Search for alpha-cluster gas state in medium heavy nuclei

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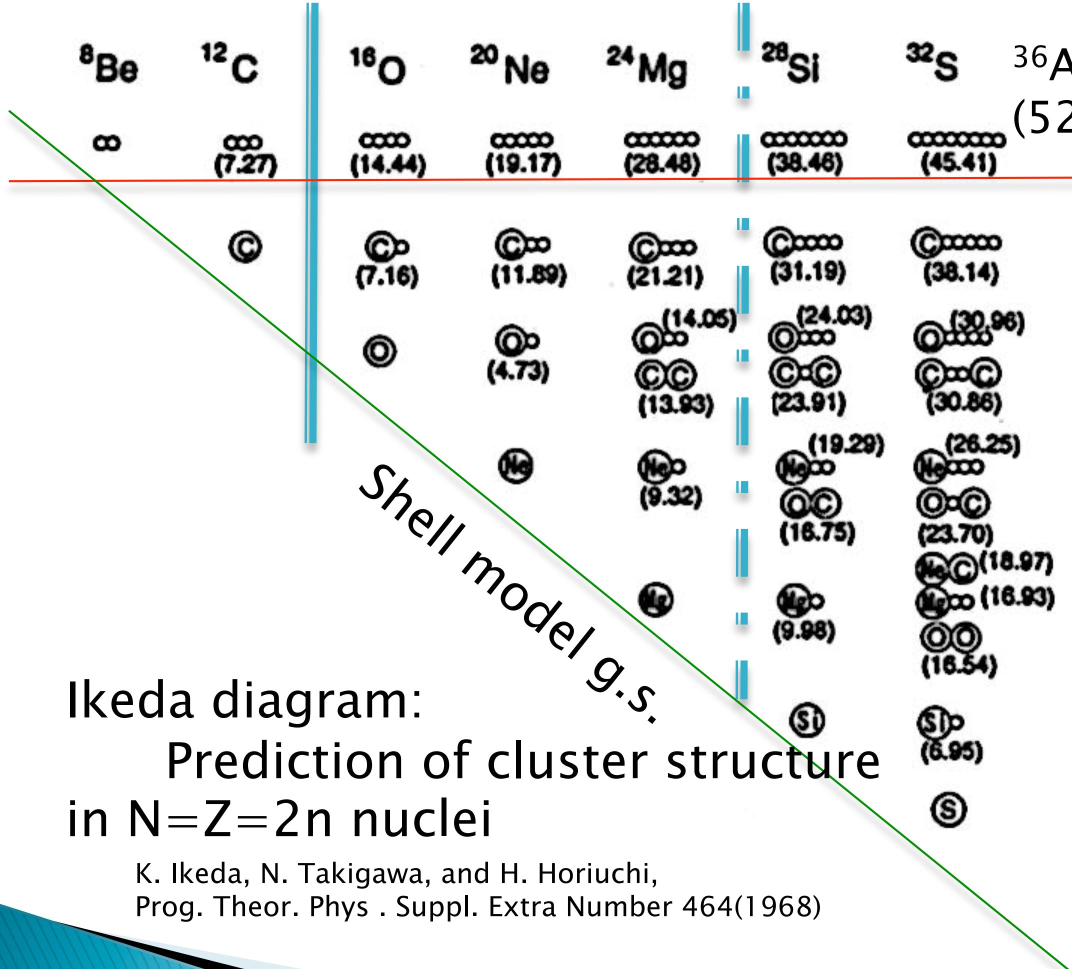
- Introduction
  - α cluster state in N=Z=2n nuclei
- Multi particle decay measurement and inverse kinematics experiment
- The first experiment
  - $^{4}He(^{56}Ni,n\alpha)$ at GANIL
- Recent experiment
  - $^{4}He(^{36}Ar,n\alpha)$ at RCNP

Alpha cluster structure in medium heavy nuclei

Stable — RI beam

^{36}Ar (52.5) ^{40}Ca (59.1) ^{44}Ti (64.2) ^{48}Cr (71.9) ^{52}Fe (79.7) ^{56}Ni (87.9)

"g.s." of nα cluster structure



Ikeda diagram:
Prediction of cluster structure in N=Z=2n nuclei

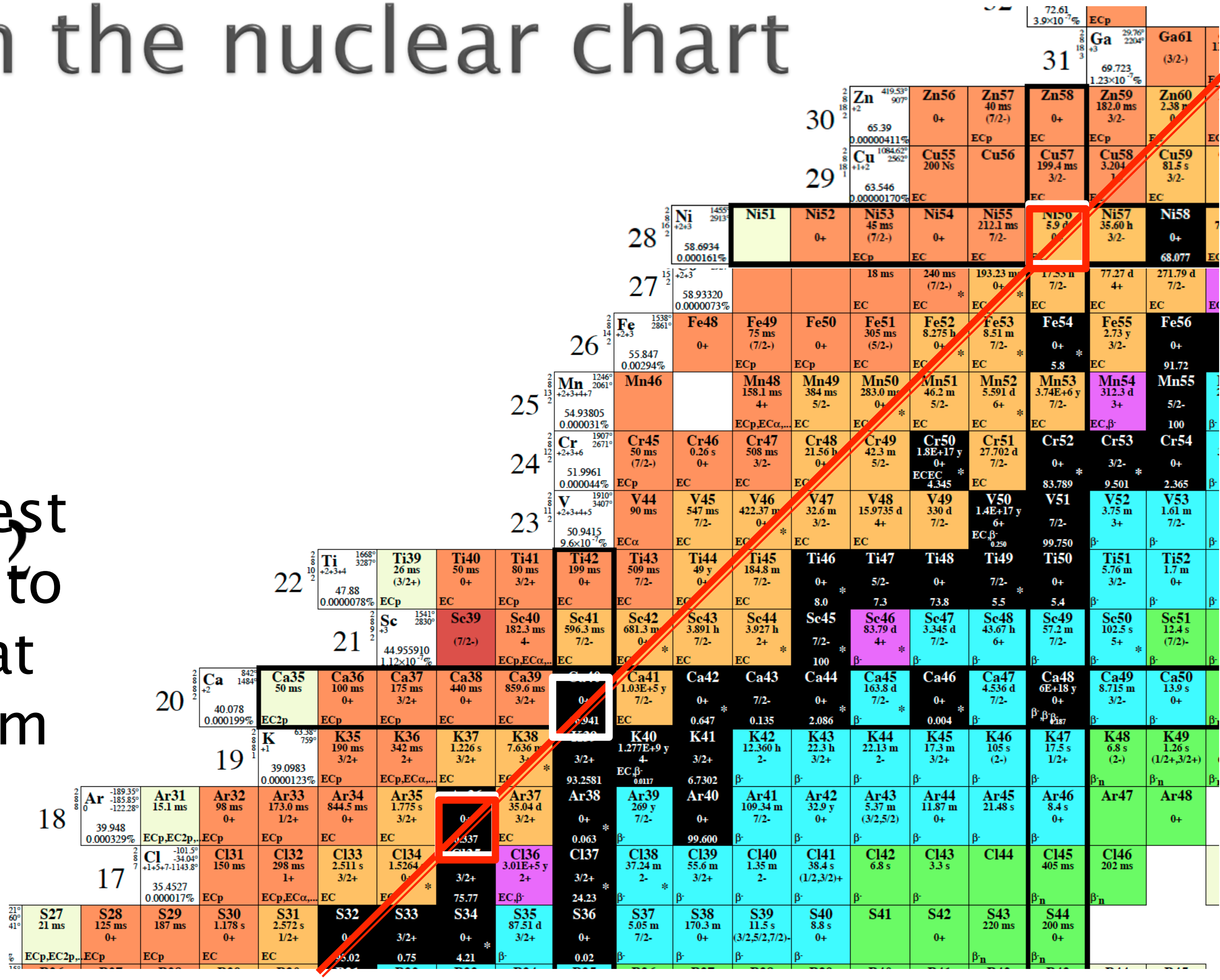
K. Ikeda, N. Takigawa, and H. Horiuchi,
Prog. Theor. Phys . Suppl. Extra Number 464(1968)

