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

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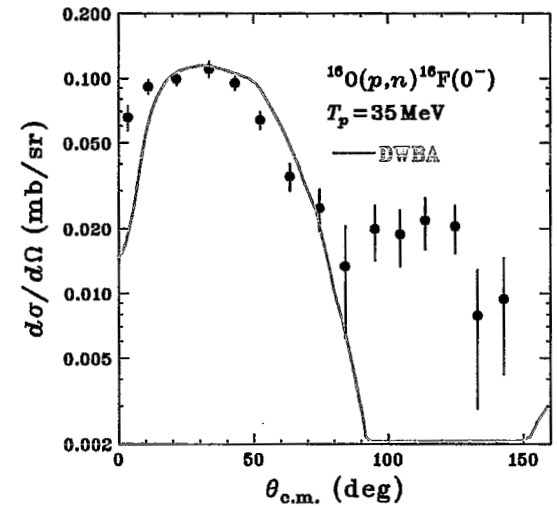
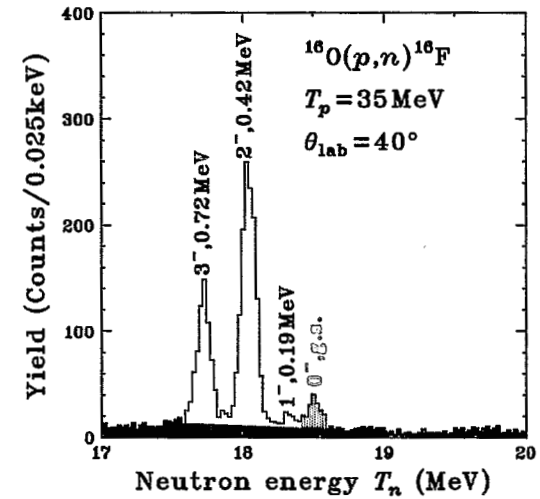
Signature of the Pion Field in Nuclei Observed in the (p,n) Reaction

- **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)

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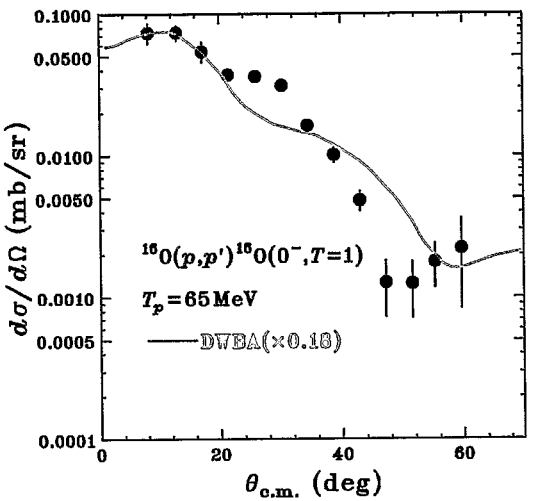
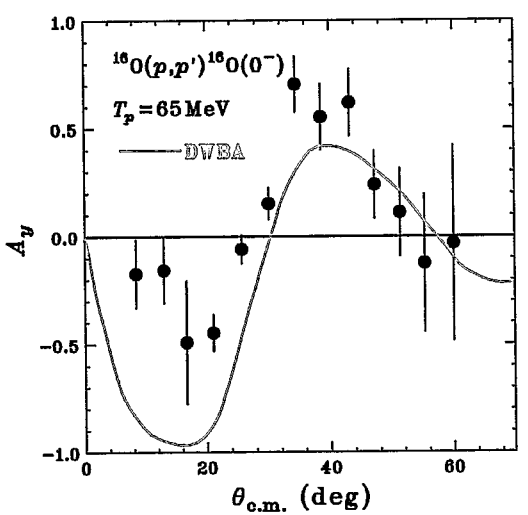
Pionic State Studied via (p,p')

- (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)

