Candidates for the 5α condensed state in ^{20}Ne

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第5回クラスター階層領域研究会 Sep. 24th, 2020

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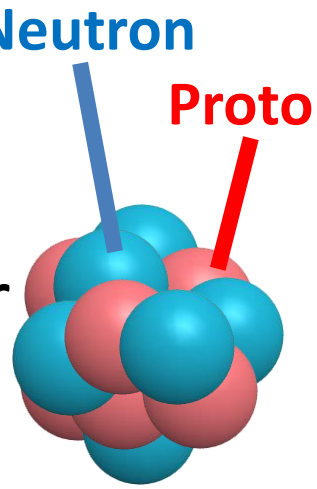
Introduction

Alpha-particle condensation in nuclear matter

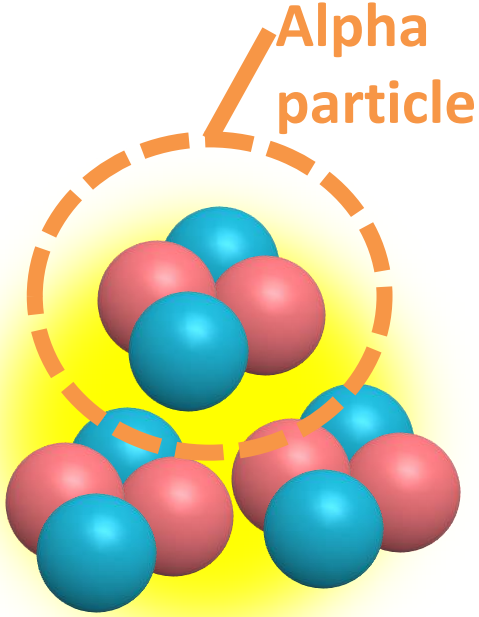
- Predicted to appear **at low temperature & low density**
- ~ **Bose-Einstein condensation**
  - alpha particle : Boson & tightly bound
- Affects the **Equation of state (EoS)** of nuclear matter



^{12}C : (g.s.)

Alpha-particle condensed state in finite nuclei

- Self-conjugate **A = 4k nuclei** (k : integer)
- ^{12}C : 0_2^+ (**Hoyle state**), $E_x = 7.65$ MeV
- Predicted to exist **up to k ~ 10** (~ ^{40}Ca)

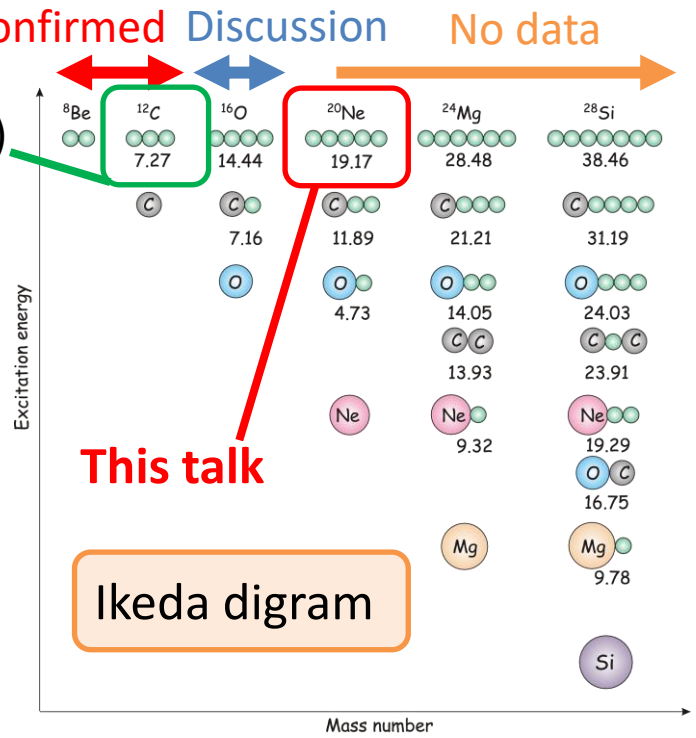


^{12}C : 0_2^+ (**Hoyle state**)

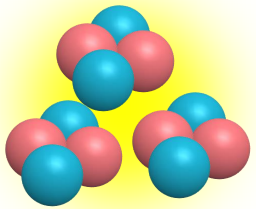
Experimental study from alpha-particle condensed state

Alpha-particle condensed states in A = 4k nuclei

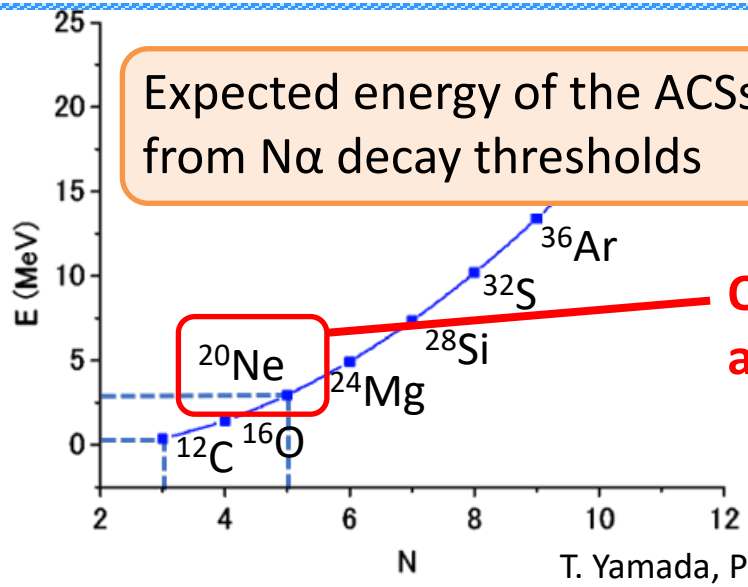
- Alpha-particle condensed state (**ACS**)
  - Predicted to exist **up to k ~ 10** (~ ^{40}Ca)
  - **"Ikeda diagram" → Threshold rule**