- Experimentally,
- only 3−α state in ^{12}C is established
- n=4, 5,,, systems are still under discussion

Candidate for α cluster state search in the nuclear chart

^{40}Ca is the heaviest in stable nuclei

^{56}Ni is the almost heaviest ? N=Z nucleus to be obtained at recent RI beam facility

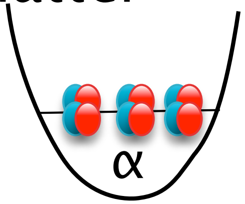


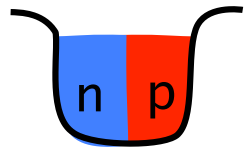
α cluster state in medium heavy nuclei

- Theoretically, existence of the α cluster states in several nuclei are actively discussed
  - Bose-Einstein condensed state of nα system
  - $r = 1.2 \sim 1.5 \times r_0$
  - $\rho \sim 1/2\ \rho_0$
  - Access to low kT, low density nuclear matter

A. Tohsaki, H. Horiuchi, P. Schuck and G.Ropke, PRL 87 (2001) 192501
T. Yamada and P. Schuck PRC 69 (2004) 024309
N. Itagaki et al. PRC 77 (2008) 037301 etc.

- Experimentally,
  - We do not know
    - how to excite α cluster state.
      - Inelastic scattering? HI-HI collision? α transfer reaction?......
    - how to detect signals.
      - One straight forward way is to see α decay. It might be a good candidate, but is it enough ?

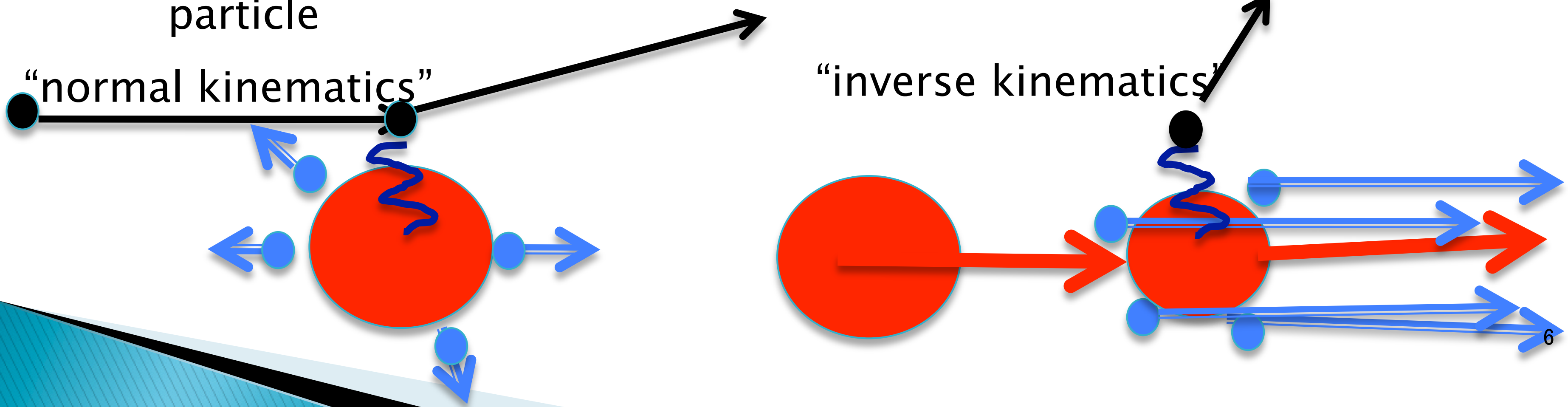




- Almost no attempts have been done to find cluster state in medium heavy nuclei experimentally

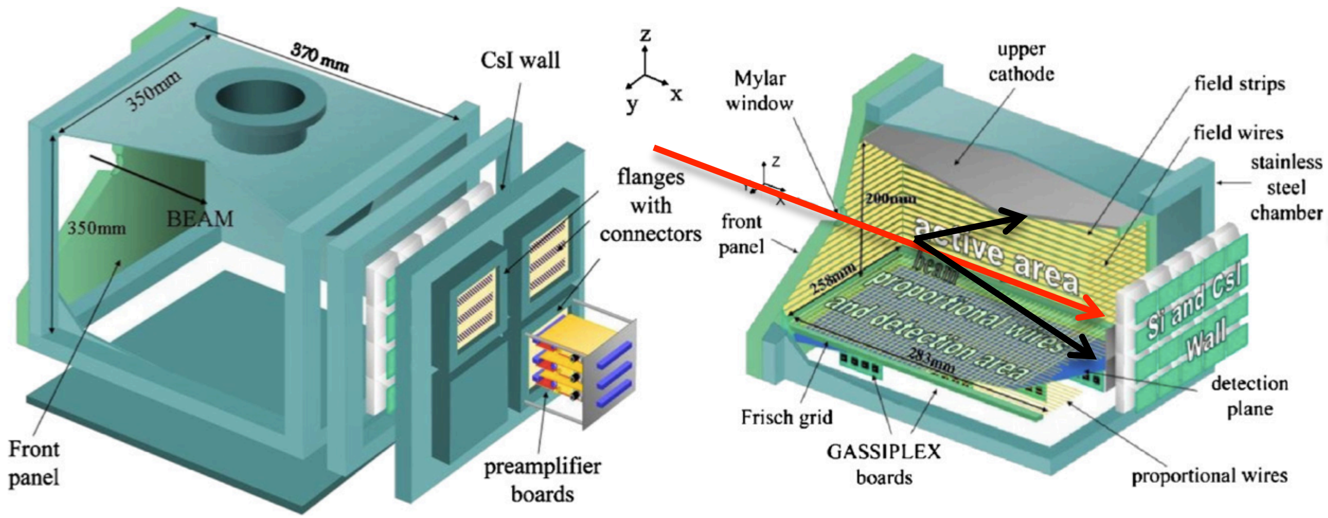
Inverse Kinematics Experiment

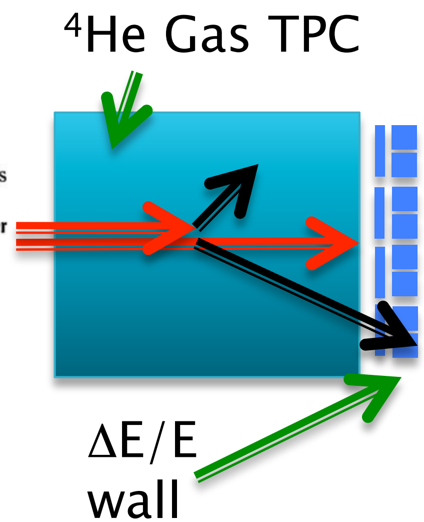
- Inverse Kinematics
  - Detect multi alphas emission from incident nuclei
  - At E = 50 MeV/u
- Inverse Kinematics <-> Normal Kinematics
  - + High acceptance for decaying particles is achievable
  - + Easy to detect decaying particles with small relative momentum to the incident particle
  - – Incident particle and decaying particle has the same P/A and P/z. This makes background at forward angles
  - – Estimation of excitation energy is not easy
    - It is not easy to measure energy and angles of recoiled target particle