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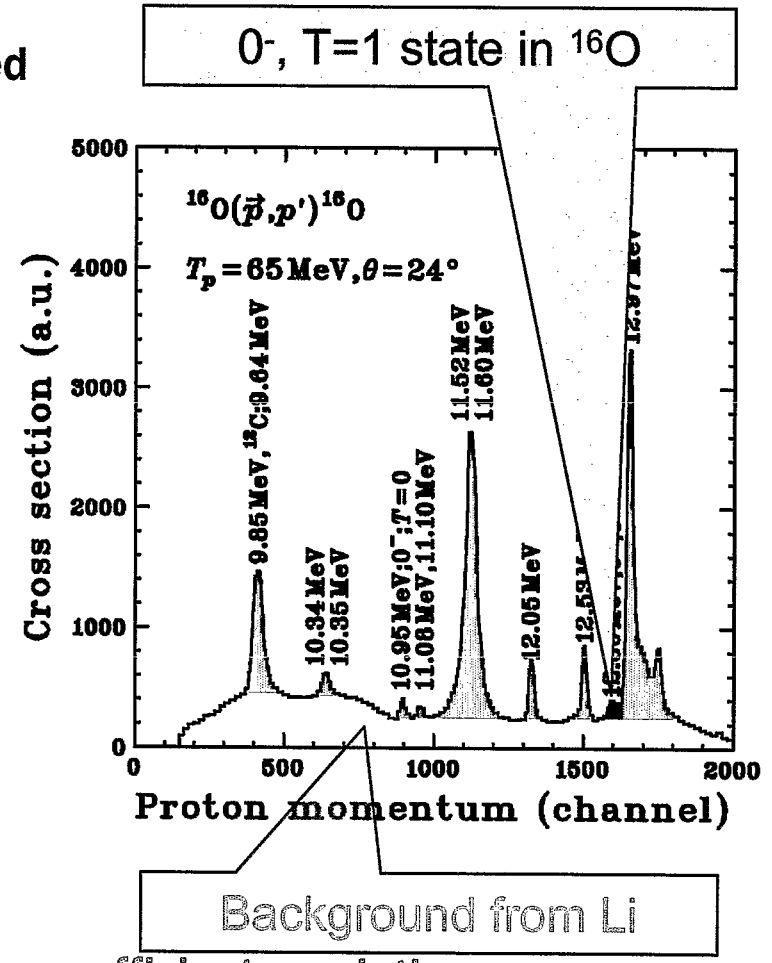
Requirement for Study of Pionic State

- **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



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Experiment

- Measure isovector 0^- state in ^{16}O
  - With a large-area (30 mm width × 6 mm height) ice target
    - *14.1 mg/cm²*
      - ***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
    - $\theta_{lab} = 14 - 30^\circ$
    - $q_{c.m.} = 0.9 - 2.1\ fm^{-1}$

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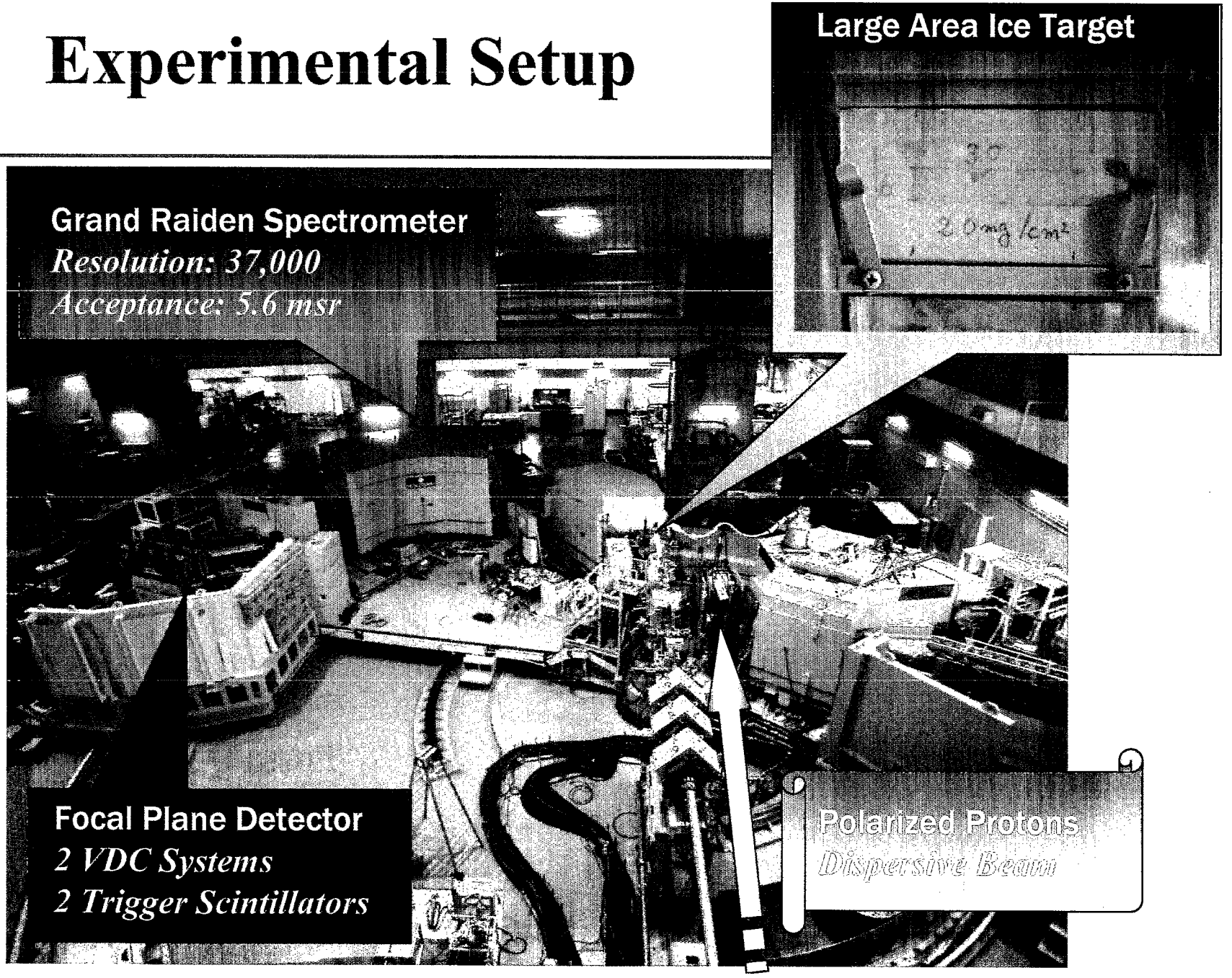
Experimental Setup



