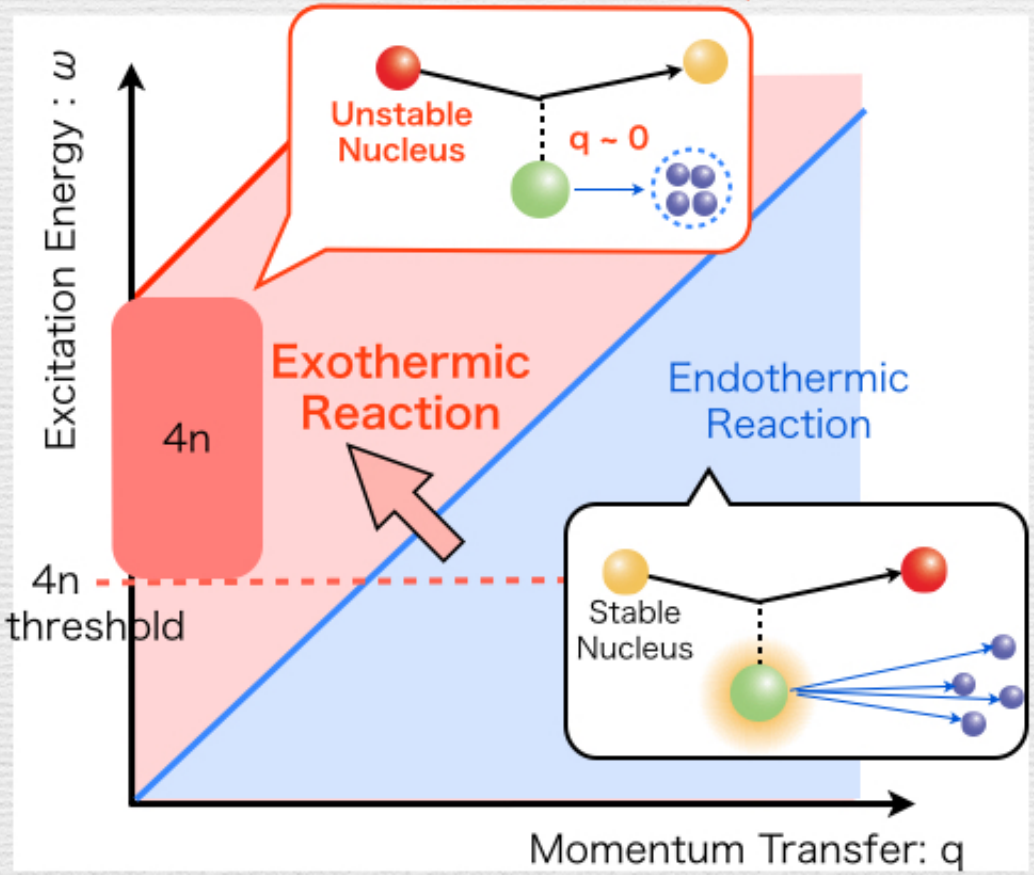

**Clarify whether the four-neutron (tetra-neutron) system can exist as a resonance state**

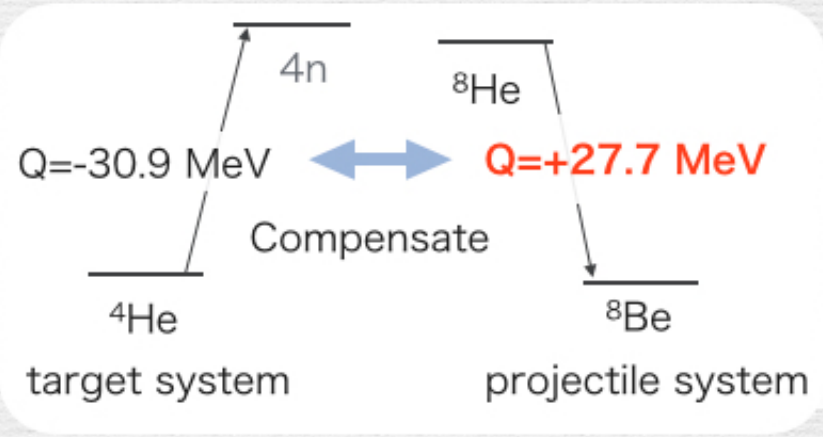
# Contents

# Reaction Kinematics

- Double-charge exchange (DCX) reaction $^{4}$He($^{8}$He,$^{8}$Be)4n

  - Exothermic reaction
    → 4n system with **small momentum transfer.**
    **(almost recoil less condition)**