E605 at GANIL (May 2011)

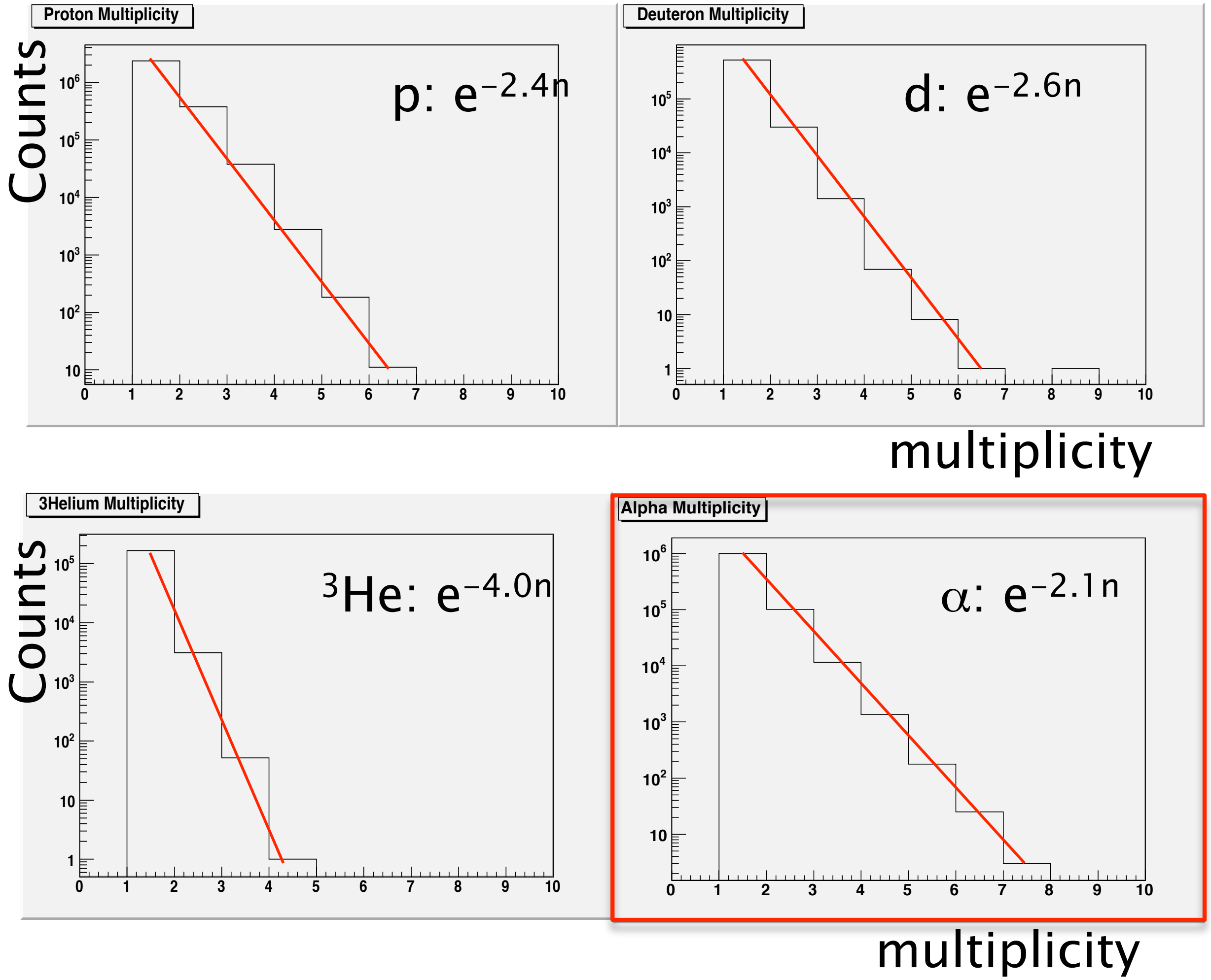
- ^{56}Ni beam with E = 50 MeV/u
- Active gas target system MAYA.
  - Charged particles scattered to
    - backward angles are tracked by ^{4}He TPC, which works as active ^{4}He target.
      - In our analysis, ^{4}He gas TPC is used only to determine the vertex point of reaction.
    - forward angles are detected by a ΔE/E counter telescope wall, which consists of 5x4 Silicon detectors and 10x8 CsI scintillaters





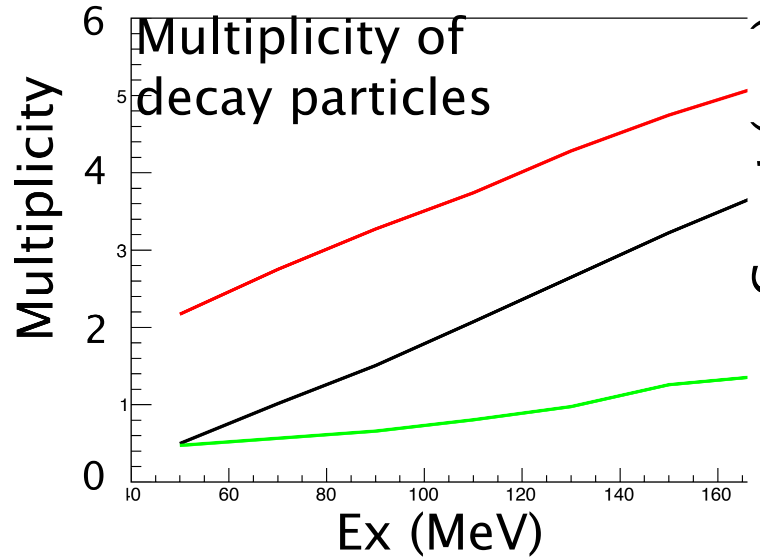
Result of $^4He(^{56}Ni,nX)$ experiment

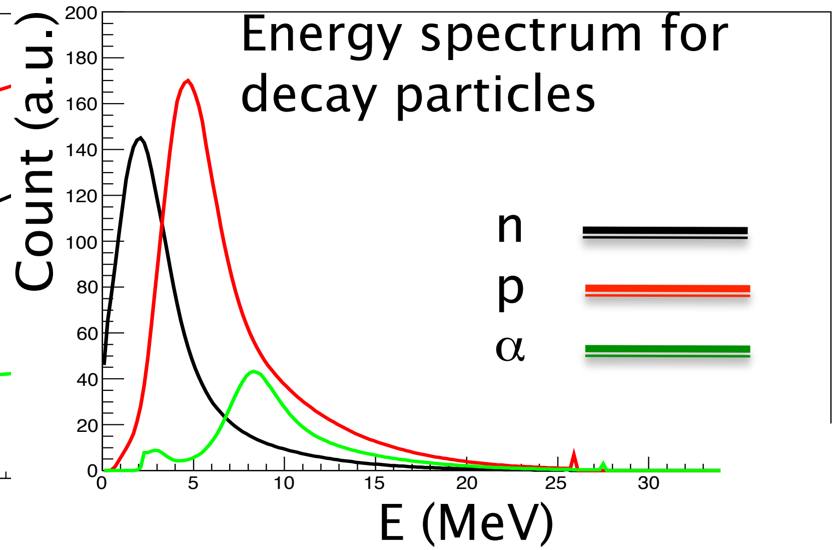
- The maximum multiplicity for α is 7!
  - Half mass of ^{56}Ni decays to α particles
- Decay constant for α is the smallest compare to other decay elements.
- Striking enhancement of α multiplicity
- Strongly suggests existence of α cluster state in ^{58}Ni



