Polarized proton scattering from polarized ^3He

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CD12

8/6/12

Outline

- Background & Motivation: *Ab Initio* Nuclear Physics
- Experiment
  - Polarized Target
  - Data Collection and Analysis
  - Phase-Shift Analysis
- Results and Comparison with Theory
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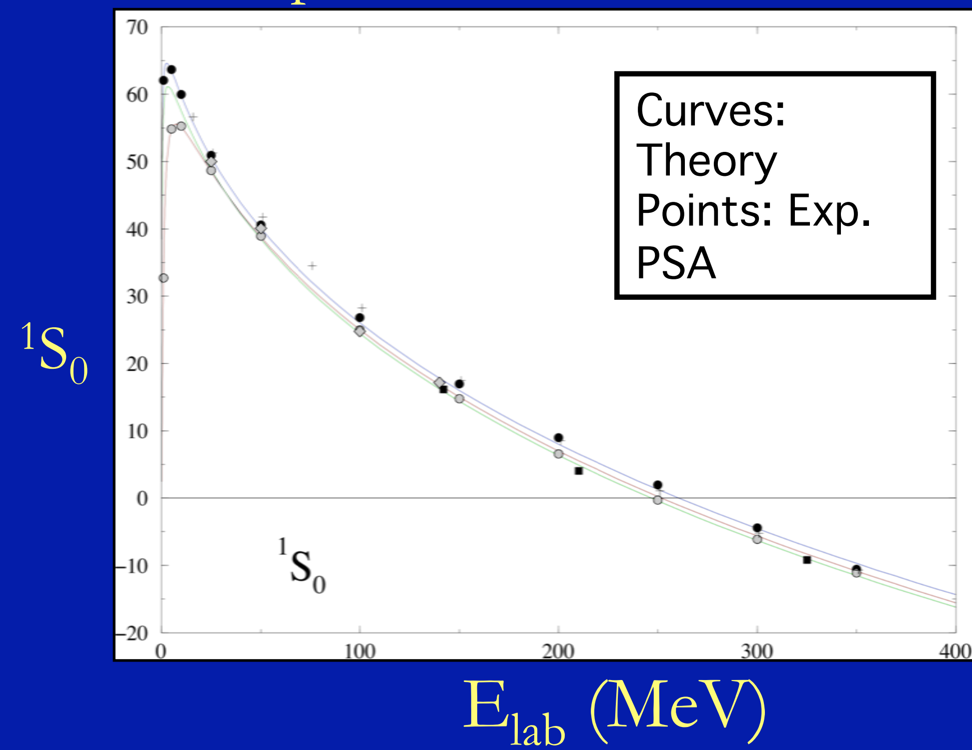
The Nucleon-Nucleon Interaction

- Known Features:
  - Approximately central
  - Repulsive core
  - Tensor components
  - Spin-dependence
- "Realistic" potential models
  - Phenomenological
  - Pion exchange
  - Free parameters
- Examples include AV18 and CD-Bonn
- ChPT offers the possibility of systematically deriving potentials

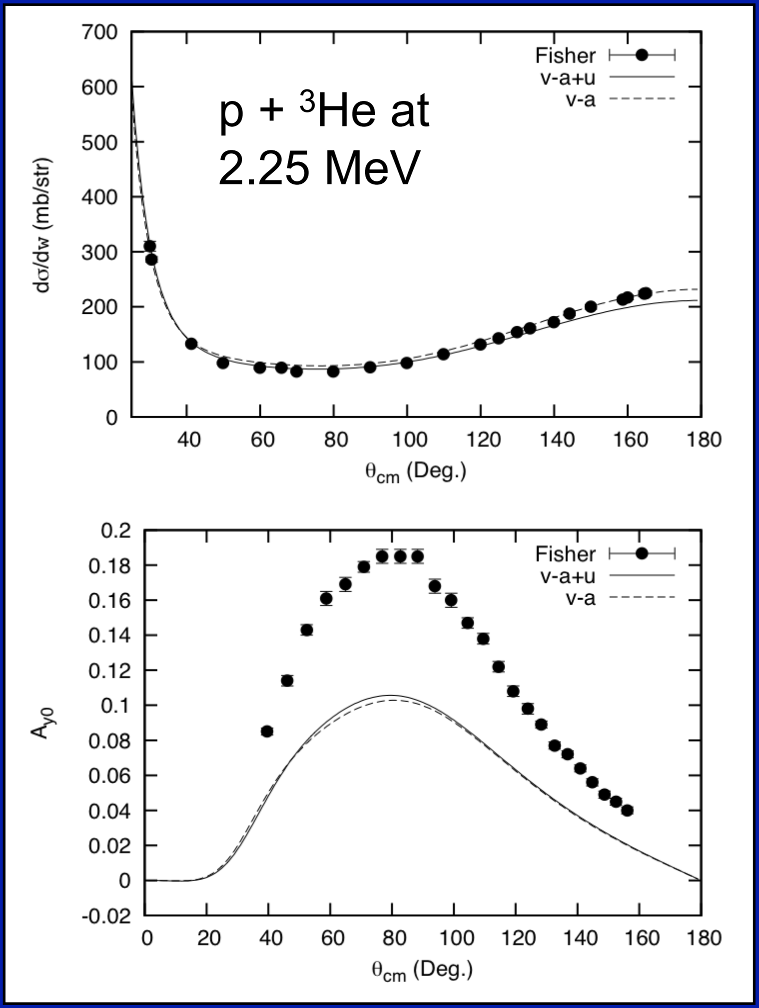
Example of fit to data: AV18



http://www.phy.anl.gov/theory/research/av18/1s0.ps

The A_y Puzzle

- Accurate calculations for scattering up to 4N system
- Need 3-nucleon force (3NF) to reproduce ^{3}He, triton, and alpha binding energies.
- 3NF: Interaction between 2 nucleons affected by presence of third.
  - Ex: Urbana-IX
- Most N+d scattering observables ok.
- 3N and 4N nucleon analyzing power underpredicted.
- Sensitive to P-waves

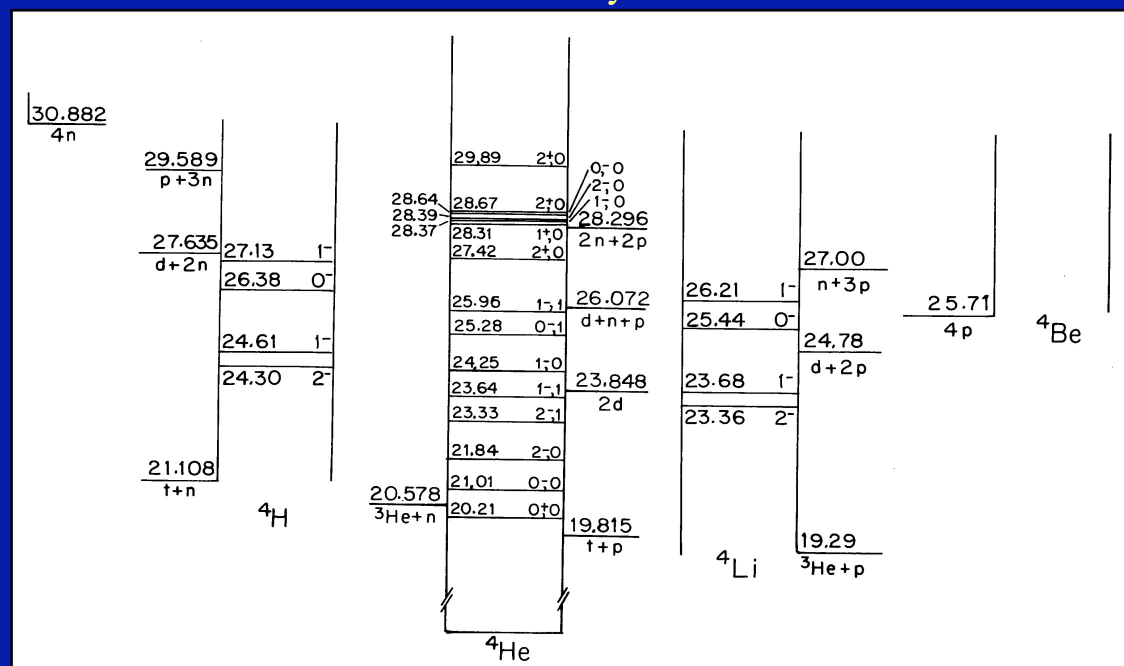


B. M. Fisher *et al.*, Phys. Rev. C 74, 034001 (2006).

4N System: "Theoretical Laboratory"

