

New Capabilities of the GRAND RAIDEN Spectrometer

Tomotsugu WAKASA
RCNP
Osaka University



Overview

- **RCNP Ring Cyclotron Facility**
- **Grand Raiden Spectrometer**
- **Dispersion Matching Technique**
- **WS Beam Line**
 - Specifications
 - Ion-optical properties
 - Lateral and angular dispersion matching
- **Recent Experimental Results**
 - (p, p')
 - $(^3\text{He}, t)$
 - $(^4\text{He}, ^6\text{He})$
 - Over-focus mode
- **Summary**

RCNP Ring Cyclotron Facility

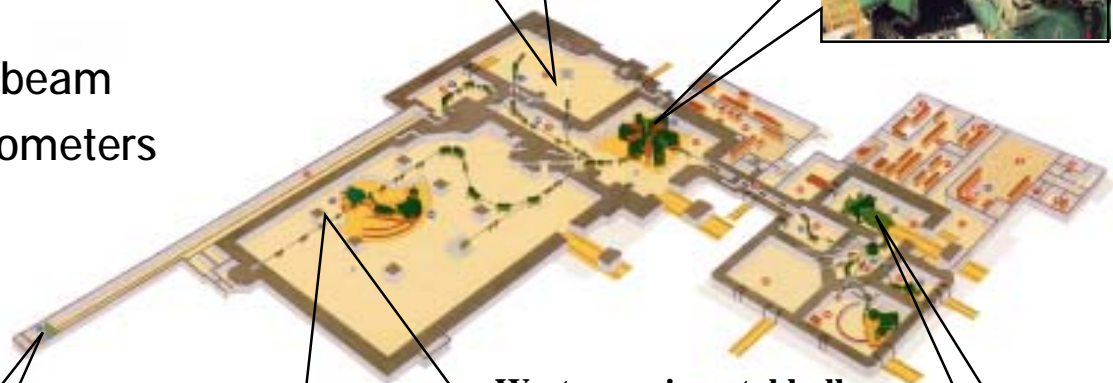
■ Unique Points

- Polarized beams
 - *Protons*
 - *Deuterons*
- High resolution beam
- Two-arm spectrometers
- Polarimeters
 - *FPP*
 - *2nd FPP*
 - *NPOL2*