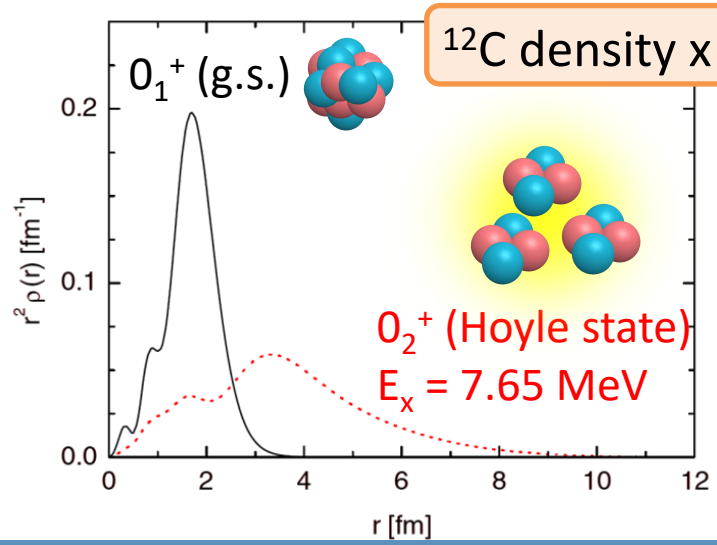
$^{12}C : 0_2^+$ (**Hoyle state**)
$E_x = 7.65$ **MeV**
Only 0.38 MeV above 3α threshold



K. Ikeda, N. Tagikawa, H. Horiuchi, Prog. Theor. Phys. 464 (Suppl.) (1968).
W. von Oertzen et al., Phys. Report 432, 43 (2006).



T. Yamada, Phys. Rev. C 69, 024309 (2004).

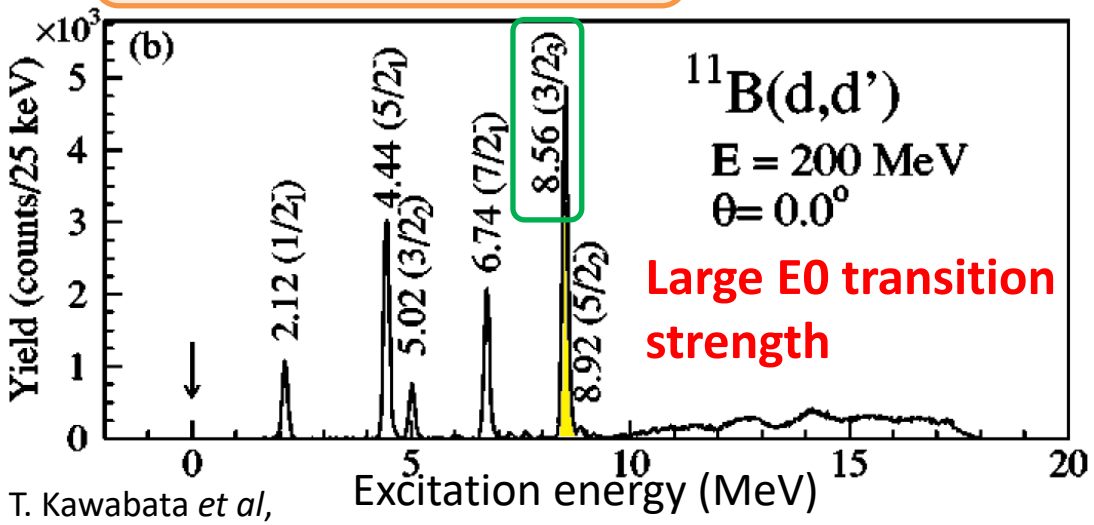


T. Yamada *et al.*,
Eur. Phys. J. A **26**, 185 (2005).

How to excite the ACSs ?

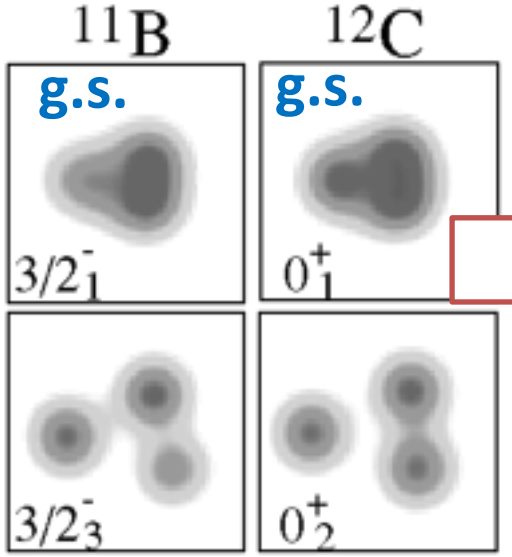
Isoscalar E0 transition

Experimentally observed ^{11}B cluster state: "2α+ t"



T. Kawabata *et al*,
Phys. Rev. C **70**, 034318 (2004), Phys. Lett. B **646**, 6 (2007).

AMD(VAP) calc.