- Important testing ground for modern nuclear potential models
- 4N system more interesting than 3N
  - Stronger binding
  - More complicated
  - Discrete levels
  - T=3/2 contribution to 3N interaction

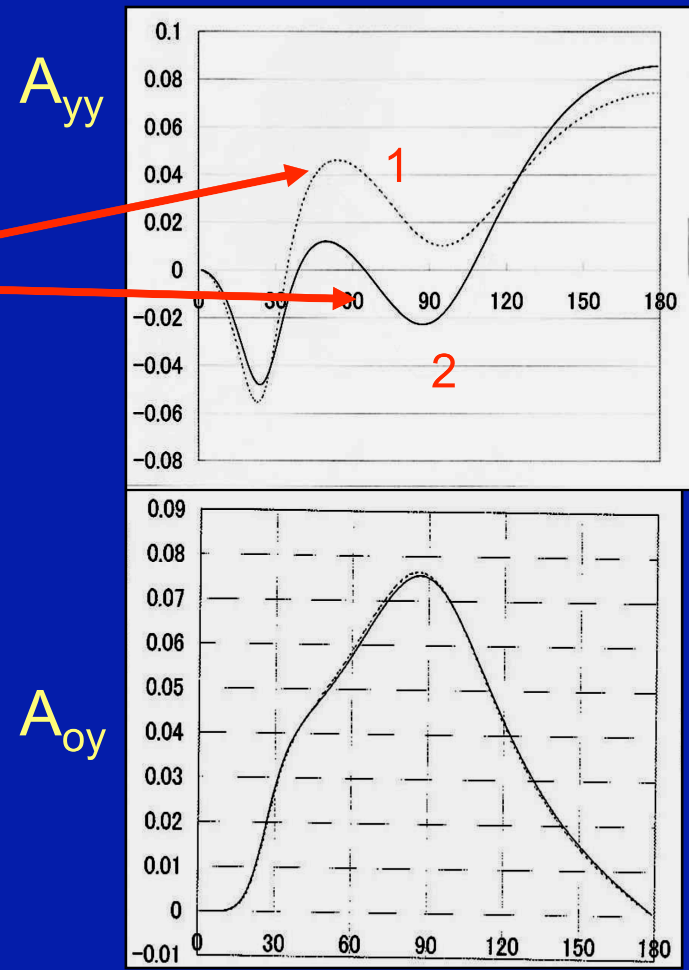
4N System



Motivation for New Measurements

- Experimental phase-shifts needed to compare with theory
- Wisconsin analysis led to two solutions
- Difference between solutions largest for spin-correlation coefficients below 4 MeV
- Underrepresented in dataset
- Project: Measure A_{yy} and A_{xx} and extract unique phase-shifts

Previous results at 3 MeV



E. A. George and L. D. Knutson, Phys. Rev. C 67, 027001 (2003).

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TUNL Laboratory

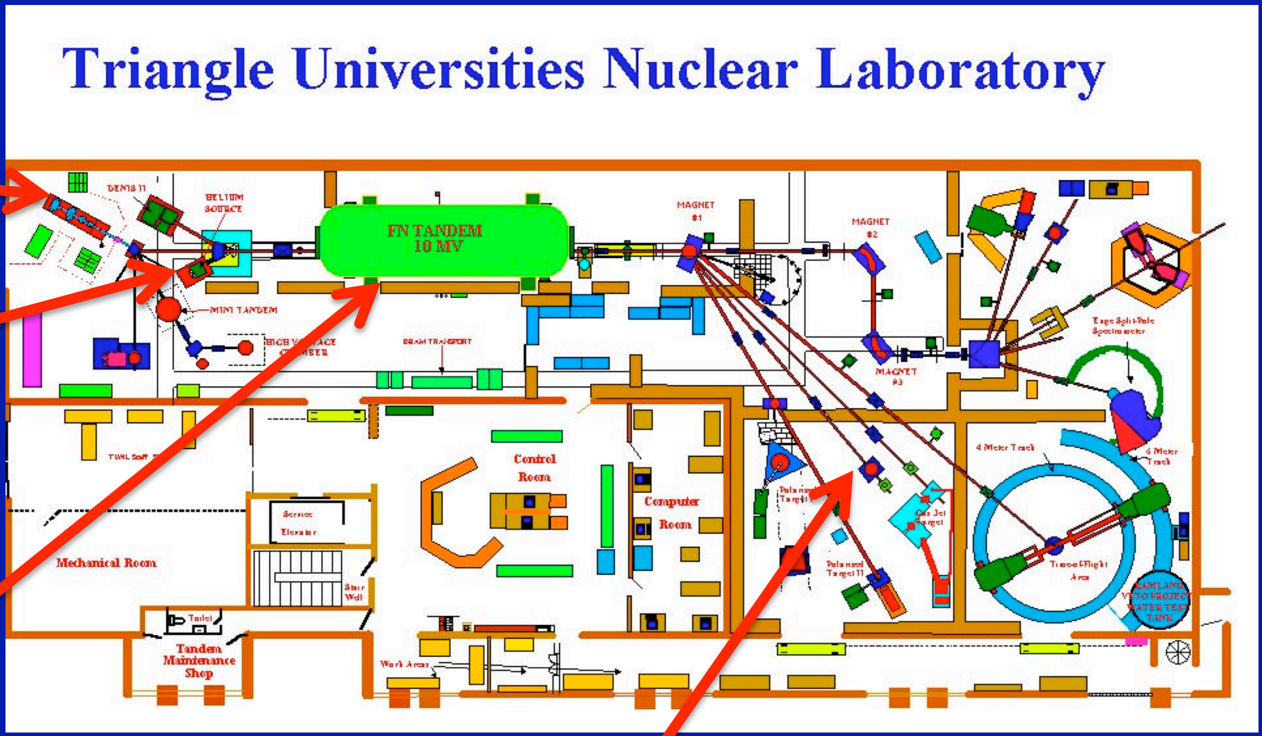
Experiment used several laboratory components:

Polarized ion source

- 2μA
- 60% pol.