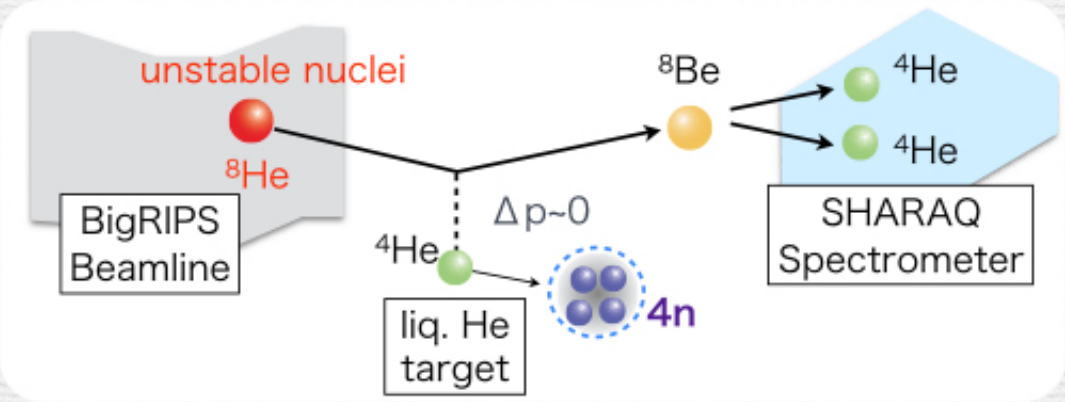




**This reaction has an sensitivity at low excitation energy region of 4n system.**

# Measurement of 4n Energy

## Missing-mass spectroscopy

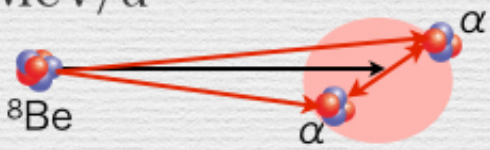
- Energy resolution: ~ 1 MeV




- $^{8}$Be($\rightarrow 2\alpha$) : High-resolution magnetic spectrometer SHARAQ
  $\delta$ p/p ~ 1/10000 (Lage-Momentum-Acceptance mode)
- $^{8}$He : BigRIPS-HBL beam line
  $\delta$ p/p ~ 1/7000 (design value)

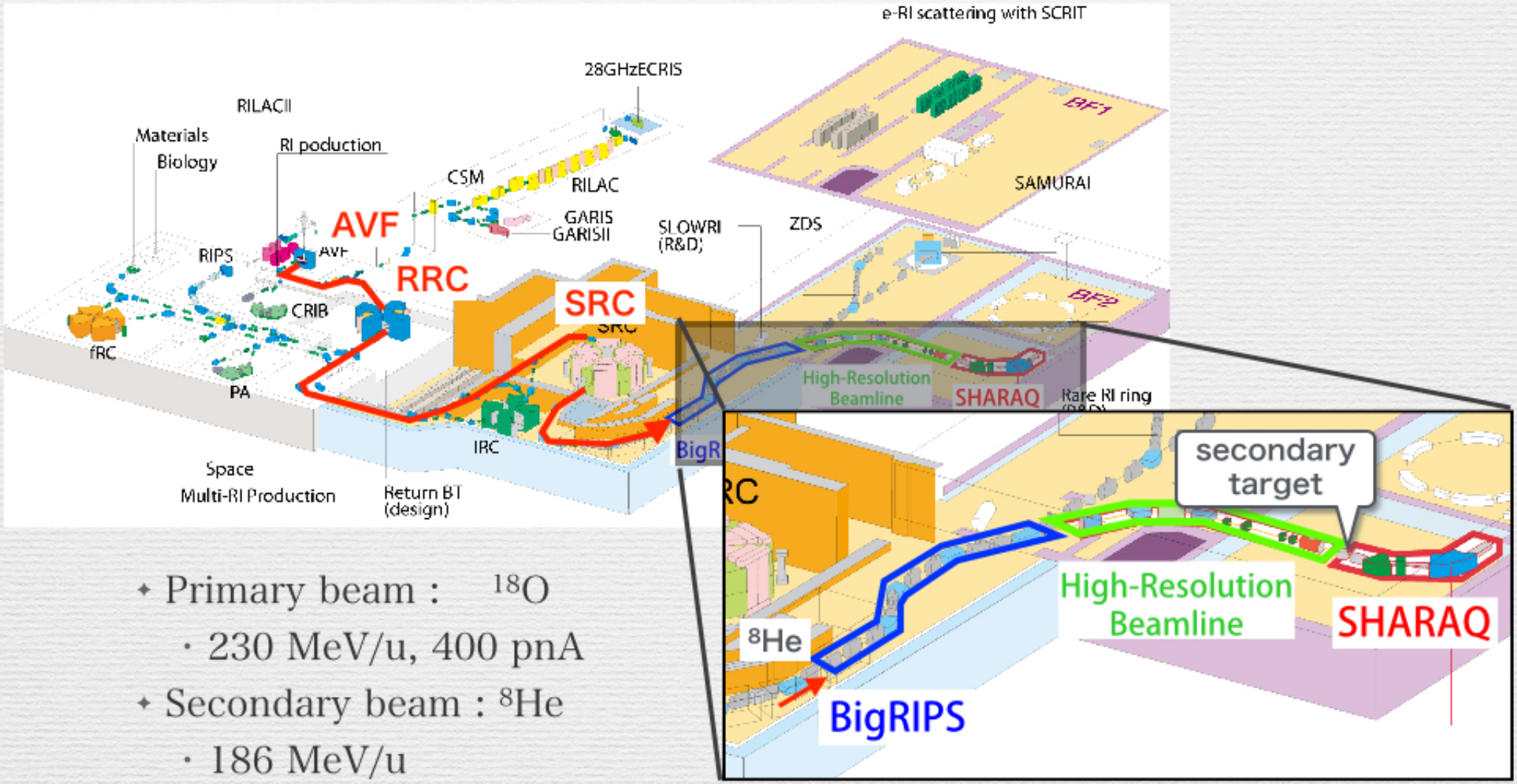
cf. RI beam : $\delta$ p/p ~ 1/50 ($\Delta$E ~ 30 MeV)

