Puzzling Over the Mysteries of the Few Nucleon Forces

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Outline

- Formalism and observables
- Experimental tools
- Experimental results
  - 2N, 3N, 4N examples
- Conclusions

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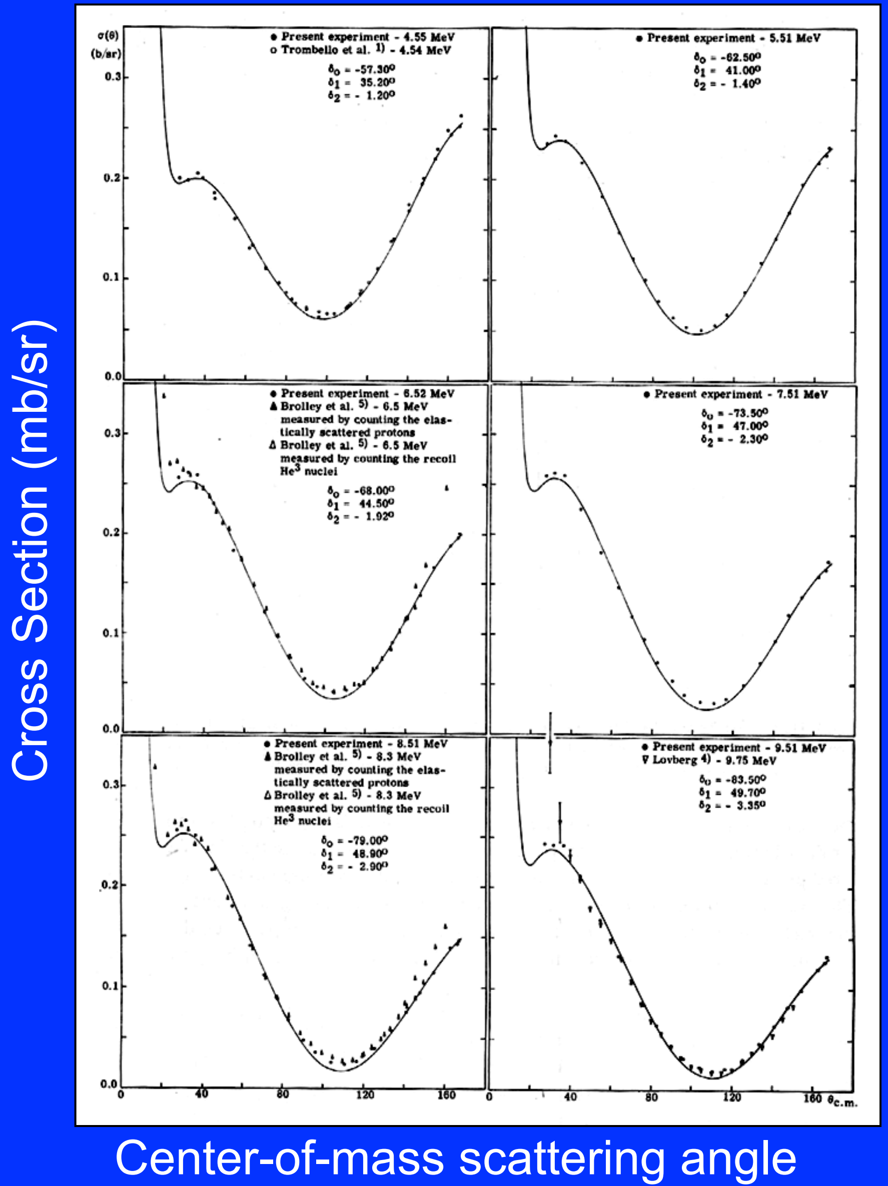
A Simple Example

- p + ^{3}He elastic scattering
- Differential cross section measured below 11.5 MeV
- Data described with a 3-parameter phase shift analysis

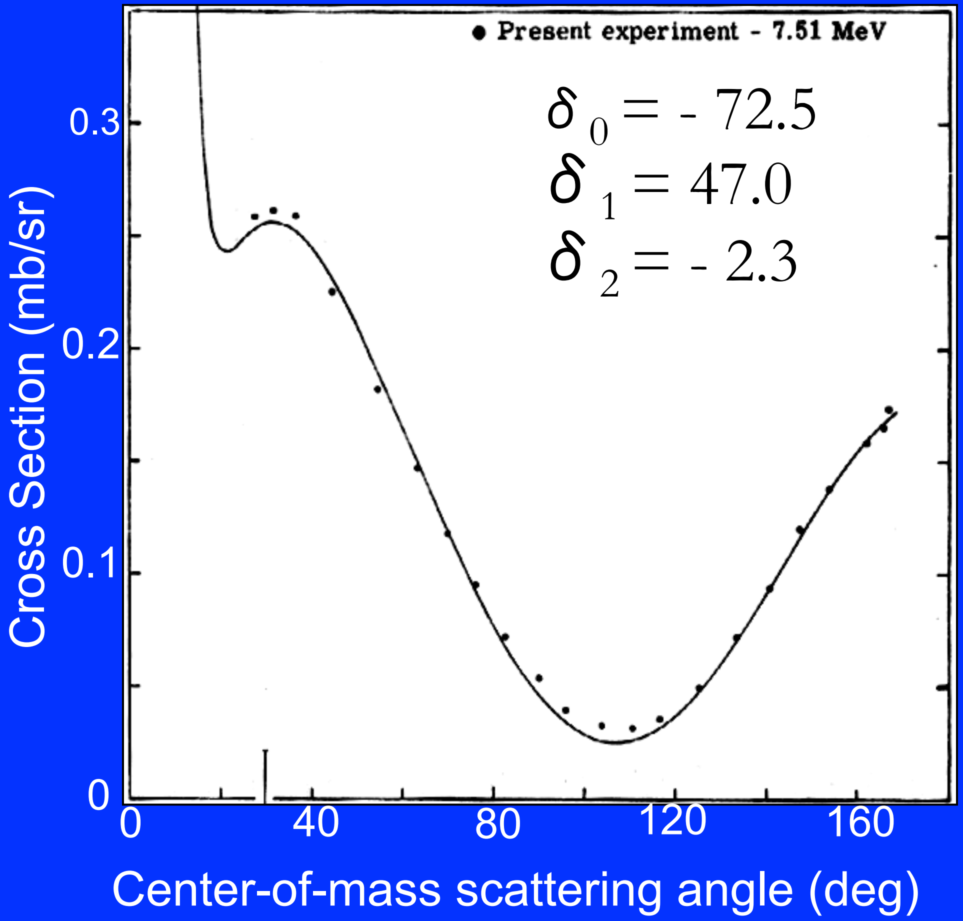


Parameterization of Data

- Major structure in the differential cross section is well described by a simple calculation

- Small difficulties remain with fits in forward and mid-angle ranges

E_p = 7.51 MeV



Partial Wave Analysis

$$\frac{d\sigma}{d\Omega} = \frac{1}{4k}\left| i\eta\csc^2(\tfrac{1}{2}\theta)\exp[i\eta\ln(\csc^2(\tfrac{1}{2}\theta)] + \sum_{l=0}^{\infty} P_l(\cos\theta)(2l+1)U_l \right|^2$$

Coulomb scattering term

Nuclear scattering term

where

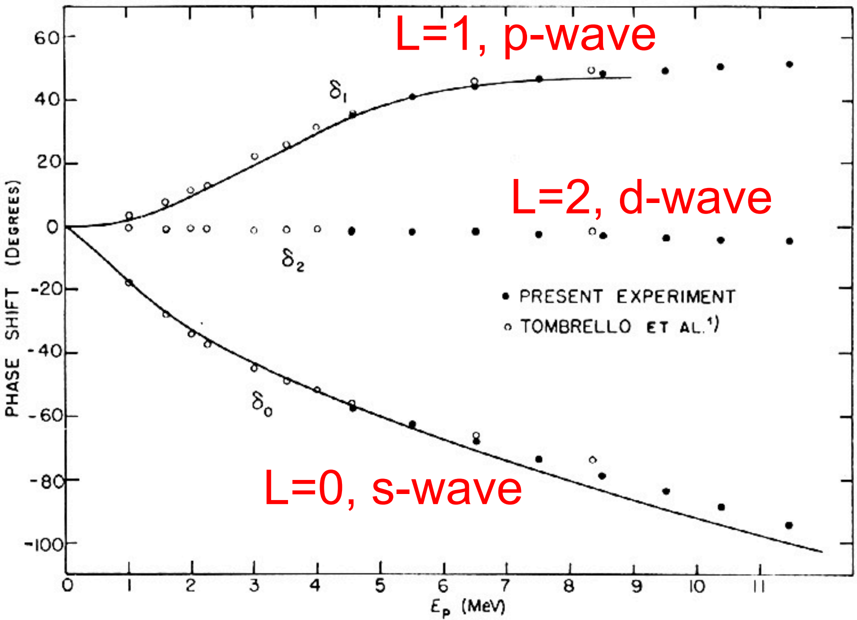
$$U_l = \exp(2i\alpha_l)[1 - \exp(2i\delta_l)]$$

Phase shift

$$\alpha_0 = 0, \qquad \alpha_l = \sum_{s=1}^{l} \tan^{-1}(\eta / s)$$

$$\eta = (Z_1 Z_2 e^2 / \hbar v) \text{ and } k = \mu v / \hbar$$

- Data are parameterized by phase shifts for individual partial waves.



E_p (MeV)

Conclusion?

- Nuclear scattering from ^{3}He is basically pretty simple.

Right?

Not quite! What about spin?

Full Phase Shift Analysis

- Real nuclei can also carry spin angular momentum
- Full phase shift analysis includes a separate partial wave and phase shift for each angular momentum state *J*

Notation

Multiplicity

$$\boxed{{}^{2S+1}L_{J=L+S}}$$

Total Angular Momentum

For pp, nn, np, or $p + {}^3\mathrm{He}$ scattering

$$\begin{array}{lll}
L = 0 & {}^1S_0 & {}^3S_1 \\
L = 1 & {}^1P_1 & {}^3P_0 \quad {}^3P_1 \quad {}^3P_2 \\
L = 2 & \underbrace{{}^1D_2}_{\text{Singlet States}} & \underbrace{{}^3D_1 \quad {}^3D_2 \quad {}^3D_3}_{\text{Triplet States}} \\
\vdots & &
\end{array}$$

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Multiplicity

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Total Angular Momentum

For pp, nn, np, or p + ^{3}He scattering

$$L=0 \qquad {}^1S_0 \qquad {}^3S_1$$

$$L=1 \qquad {}^1P_1 \qquad {}^3P_0 \quad {}^3P_1 \quad {}^3P_2$$

$$L=2 \qquad \underbrace{{}^1D_2}_{\text{Singlet States}} \qquad \underbrace{{}^3D_1 \quad {}^3D_2 \quad {}^3D_3}_{\text{Triplet States}}$$

$$\vdots$$

Split by Spin Orbit Force

Full Phase Shift Analysis

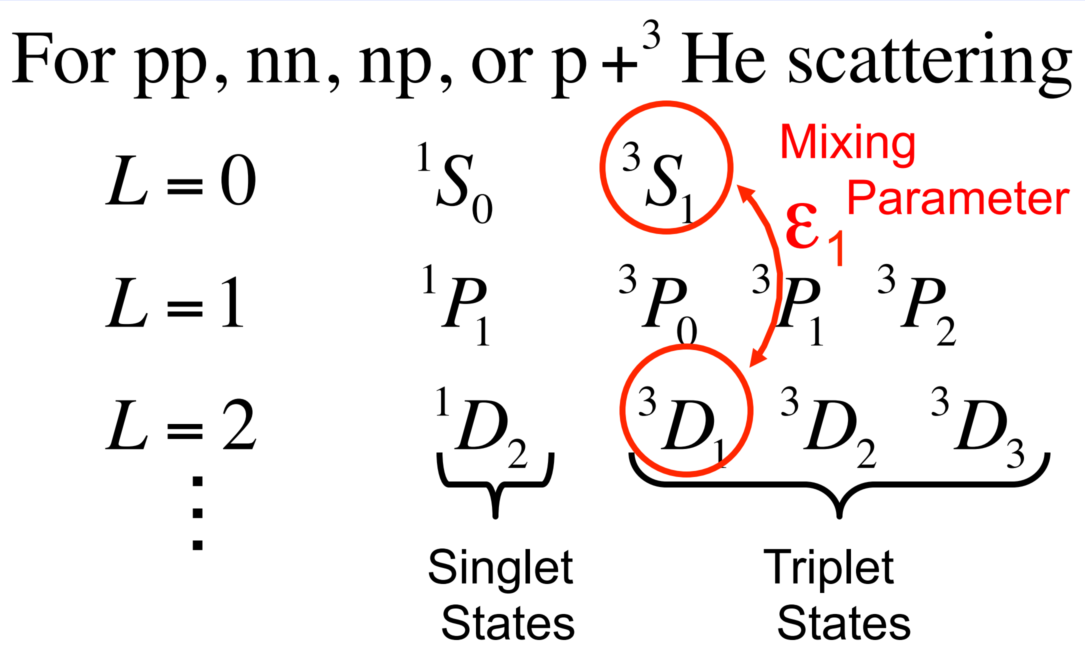
- Real nuclei can also carry spin angular momentum
- Full phase shift analysis includes a separate partial wave and phase shift for each angular momentum state *J*

Notation

Multiplicity

$$^{2S+1}L_{J=L+S}$$

Total Angular Momentum



For pp, nn, np, or p + ^{3}He scattering

$L=0 \qquad {}^1S_0 \qquad {}^3S_1$

Mixing Parameter

ε_1

$L=1 \qquad {}^1P_1 \qquad {}^3P_0 \quad {}^3P_1 \quad {}^3P_2$

$L=2 \qquad {}^1D_2 \qquad {}^3D_1 \quad {}^3D_2 \quad {}^3D_3$

$\vdots$

Singlet States

Triplet States

Mixing Parameter

- Presence of a tensor component mixes states with $\boxed{\ell = J+1}$ and $\boxed{\ell = J-1}$
- The scattering matrix then has the form