Helium source

Tandem accelerator



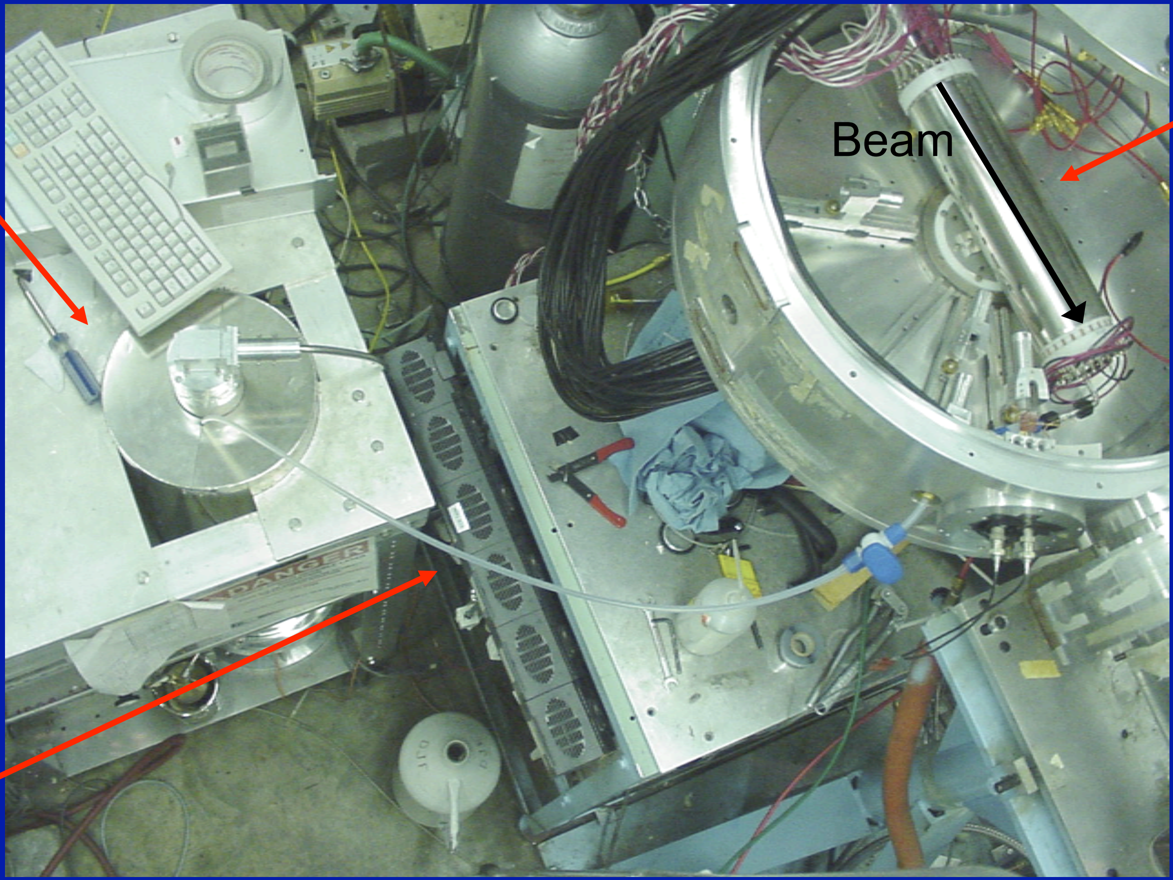
Polarized target

Polarized ^{3}He Target "Overview"

Katabuchi, *et al*., Rev. Sci. Instrum. 76, 033503 (2005)

Polarizer

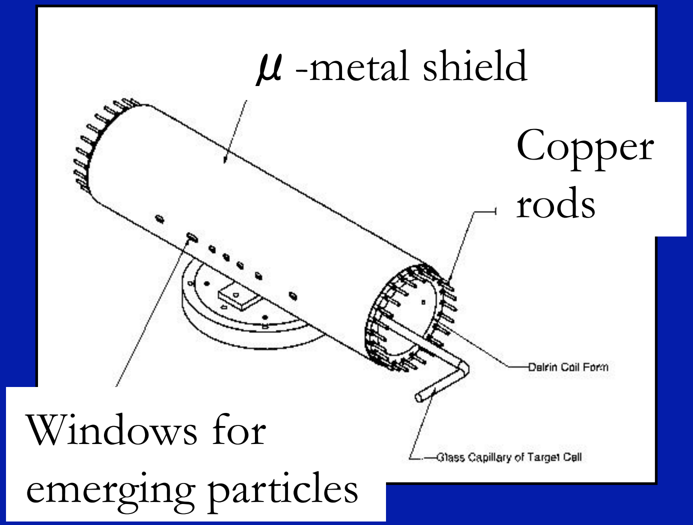
Target cell

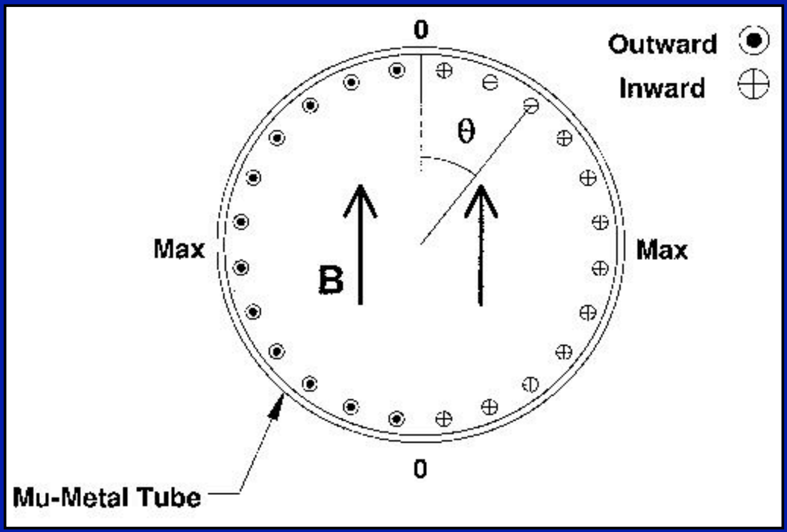


Fill tube

Sine-Theta Coil

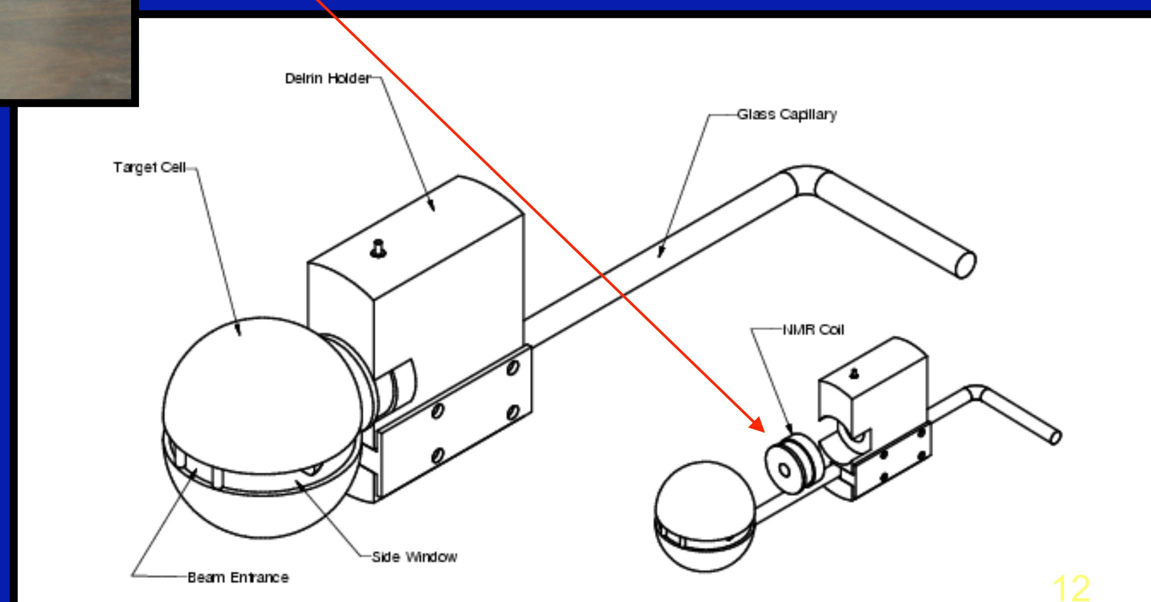
- Polarized gas requires magnetic holding field
- Need field uniformity of 1 in 10^3/cm
- Current proportional to sinθ
- "Spin-flip" by reversing field
- LabVIEW controls