- $^{8}$Be$\rightarrow 2\alpha$ detection at 200 MuV/u
  - Good signal-to-noise ratio : $2\alpha$ coincidence
  - Large acceptance for $2\alpha$ from 8Be(g.s.) at 200 MeV/u
    (acceptance of $^{8}$Be* is negligible small)



# Contents

# RIBF Facility




- Primary beam : $^{18}O$
  - 230 MeV/u, 400 pnA
- Secondary beam : $^{8}He$
  - 186 MeV/u
  - 99 % purity
  - 2 MHz @secondary target

# Experimental Setup

Primary Beam from Cyclotron (13.7 MHz)

production target

F0

F1

Collimator

F2

F3

Momentum slit Degrader

BigRIPS

- plastic scintillator
- micro hodoscope

start point of ion optics

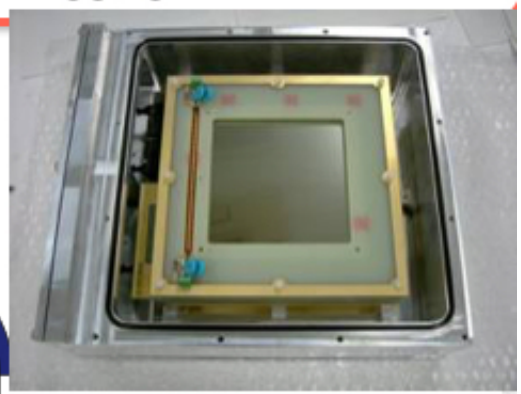
High Resolution Beam Line

F6

Dispersive Focal Plane

- MWDC (Multi-Wire Drift Chamber)

momentum tagging for $^{8}$He beam



liq. He target

120 mg/cm$^2$

$\phi$=30 mm

FH9

- plastics scintillator
- MWDCs

target position

FH10

S0

SHARAQ spectrometer

S2

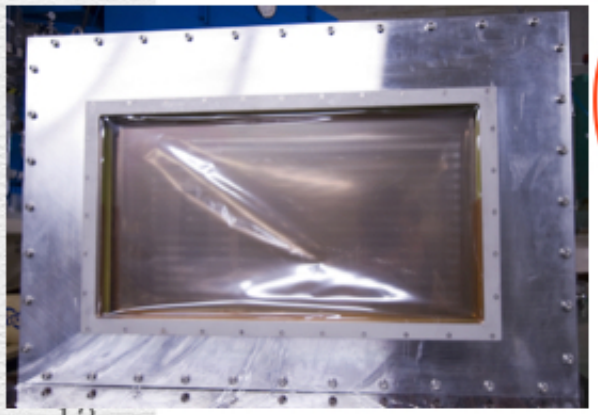
Beam

Final Focal Plane

- plastic scintillator
- CRDCs

(Cathode Readout Drift Chamber)

two $\alpha$ tracking



## Measurement

| Run | Magnet setting | | Beam intensity |
|---|---|---|---|
| | Beam Line | SHARAQ | |
| Optics tuning | $^{4}$He | $^{4}$He | $\sim 10^4$ cps |
| | $^{8}$Li | $^{8}$Li | |
| | $^{8}$He | – | |
| Physics measurement | $^{8}$He | $^{8}$Li | $\sim 10^6$ cps |
| | $^{8}$He | $^{8}$Be | |

