High Resolution Study of Pionic 0^- State in ^{16}O (RCNP E155 Collaboration)

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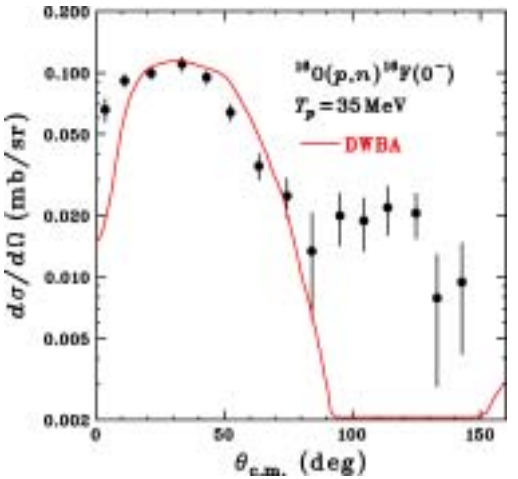
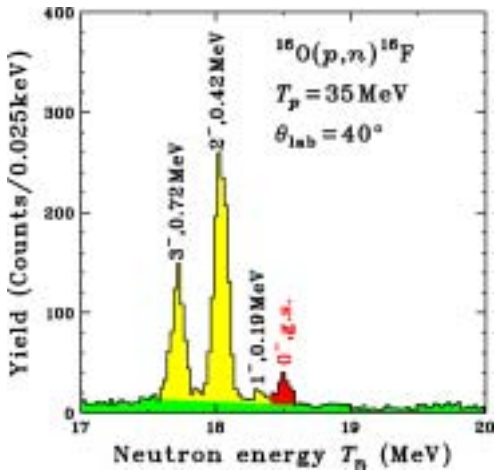
Overview

- **Motivations**
- **Experimental Requirements**
- **Experiment**
  - Experimental condition
  - Experimental setup
  - Dispersion matching
- **Results**
  - Elastic scattering
  - Peak fitting
- **Comparison with Microscopic Calculations**
  - DWBA with free t-matrix
  - DWBA with density and energy-dependent t-matrix
  - DWIA + RPA
- **Summary**

Signature of the Pion Field in Nuclei Observed in the (p,n) Reaction

- **Isovector $J^{\pi}=0^{-}$ excitations**
  - Carry the simplest pion-like quantum number
  - β-decay and μ-capture : at low q
  - (p,n), (p,p') etc. : wide q range
- **(p,n) Exp. By Orihara et al.**
  - $^{16}F(0^{-})$ excited via (p,n)
  - T_p = 35 MeV
  - q = 0.34 – 2.0 fm^{-1}
  - Large discrepancy from DWBA at large q
    - ***Signature of the pion field in nuclei ?***
- **Problems**
  - 0^{-}, g.s. is not clearly separated from 1^{-}, 190 keV state
  - Fairly large contribution from the unphysical background
  - Large systematic uncertainties

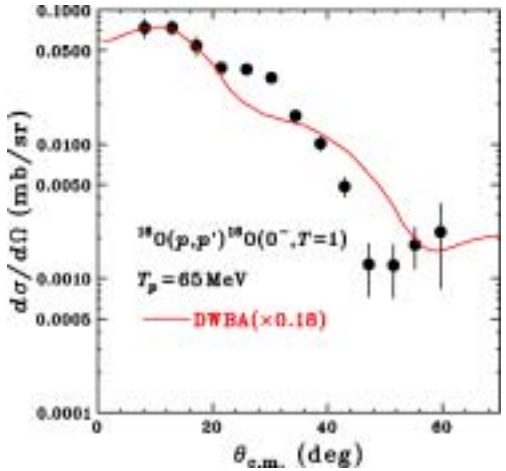


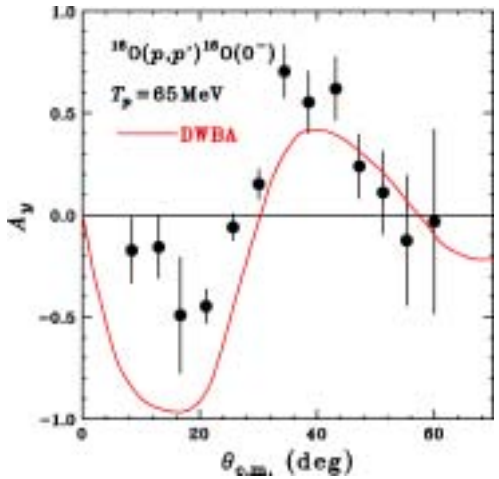


H. Orihara et al., PRL 49, 1318 (1982)

Pionic State Studied via (p,p')

- **(p,p') Exp. By Hosono et al.**
  - $^{16}O(0^-,T=1)$ via (p,p')
  - T_p = 65 MeV
  - q = 0.3 – 1.6 fm^{-1}
- **DWBA calculation (DWBA74)**
  - Pure $1p_{1/2}^{-1}2s_{1/2}$ config.
  - M3Y interaction
  - Single-particle radial W.F. generated in a Woods-Saxon pot.
  - No discrepancy from DWBA
    - ***No signature of the pion field ?***
- **Difference between (p,n) and (p,p')**
  - Complicated reaction mechanism in this low-energy region (multi-step etc.)
  - No published T=1 data in T_p > 100 MeV (simple reaction mechanism)