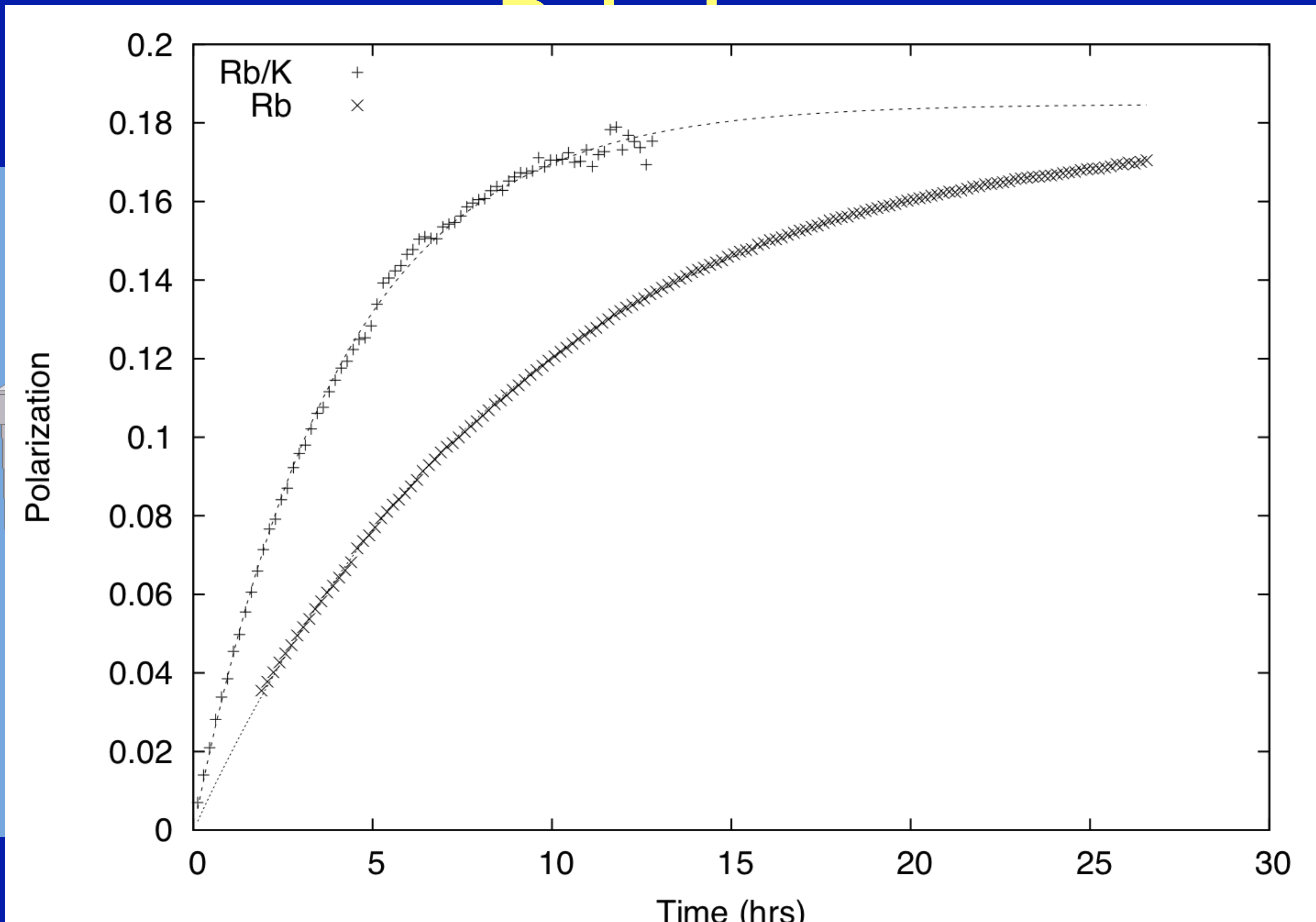


Target Cell

- Polarized container needs friendly materials:
  - Pyrex glass cell
  - Kapton windows
  - Non-magnetic materials!
- NMR coil attached to cell



- Spin relaxation time 1~3 hours
- Cell pressure ~1 atm

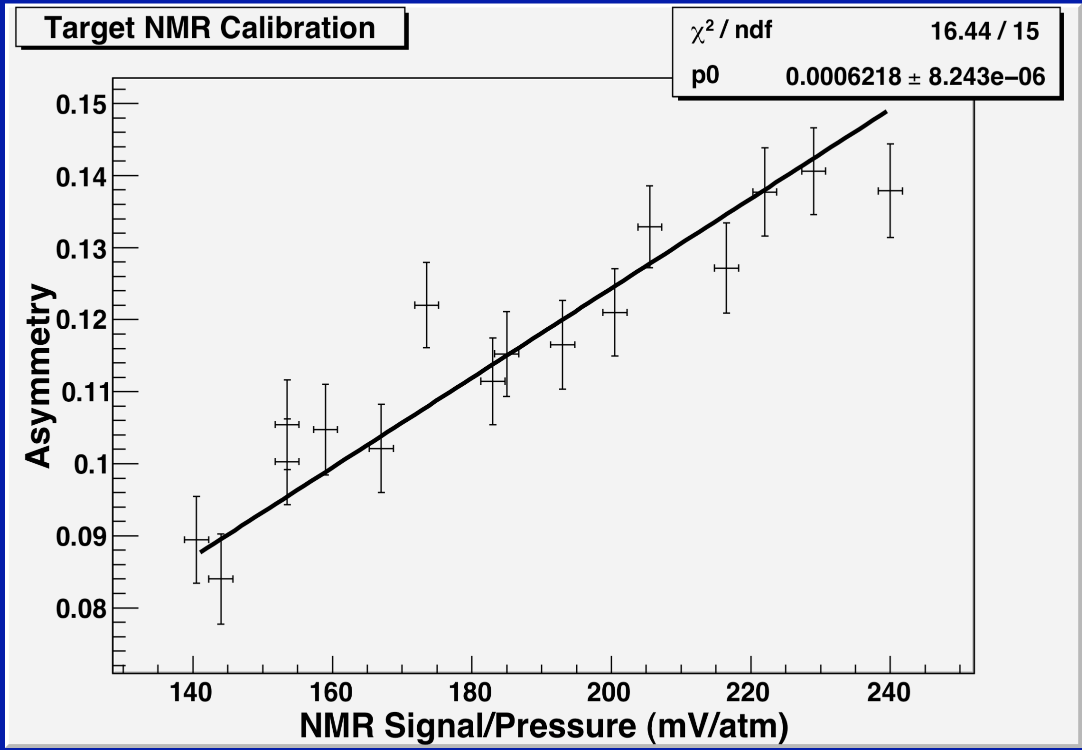

Rb/K
Rb
Polarization
Time (hrs)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0
5
10
15
20
25
30

Cell

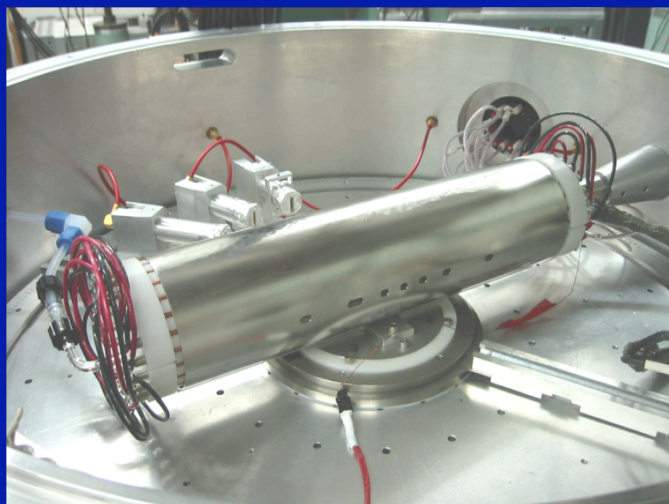
Target NMR Calibration

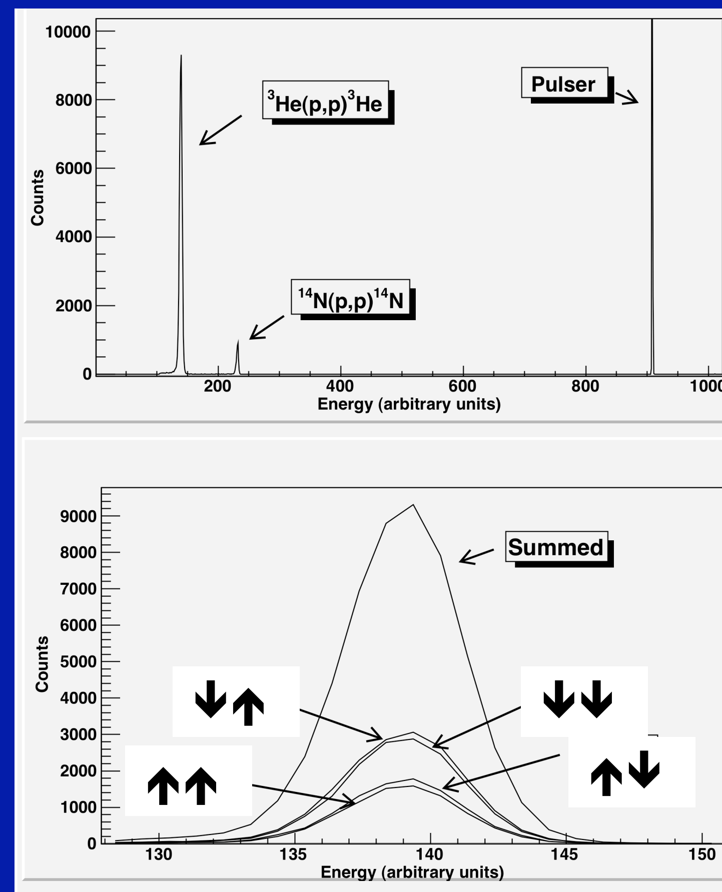
- Pulsed NMR must be calibrated by absolute measurement
- We used $^{3}\overrightarrow{\mathrm{He}}(\alpha,\alpha)^{3}\mathrm{He}$ at E_{α}=15.3 MeV and $\theta_{lab} = 45^{\circ}$
- Fit of polarization vs NMR yields the calibration factor