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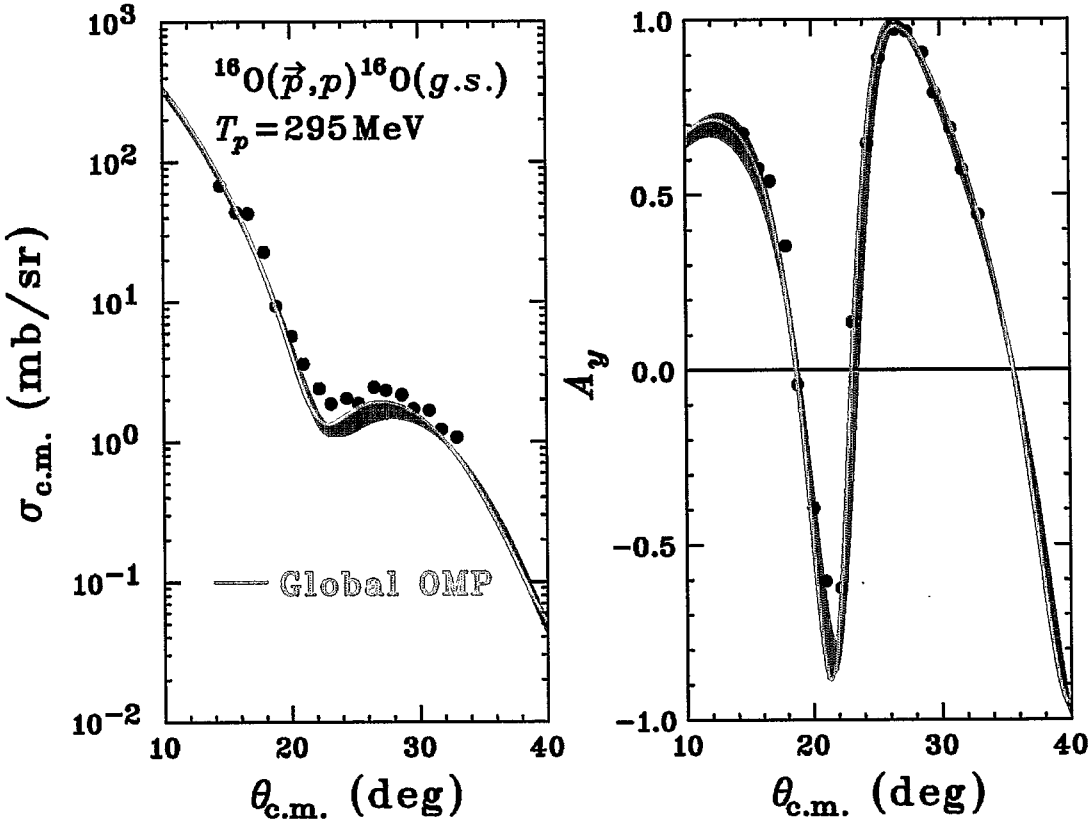
Elastic Scattering

- 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)