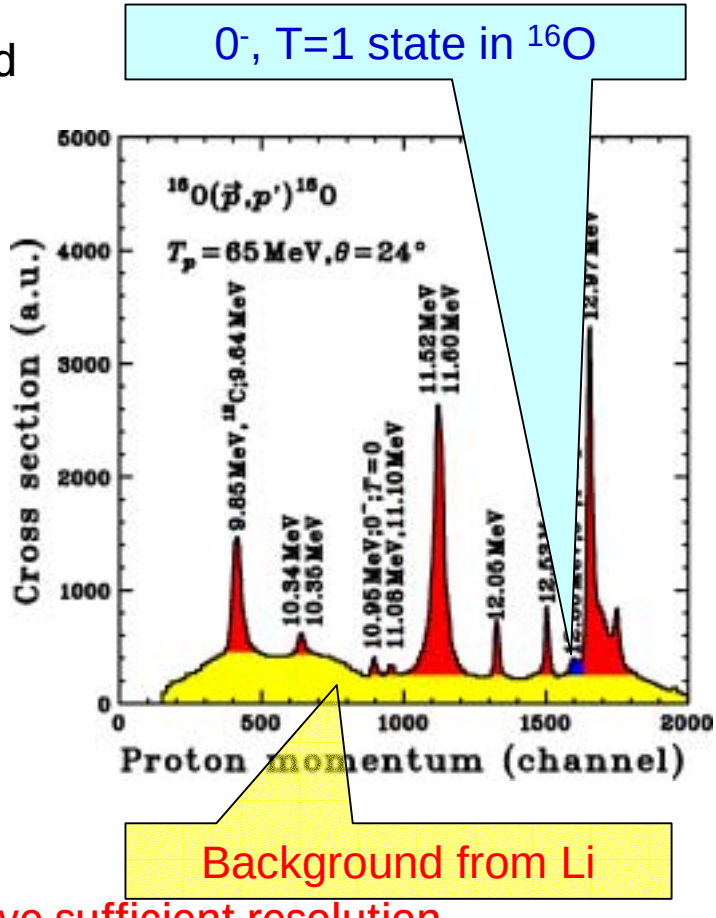
K. Hosono et al., PRC 30, 746 (1984)

Requirement for Study of Pionic State

- **Pure Oxygen Target**
  - Oxygen compounds (Li_2O,B_2O_3) were used
    - ***Large contribution from compound material (Li,B)***
  - Not suitable to study week 0^-, T=1 state
  - We used an ice (H_2O) target developed by Kawabata et al.
    - ***Extremely clean (background free) measurement is possible***
- **High Resolution**
  - Level scheme in ^{16}O around 0^-
    - ***1^-, 12.44 MeV***
    - ***2^-, 12.53 MeV***
    - ***0^-, 12.80 MeV***
    - ***2^-, 12.97 MeV***

170 keV

  - Dispersion matching is essential to achieve sufficient resolution

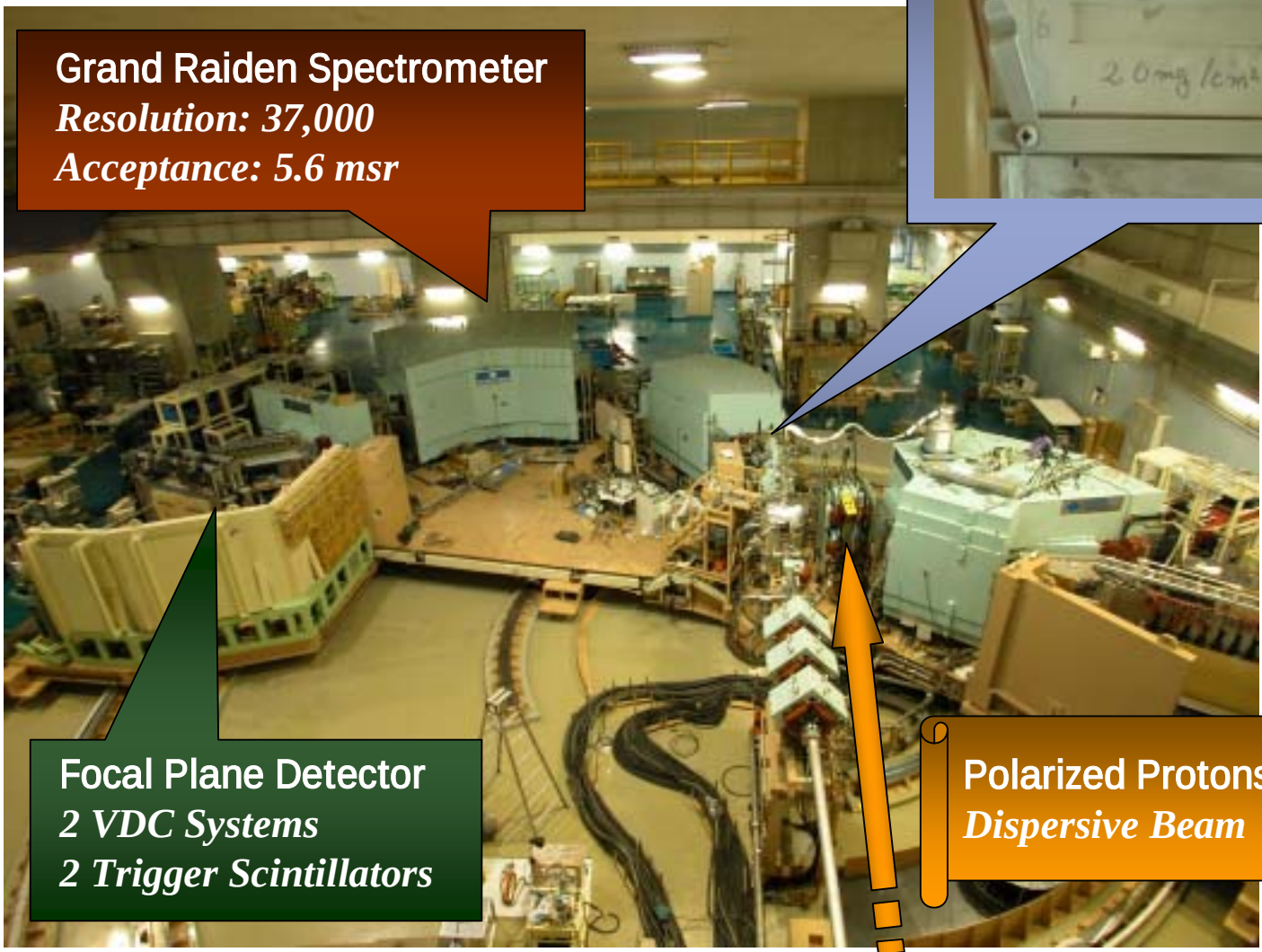


Experiment

- **Measure isovector 0^- state in ^{16}O**
  - With a large-area (30 mm width × 6 mm height) ice target
    - ***14.1 mg/cm^2***
      - ***Calibrated by p+p events from ice target***
      - ***σ from SAID***
  - With dispersive beam from WS beam line
    - ***29 – 34 keV after employing dispersion matching***
    - ***Determined by energy-loss effects in ice target***
- **Beam**
  - 295 MeV polarized protons (87 keV in achromatic mode)
  - Beam polarization:0.70±0.01
    - ***Calibrated by p+p events from ice target***
    - ***A_y from SAID***
  - Beam current: 3-6 nA
  - Solid angle: 2.4 msr
- **Observables**
  - Cross sections and analyzing powers
    - ***θ_{lab} = 14 – 30 °***
    - ***$q_{c.m.}$ = 0.9 – 2.1 fm^{-1}***