Y. Kanada-En'yo *et al*.,
Phys. Rev. C **75**, 024302 (2007).

Spatially developed cluster → Strong E0 transition strength

T. Yamada *et al.*, PTP **120**, 1139 (2008).

& E0 transition is most strong at θ = 0°

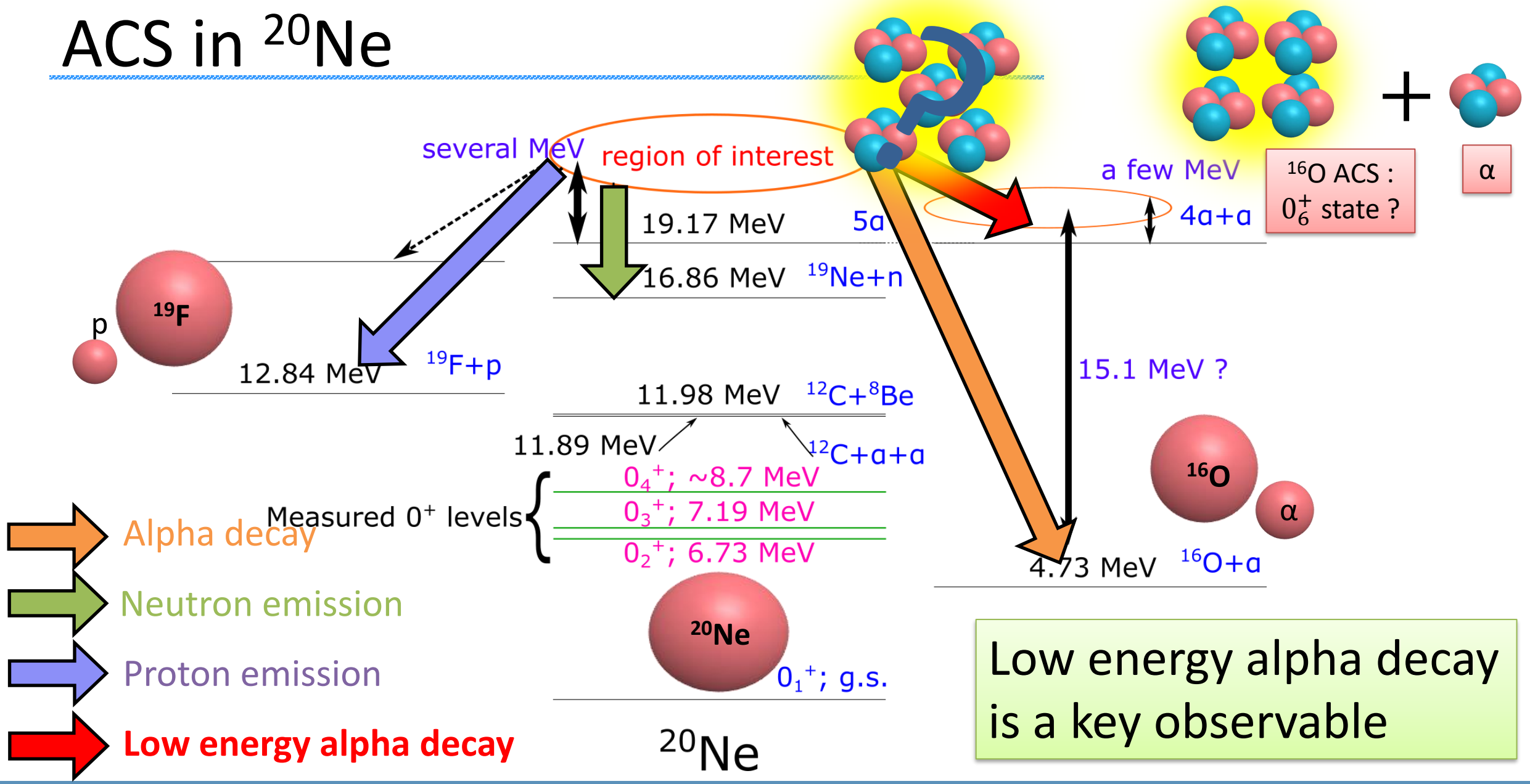
Isoscalar probe

α particle (^{4}He)
spin S = 0, isospin T = 0

Selectivity to the transition with **ΔS = 0, ΔT = 0** from the g.s.