$S = U^{-1}e^{-2i\Delta}U$, where

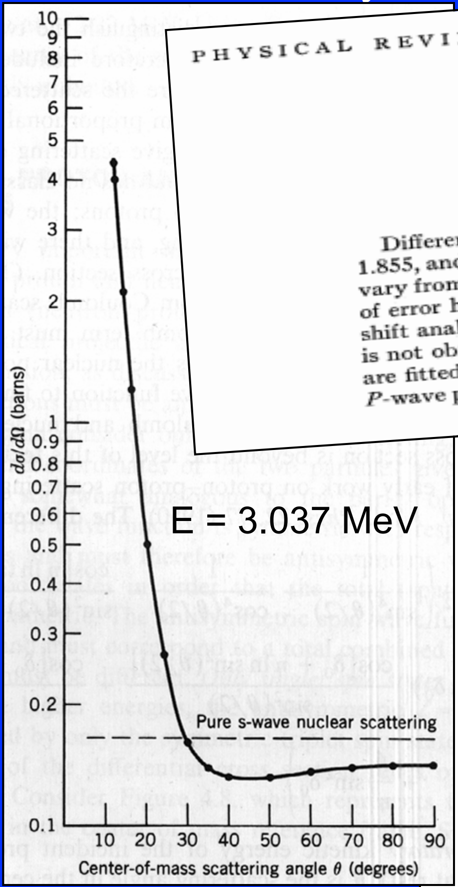
$$U = \begin{pmatrix} \cos\varepsilon_1 & \sin\varepsilon_1 \\ -\sin\varepsilon_1 & \cos\varepsilon_1 \end{pmatrix}, \quad \Delta = \begin{pmatrix} \delta_{\mathrm{J}_\alpha} & 0 \\ 0 & \delta_{J_\beta} \end{pmatrix}$$

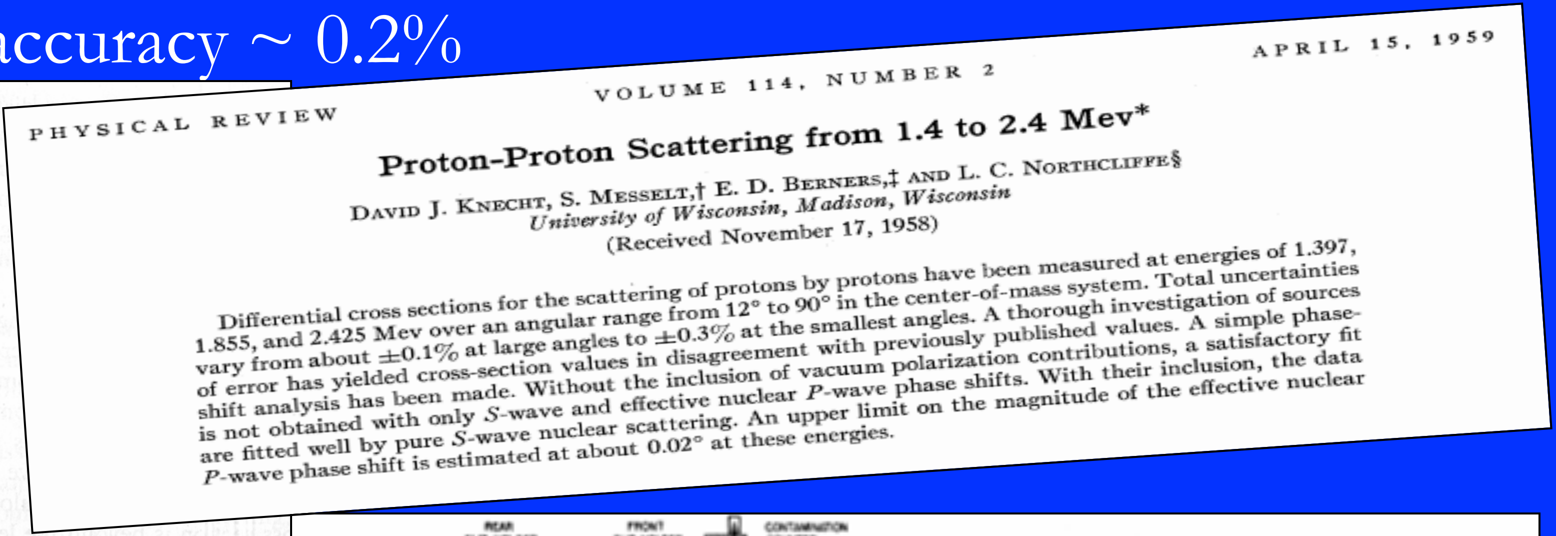
ε_J are the mixing parameters, and

$\delta_{\mathrm{J}_\alpha}$ and δ_{J_β} are the eigenphase shifts.

N-N Scattering - 1959

- p-p scattering cross sections measured with absolute accuracy ~ 0.2%





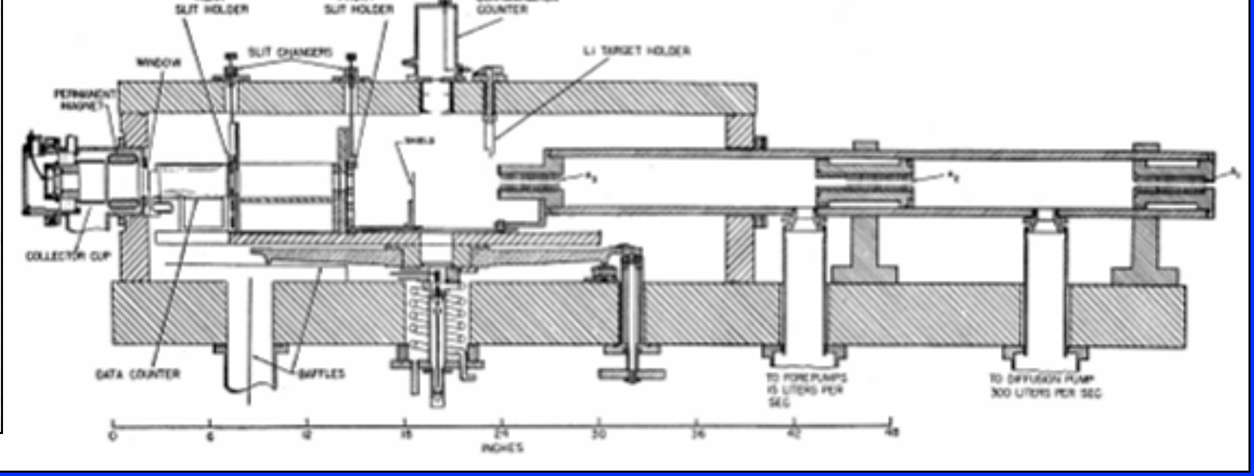
PHYSICAL REVIEW VOLUME 114, NUMBER 2 APRIL 15, 1959

Proton-Proton Scattering from 1.4 to 2.4 Mev*

DAVID J. KNECHT, S. MESSELT,† E. D. BERNERS,‡ AND L. C. NORTHCLIFFE§
University of Wisconsin, Madison, Wisconsin

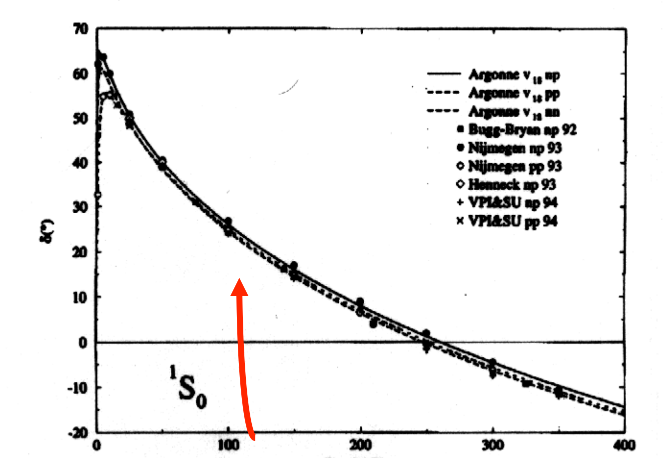
(Received November 17, 1958)

Differential cross sections for the scattering of protons by protons have been measured at energies of 1.397, 1.855, and 2.425 Mev over an angular range from 12° to 90° in the center-of-mass system. Total uncertainties vary from about ±0.1% at large angles to ±0.3% at the smallest angles. A thorough investigation of sources of error has yielded cross-section values in disagreement with previously published values. A simple phase-shift analysis has been made. Without the inclusion of vacuum polarization contributions, a satisfactory fit is not obtained with only *S*-wave and effective nuclear *P*-wave phase shifts. With their inclusion, the data are fitted well by pure *S*-wave nuclear scattering. An upper limit on the magnitude of the effective nuclear *P*-wave phase shift is estimated at about 0.02° at these energies.

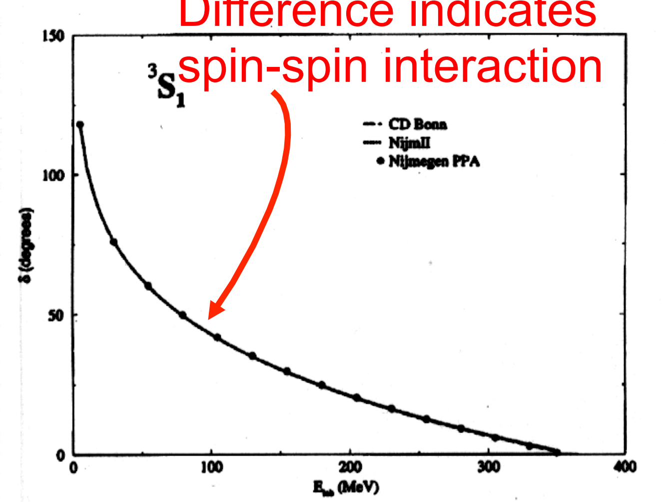


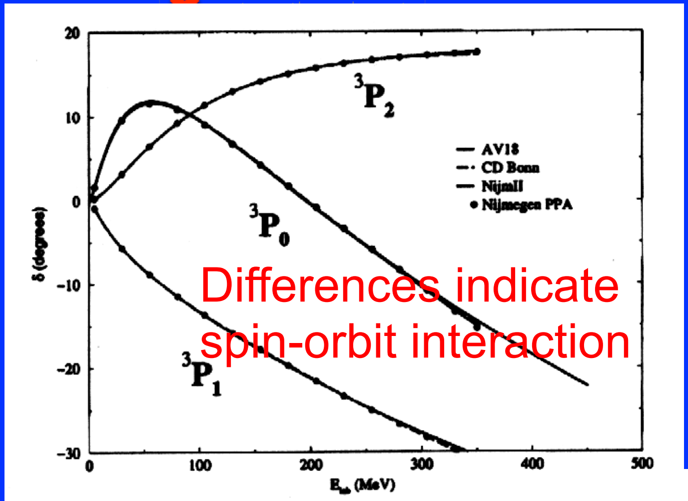
N-N Scattering Today

- Over 10,000 data points between 0 and 3 GeV are parameterized by phase shifts

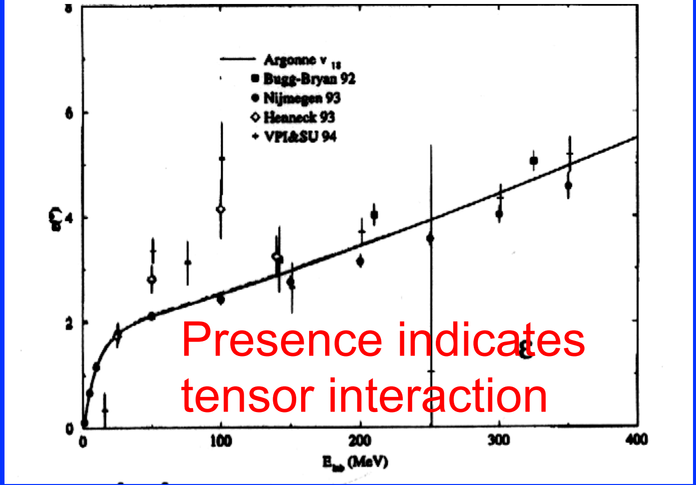


Difference indicates spin-spin interaction





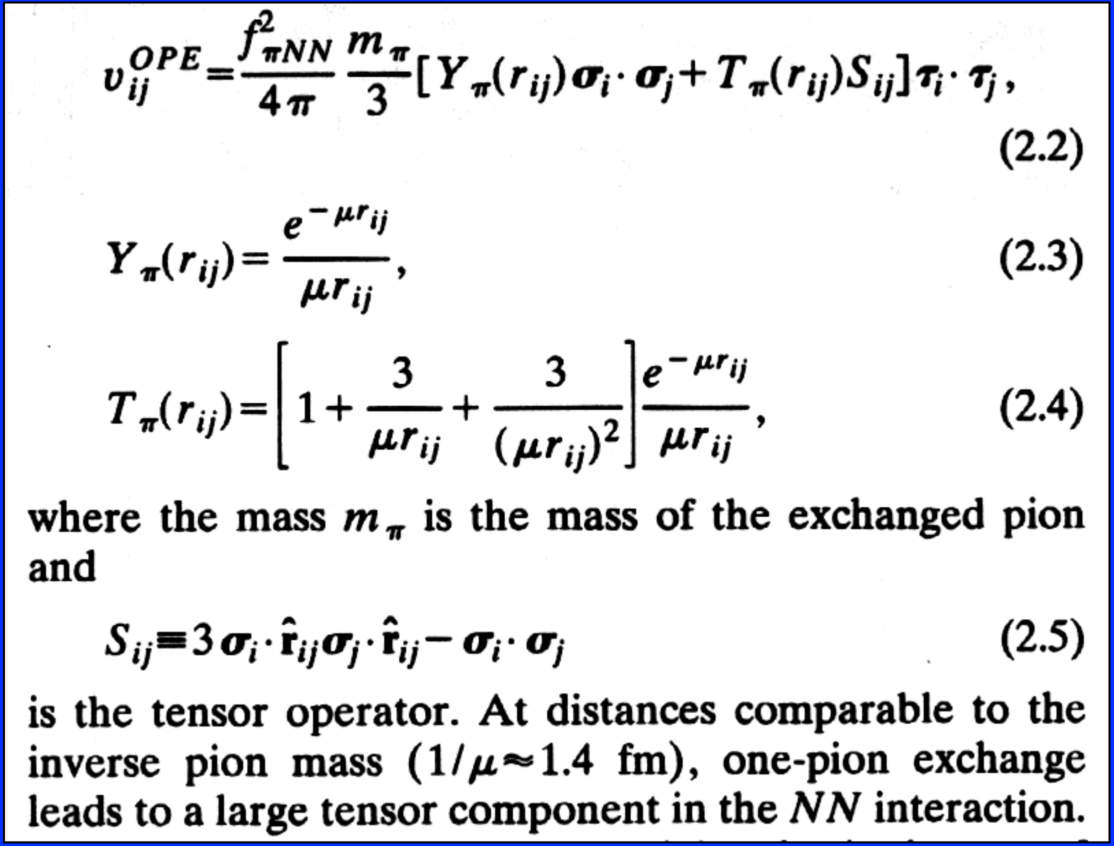
Differences indicate spin-orbit interaction