Comparison with statistical decay model

- Statistical decay model calculation code "CASCADE"
- Exact treatment of the spin, parity, isospin selection rule
- γ, n, p, α decay channels are taken into account.
- Decay thresholds energies are taken from the mass table.
- Phenomenological level densities and penetration probabilities for n, p, α





Multiplicity for α is estimated to be 1~2.
Statistical decay model can not explain the enhancement of multiplicity of α particles

Comparison with classical gas model

- In this model, excited ^{56}Ni is considered to consist of 14 free α 's
- These α's are assumed to be in classical ideal gas state
- Probability for α with momentum p is given by Maxwell-Boltzmann distribution:

$$f(\mathbf{p}) \propto \exp\left(-\frac{\mathbf{p}^2}{2mk_B T_\alpha}\right)$$

- Here
- p: momentum of α in the rest system of ^{56}Ni
- T_α: Temperature of α gas
- k: Boltzmann constant
- $Ex \sim E_{th}(n\alpha) + 3nkT_\alpha/2$

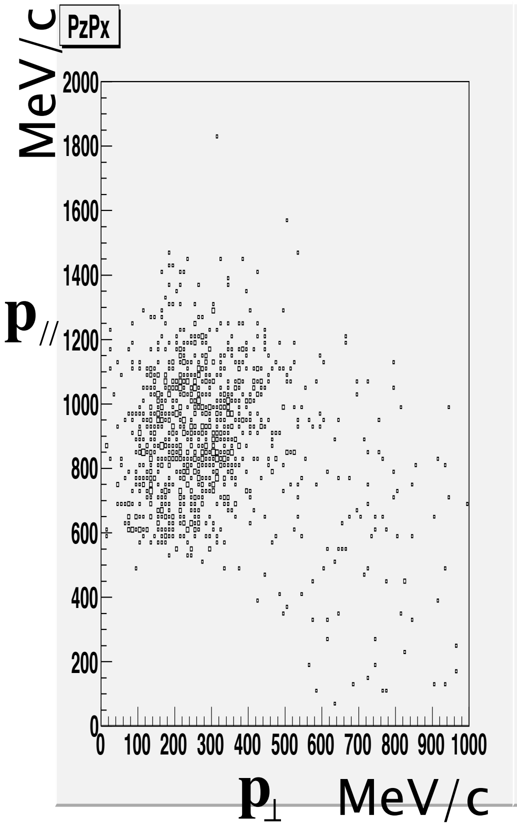
Momentum distribution of α

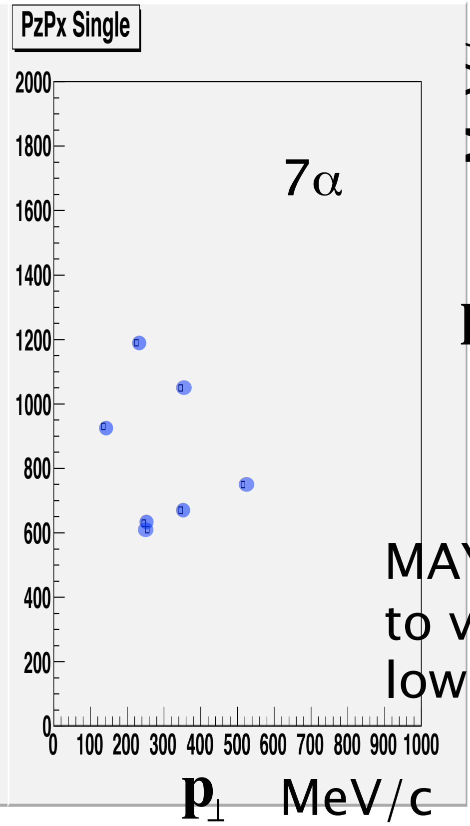
Experiment

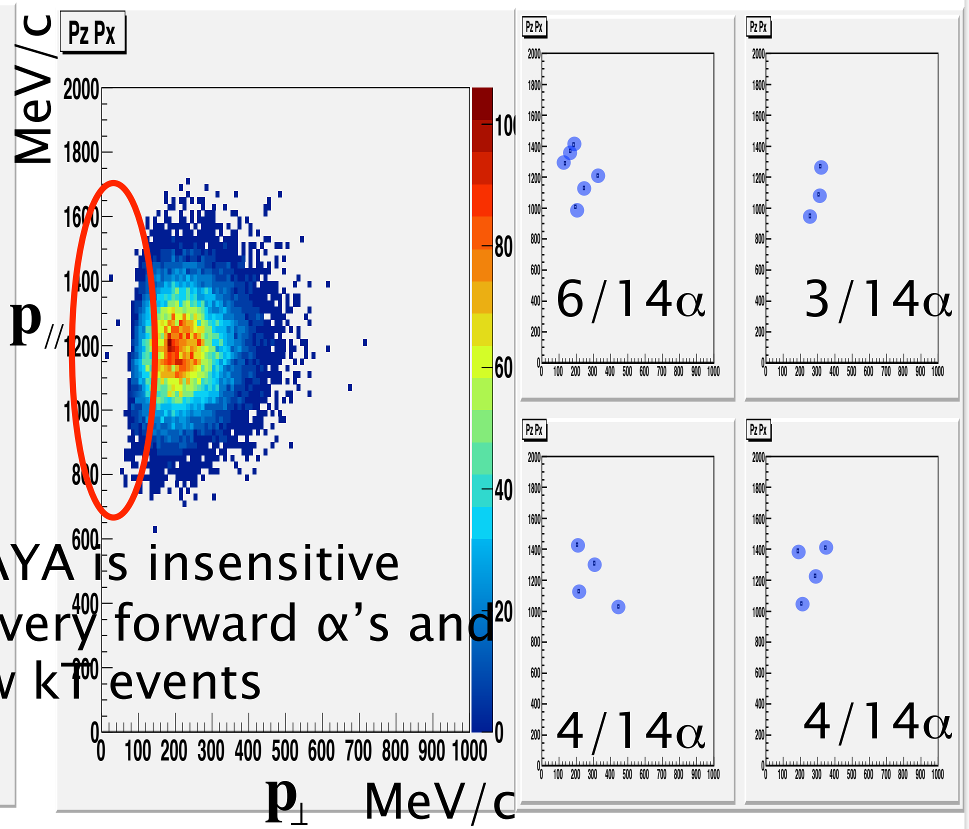
Sum of evens with M>4

Single event with M=7

Simulation for kT_{α}= 5 MeV, including the efficiency of the detector MAYA







MAYA is insensitive to very forward α's and low kT events

Classical gas model fairly well reproduces the experimental multiplicity of α and the momentum distribution.