# SHARAQ spectrometer


- Ion optical transport: Large Momentum Acceptance mode

| | LMA mode | standard |
|---|---|---|
| Momentum resolution | 1/10000 | 1/14700 |
| Angular acceptance | | |
| - vertical | ± 1.5 deg | ± 1.7 deg |
| - horizontal | ± 2.9 deg | ± 3.0 deg |
| Solid angle | 4.3 msr | 4.8 msr |
| Momentum acceptance | ±1.8 % | ±1 % |

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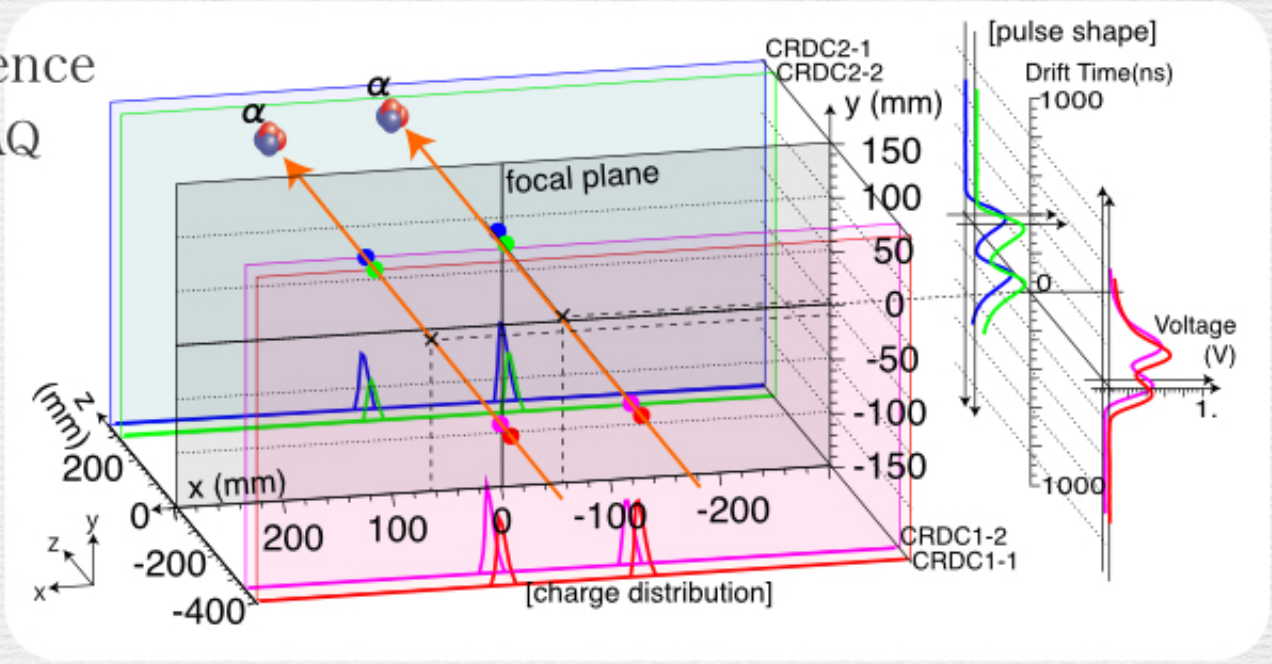
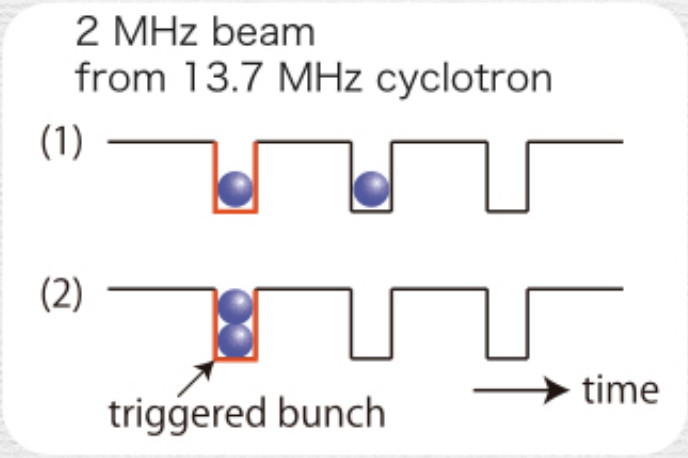
# Contents

# Analysis

- Selection of 4n Events
  - Extracting 2 $\alpha$ in coincidence
    @final focal plane of SHARAQ