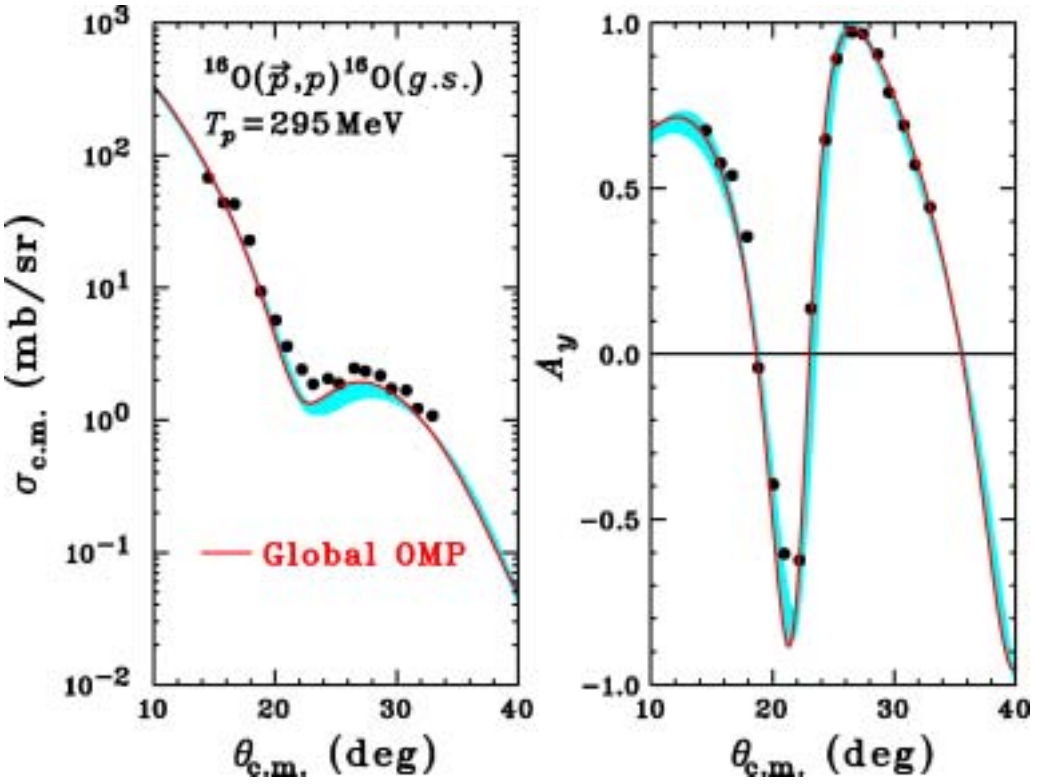
RCNP E155 Collaboration

Experimental Setup



Elastic Scattering

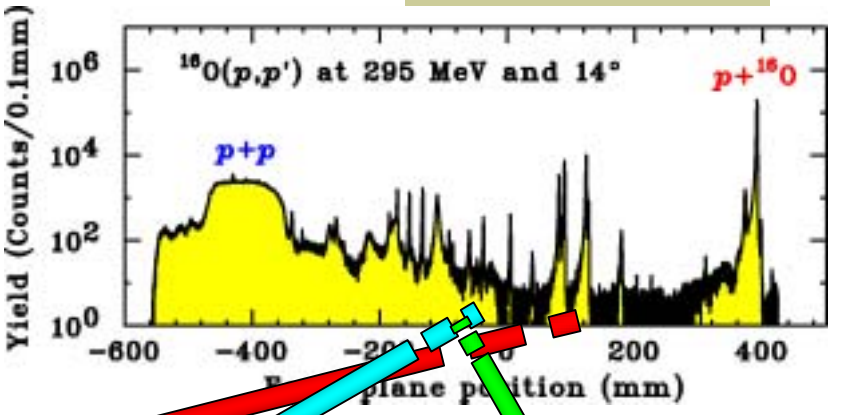
- **Global Optical Potential by Hama et al.**
  - For ^{16}O
  - For ^{12}C – ^{208}Pb Set 1
  - For ^{12}C – ^{208}Pb Set 2
  - For ^{12}C – ^{208}Pb Set 3
- **Global Potential for ^{16}O**
  - Fairly good agreement with σ
  - Good agreement with A_y

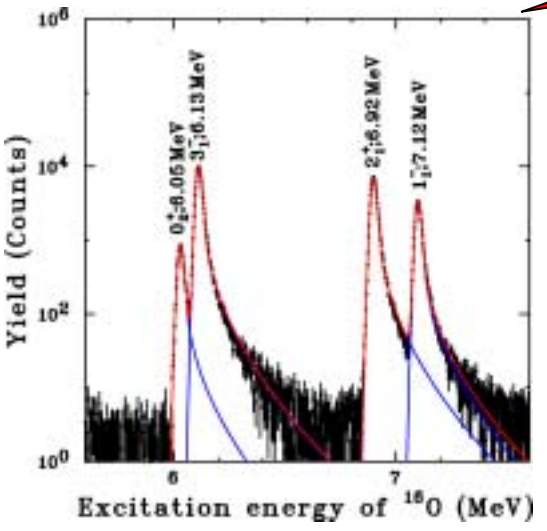


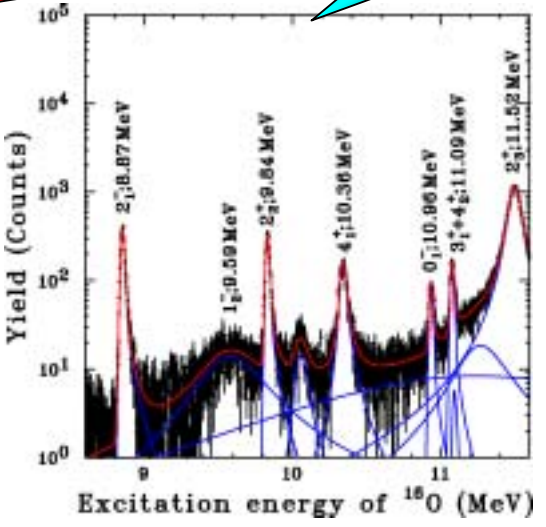
S. Hama et al., PRC 41, 2737 (1990)