Presence indicates tensor interaction

NN Interactions

- The predominant long-range component is attributed to one-pion exchange
- Additional terms are included in modern potentials, e.g.
  - **Iso-tensor dependent**
  - **Weak interaction**
  - **Two pion and other meson exchange**
  - **Three-body force**
- Potentials are used to fit the NN phase shifts, with ~40 parameters with overall $\chi^2 = 1$.



$$v_{ij}^{OPE}=\frac{f_{\pi NN}^2}{4\pi}\frac{m_\pi}{3}[Y_\pi(r_{ij})\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j+T_\pi(r_{ij})S_{ij}]\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j\,, \tag{2.2}$$

$$Y_\pi(r_{ij})=\frac{e^{-\mu r_{ij}}}{\mu r_{ij}}\,, \tag{2.3}$$

$$T_\pi(r_{ij})=\left[1+\frac{3}{\mu r_{ij}}+\frac{3}{(\mu r_{ij})^2}\right]\frac{e^{-\mu r_{ij}}}{\mu r_{ij}}\,, \tag{2.4}$$

where the mass m_π is the mass of the exchanged pion and

$$S_{ij}\equiv 3\boldsymbol{\sigma}_i\cdot\hat{\mathbf{r}}_{ij}\boldsymbol{\sigma}_j\cdot\hat{\mathbf{r}}_{ij}-\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j \tag{2.5}$$

is the tensor operator. At distances comparable to the inverse pion mass ($1/\mu\approx 1.4$ fm), one-pion exchange leads to a large tensor component in the *NN* interaction.

From J. Carlson and R. Schiavilla, Rev. Mod. Phys. 70 (1998) 743

Modeling Few-N Scattering

- Traditional phenomenological potentials
  - 2N (e.g. Nijmegen, CD-Bonn, AV-18)
  - 3N (e.g. Tucson-Melbourne, Urbana IX)
- More recent chiral potentials treat 2N, 3N, and 4N interactions consistently.
- Use these to calculate observables in 3N & 4N systems
- 4N system is a fertile ‘theoretical laboratory’
  - Lightest system with resonant states and thresholds
  - Simplest where spin and isospin couplings can be studied.

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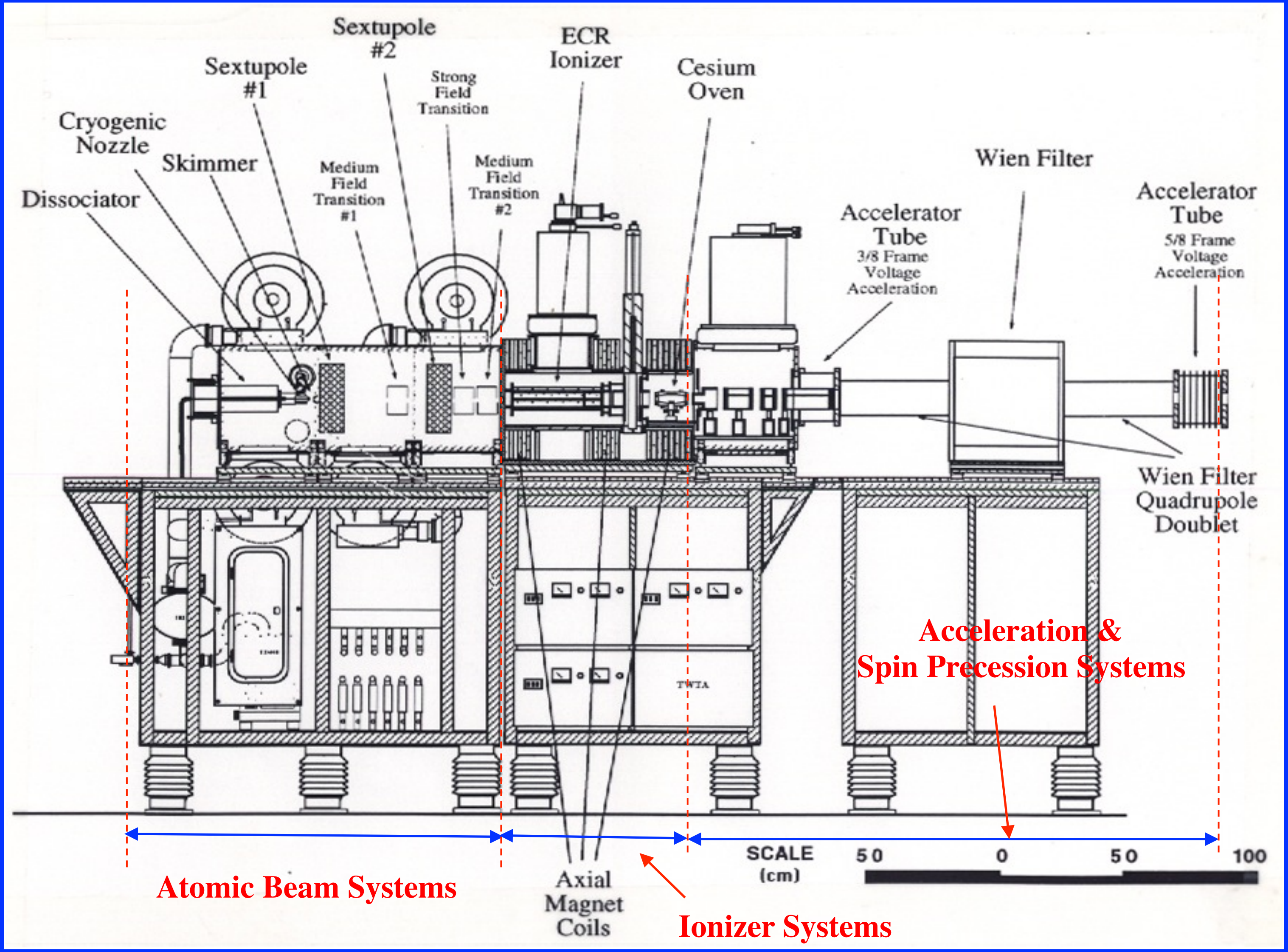
Making Spin Polarized Beams

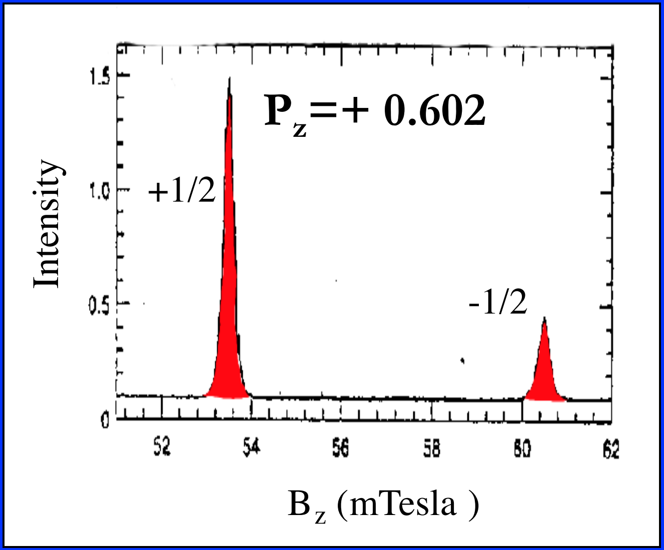
Atomic Beam Polarized Ion Source - [NIM A357 (1995)200]

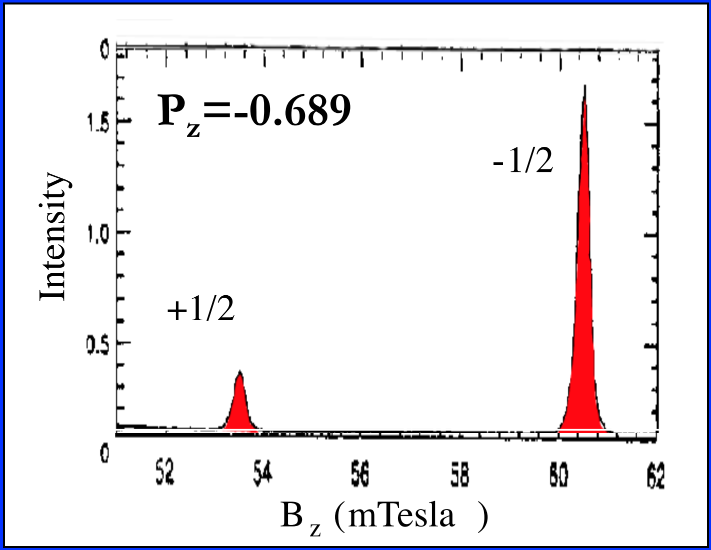


What Does Polarization Mean?

- For protons, neutrons, or ^{3}He with $spin = \frac{\hbar}{2}$, one defines

$$\text{Polarization } P_z = (N^+ - N^-)/(N^+ + N^-)$$



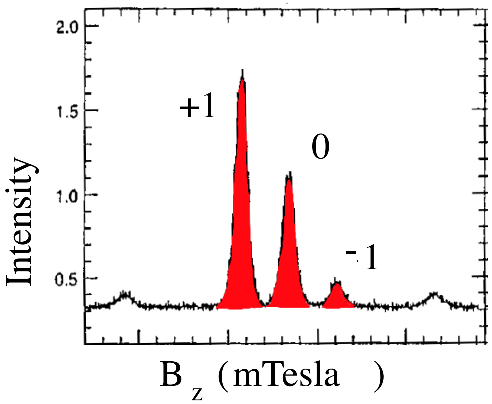


What Does Polarization Mean?

- For deuterons with $spin = \hbar$, one defines

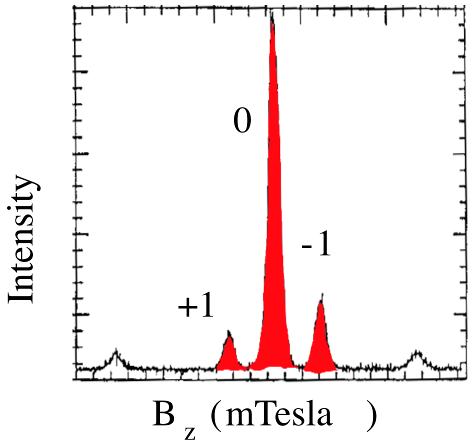
$$\text{Vector Polarization } P_z = (N^{+1} - N^{-1}) / (N^{+1} + N^0 + N^{-1})$$