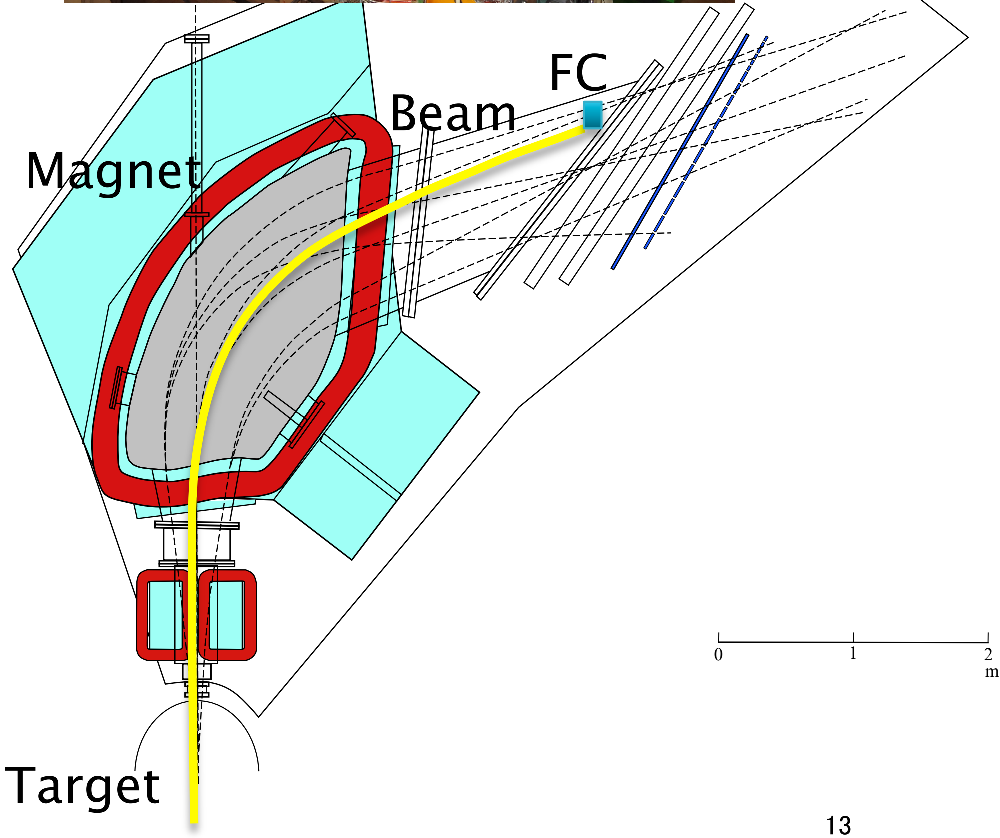
E391 at RCNP Osaka (May 2013)

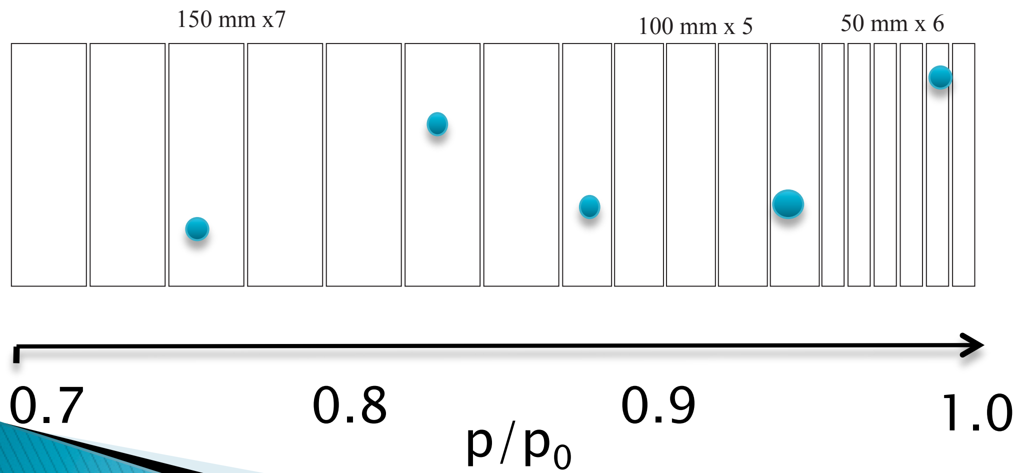
Experimental setup in E605, MAYA is insensitive for lower kT_α

- We started Inverse Kinematics experiment with stable heavy ion beam
- Primary ^{36}Ar beam with 50 MeV/u
  - ~10 pnA, 16+ ^{36}Ar
- In order to improve detection efficiency for Low kT_α,
  - Magnetic spectrometer is set at 0 deg.
- In order to detect α's at backward angles,
  - Si+CsI counter telescope array

Experimental Setup

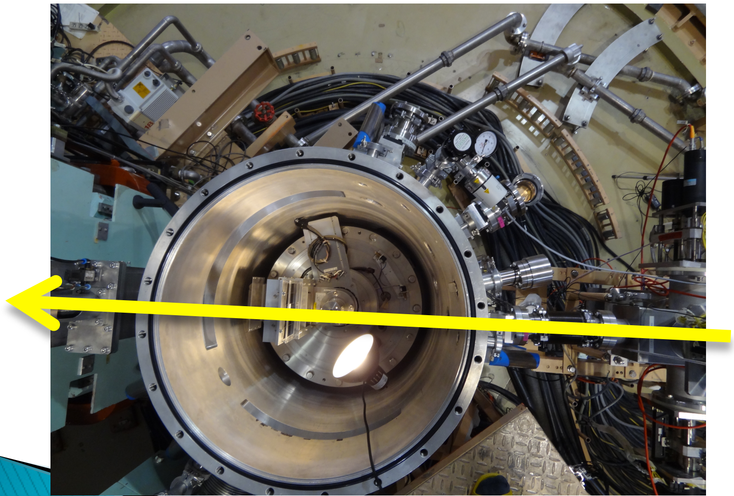
- LAS (Large Acceptance Spectrometer)
  - At 0 degree
  - ±50 mr × ±50 mr (±3deg × ±3 deg)
  - $\delta p/p$ = 30 %
- Segmented Hodoscopes
- p: momentum of α
- p_0: momentum of α rest on cm system of ^{36}Ar