East experimental hall



Ring Cyclotron



West experimental hall



Neutron Course



AVF Cyclotron

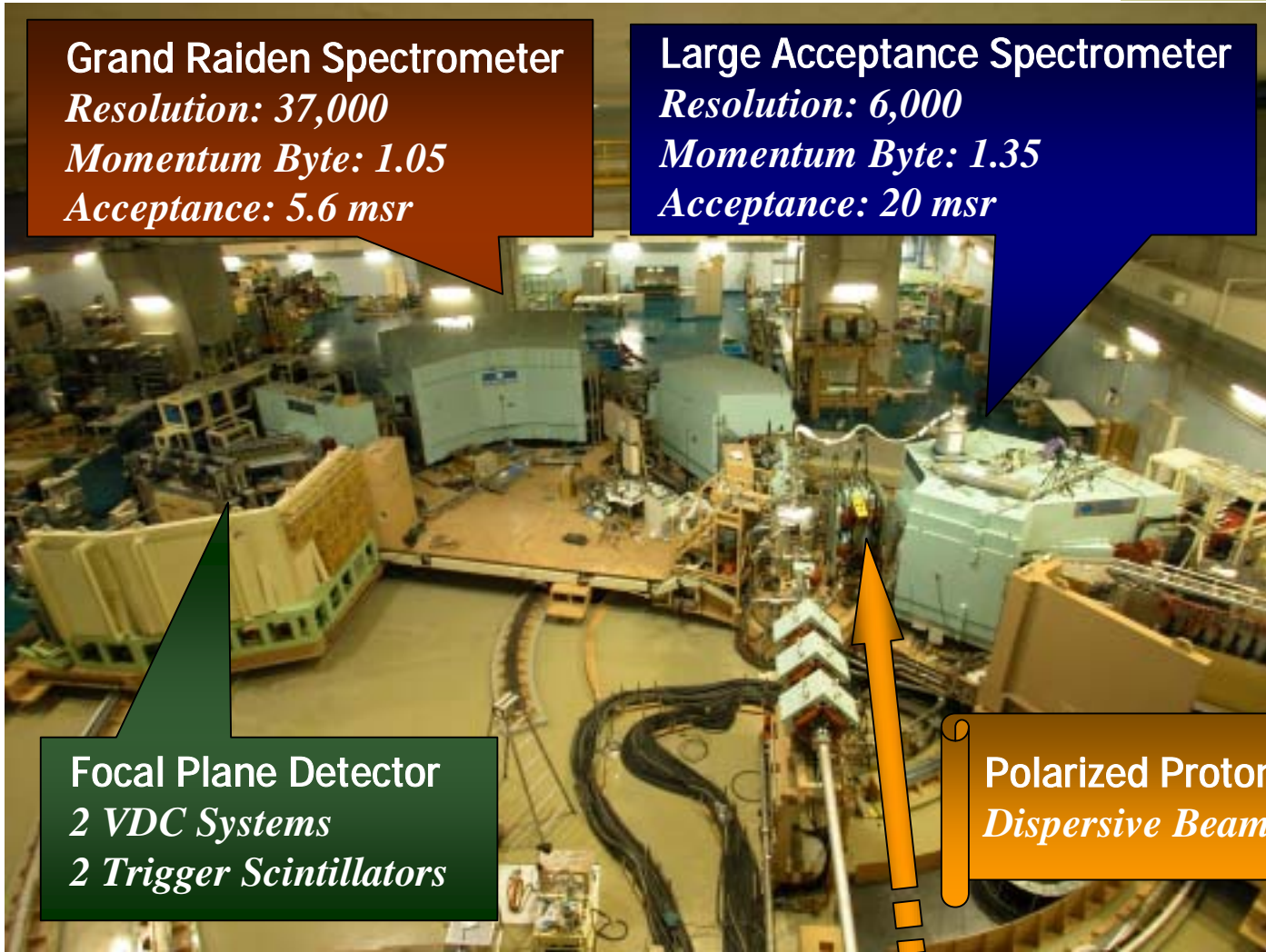
Grand Raiden Spectrometer

Grand Raiden Spectrometer
Resolution: 37,000
Momentum Byte: 1.05
Acceptance: 5.6 msr

Large Acceptance Spectrometer
Resolution: 6,000
Momentum Byte: 1.35
Acceptance: 20 msr

Focal Plane Detector
2 VDC Systems
2 Trigger Scintillators

Polarized Protons
Dispersive Beam

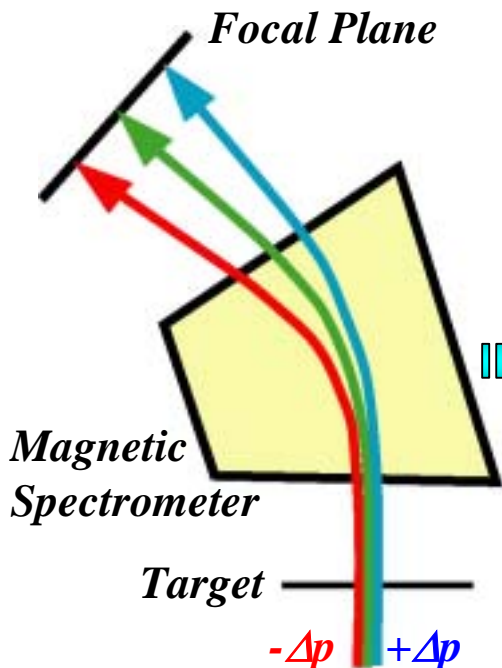


Dispersion Matching

Y. Fujita et al., Nucl. Instrum. Methods Phys. Res. B 126 (1997) 274.

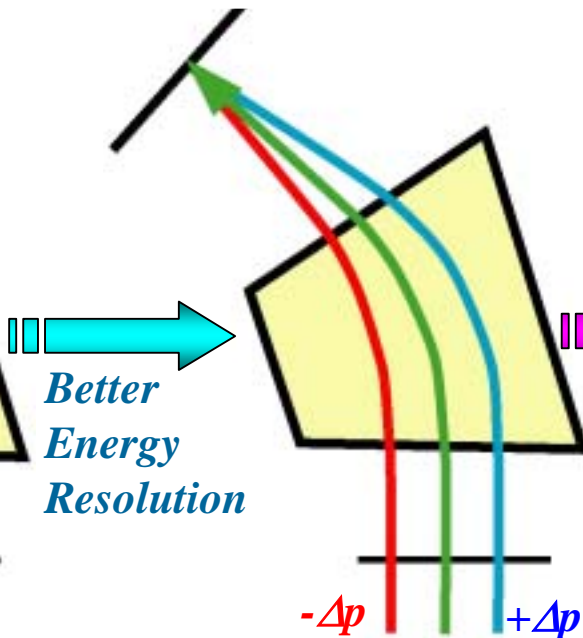
H. Fujita et al., Nucl. Instrum. Methods Phys. Res. A 484 (2002) 17.