- Multi-particle in high-intensity beam @Beamline



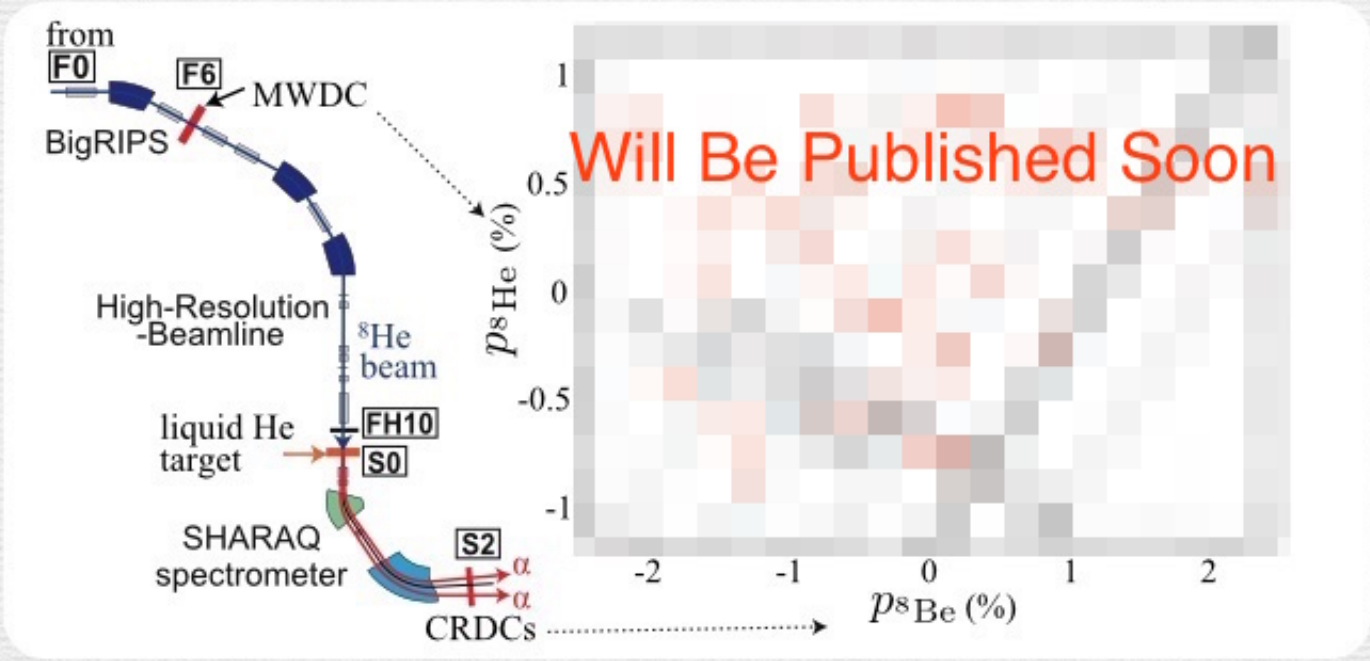

These events are possible source of background

(1) identify correct trajectory

(2) exclude

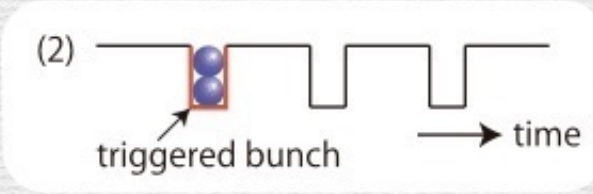
# Analysis (Cont'd)

- Candidate events




- Calibration
  - $^{1}$H($^{8}$He, $^{8}$Li(1$^{+}$))n reaction
  - B$\rho$ scaling: $^{8}$Li → $^{8}$Be

- Background estimation
  - possibility of misidentification of multi-particle
  - multi-particle in one cell at MWDC