(α,α') reaction at forward angle is one of the best probes

ACS in ^{20}Ne



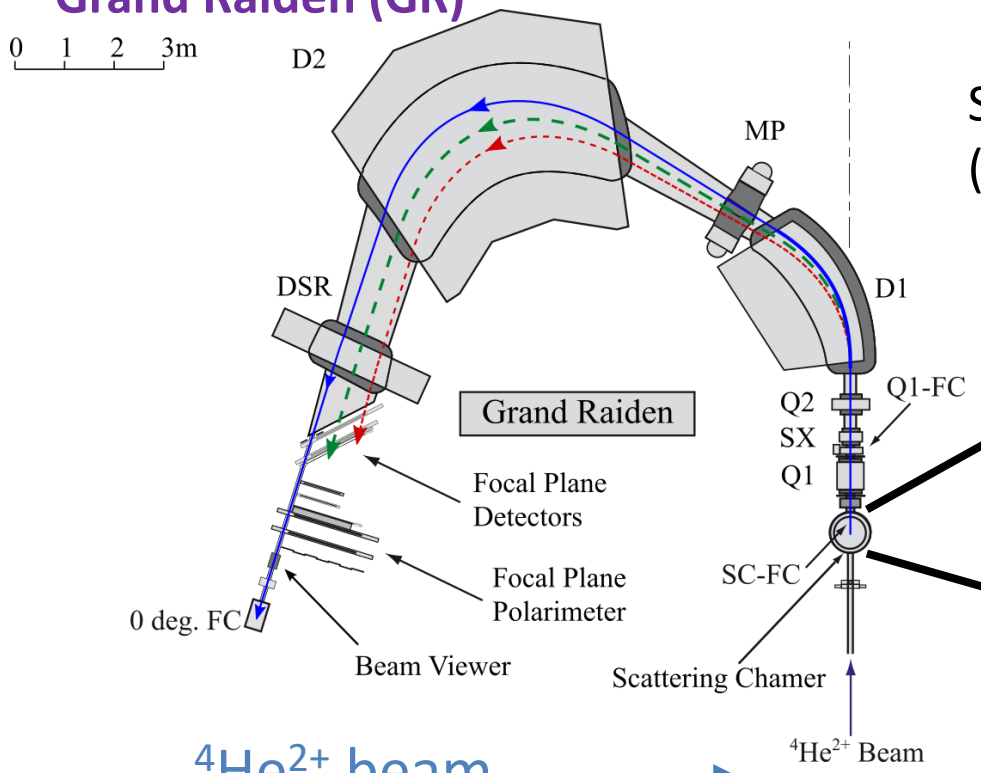
Low energy alpha decay is a key observable

Experiment

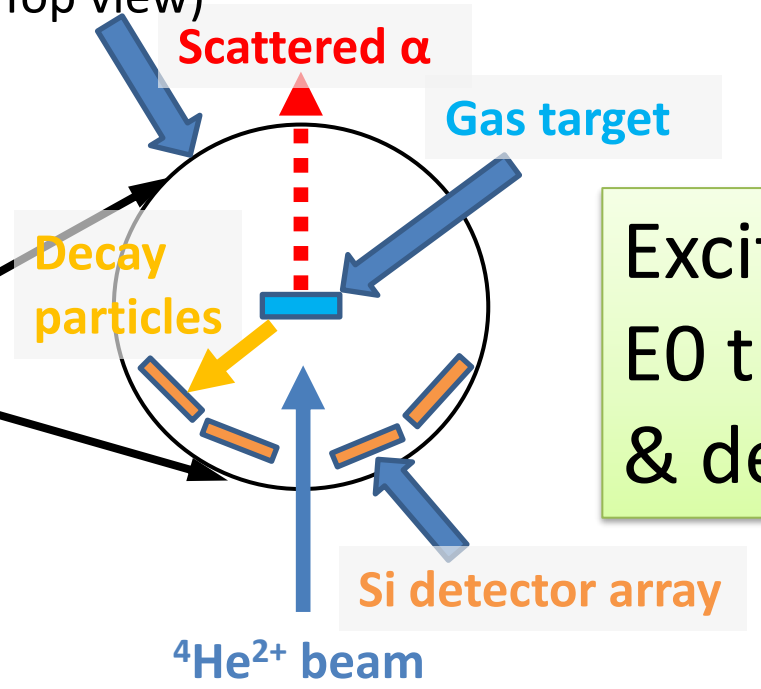
^{20}Ne(α,α'+α) at θ=0.0° , $E_α$ = 386 MeV

Performed at RCNP, Osaka University

Grand Raiden (GR)



Scattering chamber (Top view)



✓ **Scattered α : GR at 0°**

✓ **Decay particle : Si detector array**

Excitation of ^{20}Ne with
E0 transition
& decay information

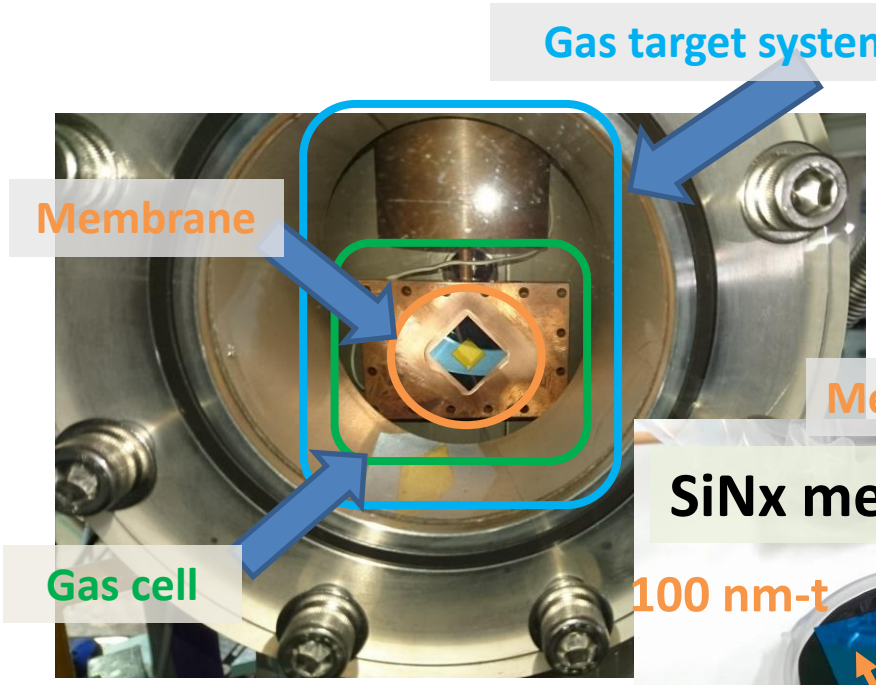
$^4He^{2+}$ beam

Scattered α (low E_x)