Achromatic Mode



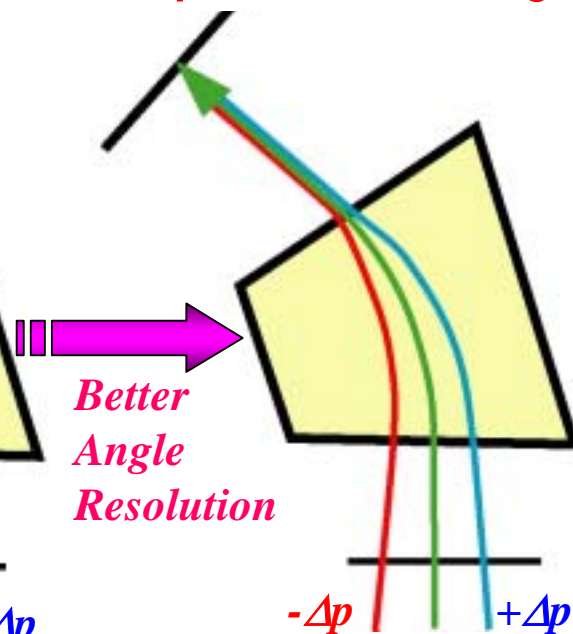
$\Delta E = 100 \text{ keV}$
for 400 MeV proton beam

Lateral Dispersion Matching



$\Delta E = 16 \text{ keV}$
x is independent of Δp
 θ depends on Δp

Lateral and Angular Dispersion Matching



$\Delta E = 16 \text{ keV}$
x is independent of Δp
 θ is independent of Δp

Specifications of WS

- Total length: 65.46m
- Total bending angle: 270 °
- Five double-focus points (Two for BLP)
- Dispersive mode
 - *Dispersion: 37.1 m*
 - *Angular dispersion: 20.0 rad*
 - *Compete matching with GR*
- Achromatic mode
 - *Lateral dispersion: 0 m*
 - *Angular dispersion: 0 rad*
 - *Double achromatic beam*



WS Beam Line and Two-Arm Spectrometers at RCNP

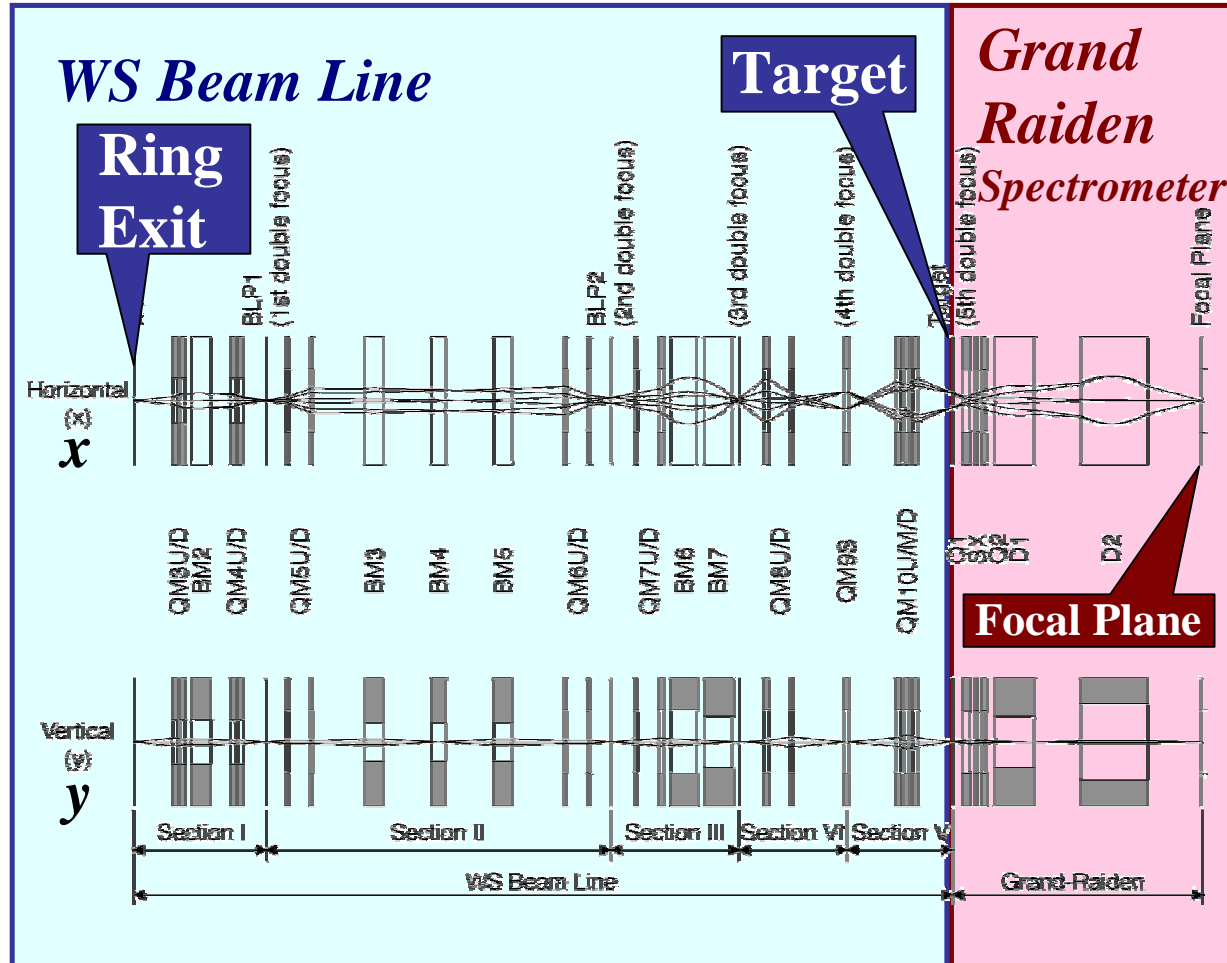
WS Beam Line and Grand Raiden in Dispersive Mode