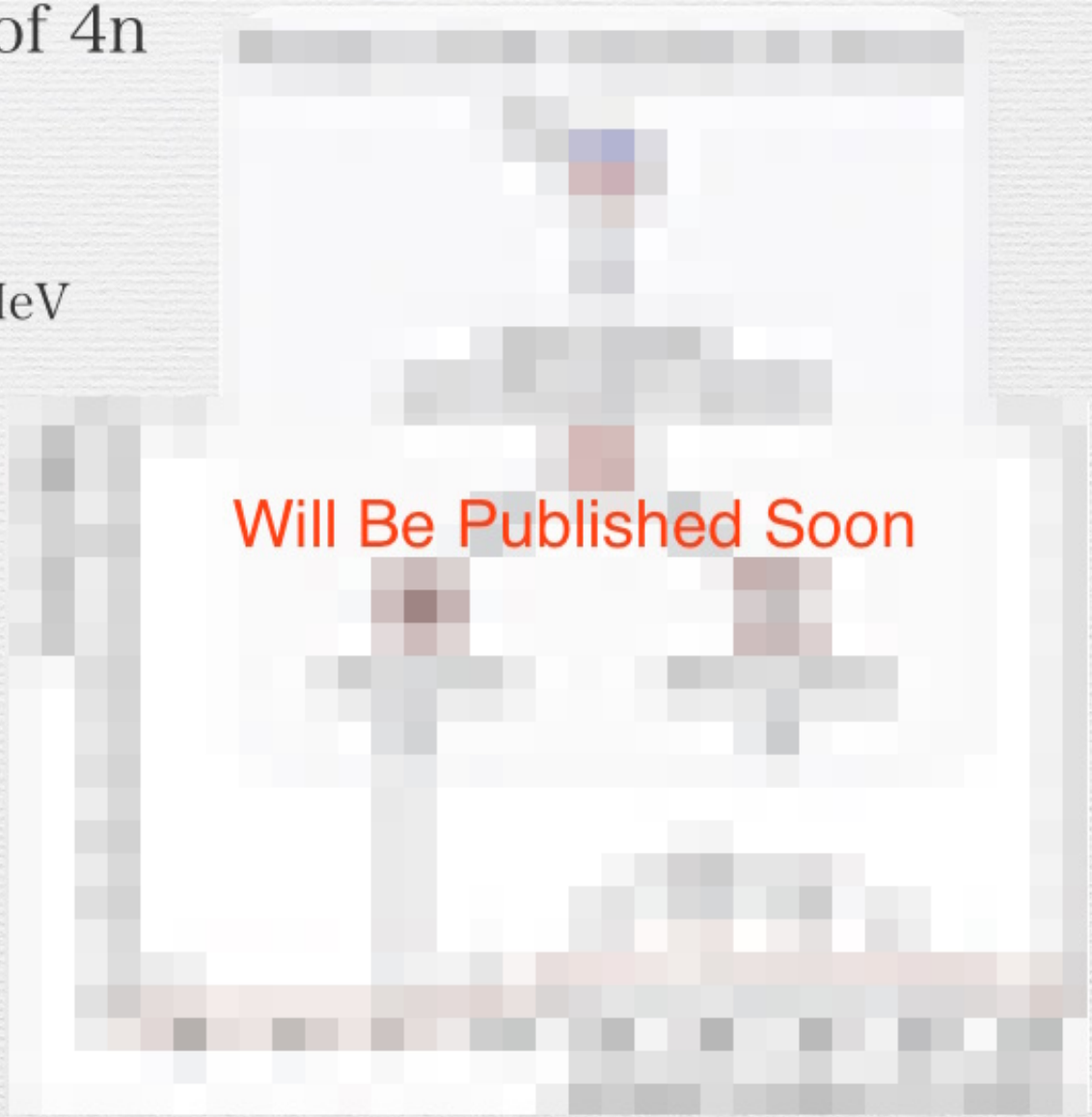


# Contents

# Result

- Missing-mass Spectrum of 4n
  - 27 events in the spectrum
  - energy resolution: 1.2 MeV ($\sigma$)
  - uncertainty of calibration: ± 1.3 MeV
  - background: 2.3±1.0 events

→ **almost background free**



# Result (Cont'd)

- Continuum spectrum w/o resonance

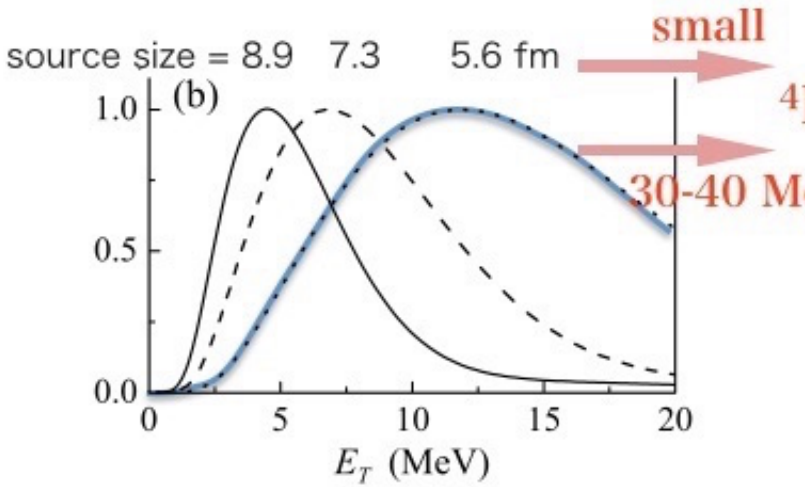
  - c.f. ) Grigorenko's paper

    - Continuum from initial Gaussian source with n-n FSI
    - reaction: **$\alpha$ knockout reaction of $^8$He**

$$\left(\hat{H}_4 - E_T\right)\Psi_4^{(+)} = \underbrace{F_{^4\mathrm{n}}^{0^+}}_{\text{source term}}$$