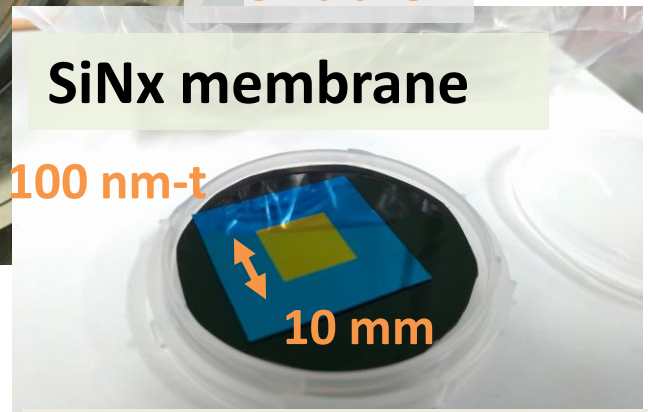
Scattered α (high E_x)

Experimental instruments

Gas target

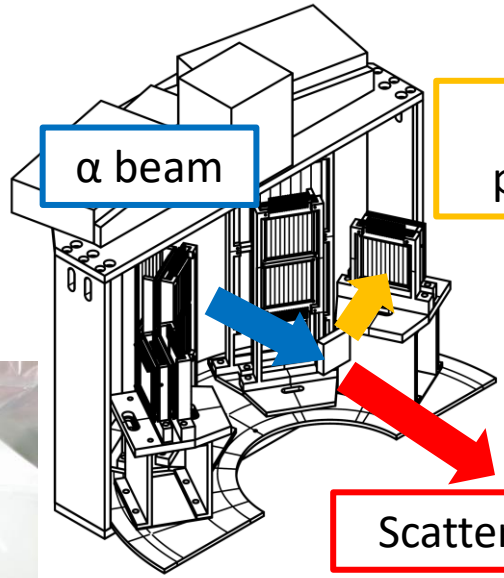


^{20}Ne target
- **14 kPa**
- **89.6 μg/cm^2**



Very thin (100 nm-t) → 32 μg/cm^2,
less stretch, good gas sealing

Si detector array

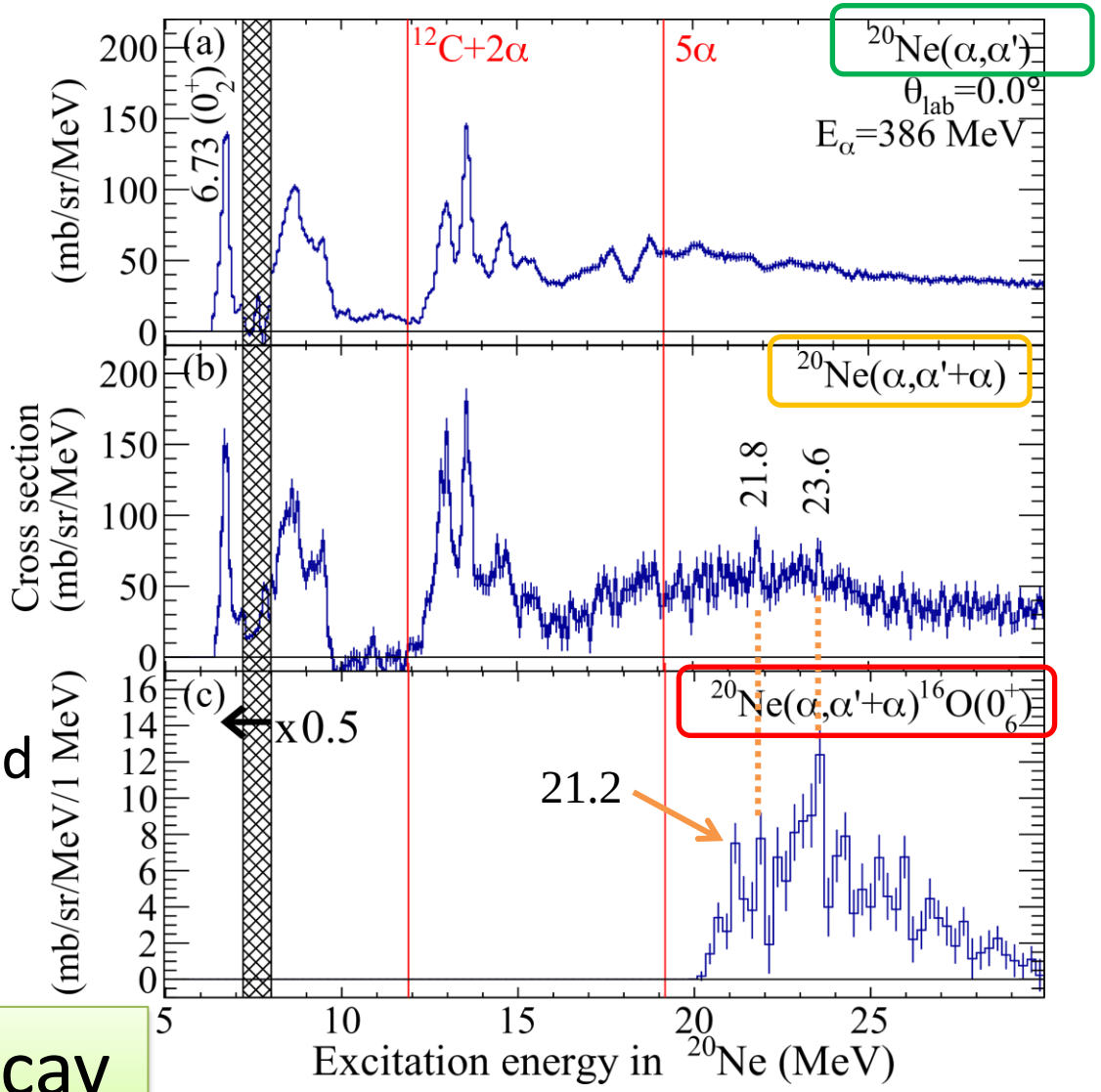


Si detector array
- **6 segments, 3-layer configuration**
- **solid angle : 3.4% of 4π**
- **E-ΔE & TOF method for PID**

Excitation-energy spectra

S. Adachi et al.,
arXiv:2008.01632, submitted to Phys. Rev. Lett.

- **Singles : ^{20}Ne(α,α')**
  - No structure above 5α threshold
- **Alpha decay in coincidence : ^{20}Ne(α,α'+α)**
  - Peaks at **23.6 & 21.8 MeV**