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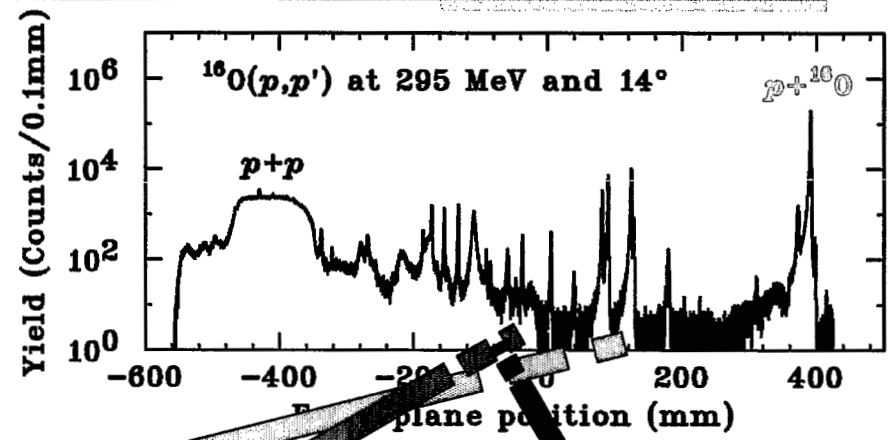
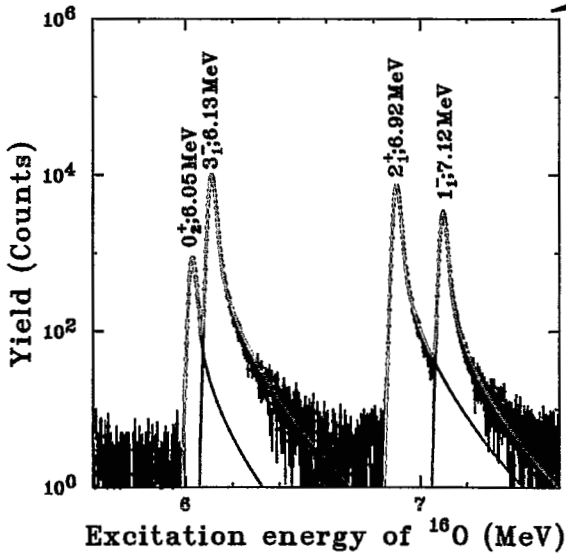
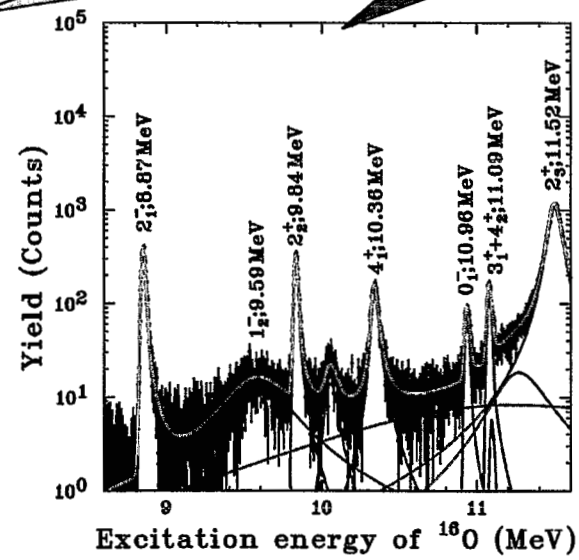
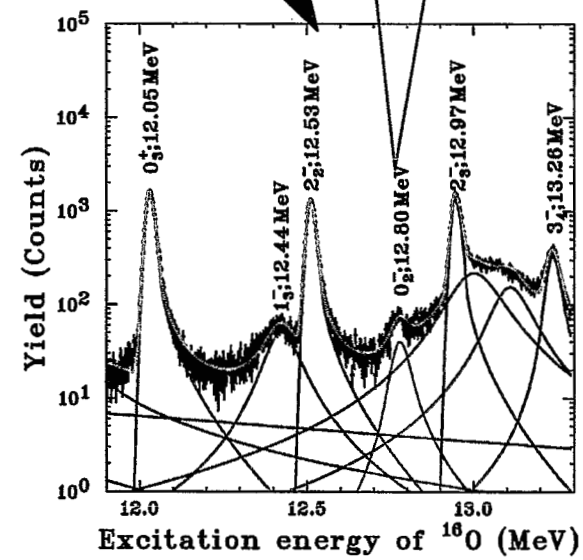
Results of Fitting at Forward Angle

- 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)