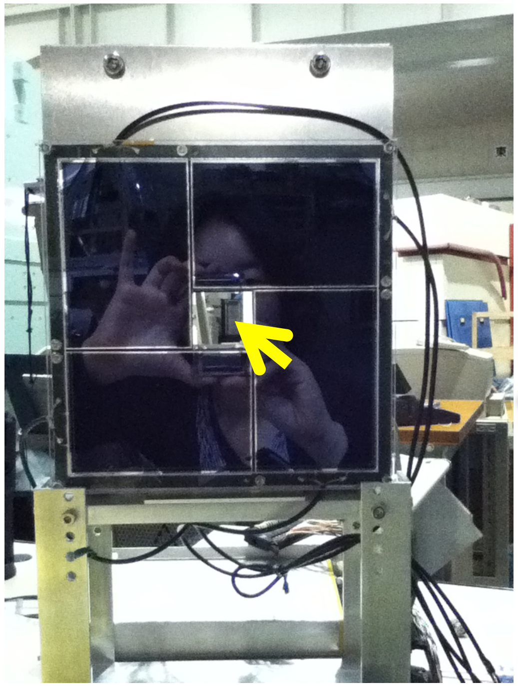


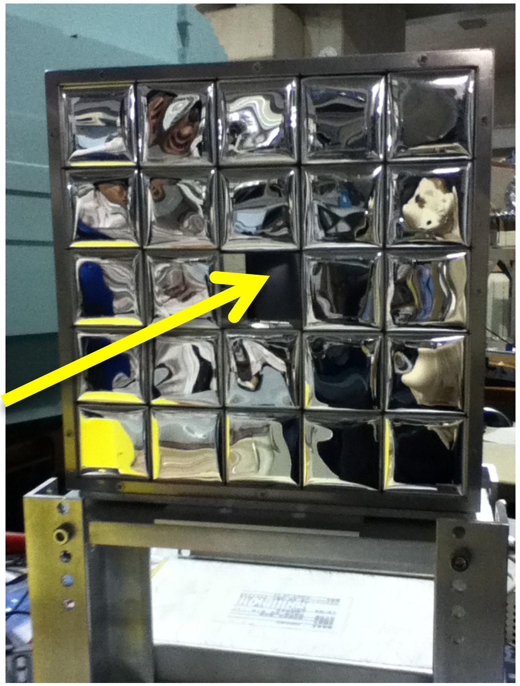


Silicon+CsI Counter array

- Alpha particles at backward angles (8 deg< θ)
  - E ΔE counter telescope array
- Silicon detector 60 mm x 90 mm x t500 μm
  - 4 sets
- CsI 30 mm x 30 mm
  - 24 sets
  -

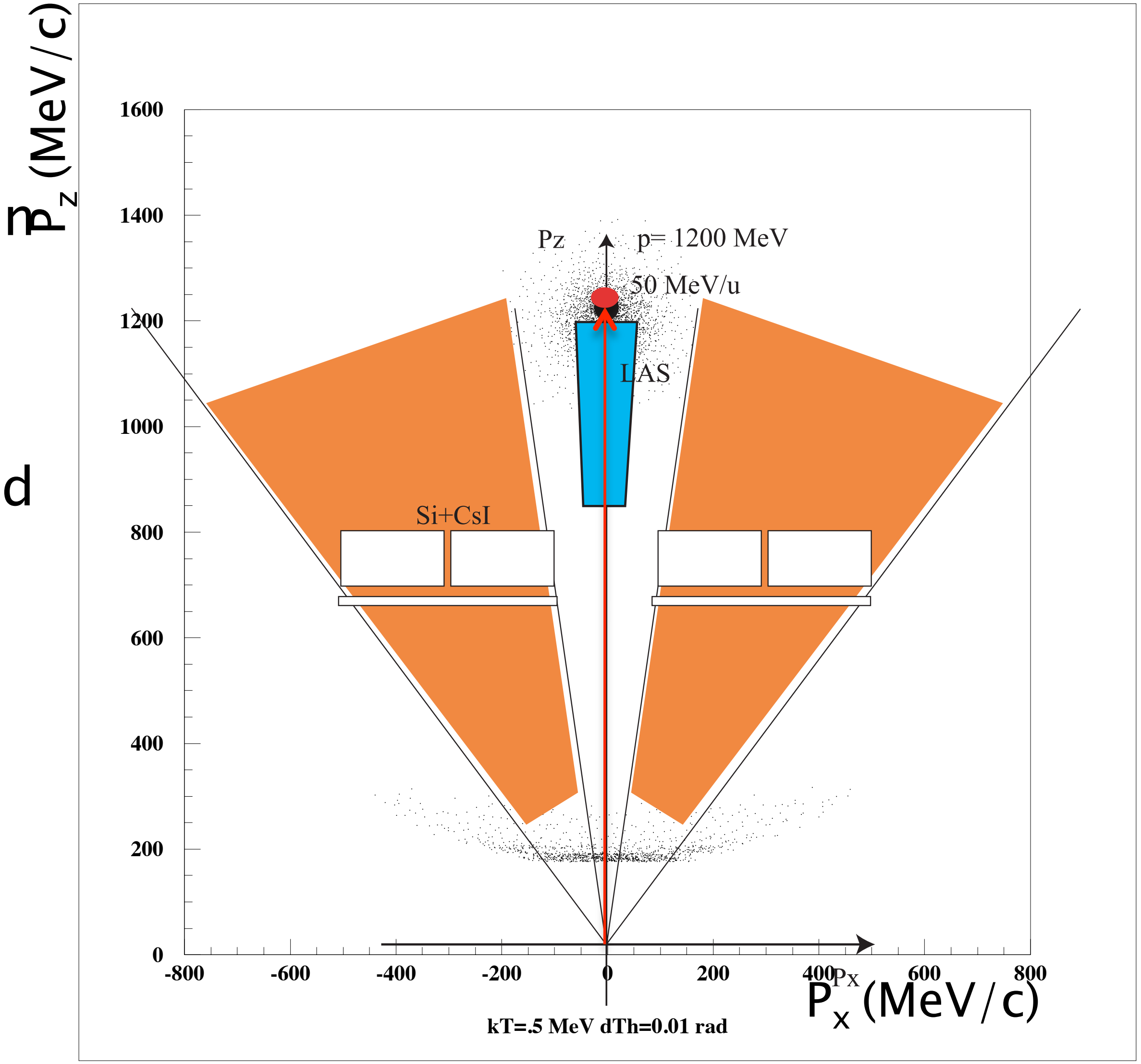






Acceptance for multi alpha event

- 9α E_{th} = 52.5 MeV
- Dot plot
  - Momentum distribution of α particles emitted from ^{36}Ar
  - For kT = 1.0 and 0.5 MeV
  - Locus at low p: recoiled α
- LAS
  - Forward angels
  - 0<θ<3 deg
- Si+CsI
  - Backward angles
  - 8<θ<40 deg
- Incident beam