  - Statistical significances are not fully high
- **Alpha decay to ^{16}O(0_6^+; Ex = 15.1 MeV) : ^{20}Ne(α,α'+α)^{16}O(0_6^+)**
  - ^{16}O(0_6^+) : Strong candidate for 4α condensed state
  - **Additional peak at 21.2 MeV**

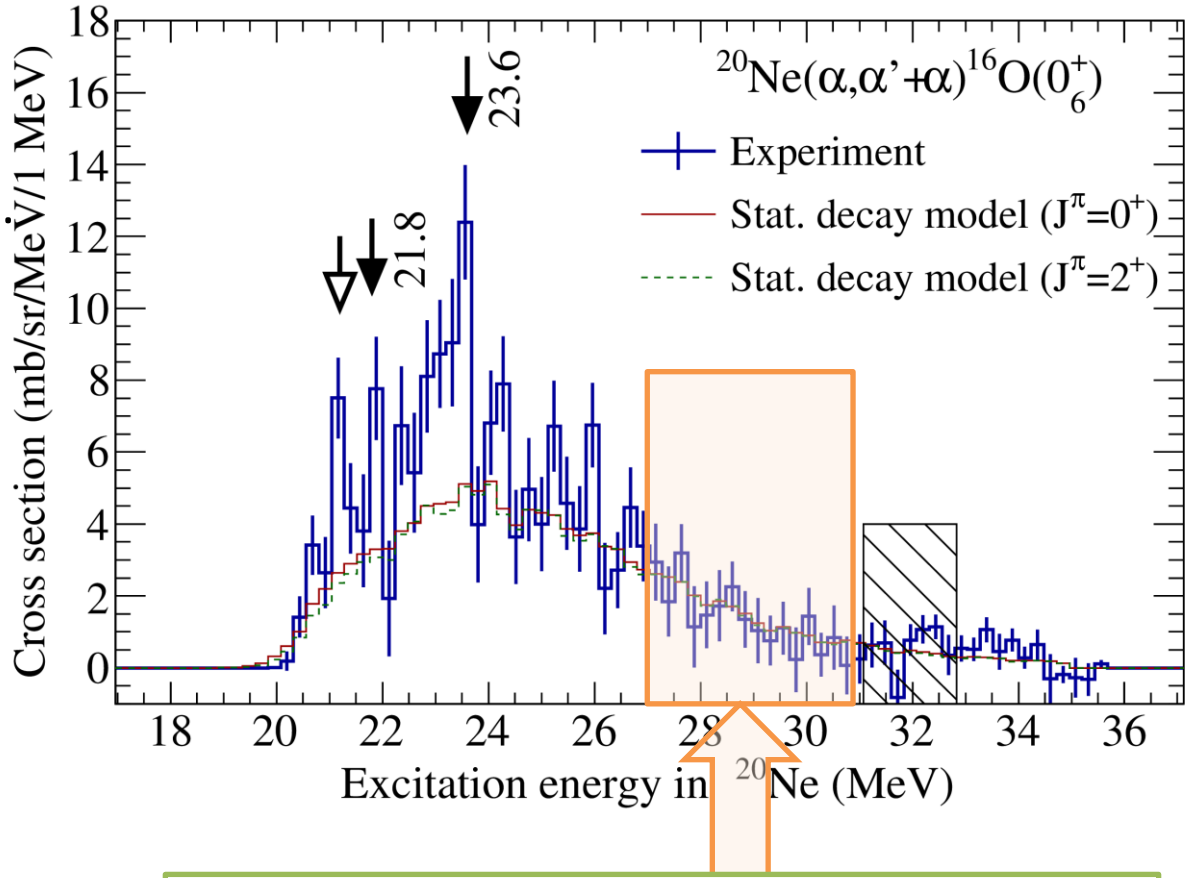


Need to compare with the statistical decay

Comparison with the statistical decay model

- **Statistical decay model**
  - Computer code : CASCADE
    - F. Pühlhofer, Nucl. Phys. A 280, 267 (1977).
    - Only level density & state matching
    - **No recoil energy → modification**
  - Monte Carlo simulation with CASCADE
  - **initial excited state in ^{20}Ne**
    - $J^{\pi} = 0^{+}, 1^{-}, 2^{+}$