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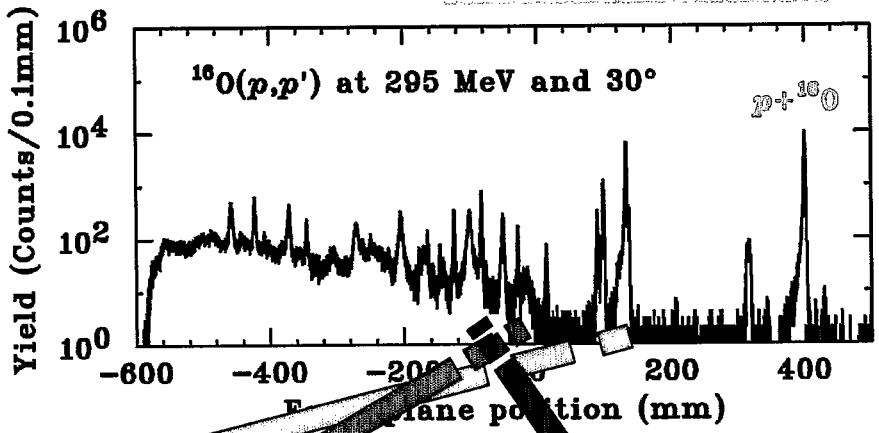
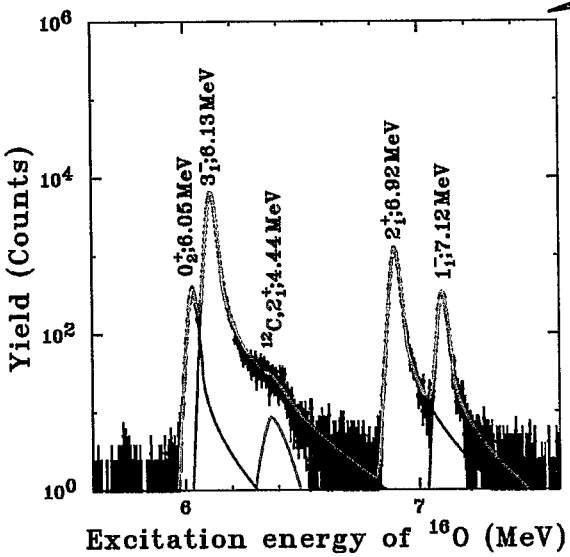
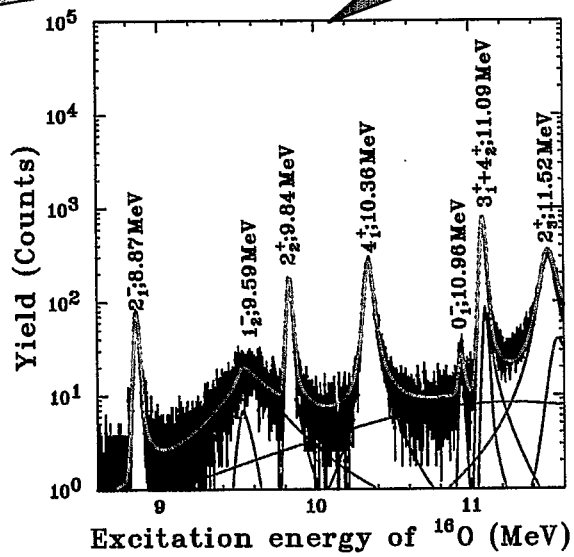
Results of Fitting at Backward Angle

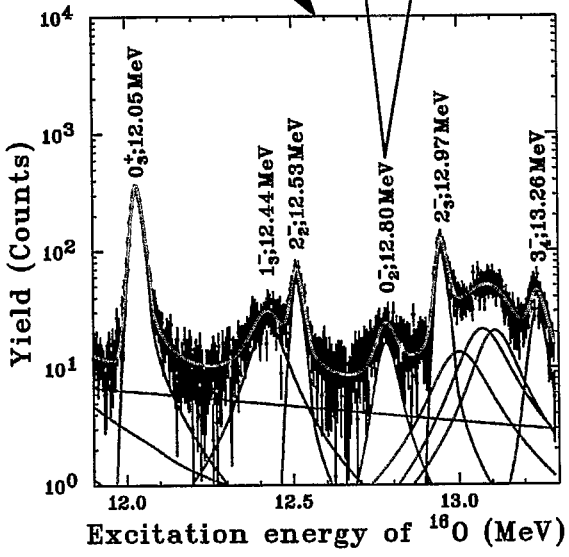
- 3 Excitation Regions
  - 5.6 – 8.0 MeV
  - 8.0 – 11.8 MeV
  - 11.8 – 13.3 MeV (includes 0^-,T=1 state)
  - Without background
- Results
  - ΔE = 34 keV (FWHM)



0^-,T=1







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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