$$\text{Tensor Polarization } P_{zz} = (1 - 3N^0) / (N^{+1} + N^0 + N^{-1})$$



$P_z = 0.518$

$P_{zz} = -0.034$



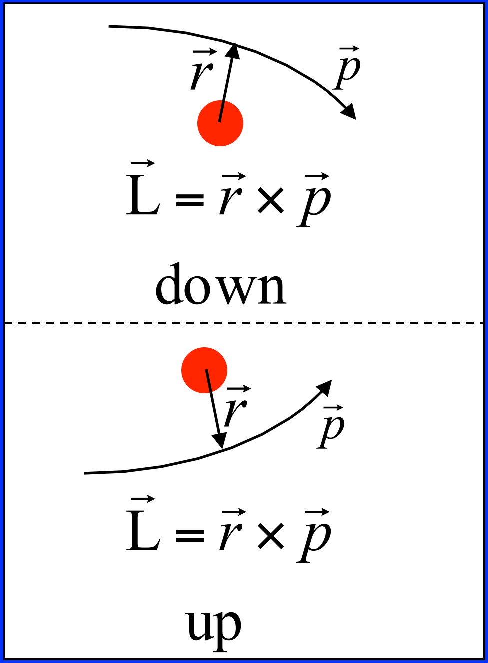
$P_z = -0.073$

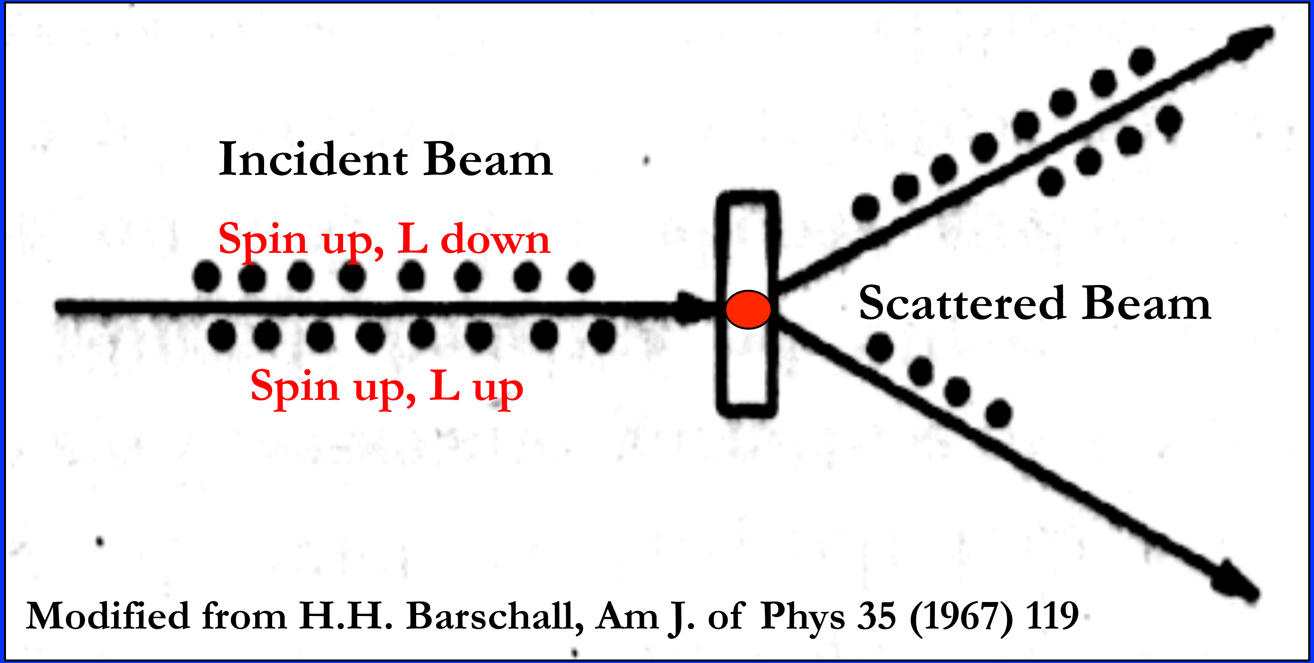
$P_{zz} = -1.352$

What Do We Measure and Why?

- Incident polarized ions experience a nuclear $\boxed{\vec{L}\cdot\vec{S}}$ force.
- More particles are scattered to one side than the other, producing a left-right scattering asymmetry,
- One extracts a vector analyzing power, A_y.

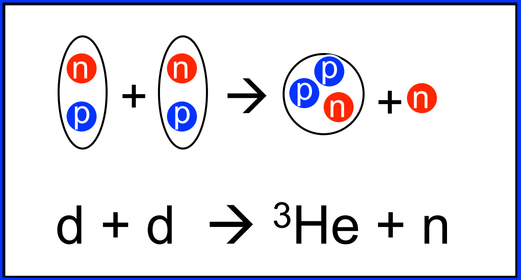
$$\boxed{\varepsilon = A_y P_b = \frac{N_{left} - N_{rignt}}{N_{left} + N_{right}}}$$





Modified from H.H. Barschall, Am J. of Phys 35 (1967) 119

Neutron Beams



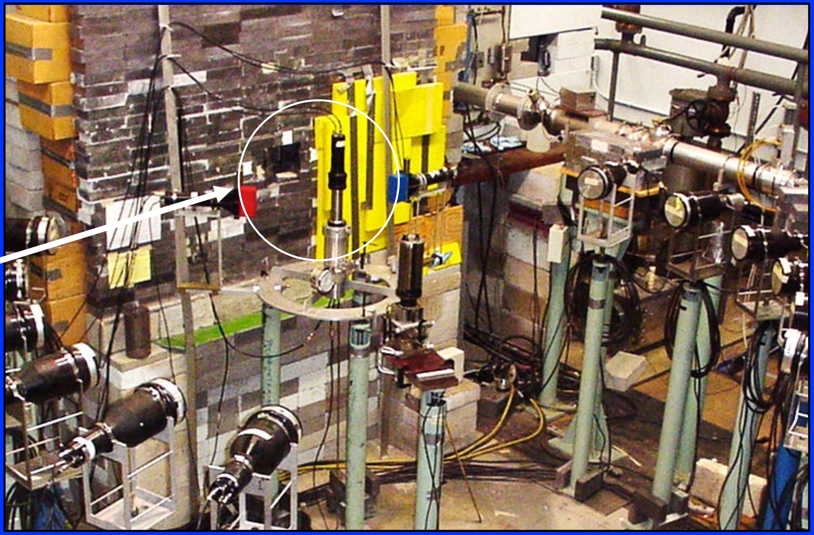
$d + d \rightarrow {}^3He + n$

- In a d stripping reaction, yield is strongly peaked at 0°.
- When the incident deuteron is polarized, the outgoing neutron largely keeps its initial polarization.
- Roughly constant neutron polarization is obtained between ~7 and 22 MeV.

P.W. Lisowski et al., Nucl. Phys A232 (1975) 298

Neutron Polarimetry

- Polarized Neutron Source: $D(\vec{d},\vec{n})^3He$
  - Neutron polarization ~70% and constant versus energy
- ^{4}He polarimeter
  - 100 bar pressure 95% He; 5% Xe
  - Utilizes $^4He(n,n)^4He$
  - Effective A_y ~ 85% at θ_{cm} = 120 degrees



^{4}He polarimeter in position to measure n beam polarization for n-d A_y measurement

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Spin-Dependence vs Nucleon Number

- Magnitude of A_y grows with # of nucleons
- Expt/theory discrepancy grows with N
- Well-known "A_y puzzle" appears in 3N and 4N

Barker *et al.*, PRL **48** (1982) 918.

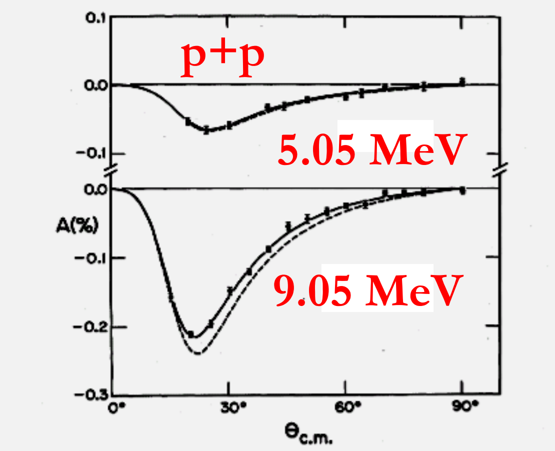
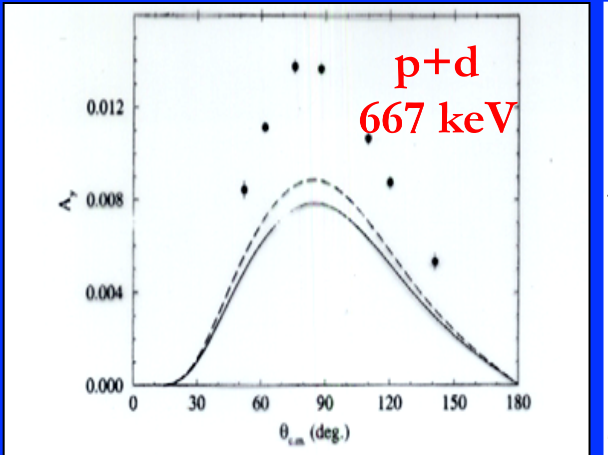


FIG. 2. Proton-proton analyzing power at 5.05 and 9.85 MeV plotted as a function of c.m. scattering angle. The solid curves through the data points are obtained from our phase-shift analyses. The dashed curves are the analyzing powers predicted from the Paris potential.

Brune, *et al.*, PR C**63**, 044013 (2001)



Angular distribution for A_y for p-d scattering at $E_{c.m.}$ = 667 keV. The errors include the uncertainty in the beam polarization as well as statistical uncertainties. The solid and dashed curves are calculations with the AV18 and AV18+UR potentials, respectively.

Fisher *et al*, PRC74 (2006) 034001

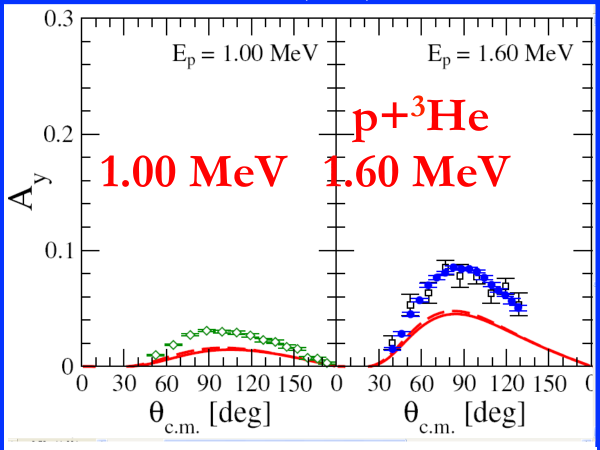
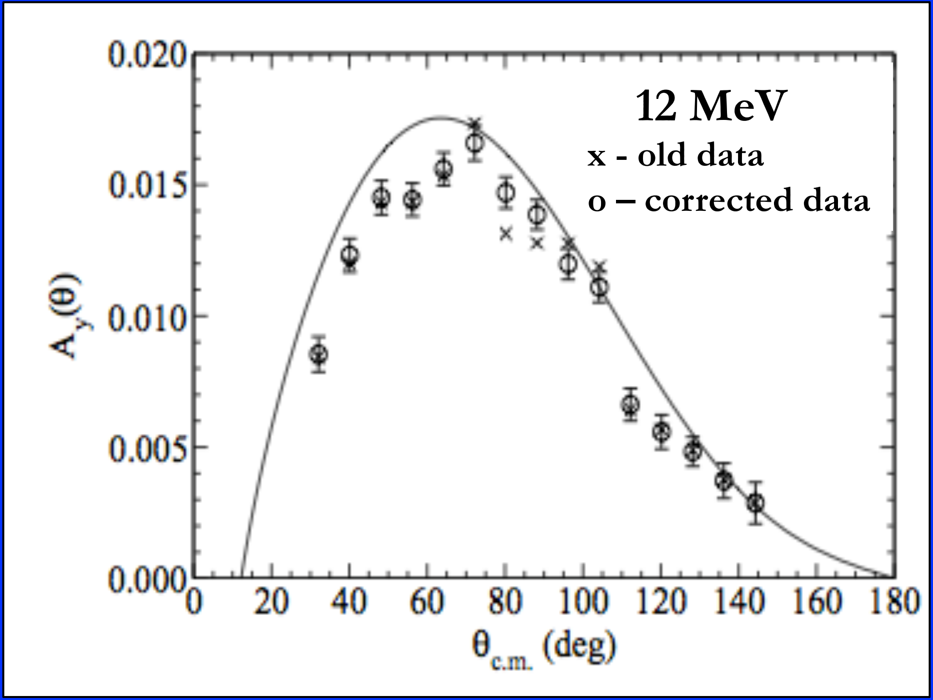


FIG. 5. (Color online) Measured p-^{3}He proton analyzing power A_y (solid circles) at five different energies are compared with the data of Ref. [10] (open squares), Ref. [22] (open diamonds), and Ref. [67] (open circles). Curves show the results of theoretical calculations for the AV18 (dashed lines) and AV18/UIX (solid lines) potential models.

Improved A_y Results for n-p

G.J. Weisel, R.T. Braun, W. Tornow, PRC **82**, 027001 (2010)

- New corrections applied to 7.6 and 12.1 MeV data for polarization-dependent detector efficiencies
- Data lie below predictions using phases of Nijmegen partial wave analysis.
- Need larger charged pion-nucleon coupling than neutral pion-nucleon coupling to fit data.



What Do We Measure and Why?