$$p_t A_y = \frac{N_{left} - N_{rignt}}{N_{left} + N_{right}}$$



Scattering Experiment

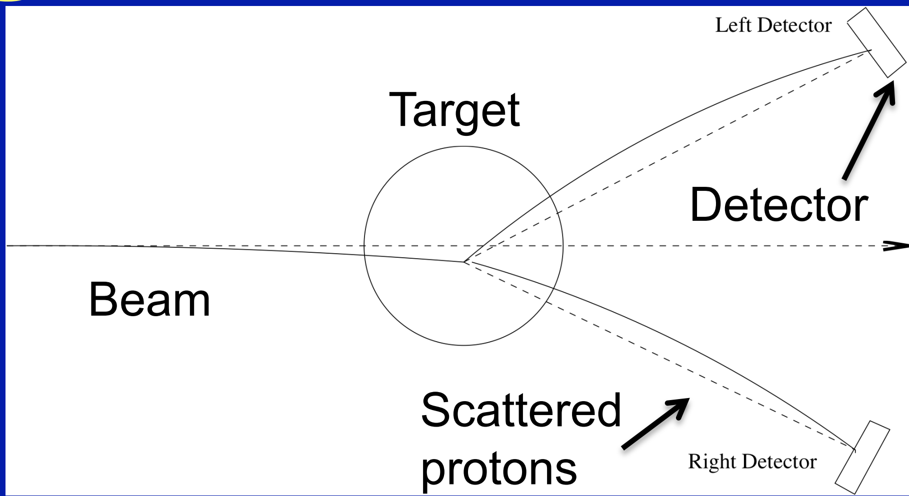


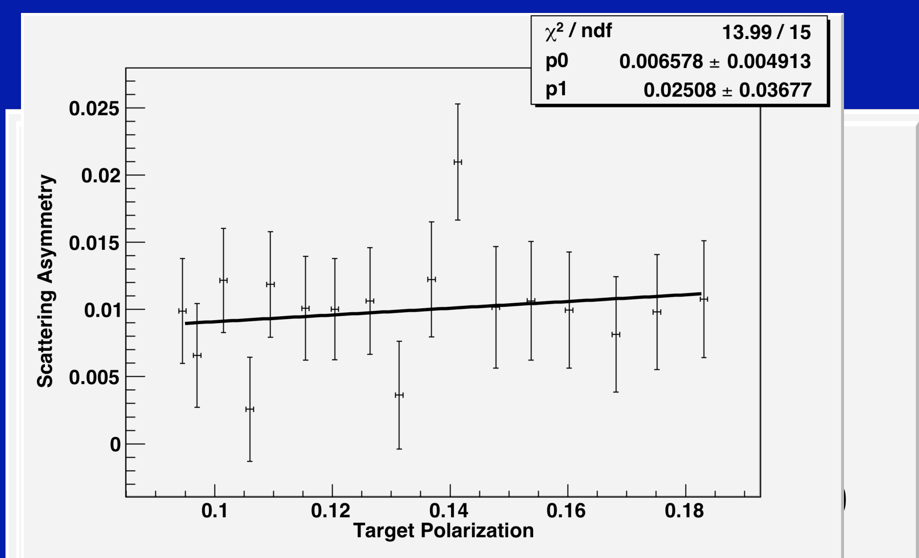


- Spin-Correlation Coefficients between 2 and 6 MeV
- Polarized beam and target
- Left/Right pairs of Si detectors
- Beam current integration by Faraday cup
- Beam spin flipped at 1 or 10 HZ.
- Spectra generally free of background
- Electronic data sorting by beam and target spin-state

Steering Effect

- Non-zero asymmetries for A_{0y} with unpolarized target
- No effect for A_{yy} or A_{xx}
- Associated with sin-theta coil B field
- Small (0.1°) angle magnetic steering of proton
  - Cross-section angle-dependent
- Measured effect subtracted from data
  - Unpolarized target
  - Extrapolation of polarized data to zero





Global phase-shift analysis

- Observables expressed as functions of phase-shifts according to the Blatt-Biedenharn convention
- Phase-shift energy dependence parameterized by modified effective range expansion
- Parameters used: $^1S_0$, $^3S_1$, $^1P_1$, $^3P_0$, $^3P_1$, $^3P_2$, $^1D_2$, ^3D_j, ^3F_j, $\varepsilon(1^+)$, $\varepsilon(1^-)$, $\varepsilon(2^-)$
- 3 effective range parameters for each → 36 total parameters

Modified effective range expansion for phase shifts and mixing parameters

$$k\cot\delta = -\frac{1}{a} + \frac{1}{2}k^2 r_0 + . \quad . \quad .$$

$$C(\eta)k^{2l+1}\left[\cot\delta^j_{ls} + \frac{2\eta H(\eta)}{C_0^2(\eta)}\right] = \sum_{n=0} a_n^{jls} k^{2n}$$

$$\tan\varepsilon(j^\pi) = \sum_i a_i^j k^{2i}$$

- Wisconsin group's chisq search routine used to find best-fit solution to 1000-point global database

M. T. Alley and L. D. Knutson, Phys. Rev. C 48, 1901 (1993).

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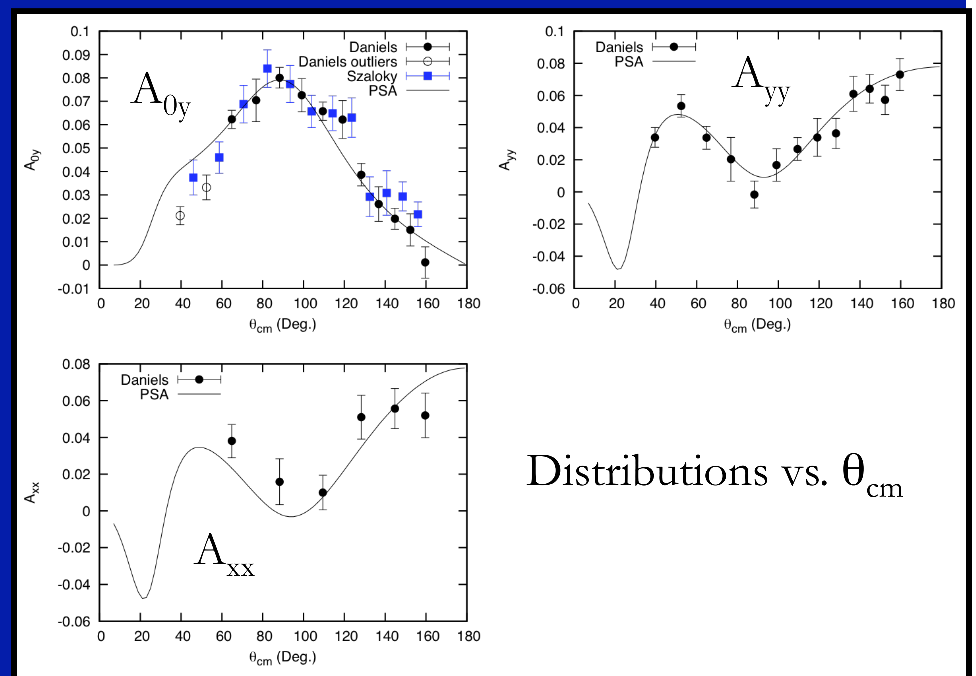
Results: Observables

- Distributions at 2.25, 2.7, 3.13, 4.00, and 5.54 MeV
- Lowest-energy spin-correlation data for p + ^3He
- Observables fit well by phase-shift analysis
- Agreement with available previous data