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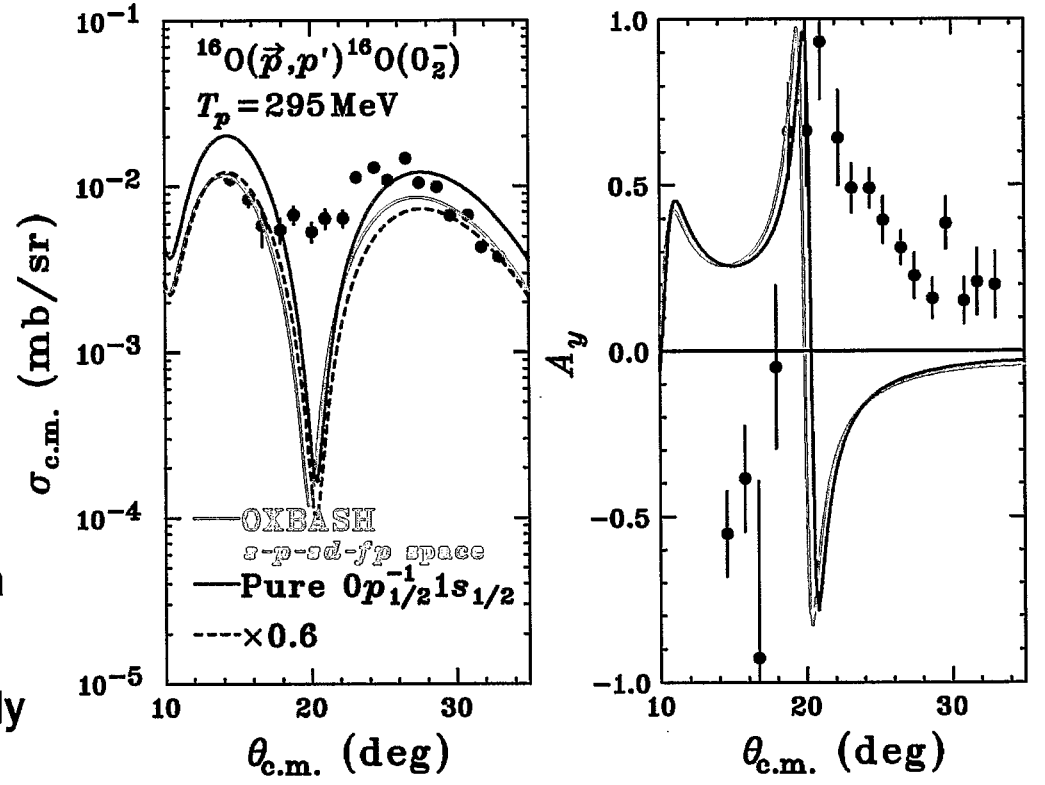
Configuration Dependence

- 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

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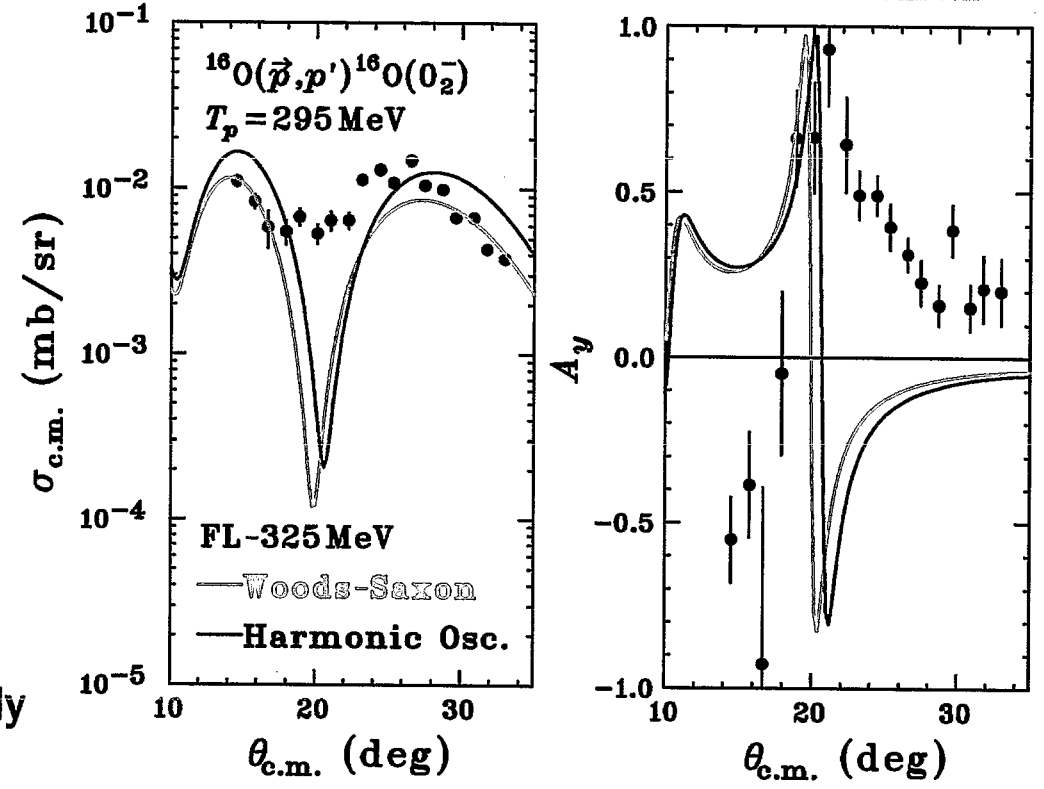
Dependence on Single-Particle Radial Wave Functions