- One measures the tensor force by manipulating spins of both beam and target and observing the effect on the total scattering cross section.

$$\Delta\sigma_L = \sigma(\rightleftarrows) - \sigma(\rightrightarrows),$$

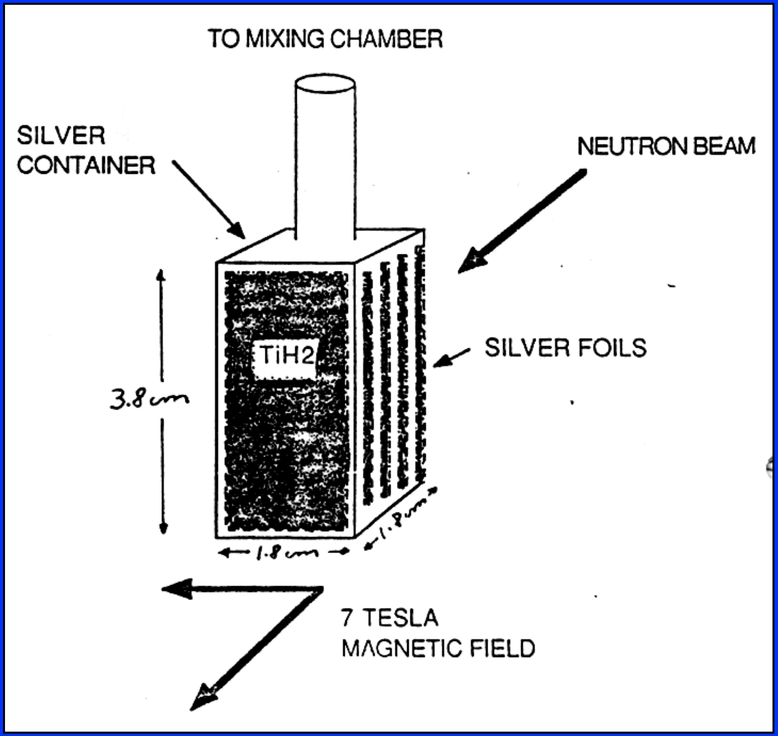
$$\Delta\sigma_T = \sigma(\uparrow\downarrow) - \sigma(\uparrow\uparrow).$$

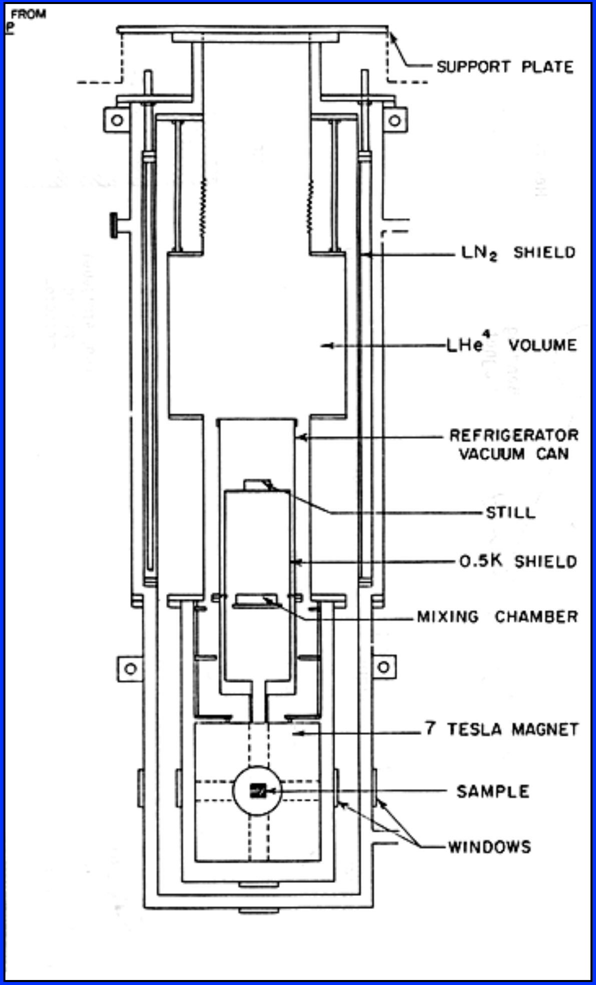
- Then a sensitive measurement of the ${}^3S_1$-${}^3D_1$ mixing parameter is obtained from

$$\Delta = \Delta\sigma_L - \Delta\sigma_T$$

Cryogenic Polarized H Target

- Brute force polarization of target by cooling sample to ~10 mKelvin in a 7 Tesla B-field





B W Raichle, *et al.*, Phys Rev Lett 83 (1999) 2711

n-p Tensor Force - Experiment

- Measure neutron transmission changes when spins are flipped
- Find the asymmetries

$$\epsilon_n = \frac{1}{2} P_n P_T x \Delta\sigma_{L(T)}$$

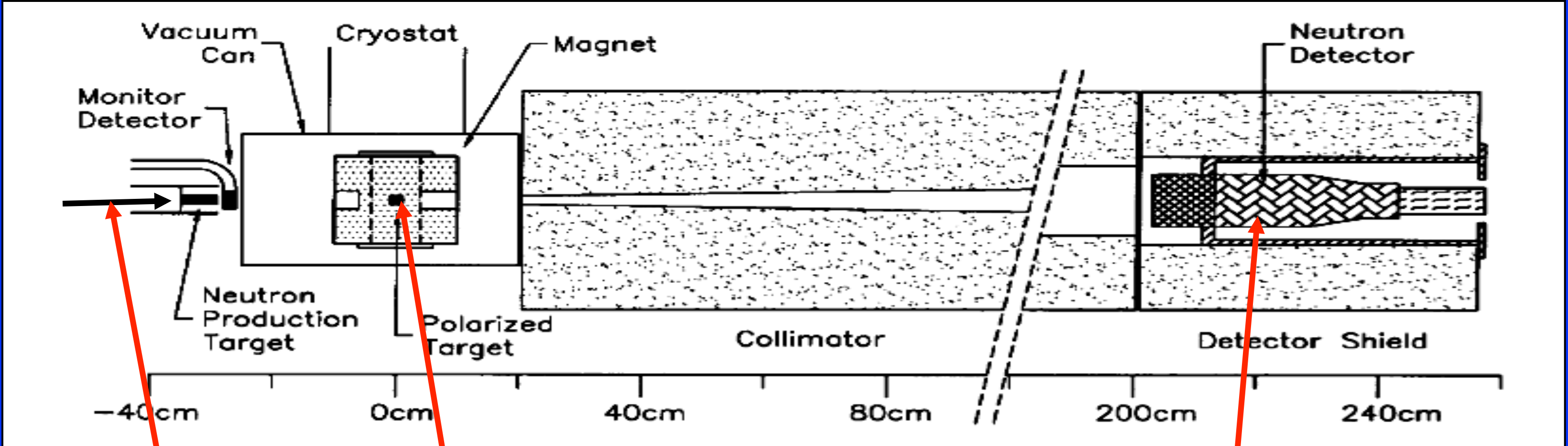


FIG. 1. Schematic of the experimental setup from the neutron production cell to the 0° detector.

Polarized Target

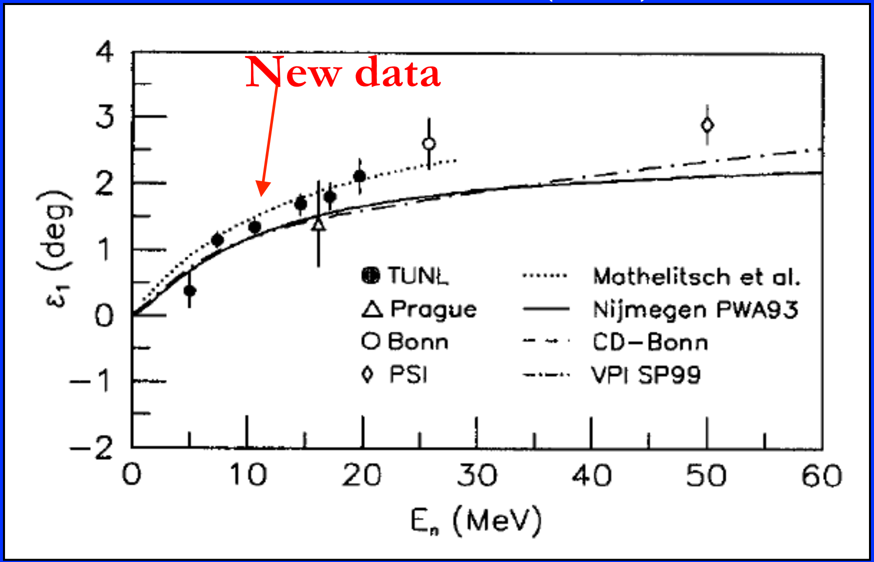
Neutron Detector

Incident Polarized Neutron Beam

n-p Tensor Force - Results

- The ${}^3S_1$-${}^3D_1$ coupling parameter ε_1 measures strength of the tensor force.
- Most popular n-p potentials underpredict ε_1; the data require a stronger tensor force.
- Data can be fit using a CD-Bonn-type charge-dependent π *NN* form factor, but without ρ - and heavier meson-exchange contributions

Raichle, *et al.*, PRL **83** (1999) 2711

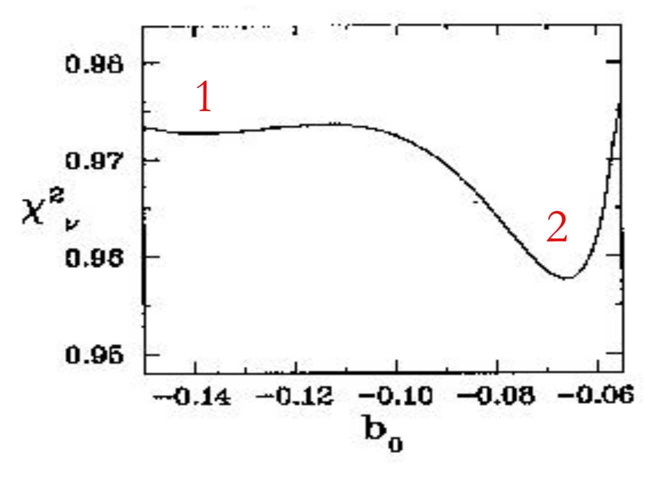


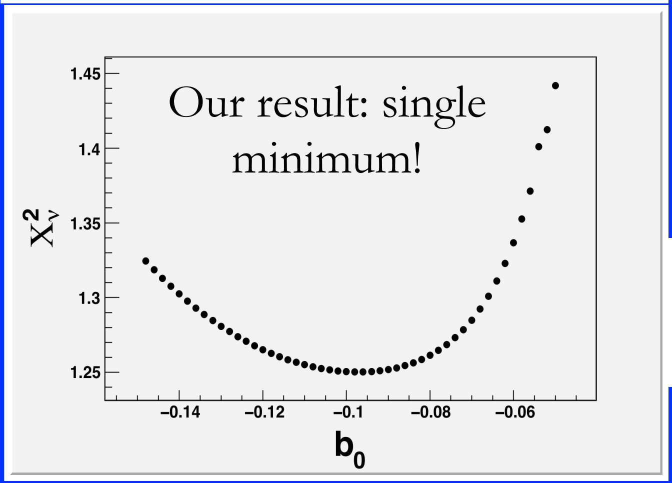
What Do We Measure and Why?

Low energy p+^{3}He phase shifts are not uniquely determined by σ and Ay data

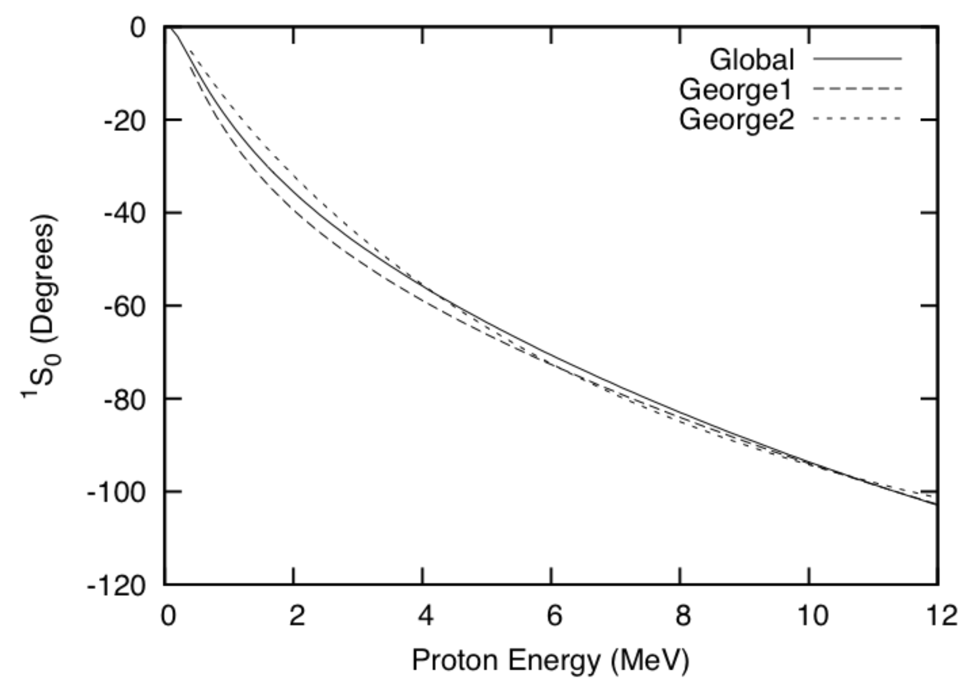
Low S-wave Phase Shift Parameter “scan”

E. A. George and L. D. Knutson, PRC 67, 027001 (2003)





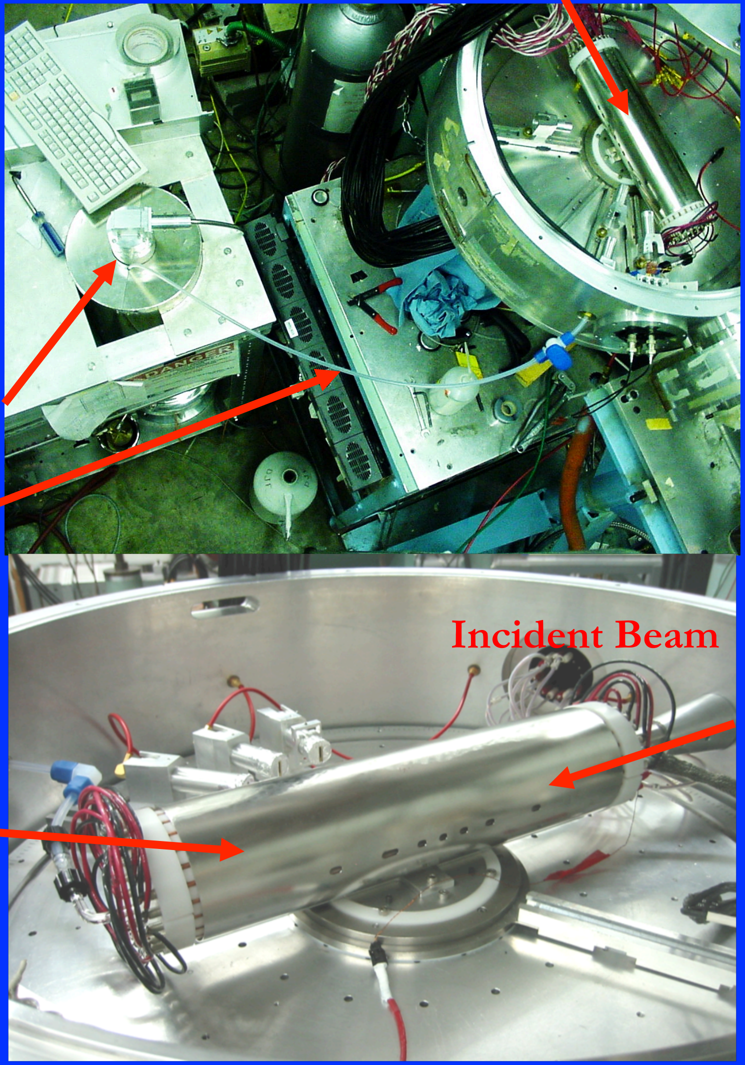
Our result: single minimum!