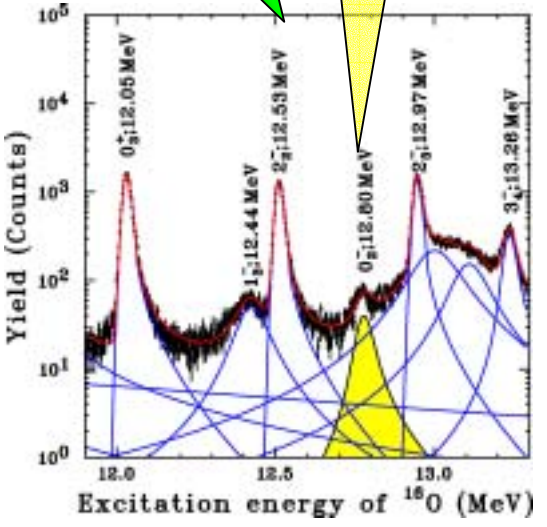
Results of Fitting at Forward Angle

- **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**
  - ΔE = 29 keV (FWHM)



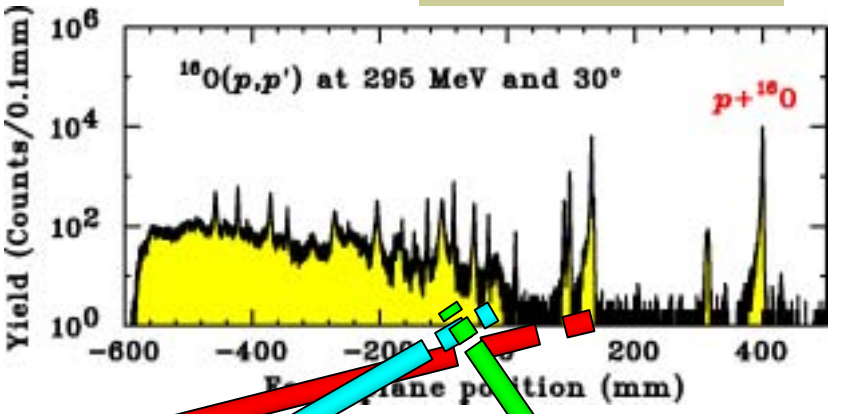


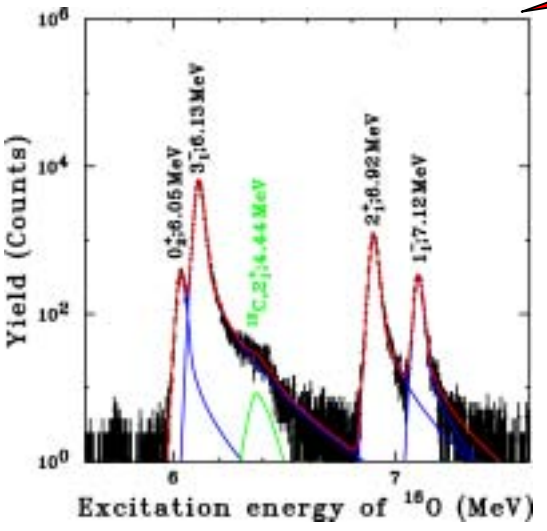


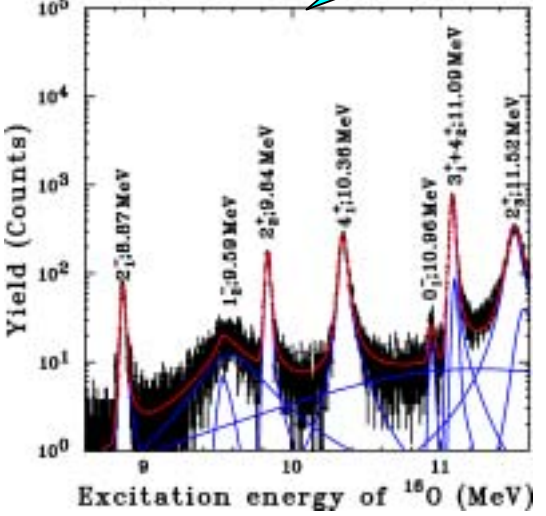


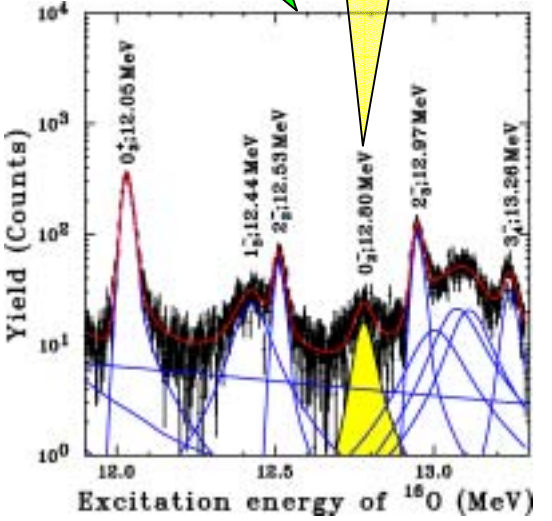
Results of Fitting at Backward Angle

- **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**
  - ΔE = 34 keV (FWHM)