Example at 3.13 MeV

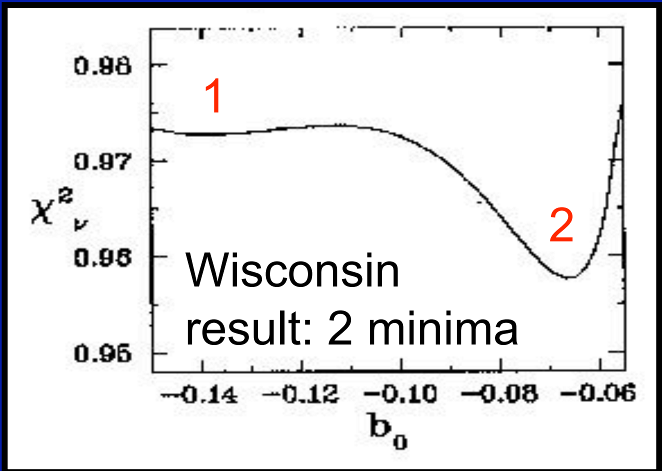


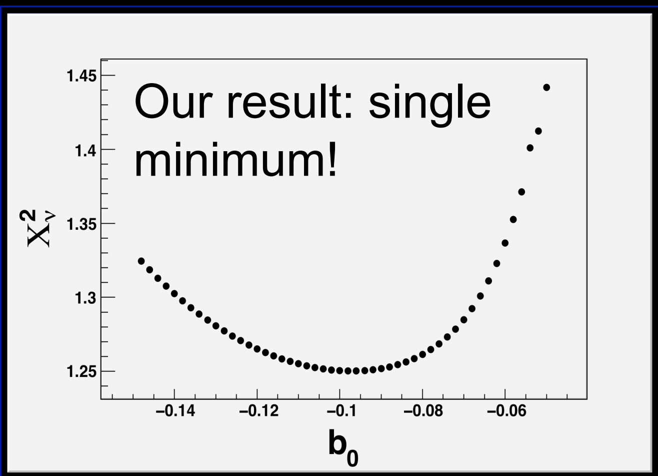
Distributions vs. θ_{cm}

T. V. Daniels *et al.*, Phys. Rev. C 82, 034002 (2010)

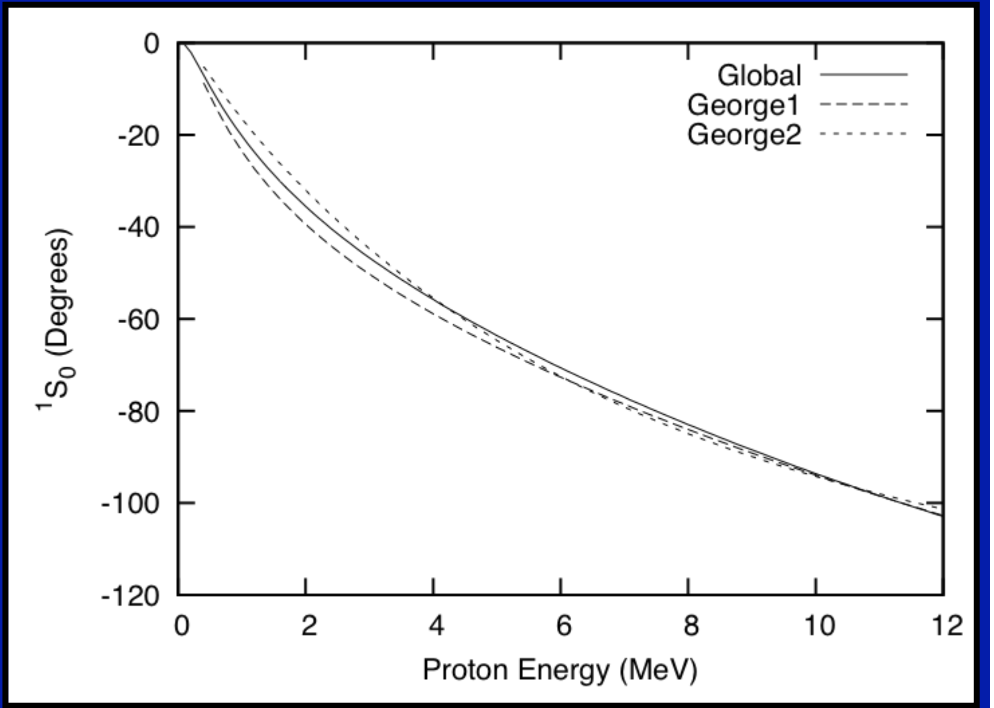
Results: Phase-shifts

Parameter χ^2 "scan"





$^1S_0$ vs energy

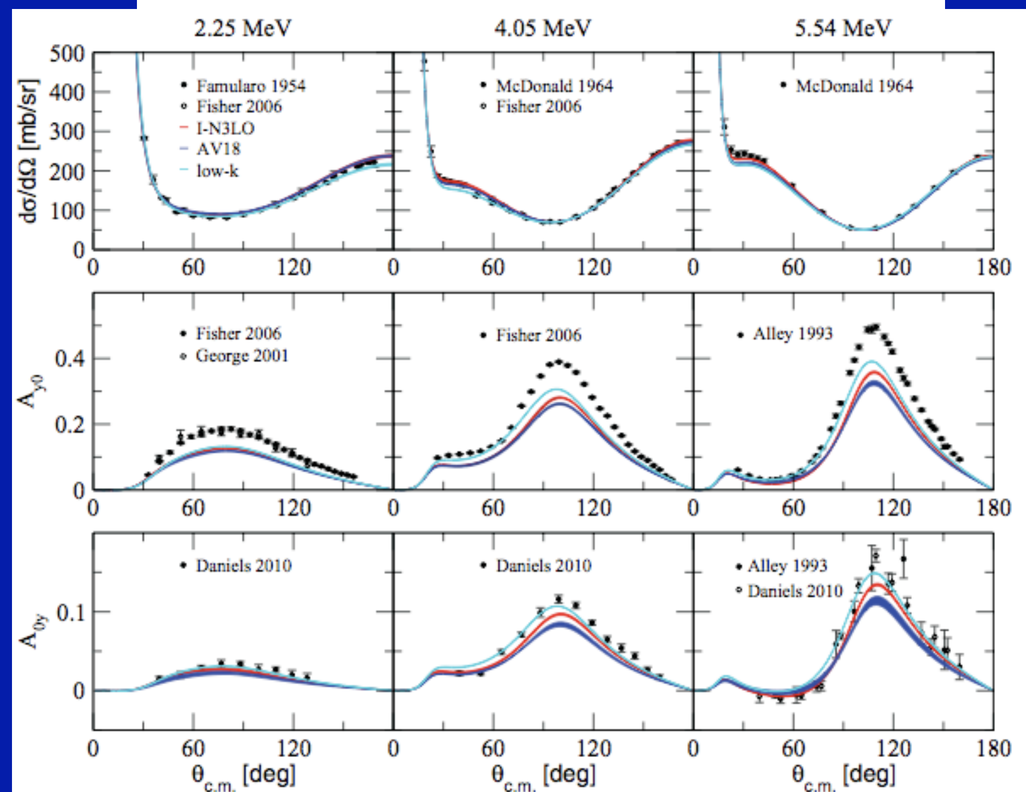


The addition of new data removes ambiguity and establishes unique solution!

Comparison to Theory (NN):

- "Benchmark" calculations using 3 different methods (HH, AGS, FY)
- Potentials considered include AV18 and I-N3LO (ChPT)
- Cross-sections well-described
- Analyzing powers underpredicted (A_y Puzzle)
- Spin correlation coefficients somewhat underpredicted at forward angle, less sensitive to choice of potential.