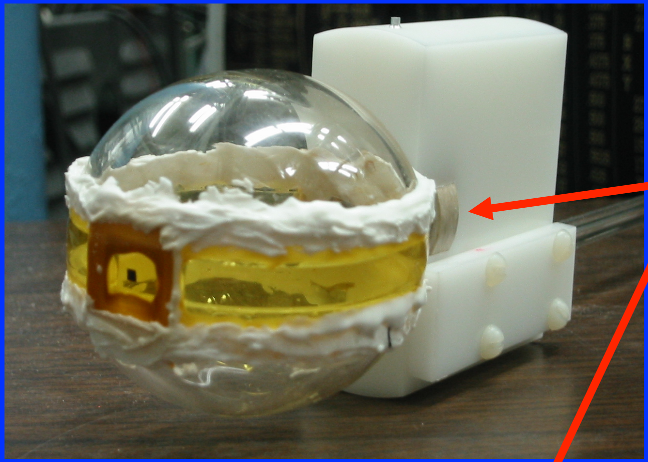
The addition of spin correlation data removes ambiguity and establishes a unique solution!

Spin Correlation Expt - p+^{3}He

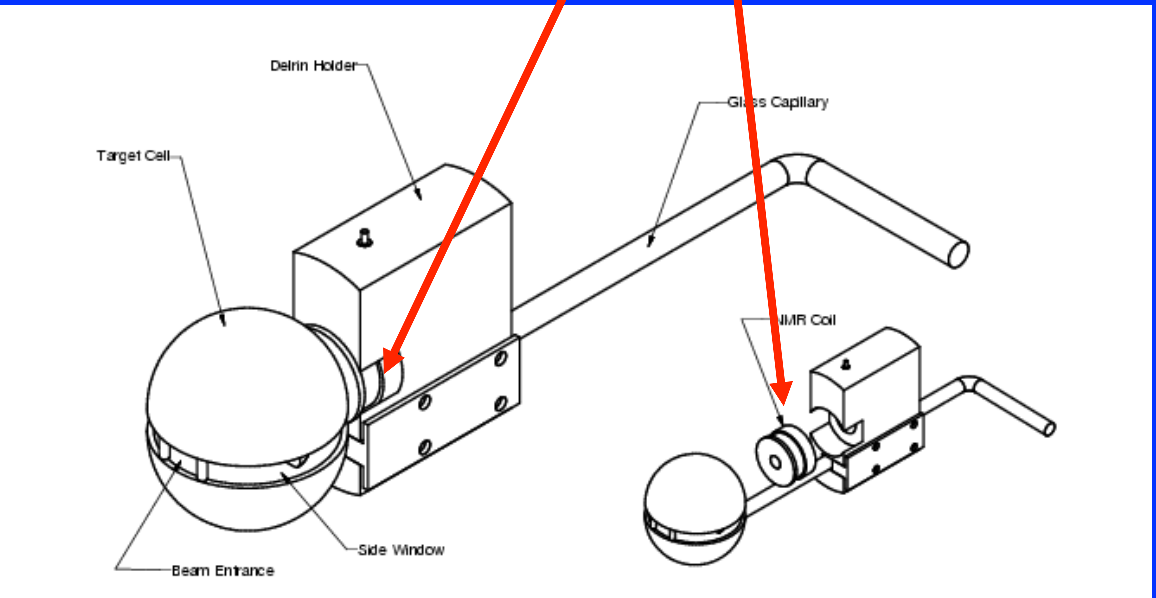
- Incident polarized proton beam
- Beam polarization measured with ^{4}He(p,p)^{4}He
- ^{3}He target gas polarized with Rb-spin-exchange optical pumping
- Polarized gas repeatedly loaded to target
- Target placed inside μ -metal-shielded “sine-theta coil”

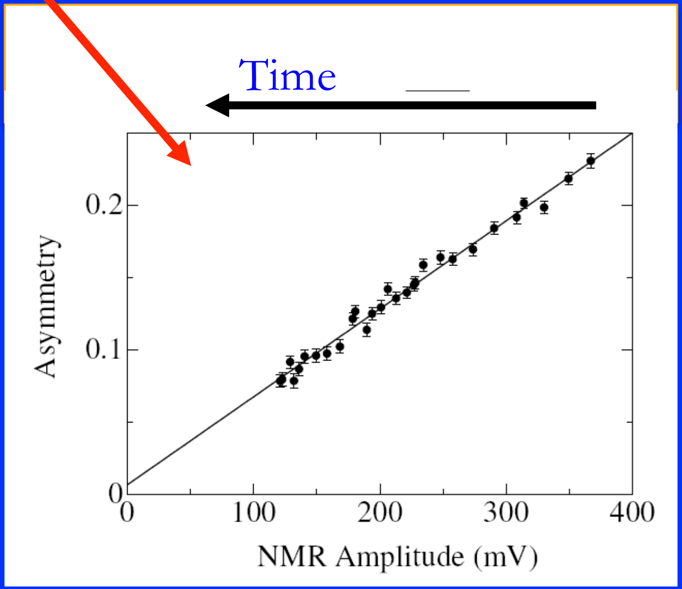


Polarized ^{3}He Target Cell



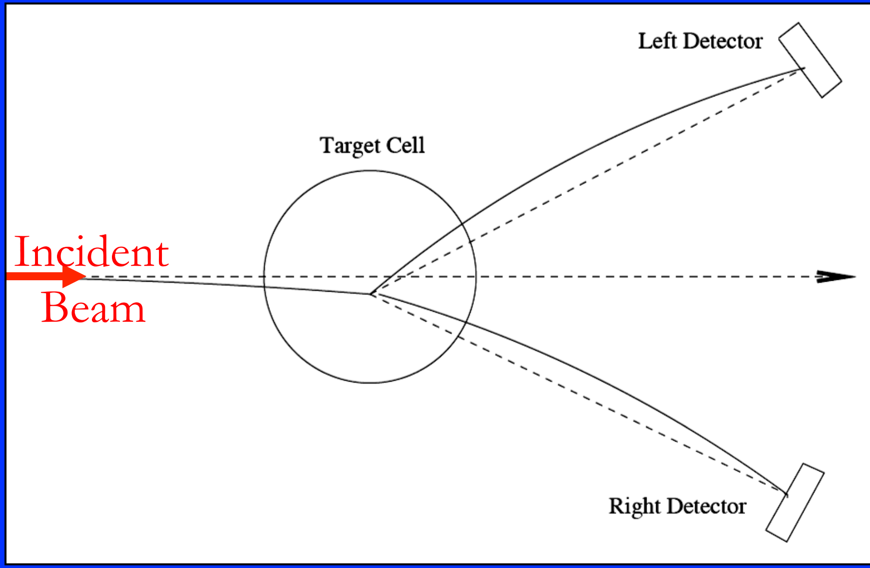
- Pyrex target cell with Kapton windows
- ^{3}He pressure ~1 ATM
- NMR monitored ^{3}He target polarization
- Calibrated NMR by ^{4}He+^{3}He scattering
- Polarization 1/e lifetime ~ 2 hrs





Experimental Challenge

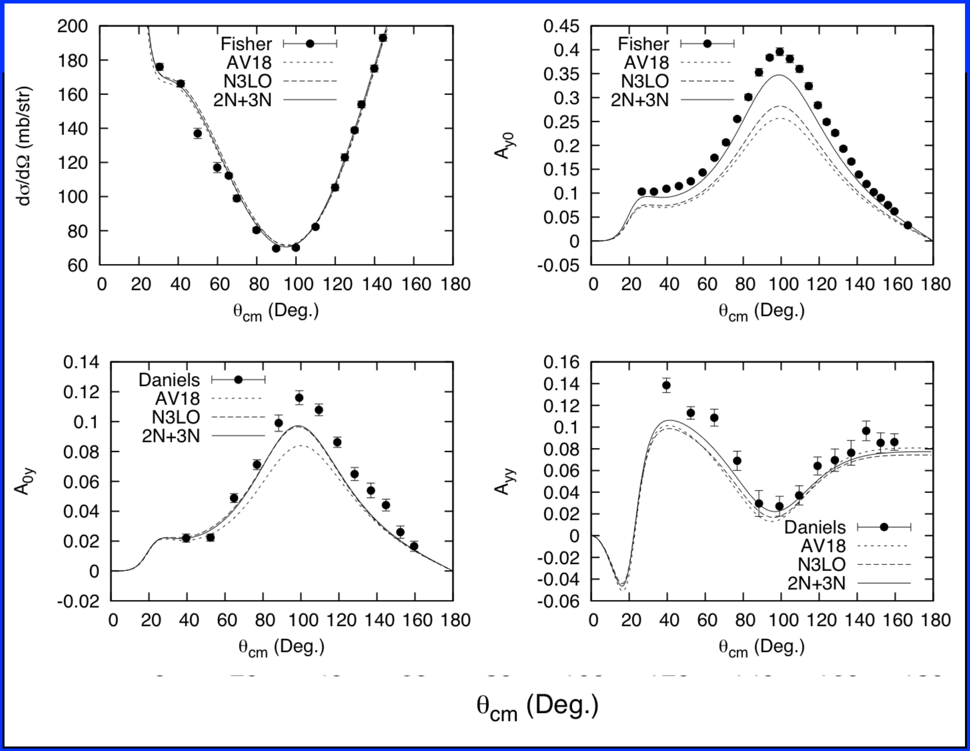
- Target 7 Gauss B-field steered incident beam and scattered particles
  - Required instrumental asymmetry measurement
  - Largest effects present and corrections applied at lowest energy and forward angles



Comparison with Theory: p+^{3}He

- Promising theoretical χ PT calculations using
  - 2N at N3LO - Entem and Machleidt, PRC **68**, 041001(R)(2003)
  - 3N at N2LO – V. Bernard *et al.*, PRC **77**, 064004 (2008)
- Agreement for scattering lengths extracted from phase shifts
  - This experiment: a_s=11.1±0.4 fm; a_t=9.07±0.11 fm
  - Viviani: a_s =11.5 fm; a_t = 9.13 fm

Example comparisons at 4.02 MeV



Data: T.V. Daniels, *et al.*, Phys. Rev. **C82**, 034002 (2010).

Calculations: M. Viviani, *et al.*, 19th Intern IUPAP Conf on Few-Body Problems, Bonn, June 2009

What Do We Measure and Why?

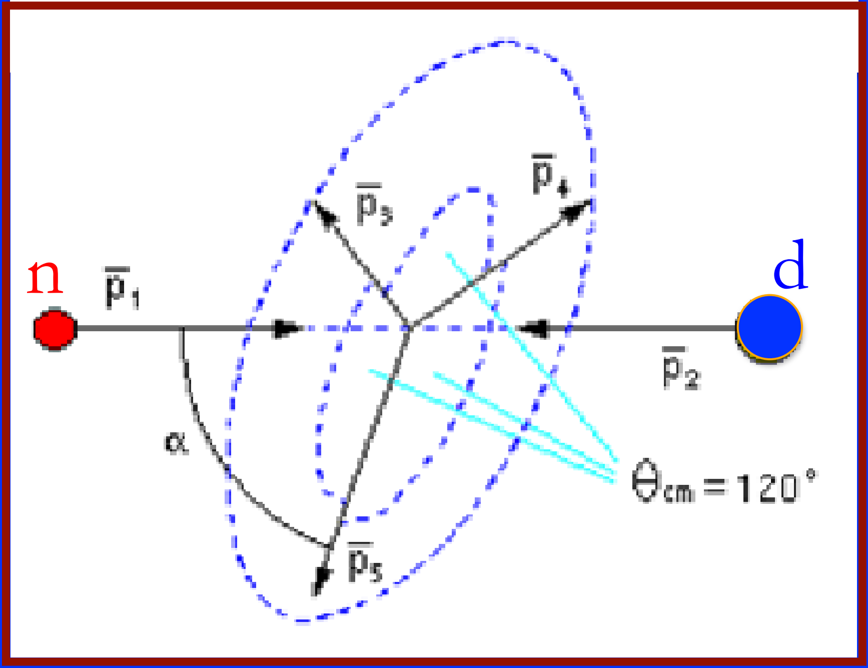
- In breakup reactions, some configurations of outgoing nucleons may be selectively sensitive to 2N or 3N forces.