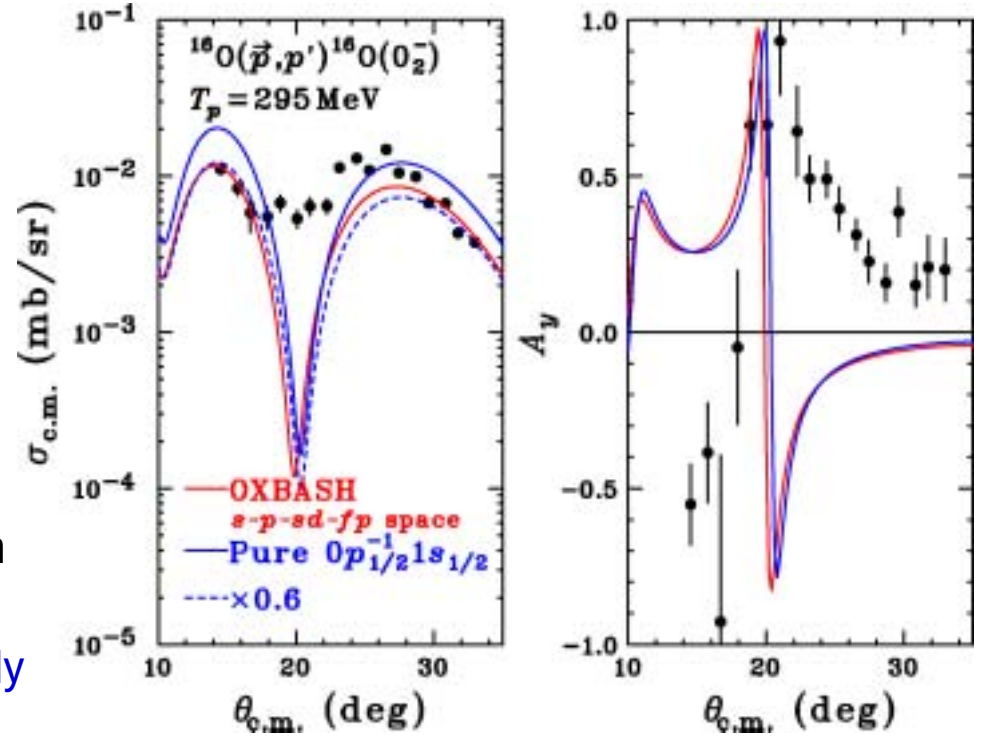


Microscopic Calculations of (p,p')

- **Optical Potential**
  - Global optical potential for ^{16}O (reproduce the elastic data)
- **Single-Particle Radial Wave Functions**
  - Generated in a harmonic oscillator potential
  - Generated in a Woods-Saxon potential
- **Effective Interactions**
  - Franey and Love t-matrix (Free)
    - ***270 MeV parameterization***
    - ***325 MeV parameterization***
  - Density and energy-dependent t-matrix (In-Medium)
    - ***G-matrices based on the Paris NN potential***
- **Configurations**
  - Pure $1p_{1/2}^{-1}2s_{1/2}$
  - Shell model calculation by OXBASH
- **Nuclear Correlations**
  - DWIA + RPA calculations

Configuration Dependence

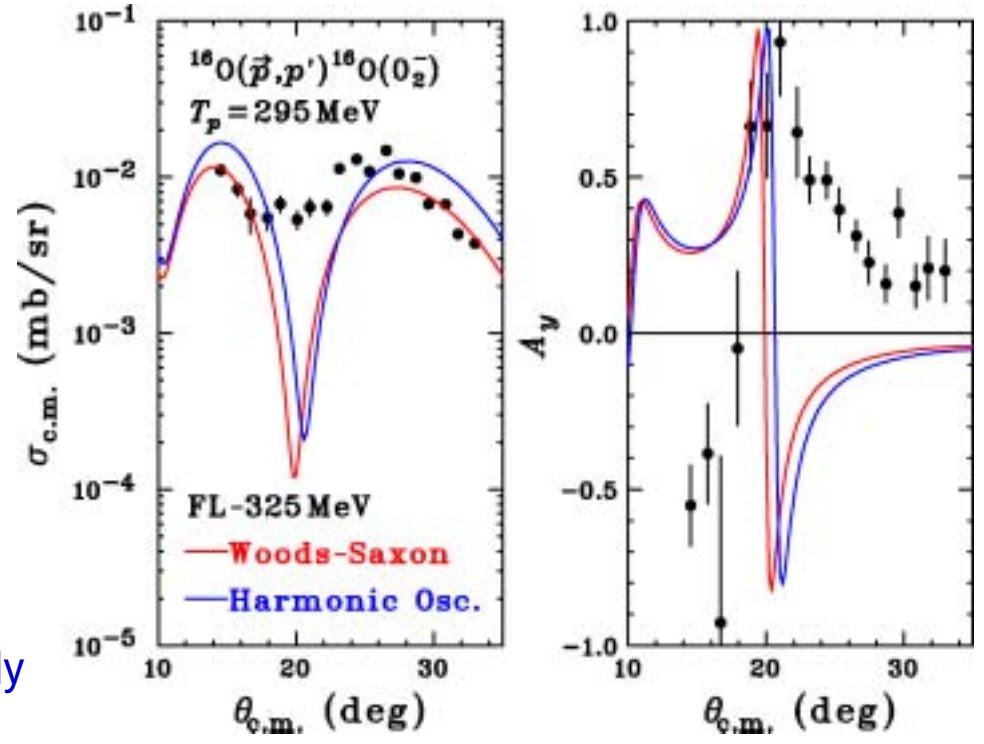
- **p-h Configurations**
  - OXBASH (B.A.Brown)
    - ***s-p-sd-pf shell model space***
  - Pure $0p_{1/2}^{-1}1s_{1/2}$
- **Cross sections**
  - Similar shape
  - OXBASH
    = 0.6× Pure Configuration
  - Not reproduce both 2nd & 3rd maxima simultaneously
- **Analyzing powers**
  - Similar shape
  - Opposite sign



- **Parameters**
  - Global OMP by Hama et al.
  - Franey and Love t-matrix at 325 MeV
  - Single-particle radial W.F. generated in Woods-Saxon potential