■ Beam Envelopes

- P: $\pm 0.03\%$
- θ : $\pm 2\text{mrad}$
- ϕ : $\pm 2\text{ mrad}$

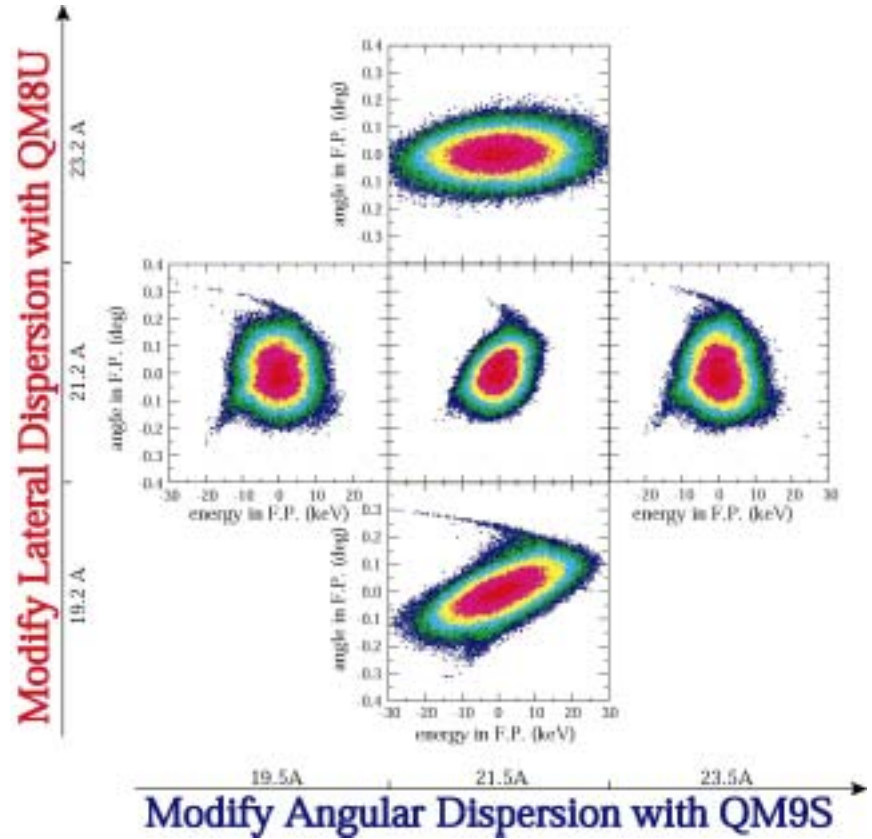
■ Ion-optical properties

- M_x : 0.41
- D: 0 m
- $(\theta|p)$: 0 rad



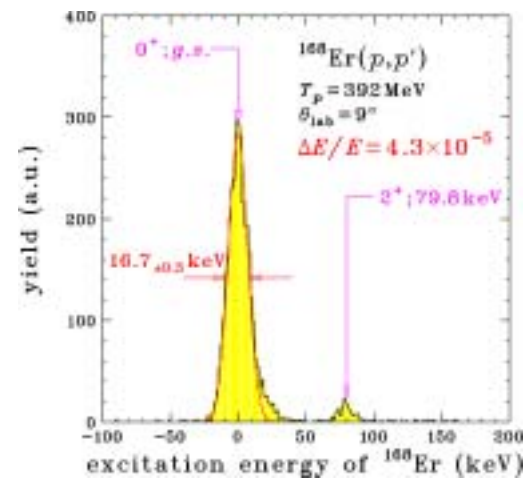
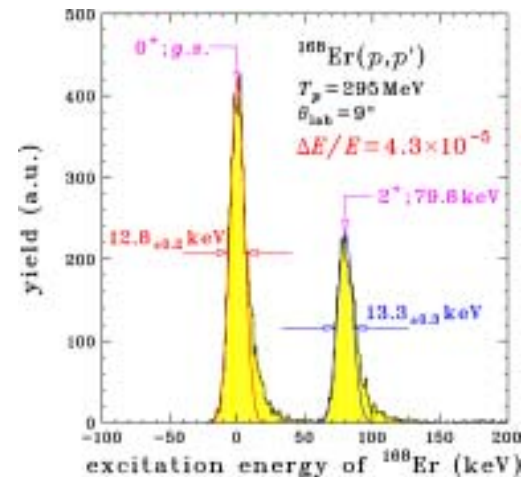
Dispersion Matching and Horizontal Beam Profiles in the Focal Plane of Grand Raiden