→ Fourier transform of the overlap $^8$He and $\alpha$

$$F_{^4\mathrm{n}}^{0^+} \sim \Phi_{^4\mathrm{n}}^{0^+} = \int \mathrm{d}\mathbf{r}\, e^{i\mathbf{q}\mathbf{r}} \langle \Psi_\alpha | \Psi_{^8\mathrm{He}} \rangle$$




L. Grigorenko, Eur. Phys. J. A 19, 187-201 (2004)

  - decay to two di-neutron pair after DCX

$^4$He $\Phi[(0s)^4]$

⇩ DCX reaction (double dipole)

$\Phi[(0s)^2(0p)^2]$ (J=0)

⇩ decay

FSI : di-neutron($^1$S$_0$)
two di-neutron paris

$^4$He

30-40 MeV (?

Will Be Published Soon

# Result (Cont'd)

- Bin-by-Bin Goodness-of-Fit
  - trial function

$$a f_{\mathrm{cont}}(E_{4n}) + f_{\mathrm{BG}}(E_{4n})$$

  - likelihood ratio test

$$\chi^2_\lambda = -2 \ln \left[ L(\boldsymbol{y}; \boldsymbol{n}) / L(\boldsymbol{n}; \boldsymbol{n}) \right]$$

    - Significance:

$$s_i = \sqrt{2[y_i - n_i + n_i \ln (n_i / y_i)]}$$

$n_i$ : num. of events in the $i$-th bin
$y_i$ : trial function in the $i$-th bin

- Look elsewhere effect

E. Gross, Eur. Phys. J. C70, 525-530 (2010)

Considering the probability that strength originated from the fluctuation of continuum