Dependence on Single-Particle Radial Wave Functions

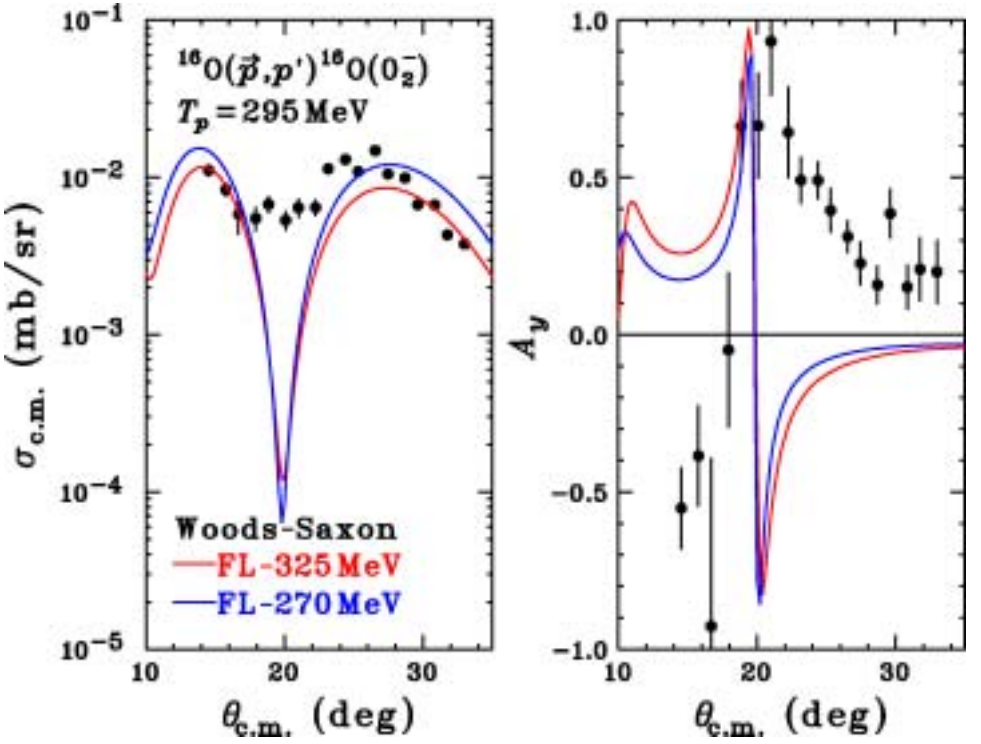
- **Single-Particle Radial Wave Functions generated in**
  - Woods-Saxon (WS) potential
  - Harmonic-Oscillator (HO) potential
- **Cross sections**
  - Similar shape
  - WS = 1.4 × HO
  - Not reproduce both 2nd & 3rd maxima simultaneously
- **Analyzing powers**
  - Similar shape
  - Opposite sign



- **Parameters**
  - Global OMP by Hama et al.
  - OBTD calculated by OXBASH in s-p-sd-pf space
  - Franey and Love t-matrix parameterized at 325 MeV

Effective Interaction Dependence

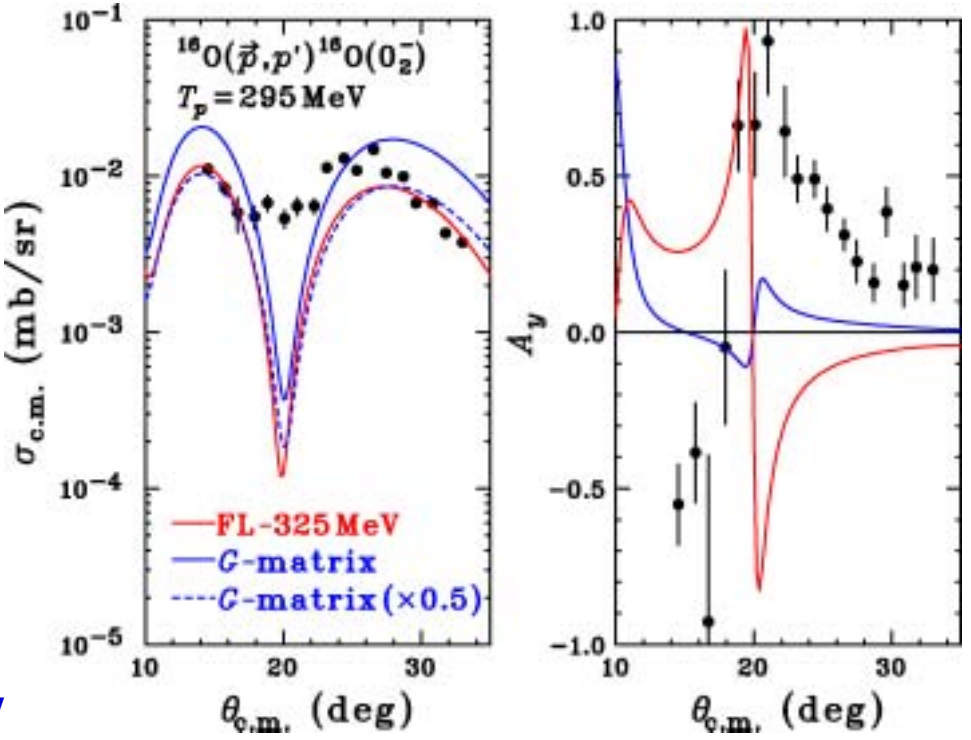
- **Franey and Love t-Matrix**
  - 325 MeV param.
  - 270 MeV param.
- **Cross sections**
  - Similar shape
  - 270 MeV = 1.4 × 325 MeV
  - Not reproduce both 2nd & 3rd maxima simultaneously
- **Analyzing powers**
  - Similar shape
  - Opposite sign



- **Parameters**
  - Global OMP by Hama et al.
  - OBTD calculated by OXBASH in s-p-sd-pf space
  - Single-particle radial W.F. generated in Woods-Saxon potential