Cross-section and analyzing powers



M. Viviani *et al.*, Phys. Rev. C 84, 054010 (2011)

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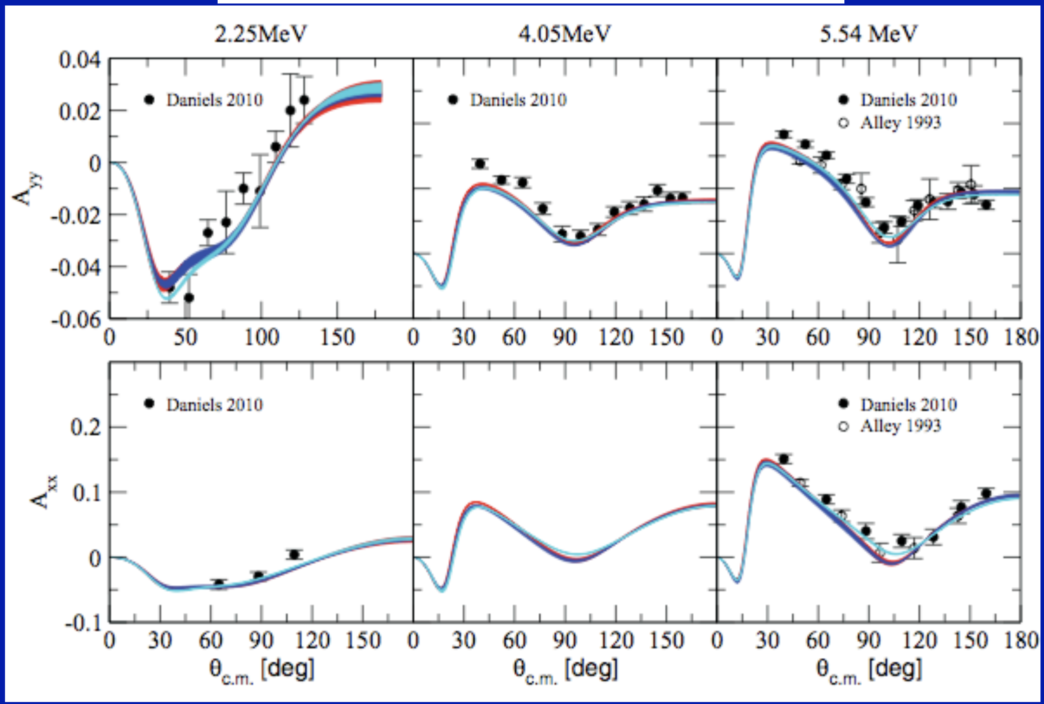
Spin-correlation coefficients

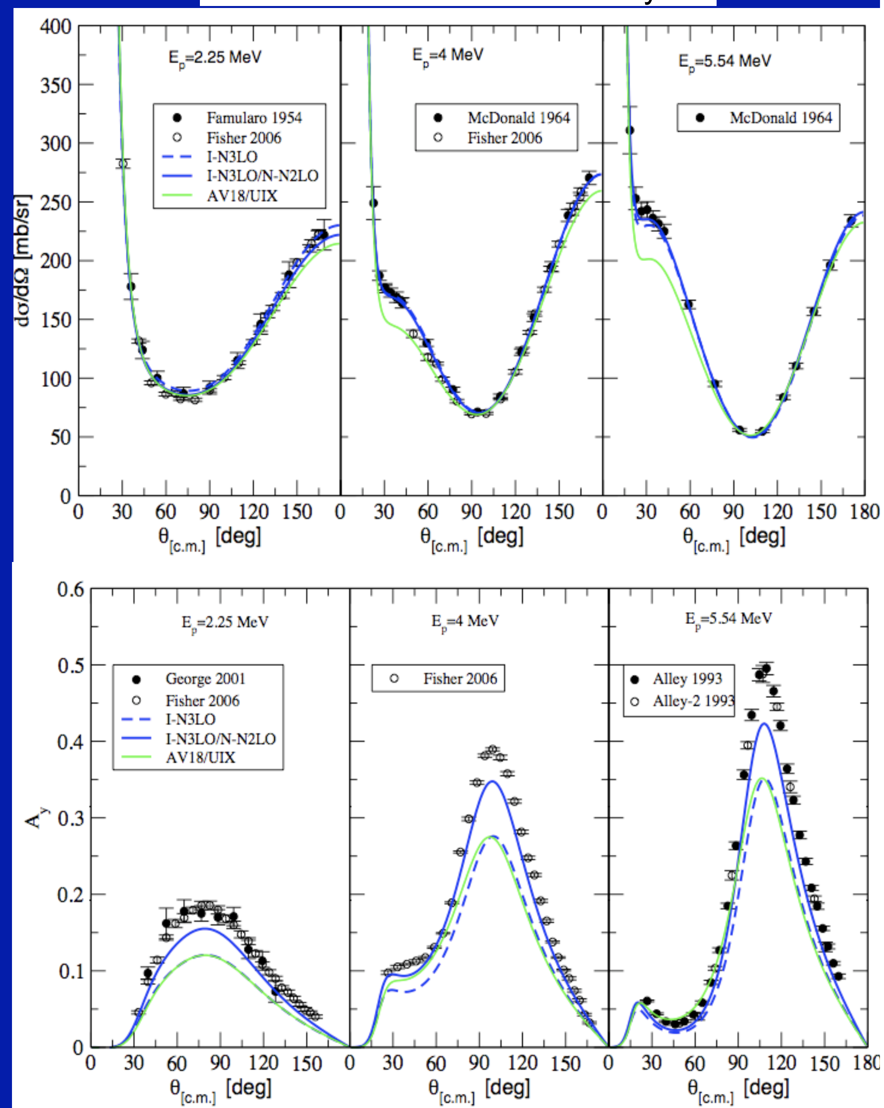


M. Viviani *et al.*, Phys. Rev. C 84, 054010 (2011)

Comparison to Theory (NN+3NF)

- AV18+URIX and I-N3LO+I-N2LO (ChPT) potentials solved with HH method
- AV18+URIX still substantially underpredicts A_{y0}. Also underpredicts σ, A_{yy}, and A_{xx} at forward angles.
- I-N3LO+I-N2LO improves agreement for all observables, especially Ay0!

Cross-section and A_{y0}



M. Viviani *et al.*, *EPJ Web of Conferences* ***3*, *05011 (2010)***

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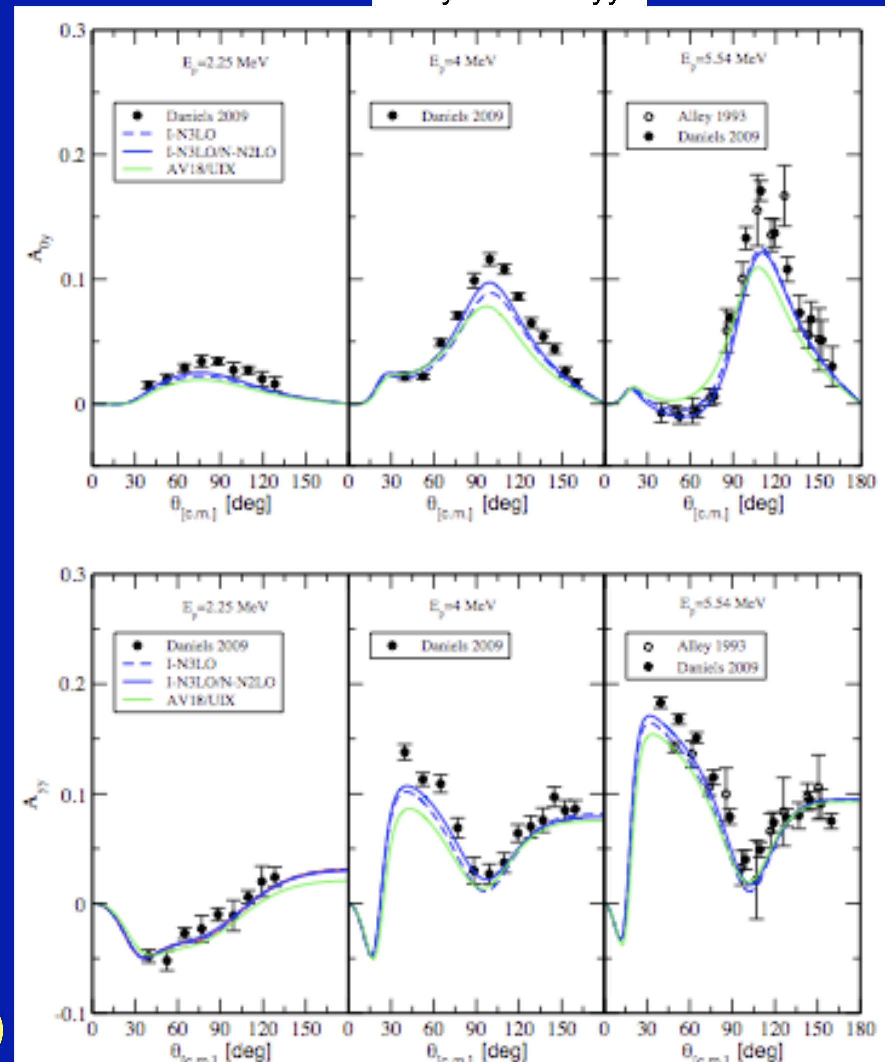
A_{0y} and A_{yy}