- 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

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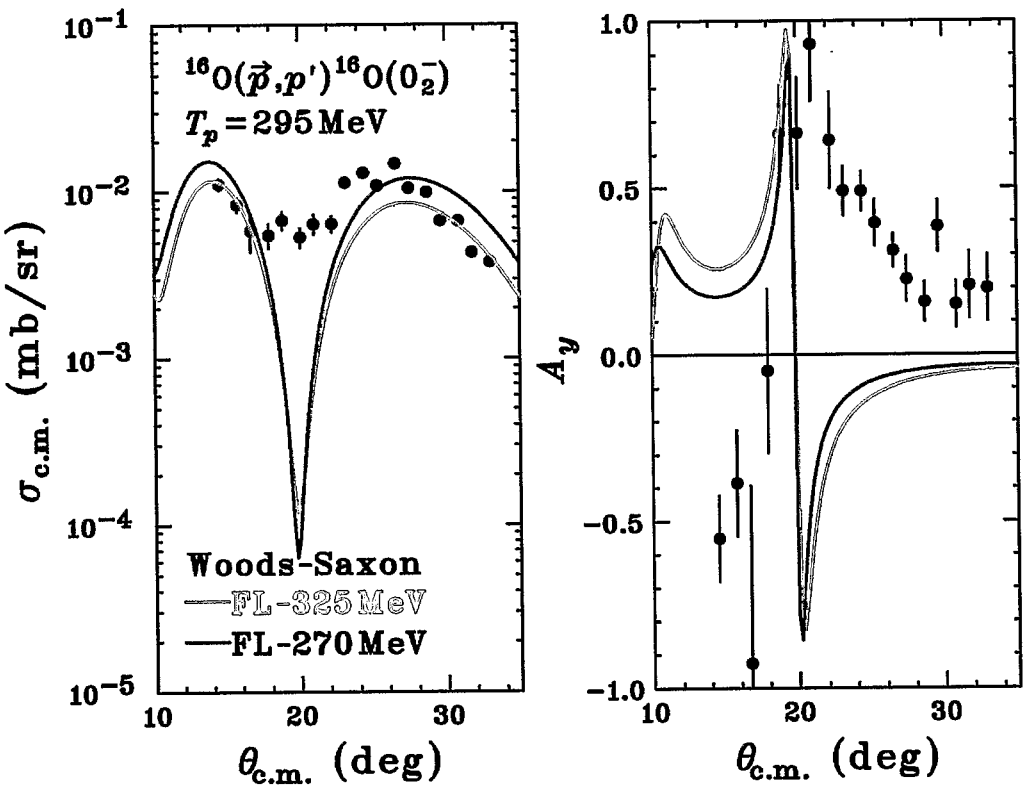
Effective Interaction Dependence