Effects on In-Medium Modification

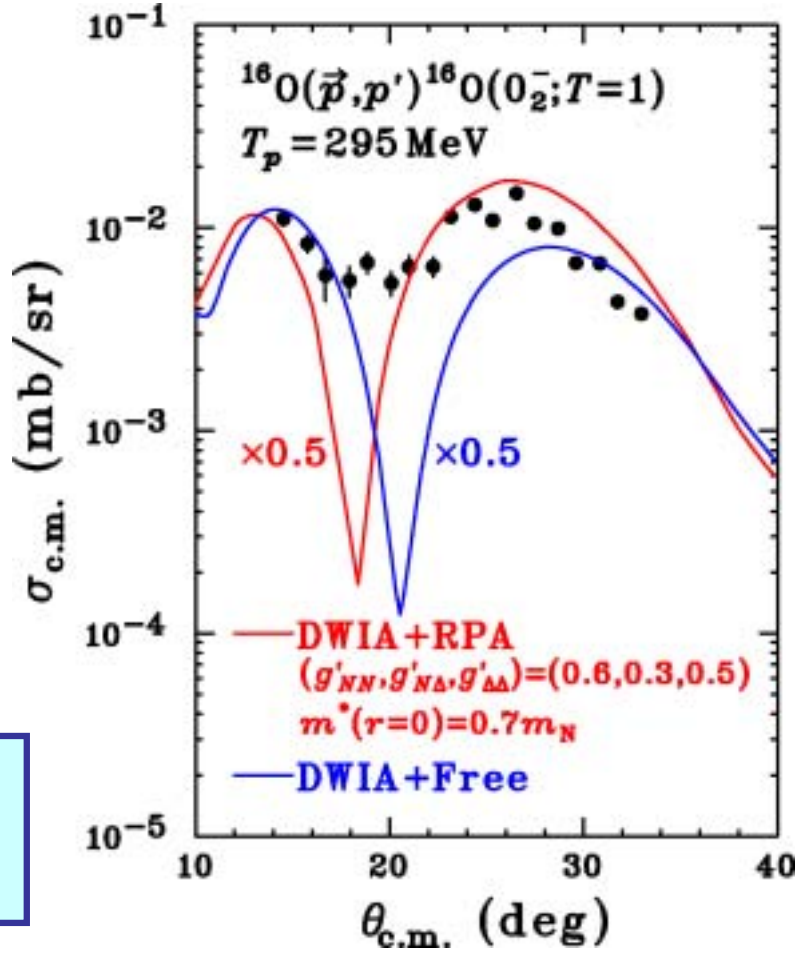
- **In-Medium t-Matrix**
  - Density and energy dependent effective interaction
  - G-matrices based on Paris NN potential *by H.V. von Geramb*
- **Cross sections**
  - Similar shape
  - G-Matrix = 2 × FL325MeV
  - Not reproduce both 2nd & 3rd maxima simultaneously
- **Analyzing powers**
  - Correct sigh in calculation with G-matrix
  - Small magnitude



- **Parameters**
  - Global OMP by Hama et al.
  - OBTD calculated by OXBASH in s-p-sd-pf space
  - Single-particle radial wave functions generated in Woods-Saxon potential

Nuclear Correlation Effects

- **DWIA+RPA**
  - Codes developed by Ichimura Group
  - With RPA correlation (RPA response)
  - Without correlation (Free response)
- **Cross sections**
  - Predict the enhancement of the 3rd peak (q=1.7fm^{-1})
    - ***Pion-exchange interaction is most attractive***
  - Our data support the enhancement
    - ***Signature of the pion field in nuclei***



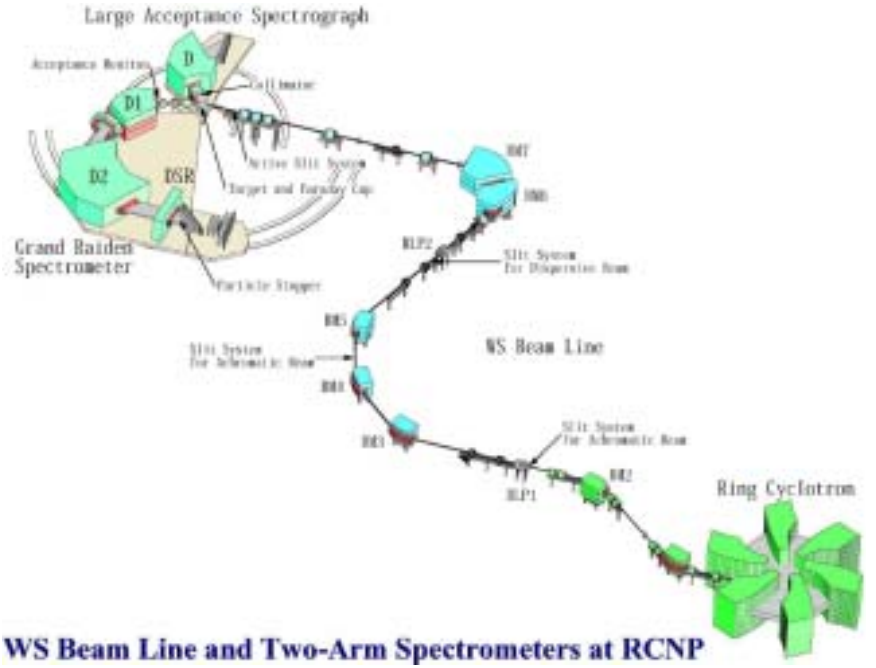
M. Ichimura, Private Communication

Summary

- **The isovector 0^- state in ^{16}O were clearly observed**
  - Dispersion matching method (WS beam line and Grand Raiden)
  - Large area (30mm×6mm) ice target
- **Elastic Scattering**
  - Fairly well reproduced by the global optical potentials
- **Cross Section**
  - DWIA without nuclear correlation effects could not reproduce the data
    - *Configuration dependence*
    - *Effective interaction dependence*
    - *In-medium effects of the effective interaction*
  - DWIA+RPA predicts the enhancement around q=1.7 fm^{-1}
    - ***Our data support the enhancement***
    - ***Signature of the pion field in nuclei***
- **Analyzing Power**
  - Free interaction could not reproduce the sign
  - Density-dependent effective interaction reproduces the sign
    - ***Our data support the in-medium modification of the effective interaction***