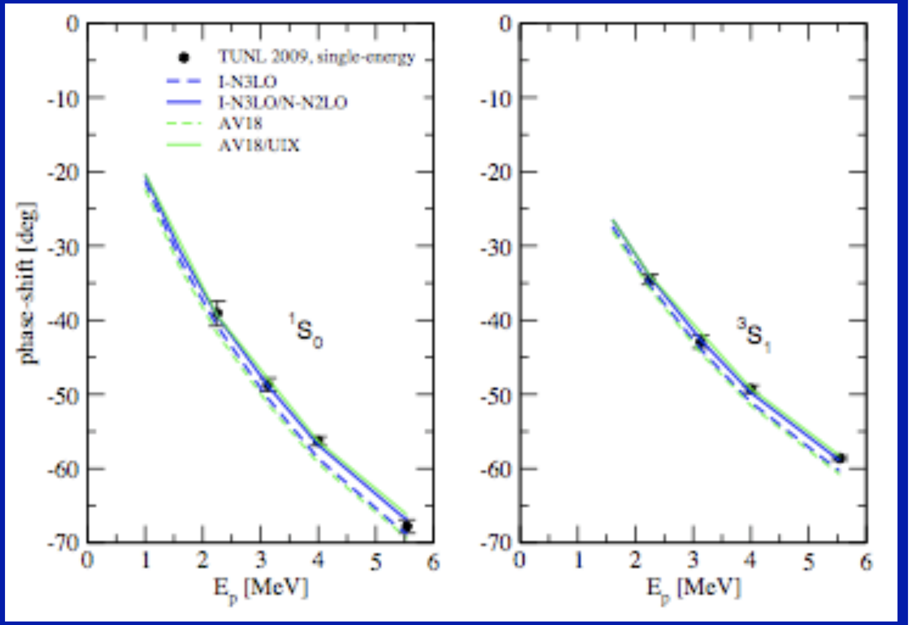


M. Viviani *et al.*, *EPJ Web of Conferences* ***3, 05011 (2010)***

Comparison to Theory (NN+3NF): Phase-shifts

- S-Waves: Slightly overpredicted by NN models, well-reproduced with 3NF
- P-Waves: AV18+URIX underpredicts 3P2 and 3P1, well reproduced by I-N3LO+N-N2LO
- Mixing parameters: large experimental uncertainties, but I-N3LO+N-N2LO preferred
- I-N3LO+N-N2LO generally in good agreement with experimental phase-shifts

S-waves (L=0)



M. Viviani *et al., EPJ Web of Conferences* ***3, 05011 (2010)***

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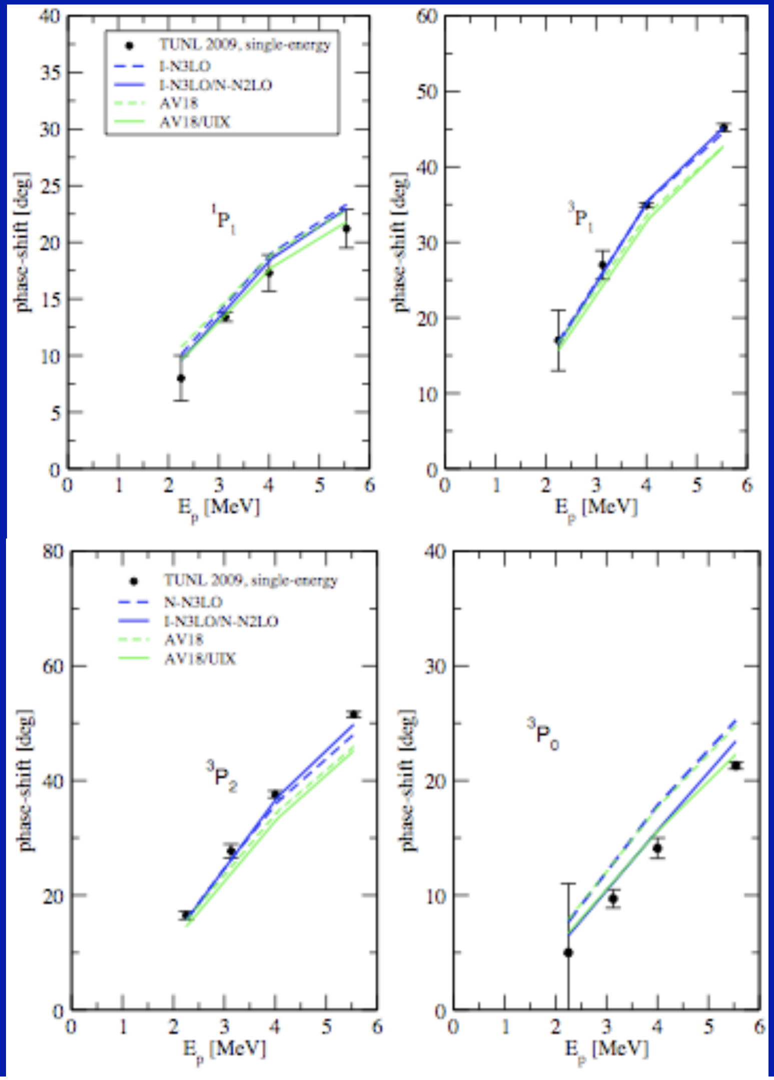
P-waves (L=1)



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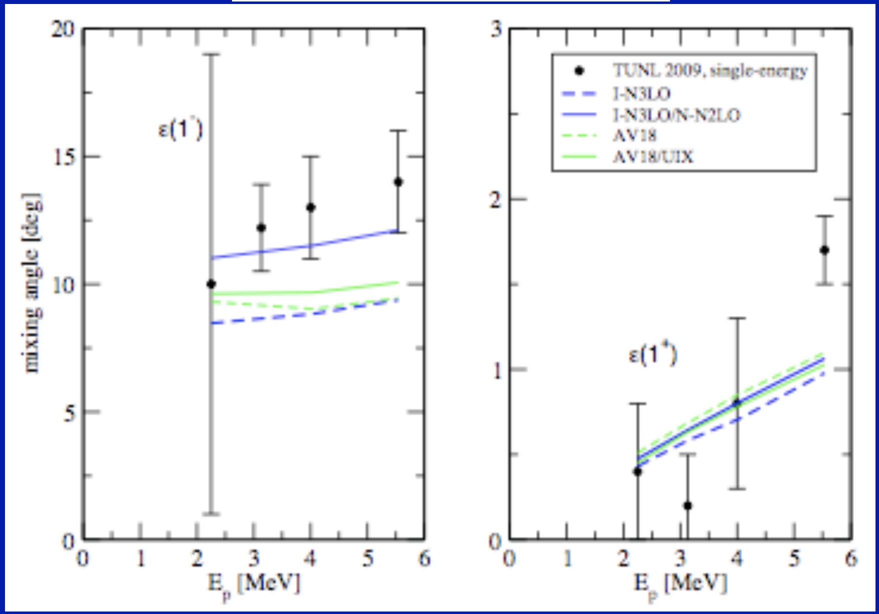
Mixing Parameters



M. Viviani *et al.*, *EPJ Web of Conferences* ***3*, *05011 (2010)***

Conclusions

- A new SEOP polarized ^3He target was used to measure spin-correlation coefficients between 2 and 6 MeV
- These new measurements have been used to resolve the ambiguity in the global phase-shift analysis
- Precise 4N theoretical calculations using a variety of potential models available for comparison
- Best agreement with ChPT-derived I-N3LO+I-N2LO (NN +3NF) potential
- This model, which is closer to the experimental A_{y0}, better-reproduces the experimental partial waves, especially $^3P_2$, $^3P_1$, and ε (1^-)

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