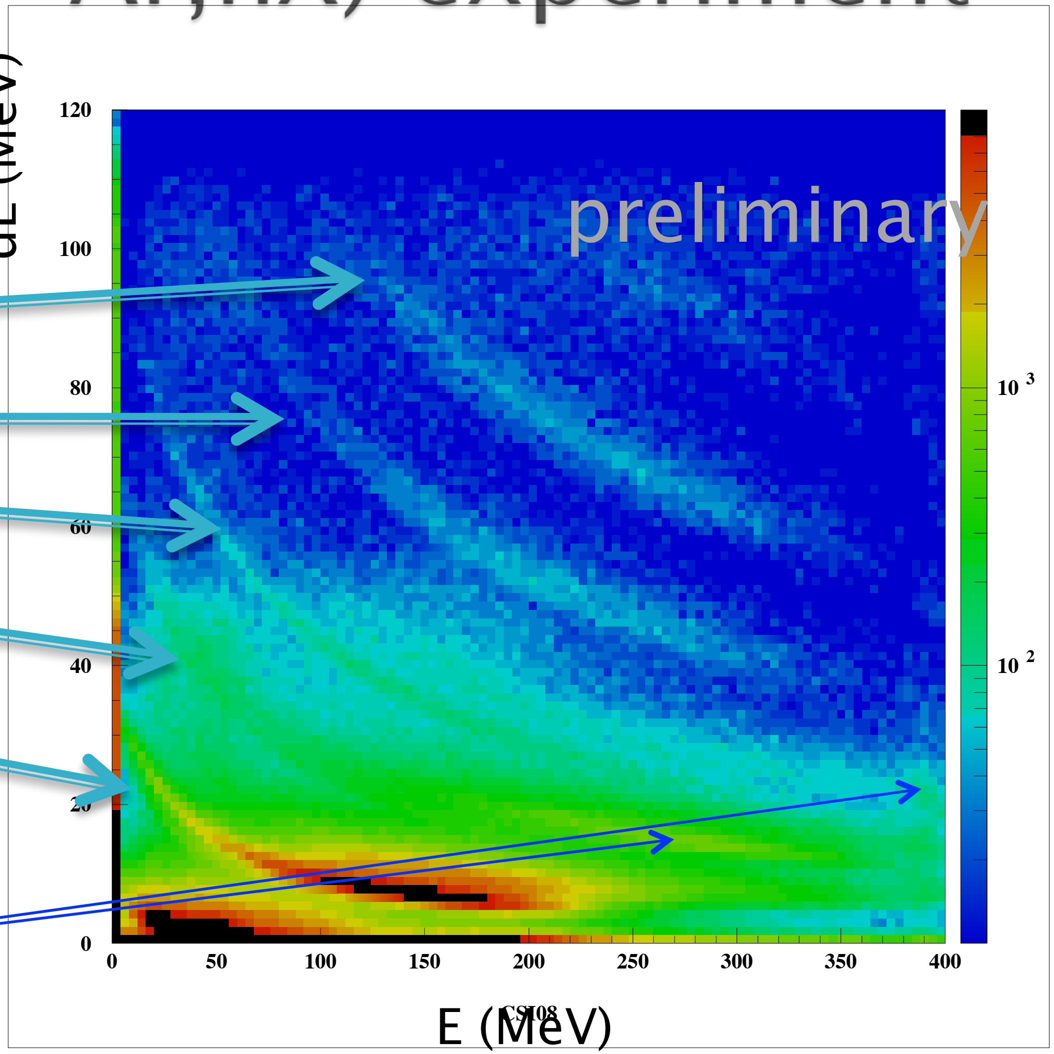


Result of $^{4}He(^{36}Ar,nX)$ experiment

- Silicon + CsI
  - Particle Identification works very well
  - ^{12}C,,,
  - ^{10}B, ^{11}B
  - ^{7}Be, ^{9}Be
  - ^{6}Li, ^{7}Li
  - α