- In the SCRE configuration, momenta of outgoing nucleons are separated by 120° in center-of-mass system

- α gives the tilt of plane relative to incident beam

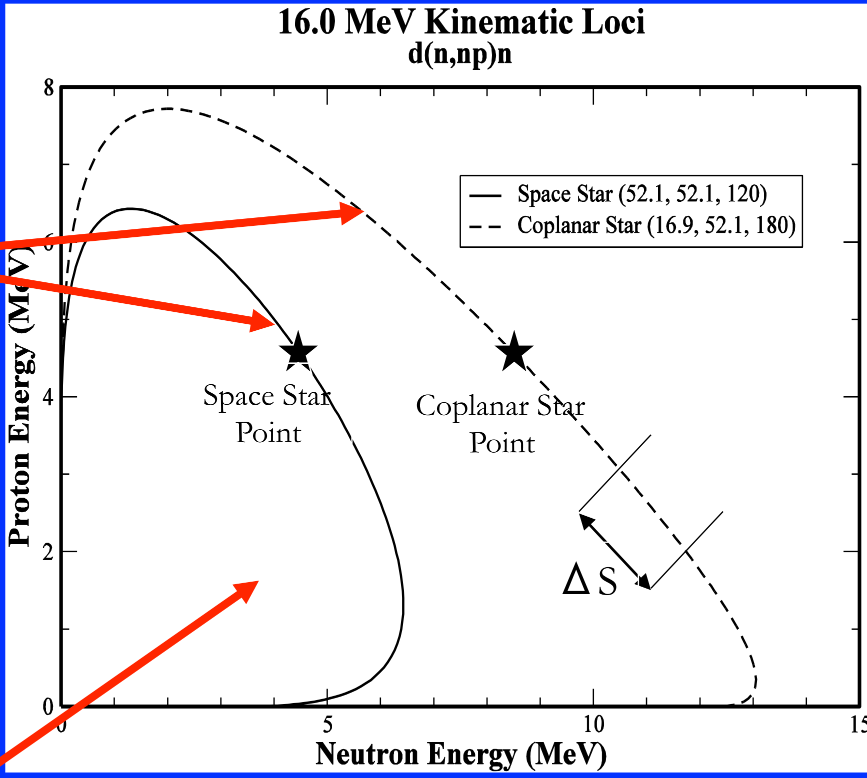
- $\alpha = 90°$: space star (SST)
  $\alpha = 0°$: coplanar star (CST)

n-d Breakup Reaction



Kinematic Loci for n-d Breakup

- With two detectors, the undetected particle scatters within a conical region determined by how outgoing energy and momentum are shared.
- Energies of the two detected particles form kinematical locus.
- S is the length along locus, with S=0 at intercept with neutron energy axis.
- Graph based on point geometry kinematic calculations.
- Finite geometry corrections can be significant.



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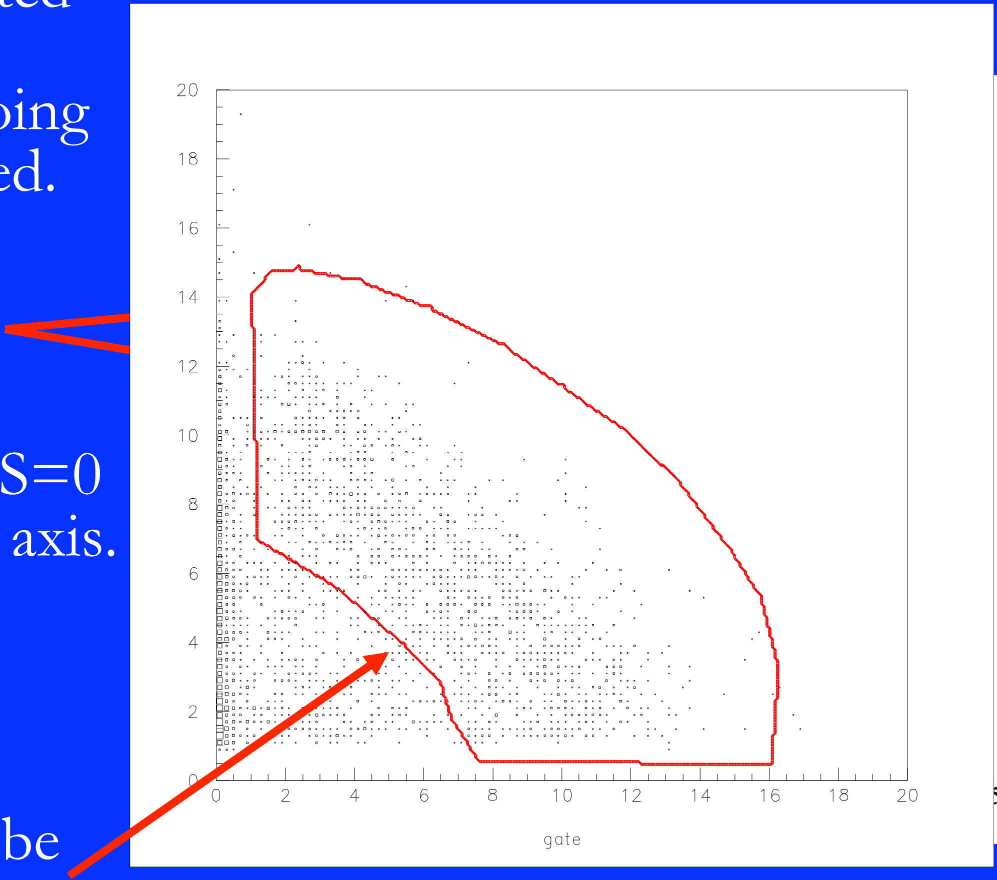
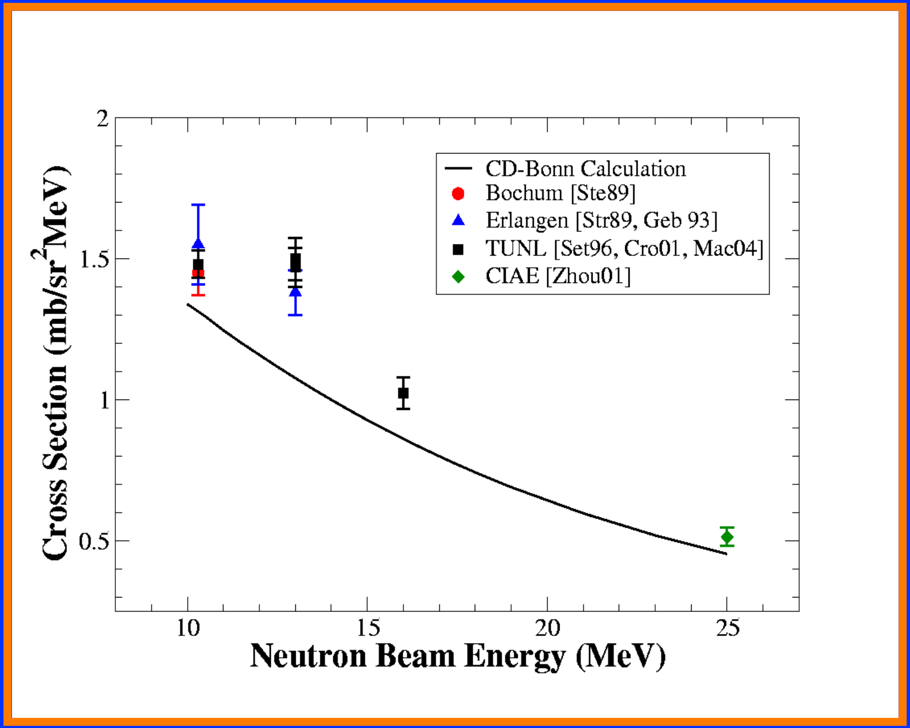
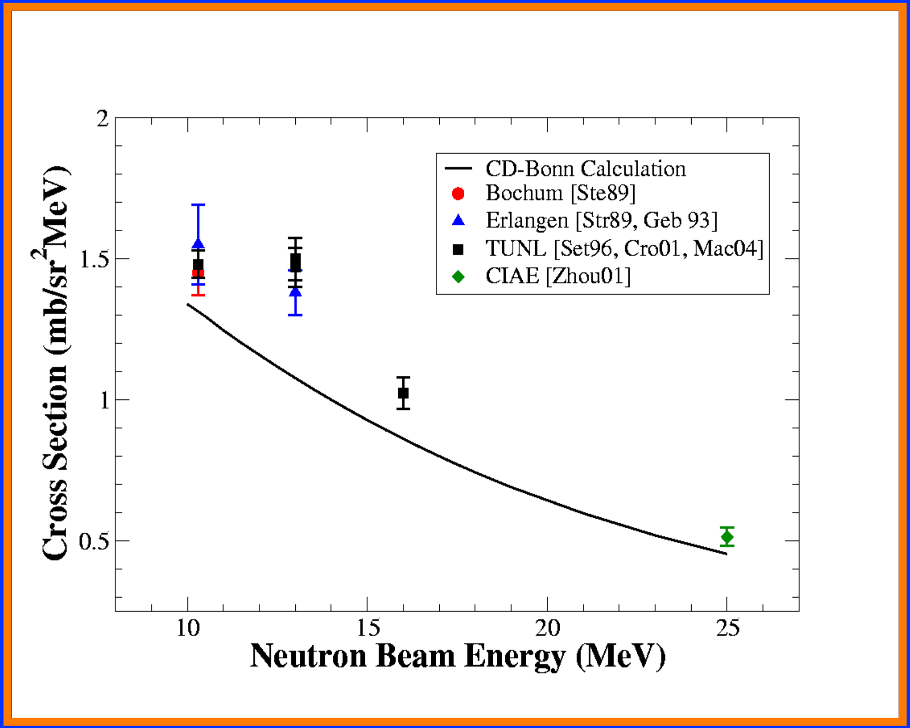


Motivation



- All prior measurements higher than theory
- All detected two neutrons in coincidence
- All used *thick* deuterated scintillating target
- All normalized to d(n,n)d

Motivation



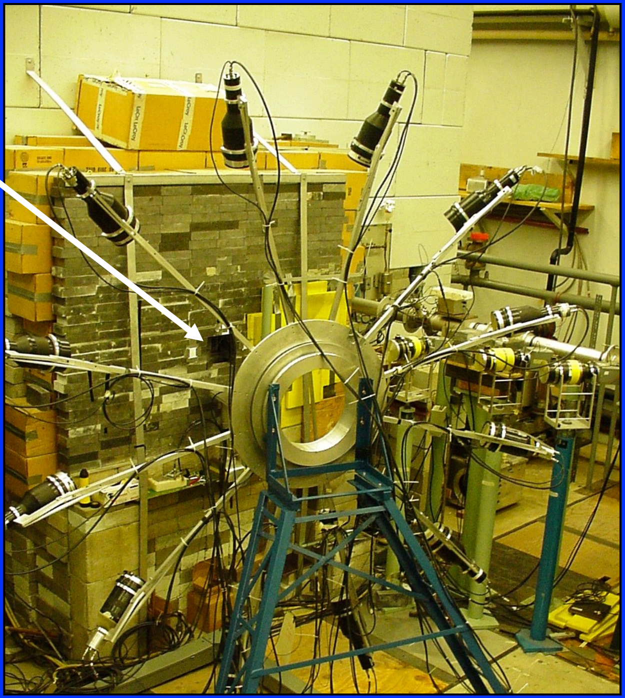
- We detected a neutron and proton in coincidence
- We used *thin* deuterated polyethelyne target
- We normalized to d(n,d)n
- This altered the sensitivity to systematic uncertainties

Former n-d Breakup Experiments

- Shielded Neutron Source
  - D(d,n)^{3}He with 8 ATM D$_2$ target cell behind shielding wall irradiated by 2 μA beam
  - Neutron flux at 1.3 m is ~ 5 x 10^4/sec-cm^2-μA

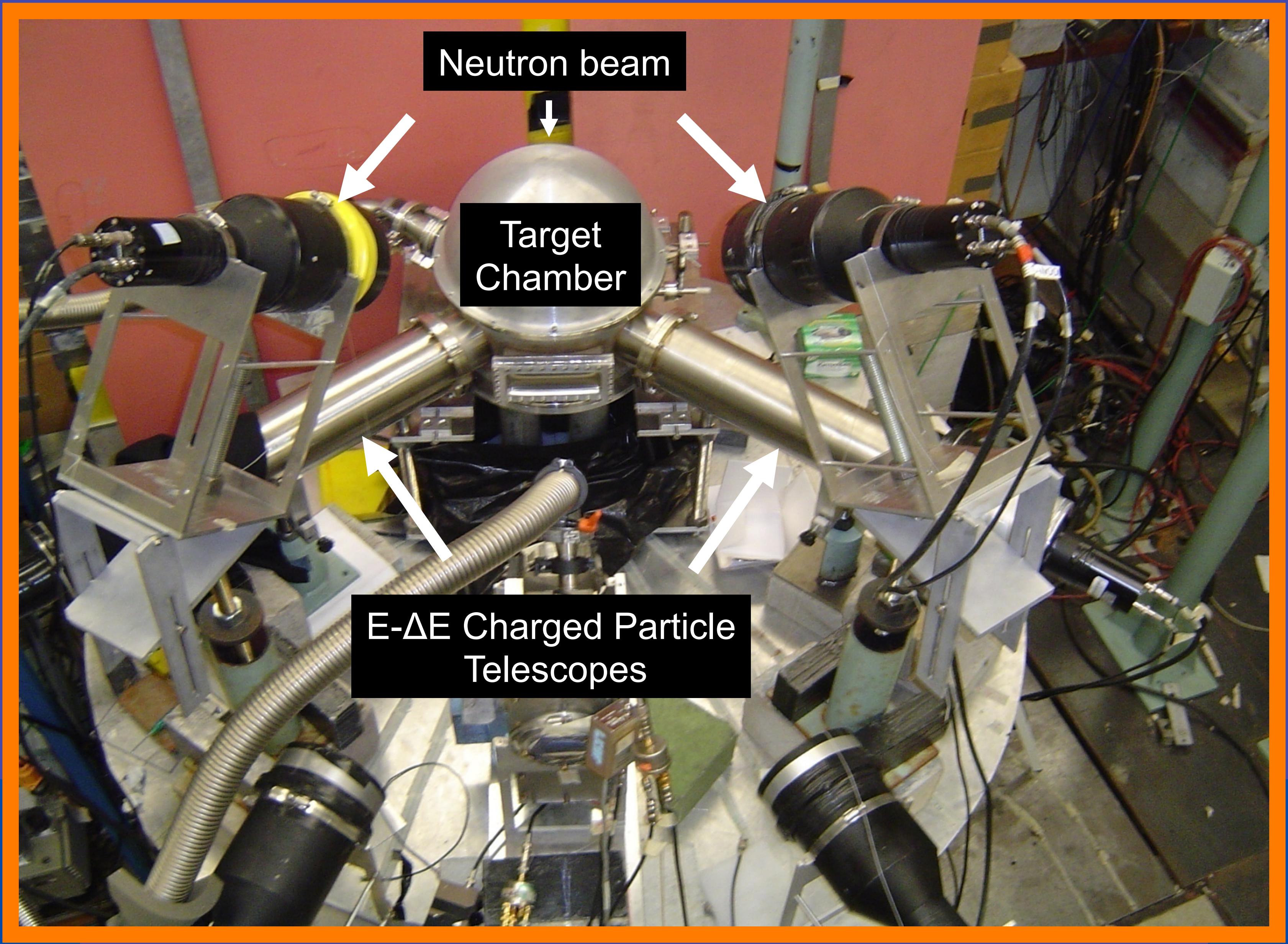
    ~ 10^6/sec-cm^2-μA possible

    at E$_d$= 10 MeV



n-d-star break-up measurement system behind shielded source - A. Crowell *et al.*