- **Horizontal Beam Profiles in F.P.**
 - Horizontal: Beam-oriented energy spread
 - Vertical: Beam-oriented angular spread
- **Control Lateral and Angular Dispersions Independently**
 - Lateral dispersion: QM8U
 - Angular dispersion: QM9S
- **References**
 - T. Wakasa et al. NIMA 482, 79 (2002)



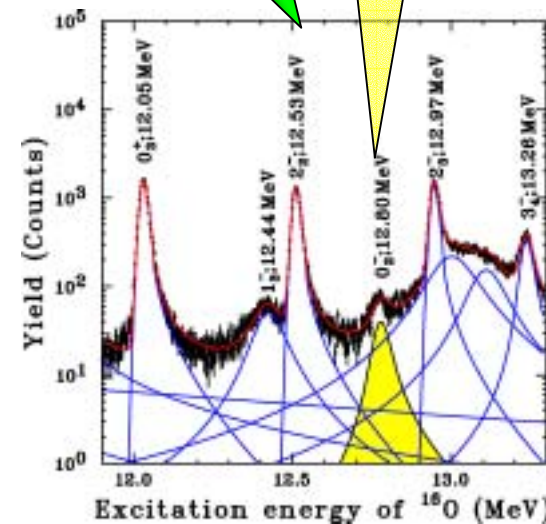
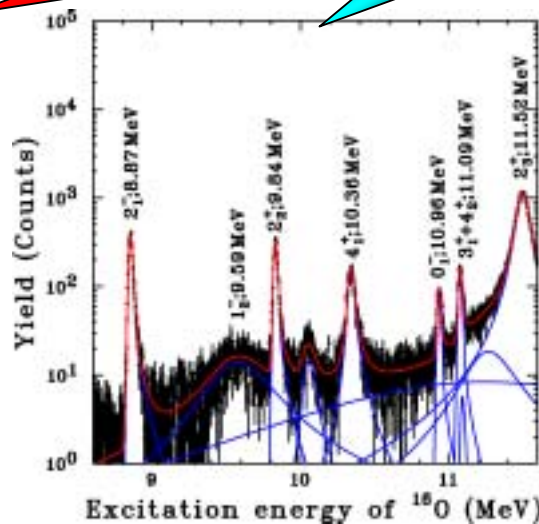
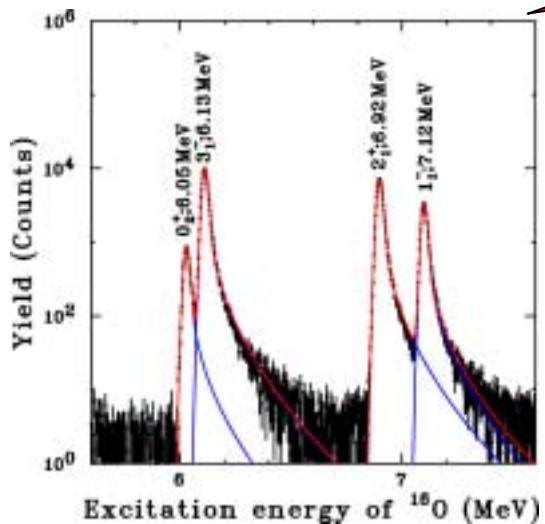
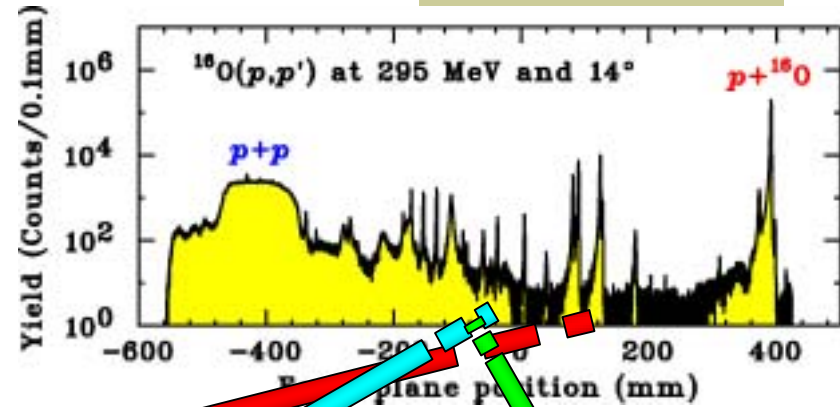
Typical Spectrum of $^{168}\text{Er}(p,p')$ after Employing Dispersion Matching

- **Beam energy**
 - 295 MeV (April 2000)
 - 392 MeV (June 2000)
- **Beam energy spread**
 - ΔE : 150 keV(FWHM)
- **Target**
 - ^{168}Er : 2 mg/cm²
- **Energy resolution**
 - 13.0 keV for 295 MeV
 - 16.7 keV for 392 MeV
- Energy resolutions are consistent with the resolving power limit of Grand Raiden