- **Comparison with our spectrum**
  - **No peak structures are reproduced**
  - **E_x > 27 MeV : good agreement**



Statistical-decay-model calculations are fitted to the exp. data

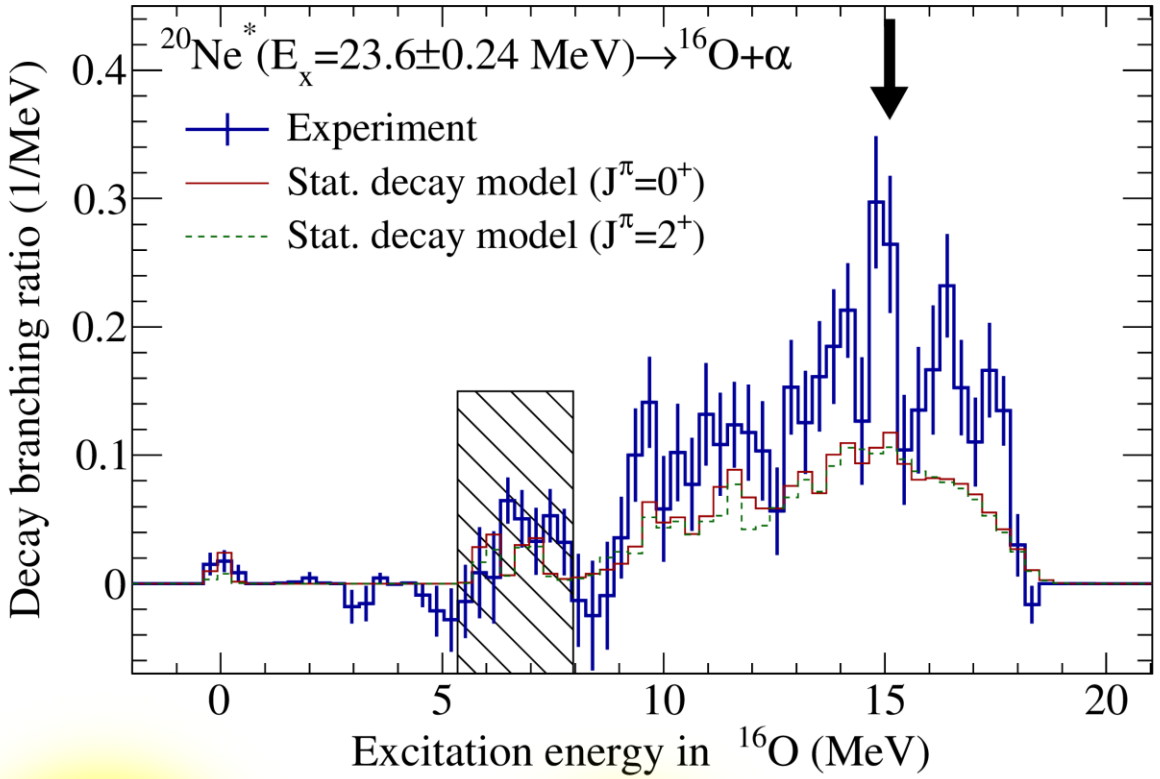
Decay property of the 23.6-MeV state

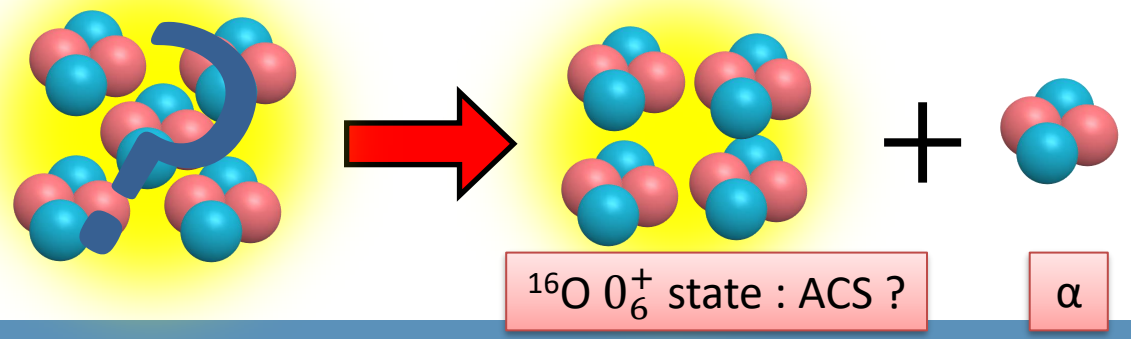
- **Decay branching ratio**
  - from the 23.6-MeV state
  - **Which state in ^{16}O does ^{20}Ne decay into?**
  - **^{16}O(0_6^+; E_x = 15.1 MeV) : Strong candidate for 4α condensed state**

- Comparison with the model
  - E_x = 15.1 MeV : large decay branching ratio

  → decay into the 4α + α channel ?