Specifications of WS

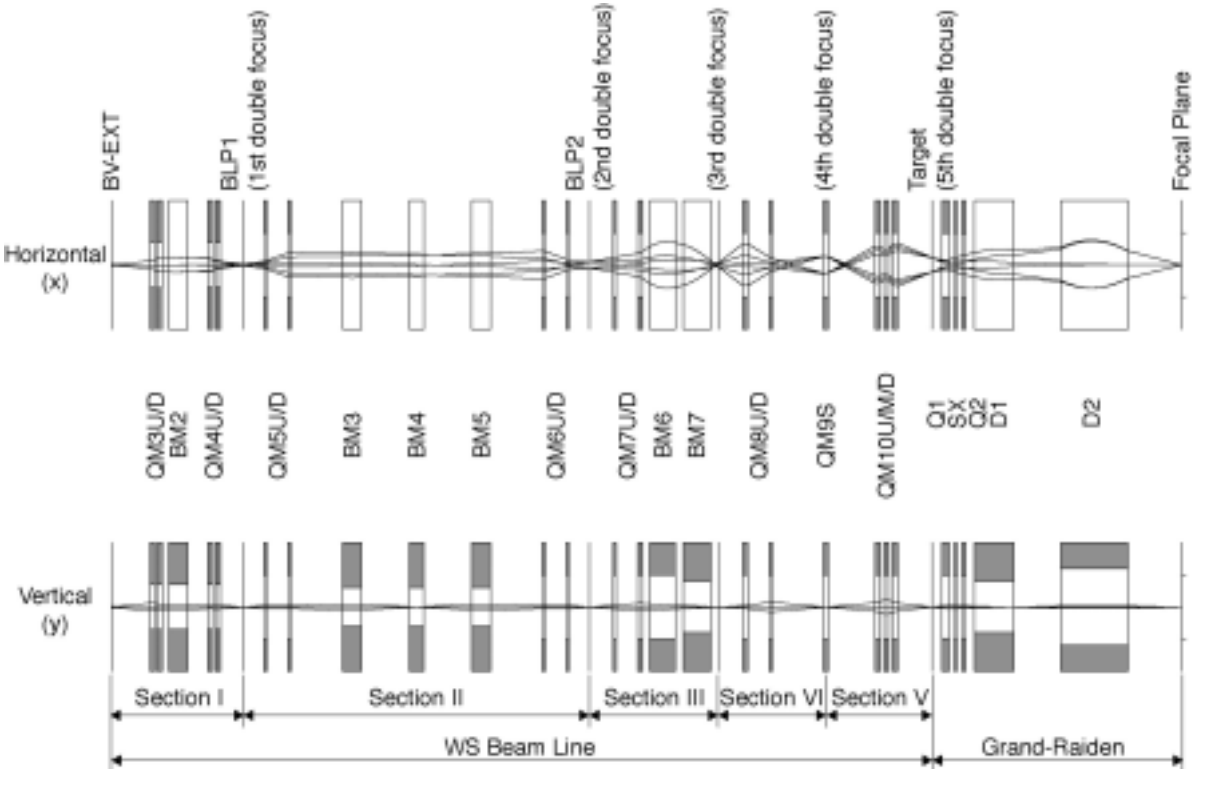
- Total length: 65.46m
- Total bending angle: 270 °
- Five double-focus points (Two for BLP)
- **Dispersive mode**
  - ***Dispersion: 37.1 m***
  - ***Angular dispersion: 20.0 rad***
  - ***Compete matching with GR***
- **Achromatic mode**
  - ***Lateral dispersion: 0 m***
  - ***Angular dispersion: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



WS Beam Line and Two-Arm Spectrometers at RCNP

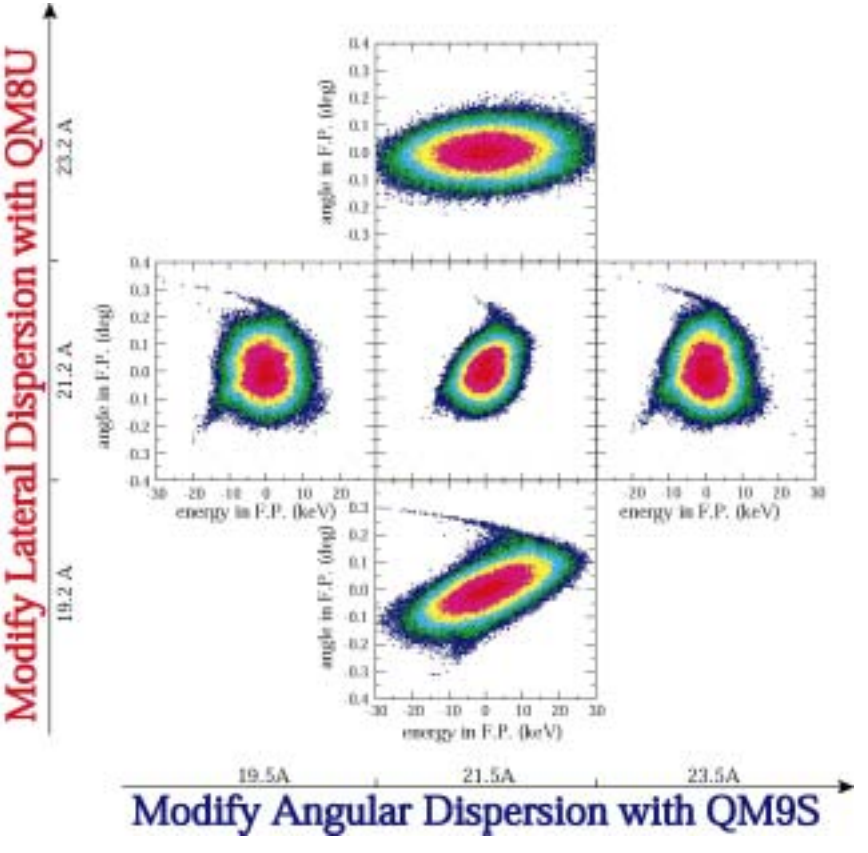
WS Beam Line and Grand Raiden in Dispersive Mode

- **Beam Envelopes**
  - P: ±0.03%
  - θ: ±2mrad
  - ϕ: ±2 mrad
- **Ion-optical properties**
  - M_x: 0.41
  - D: 0 m
  - (θ|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}Er(p,p') after Employing Dispersion Matching

- **Bean energy**
  - 295 MeV (April 2000)
  - 392 MeV (June 2000)
- **Beam energy spread**
  - ΔE: 150 keV(FWHM)
- **Target**
  - ^{168}Er: 2 mg/cm^2
- **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**