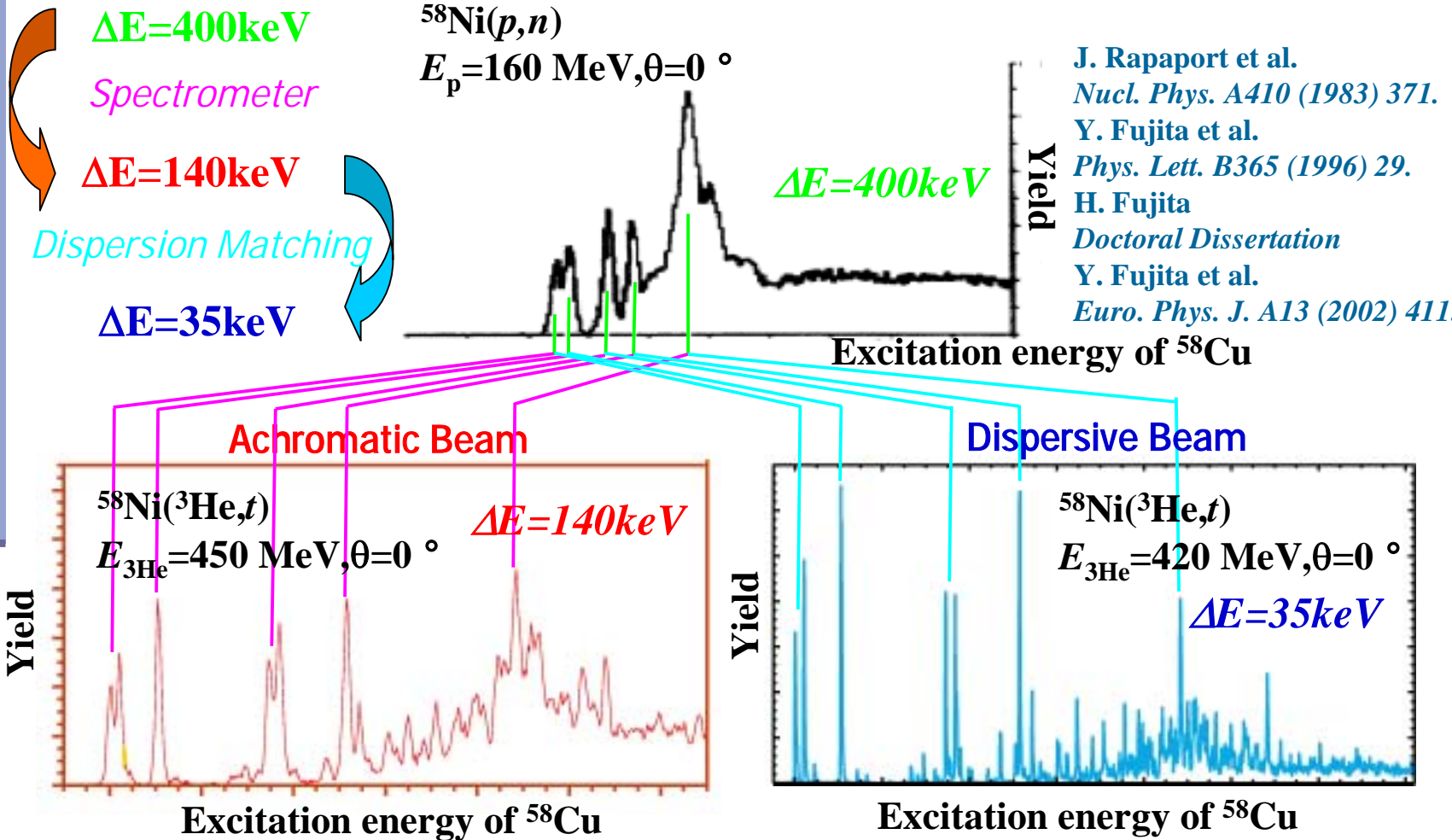


Results of Fitting at Forward Angle

- **3 Excitation Regions**
 - 5.6 – 8.0 MeV
 - 8.0 – 11.8 MeV
 - 11.8 – 13.3 MeV
(includes $0^-, T=1$ state)
 - Without background
- **Results**
 - $\Delta E = 29$ keV (FWHM)