- The 21.8 & 21.2-MeV states
  - too statistically poor to check

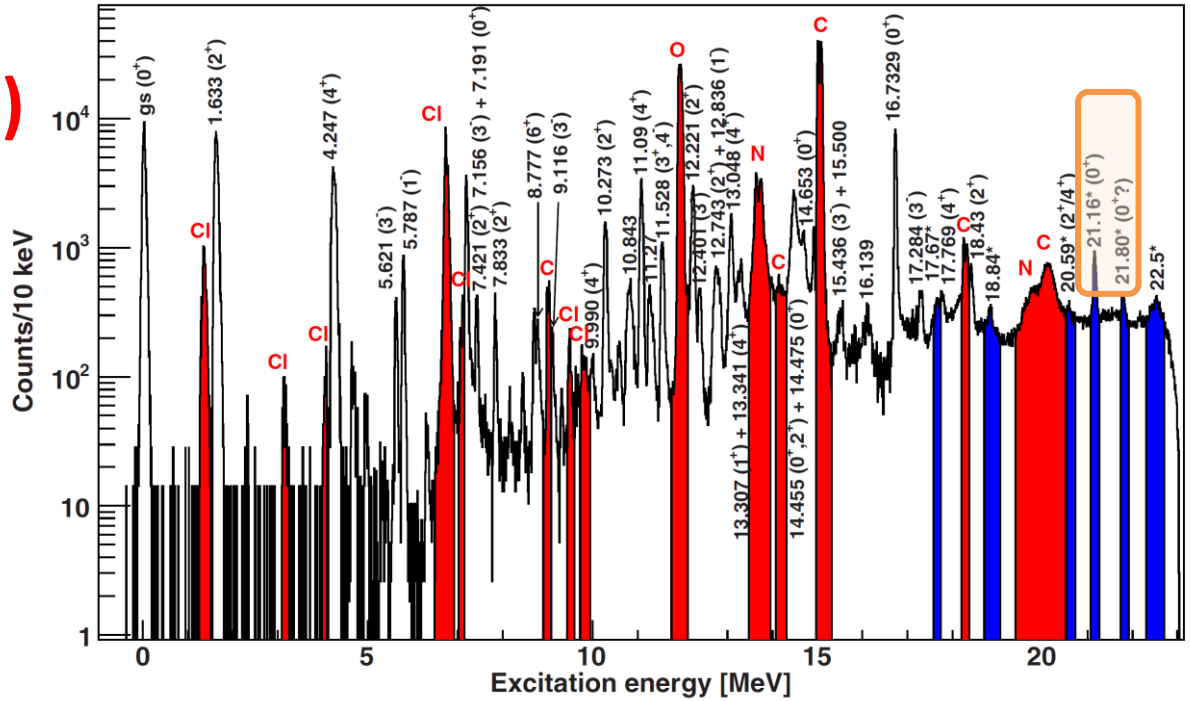




Some more discussion

- ^{20}Ne excited states above the 5α threshold
  - Alpha decay channel
  - **23.6 MeV : a little bit high E_x** from the threshold
    - **Excited state of ACS ? (like $^{12}C(2_2^+)$)**
  - **21.8 MeV : 0^+ ?**
    - Observed state at iThemba LABS?
    - (explained by the shell model)
  - **21.2 MeV : 0^+ ?**
    - Observed state at iThemba LABS?
    - (explained by the shell model)
    - Nearest to the 5α threshold → ACS?

^{22}Ne(p,t)^{20}Ne reaction
@ iThemba LABS, South Africa



J. A. Swartz et al., Phys. Rev. C 91, 034317 (2018).

Summary & Prospect

- Alpha-particle condensed state in finite nuclei
  - **Alpha particle as a cluster in nuclei : Semi-hierarchy**
  - Clue to study alpha-particle condensation in nuclear matter & EoS at low density
- Experiment
  - **^{20}Ne(α,α'+α) at θ = 0.0°** using E_α = 386 MeV beam
  - Gas target with very thin windows & Si detector array
- Results
  - **New states at 23.6, 21.8 and 21.2 MeV : Candidates for the 5α condensed state**
  - Can not be explained by the statistical decay model
  - **23.6-MeV state : strong decay to ^{16}O(0_6^+)+α**
- **Near-future prospect**
  - More statistics & J^π determination of these states
  - Statistics of ACS ?

S. Adachi et al.,
arXiv:2008.01632, submitted to Phys. Rev. Lett.

New Experiment
- LN_2 cooled ^{20}Ne target
- Large solid angle Si
- Angular distribution

RCNP E402 experiment

S. Adachi[1], Y. Fujikawa[2], T. Kawabata[1], H. Akimune[3], T. Doi[2], T. Furuno[4], T. Harada[2], K. Inaba[2], S. Ishida[5], M.Itoh[5], C. Iwamoto[6], N. Kobayashi[4], Y. Maeda[7], Y. Matsuda[5], M. Murata[4], S. Okamoto[2], A. Sakaue[8], R. Sekiya[2], A. Tamii[4], and M. Tsumura[2]

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[4]RCNP, Osaka University, [5]CYRIC, Tohoku University

[6]RIKEN Center for Advanced Photonics, [7]Miyazaki University

[8]RIKEN Center for Accelerator Based Science