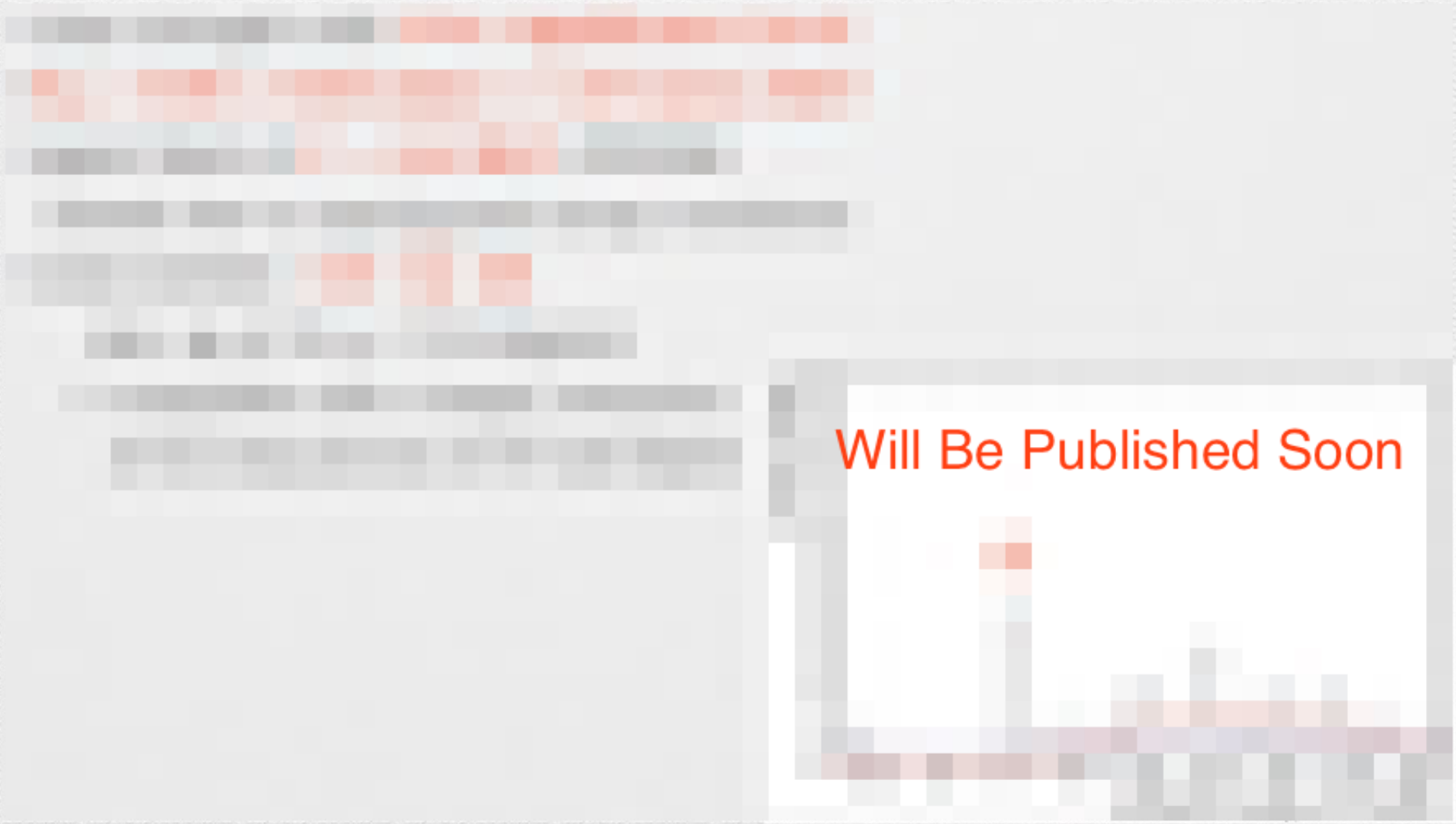
- region of interest [-2, 10] MeV

**4.9 $\sigma$ significance** ($E_{4n}$~2 MeV)

➡ **possible resonance state**

# Conclusion

- Candidate of the resonant state near the threshold



# Discussion

- Possible reason of forming the resonant state
  - **Strong many-body force** : isospin T=3/2 3N, 4N force

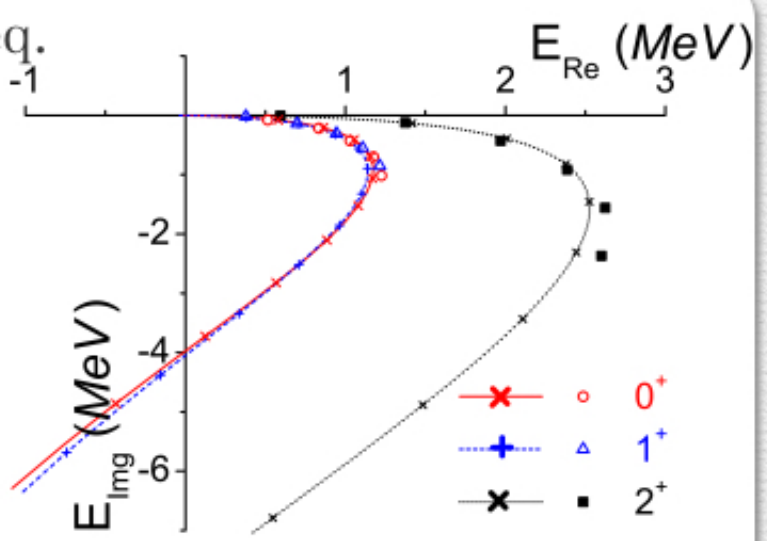
・ Solving Faddeev-Yakubovsky eq.

i) artificially attractive 4N force to bing tetra-neutron

$$V_{4n} = -W\rho e^{-\frac{\rho}{\rho_0}}$$

ii) resonance pole trajectory

$$E_{\mathrm{res}}(W \to 0)$$




R. Lazauskas, et al., Phys. Rev. C 72, 034003 (2005)

  - **Compound system**, where $^{3}$n+n and $^{2}$n+$^{2}$n coupled cluster configurations coexist

    → The attractive interaction was obtained to ensure the existence of the resonance state.

    Y. A. Lashko, et al., Phys. of Atomic Nucl., 71, 2 (2008)

→ **The result leaves room for further investigation.**

# Perspective

- More statistics and resolution
  - double-charge exchange reaction
    - → $E_{4n}$, $\Gamma_{4n}$
      - statistics > 5 times
      - resolution ~ 1/3
- Another method
  - knockout reaction
    - $^{8}He(p,2p)^{7}H \rightarrow t + 4n$ (will be proposed)
    - $^{8}He(p,p\alpha)4n$ (S. Paschalis)
    - $^{28}F(p,2p)^{28}O^{*} \rightarrow ^{24}O+4n$ (Y. Konodo)

# Contents

# Summary

- We performed missing-mass spectroscopy of the tetra-neutron system via the double-charge exchange reaction $^{4}$He($^{8}$He,$^{8}$Be)4n with the SHARAQ spectrometer at RIBF. The secondary beam $^{8}$He had a large mass excess, which enabled us to produce the tetra-neutron system with small momentum transfer.
- In the careful analysis to identify multi-particle, the missing-mass spectrum of tetra-neutron system containing 27 events was obtained with almost background free.
- The spectrum had a clear strength with 4.9 $\sigma$ significance level near the four-neutron threshold by a comparison with the theoretical curve assuming the direct decay to the two correlated di-neutron pairs.
- The mean of strength was 0.83±0.65(stat.)±1.25(sys.) MeV and upper limit of width was 2.6 MeV (FWHM). The result suggests a possible resonant state of the tetra-neutron system.

# SHARAQ06 Collaboration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