New Experimental Setup

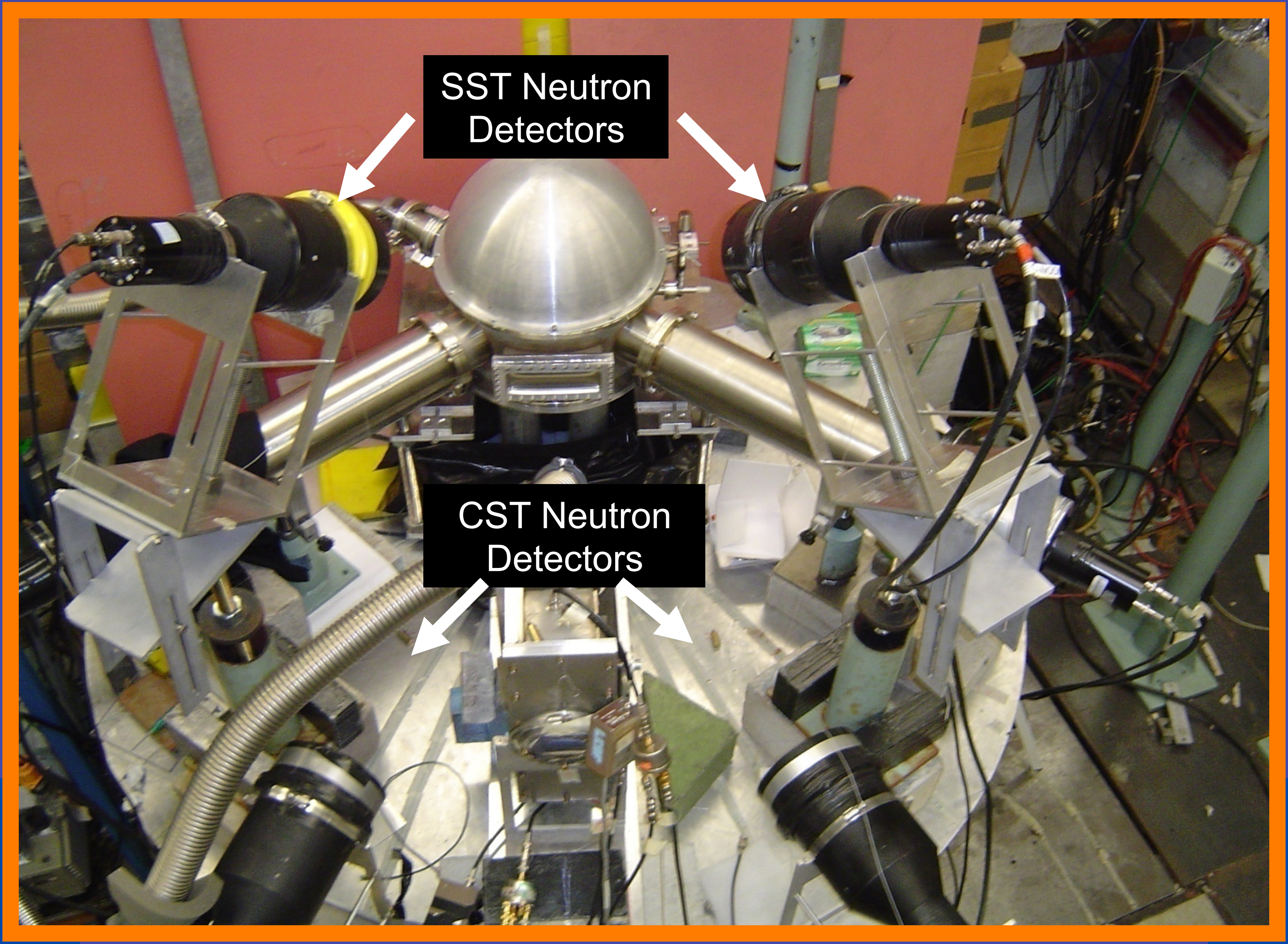


Neutron beam

Target Chamber

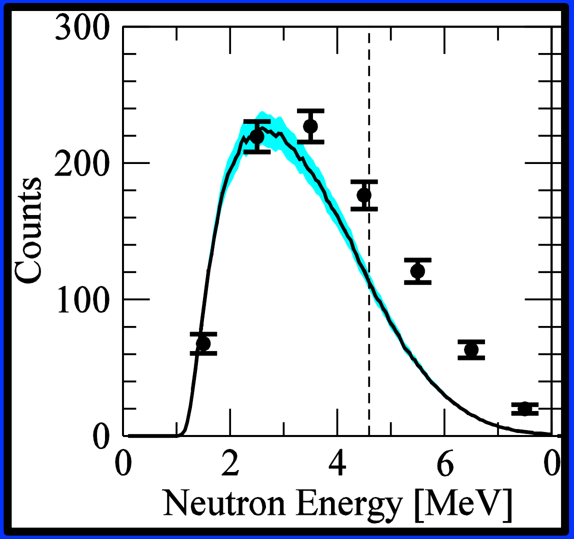
E-ΔE Charged Particle Telescopes

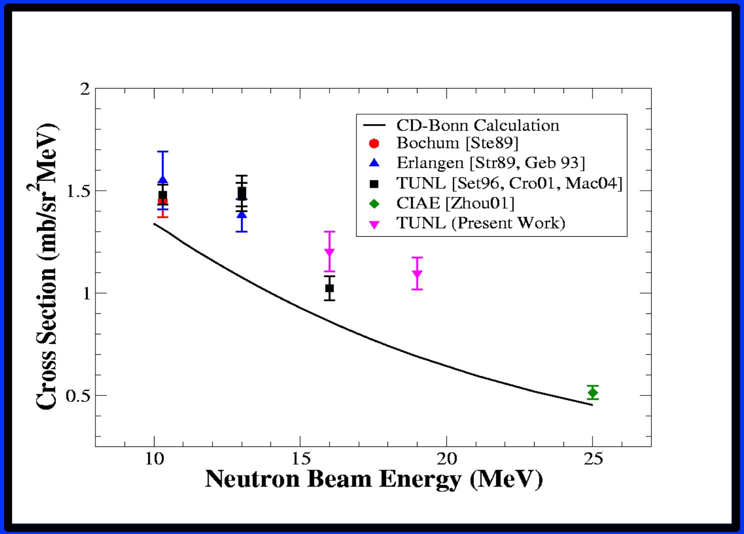
New Experimental Setup



Latest Space Star Results

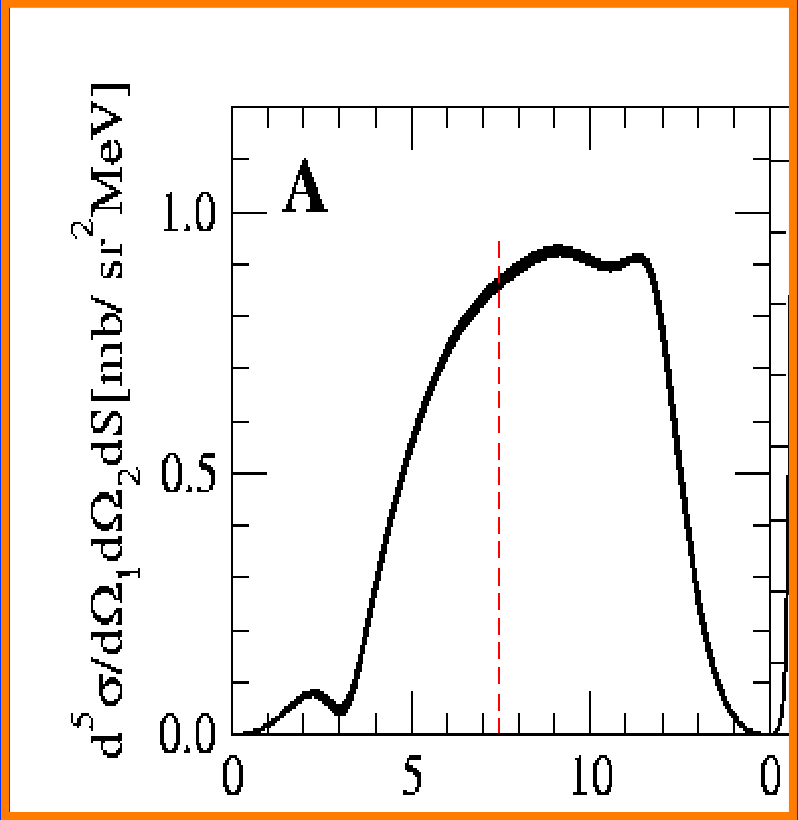
- Our value for cross section is ~40% higher than CD-Bonn prediction.
- It supports the earlier measurements
- Preliminary 19 MeV results follow trend.





A Couture, *et al.*, DNP 10, Santa Fe, 2010

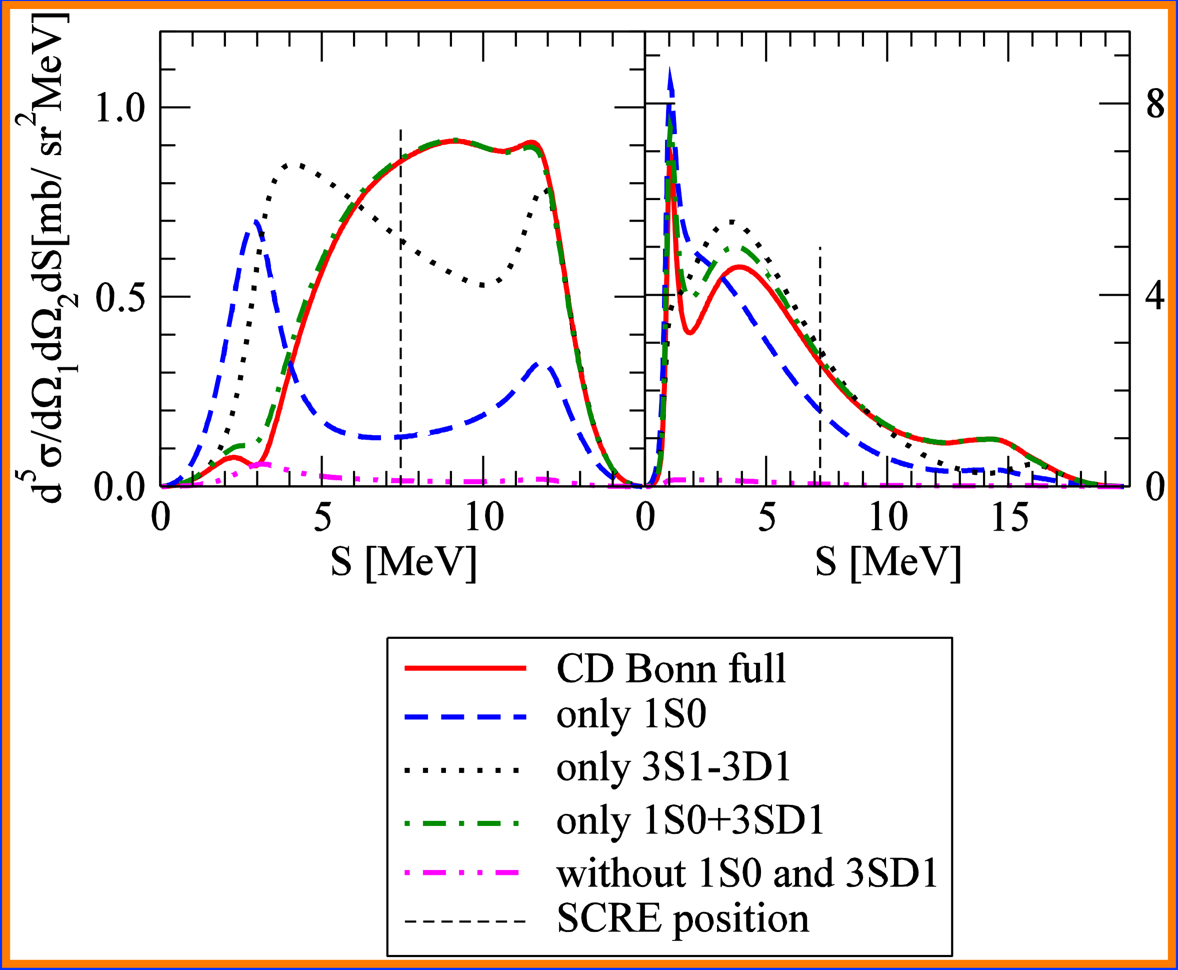
Sensitivity to Potential Models



Space Star Result

- Black band contains Faddeev cross section predictions [Glo96] from H. Witala using 24 different potential models.
- The results vary by about ±1% at the SCRE condition.

Sensitivity to Partial Waves



Outline

- Formalism and observables
- Experimental tools
- Experimental results
  - 2N, 3N, 4N examples
- Conclusions

Conclusions

- Unique, low-energy partial wave description of 2N systems will usually require measurements with both polarized beam and target.
- Experimental difficulties are large
- Strong theoretical motivation for such experiments will be needed in the future.

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- Faculty mentors/colleagues from Rice, Wisconsin, TUNL
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- LOTS of graduate students
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