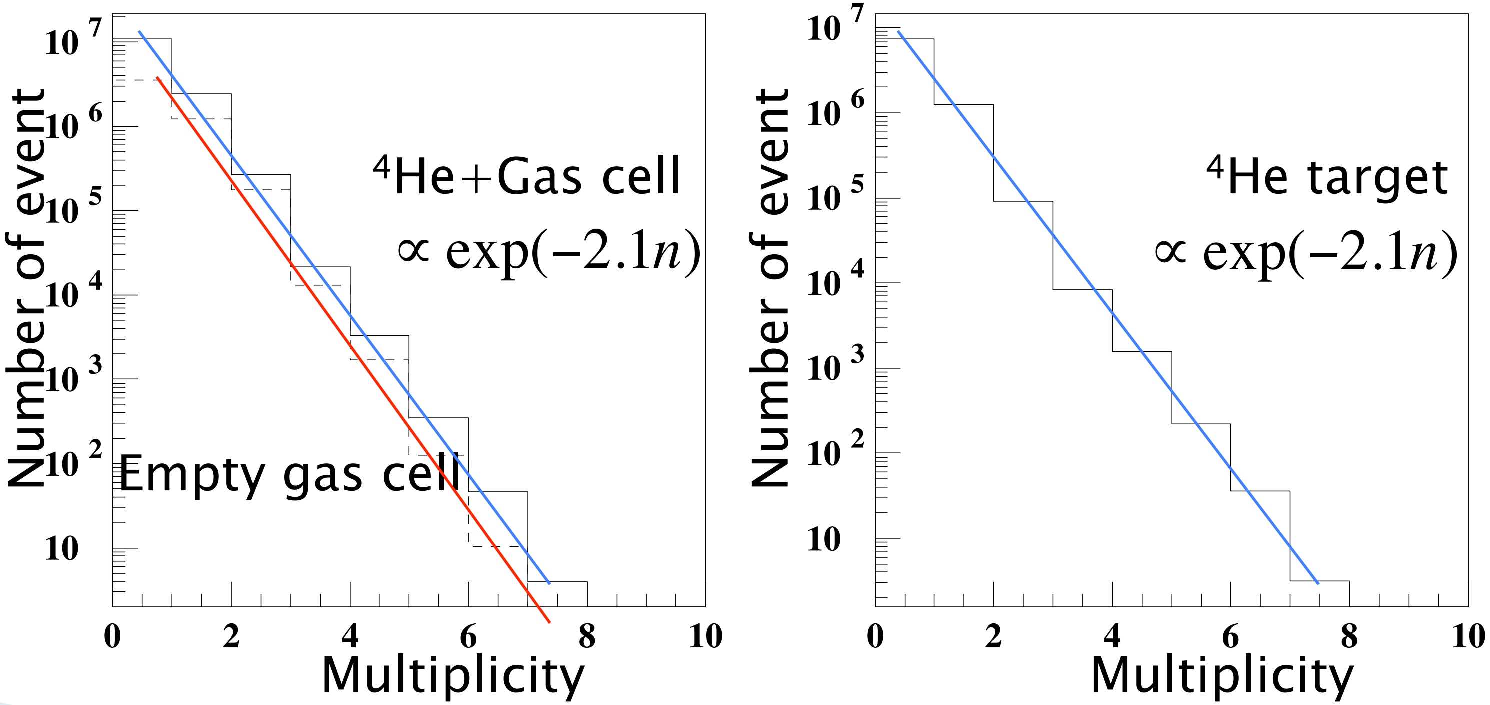
Broad loci

2α、3α？



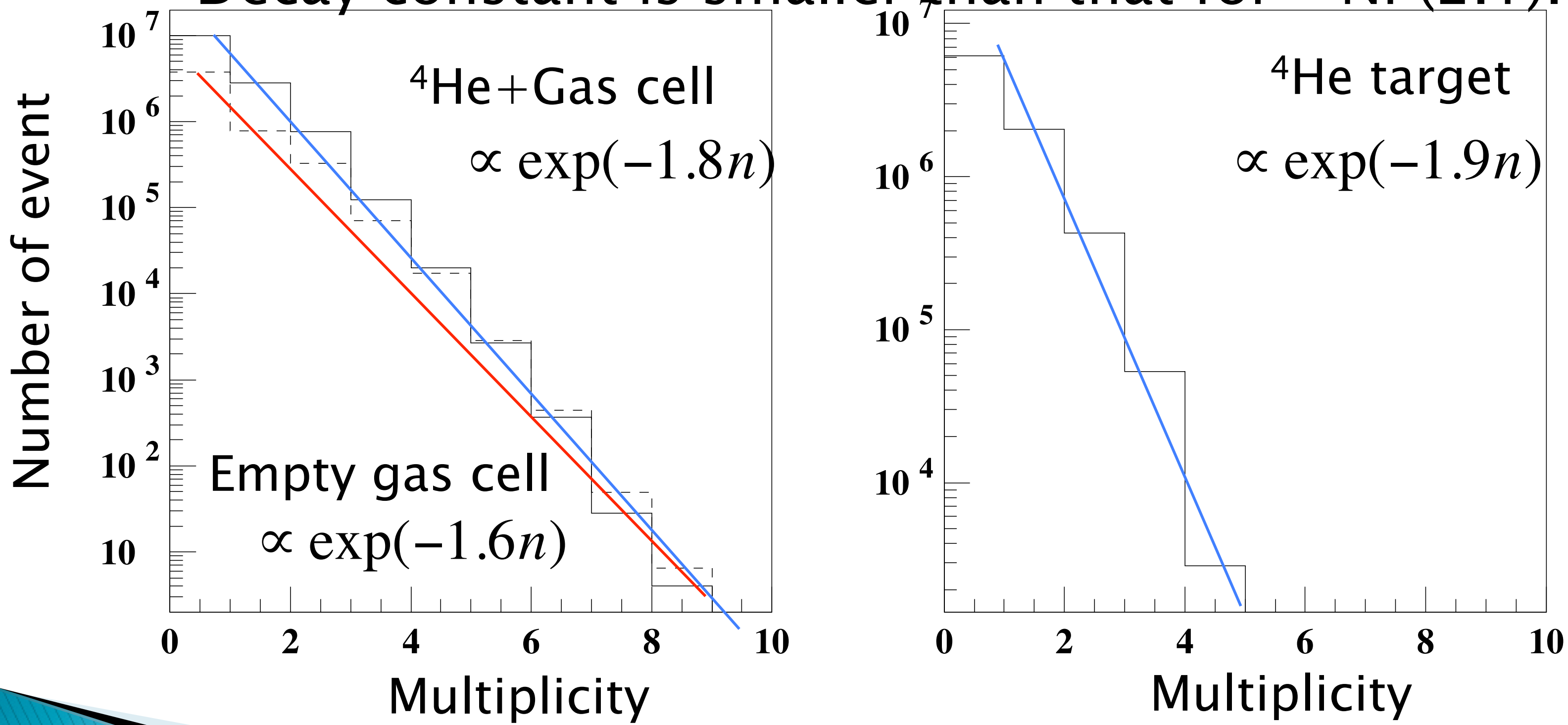
Multiplicity of alpha particles I

- Number of α's at forward angles (LAS)
  - $\theta_\alpha < 3$ deg, 100 MeV $< E_\alpha <$ 200 MeV
    - Decay constants for ^{4}He target and heavier nuclei targets such as C, N, O are almost same.



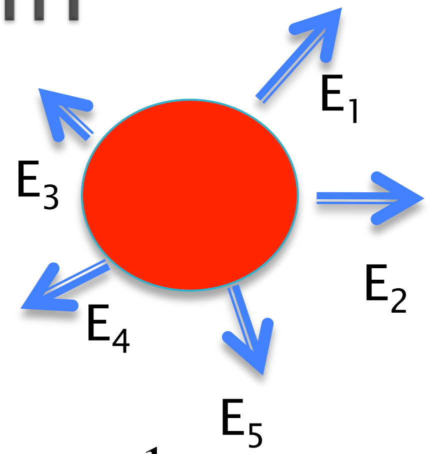
Multiplicity of alpha particles II

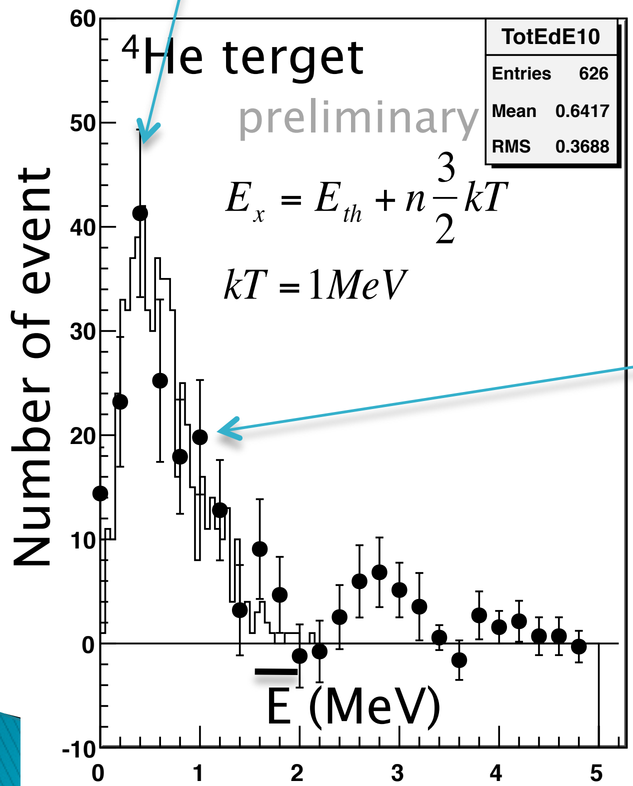
- Number of α's at backward angles (Si+CsI)
  - 8 deg < θ_α < 40 deg, 100 MeV < E_α <300 MeV
    - Decay constant for ^{4}He target is larger than other heavier nuclei targets such as C, N, O (cell material)
    - Decay constant is smaller than that for ^{58}Ni (2.1).

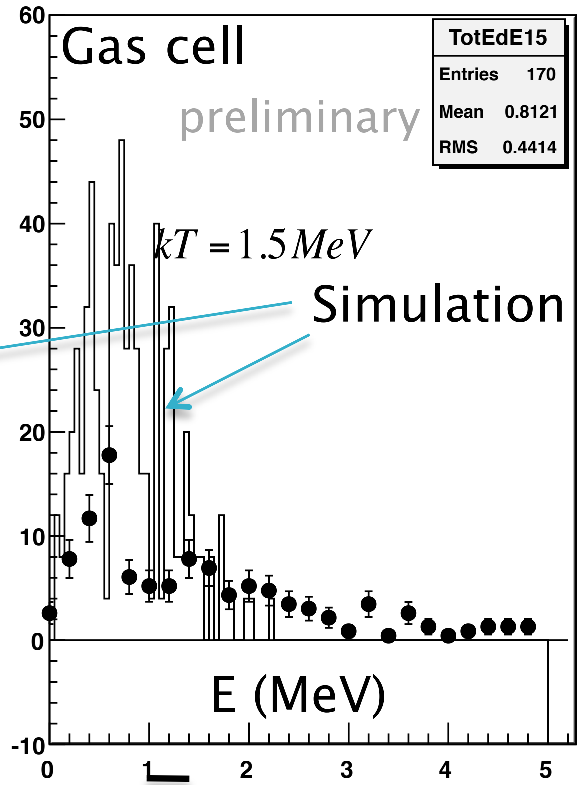


Mean kinetic energy of α's in ^{36}Ar's cm system

- Peak at E ~ 0.5 MeV
  - Simulation with $kT_\alpha = 1$ MeV well reproduces the experimental result







$$\overline{E} = \frac{1}{n}\sum E_i$$

$$E_i = \frac{(p_i - p_0)^2}{2m_\alpha}$$

i: the i_th α in one event
n: Multiplicity of α

events with n = 5 are selected

Summary

- $^4He(^{56}Nr,n\alpha)$ experiment has been performed at GANIL
- $^4He(^{36}Ar,n\alpha)$ experiment has been performed at RCNP
- In both experiments, high α multiplicity events were detected
- At backward angles, excitation energies for multi α decay events are estimated to be about

  kT_α=5 MeV
  - Both experimental results are consistent
- Magnetic spectrometer was applied to measure α particles at forward angles
- At forward angels. excitation energies are estimated to be about
- kT_α= 1MeV.
- These experimental result suggest excitation of α cluster state in medium heavy nucle
  - Questions arise from our experiment
    - May we call it "α gas state"?
    - Is multi α decay is unique for A=4n, N=Z=2n nuclei?
    - For the incident energy, how much energy is suitable?
    - 50 MeV/u: Energy region where ISGMR is strongly excited is suitable