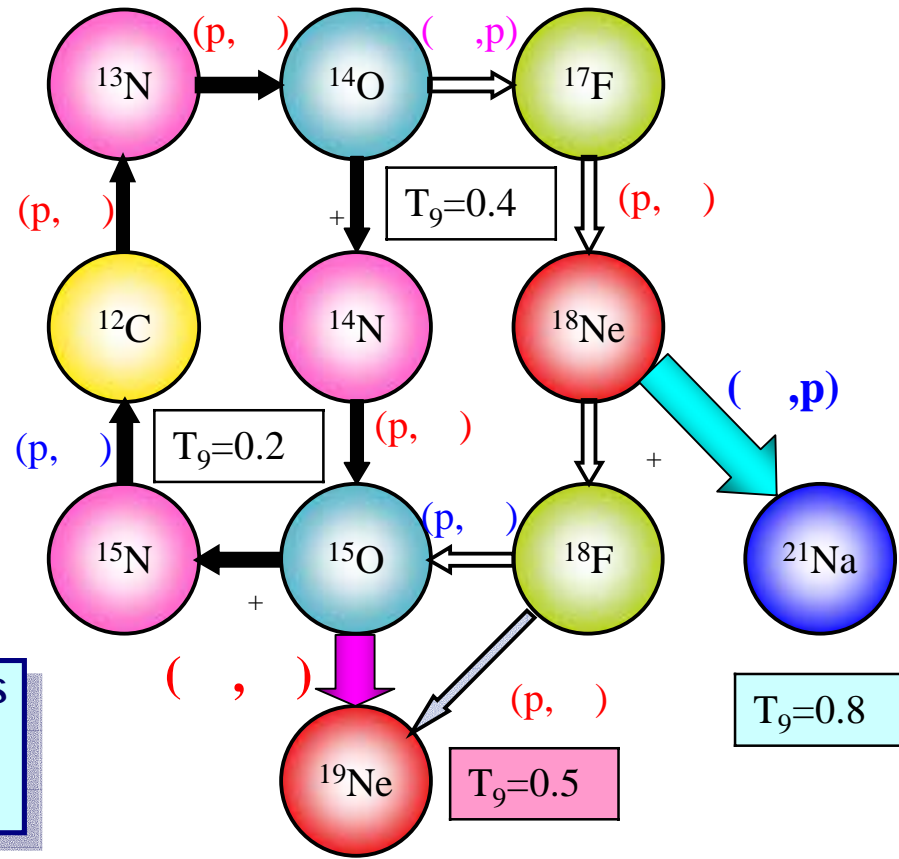
Typical ($^3\text{He},t$) Spectra



H-CNO Cycle

- At $T_9=0.2$
 - CNO cycle only
- At $T_9=0.4$
 - Start bypass cycle through $^{14}\text{O}(\alpha, p)^{17}\text{F}$
- At $T_9=0.5$
 - Breakout from CNO cycle through $^{15}\text{O}(\alpha, \gamma)^{19}\text{N}$
- At $T_9=0.8$
 - If there are some levels in $^{22}\text{Mg}^*$ in low energy region ($E_x > 8$ MeV)

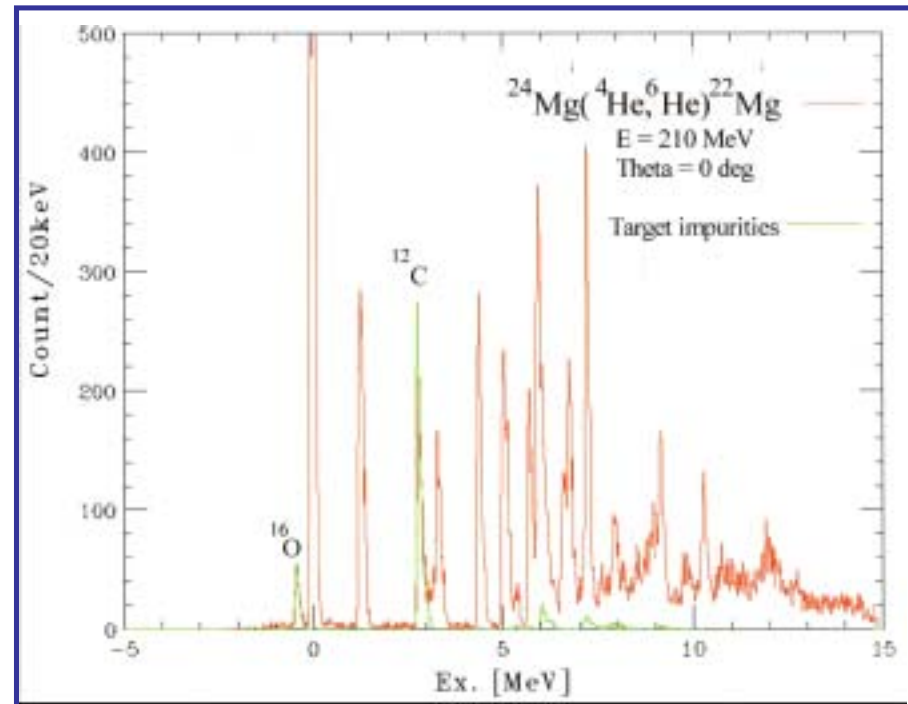
Breakout from CNO cycle is accelerated through $^{18}\text{Ne} + \alpha \rightarrow ^{22}\text{Mg}^* \rightarrow ^{21}\text{Na} + p$