- 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

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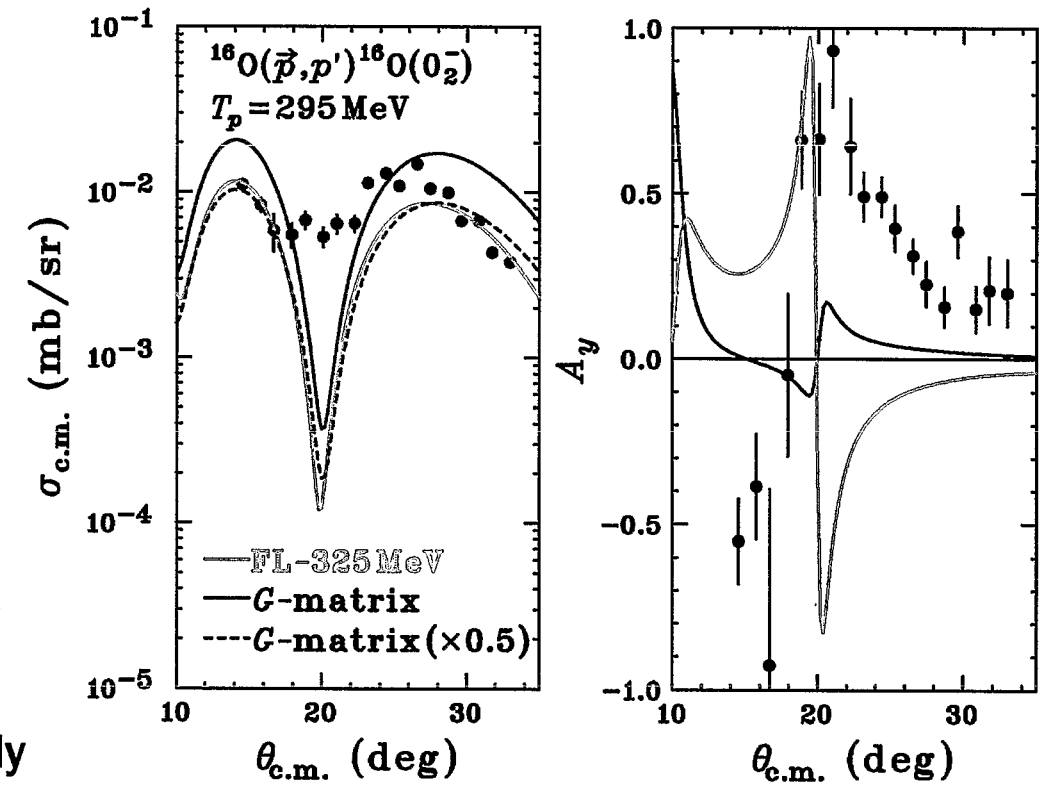
Effects on In-Medium Modification

- **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

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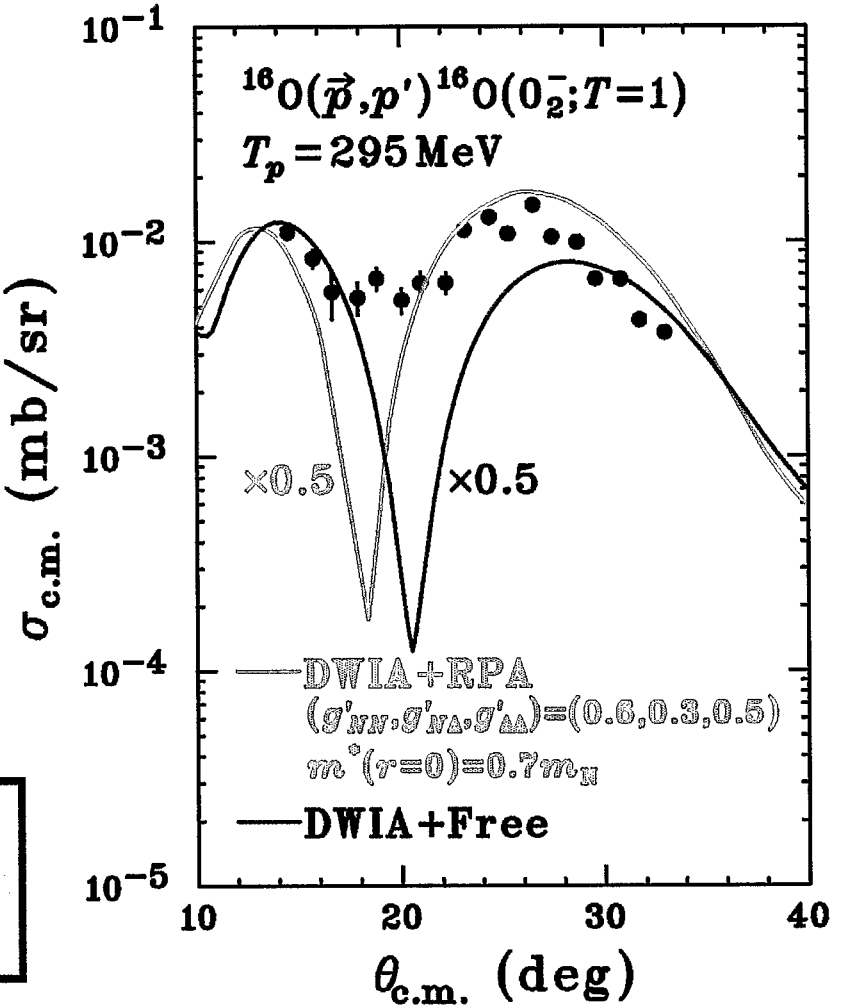
Nuclear Correlation Effects

- **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 ($q=1.7\,fm^{-1}$)
    - *Pion-exchange interaction is most attractive*

- Our data support the enhancement
  - ***Signature of the pion field in nuclei***



M. Ichimura, Private Communication

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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*