Levels of ^{22}Mg

Y. Kitamura, N. Sakamoto, G.P.A.Berg et al.

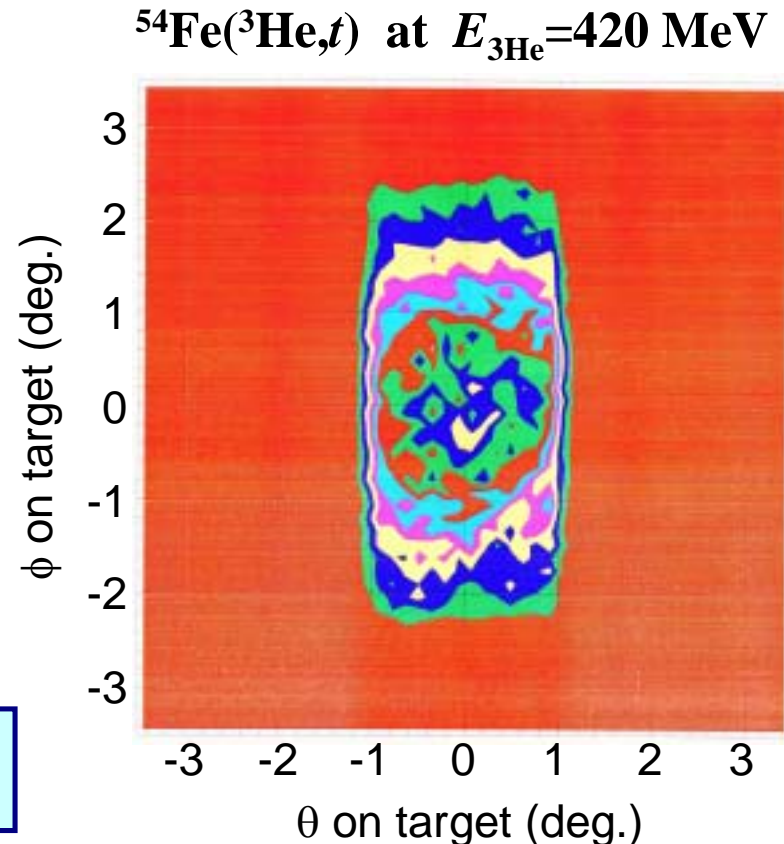
- Resonance states in ^{22}Mg studied via the $^{24}\text{Mg}(\alpha, ^6\text{He})^{22}\text{Mg}$ reaction
- Experimental conditions
 - ^{22}Mg : 1.8 mg/cm²
 - α -beam: 206 MeV, 80 enA
 - Beam resolution: >150 keV
 - Final resolution after dispersion matching: 72 keV (determined by target multiformity)
- Several levels have been clearly observed
- Peak assignment (E_R and Γ) is now in progress



Over-Focus Mode

H. Fujita et al., Nucl. Instrum. Methods Phys. Res. A 469 (2001) 55.

- **Normal Setting of Grand Raiden**
 - $(x|\theta) = (y|\phi) = 0$
 - $M_x=0.42, M_y=6.0$
 - $M_\theta=2.4$ θ on target
 - $M_\phi=0.17$ ϕ on target \times
- **Over-Focus Mode**
 - $(y|\phi) = 0.47$
 - **y on Focal-Plane** ϕ on target
- **Reconstructed (θ, ϕ) image for $L=0$**
 - At 0 deg. $\theta = \phi$
 - **Typical $L=0$ angular distribution as a function of ϕ**
 - Sufficient ϕ resolution has been achieved with over-focus mode



Summary

- **Lateral and Angular Dispersion Matching between WS Beam Line and Grand Raiden Spectrometer is Available and Stable**
 - Only 1 hour from achromatic mode to dispersive mode
 - Dispersion matching conditions were kept during the experiment (about 3 days)
- **Dispersion Matching Techniques have been applied to**
 - (p,p') $\Delta E = 16 \text{ keV at } 400 \text{ MeV}$
 - ($^3\text{He},t$) $\Delta E = 35 \text{ keV at } 420 \text{ MeV (140 MeV/u)}$
 - ($^4\text{He},^6\text{He}$) $\Delta E = 72 \text{ keV at } 206 \text{ MeV (51 MeV/u)}$
limited by the target effect
- **Over-Focus Mode of Grand Raiden**
 - Good angle resolution for ϕ has been achieved
 - Angular distribution measurements at very forward angles including zero degrees ($\theta = \phi$) are possible

Thanks

- ◆ **WS Beam Line Construction Group**
- ◆ **RCNP Accelerator Group**
- ◆ **Experimental Groups who use the Grand Raiden Spectrometer and WS Beam Line**

Osaka University

**Y. Fujita, H. Fujita, K. Shimbara,
T. Adachi**

Kyoto University

**H. Sakaguchi, M. Yosoi, T. Kawabata,
M. Uchida, H. Takeda, M. Itoh**

Kyushu University

T. Noro

Fukui Med. University

K. Tamura

RIKEN

H. Ueno

RCNP

**K. Hatanaka, Y. Sakemi, G.P.A.Berg,
H. Fujimura, H. Yoshida, J. Kamiya,
D. Hirooka, Y. Shimizu, Y. Kitamura,
N. Sakamoto, K. Fujita, M. Uraki,
K. Nagayama**

.....

.....