Photodisintegration of ^{3}He with double polarizations at High Intensity Gamma Source (HIγS)

- Introduction
- New results on Three-body Photodisintegration
- Future experiment on Two-body process
- Photodisintegration of ^{4}He
- Summary

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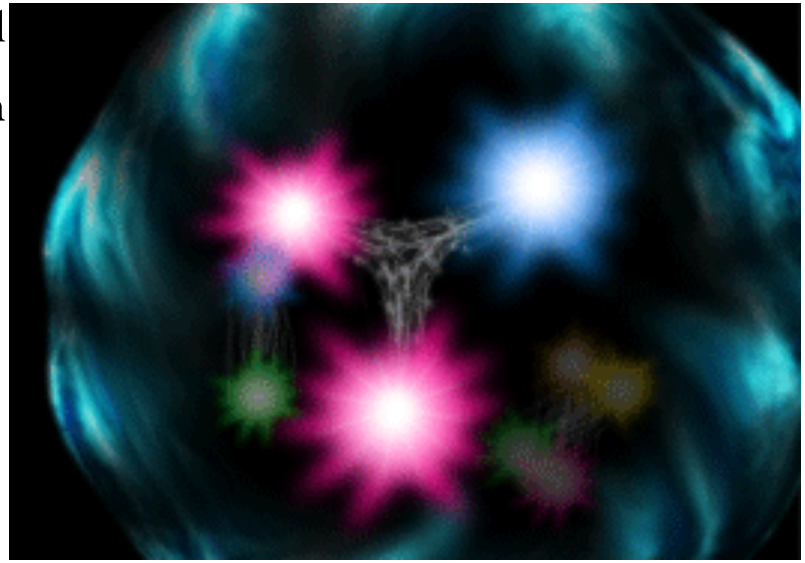
QCD ⟷ Nucleon Structure

- Strong interaction, running coupling ~1
  - -- QCD: the theory of strong interaction
  - -- asymptotic freedom (2004 Nobel)
    - perturbation calculation works at high energy
  - -- interaction significant at intermediate energy
    - quark-gluon correlations
  - -- confinement
    - interaction strong at low energy
    - coherent hadron
  - -- Chiral symmetry
  - -- theoretical tools:
    - pQCD, OPE, Lattice QCD, ChPT

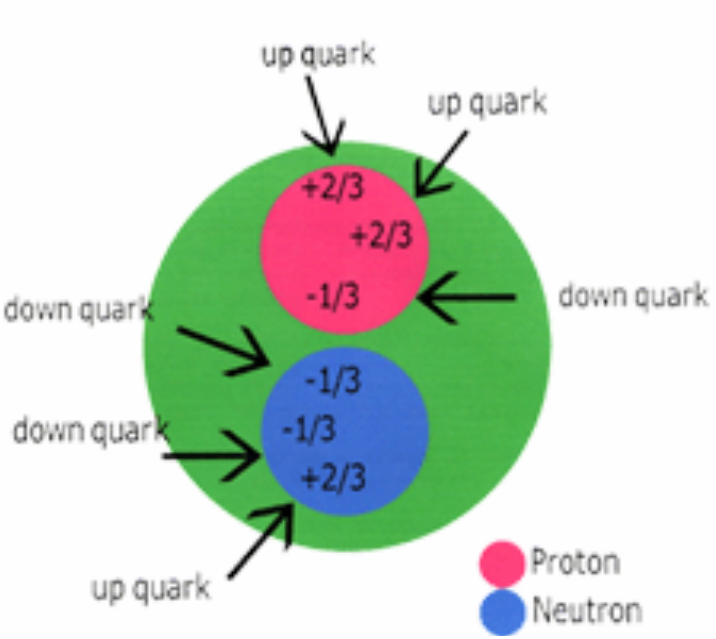


- *Charge and magnetism (current) distribution*
- *Spin distribution*
- *Quark momentum and flavor distribution*
- *Polarizabilities*
- *Strangeness content*
- *Three-dimensional structure*
- *……*

E

Spin as an important knob

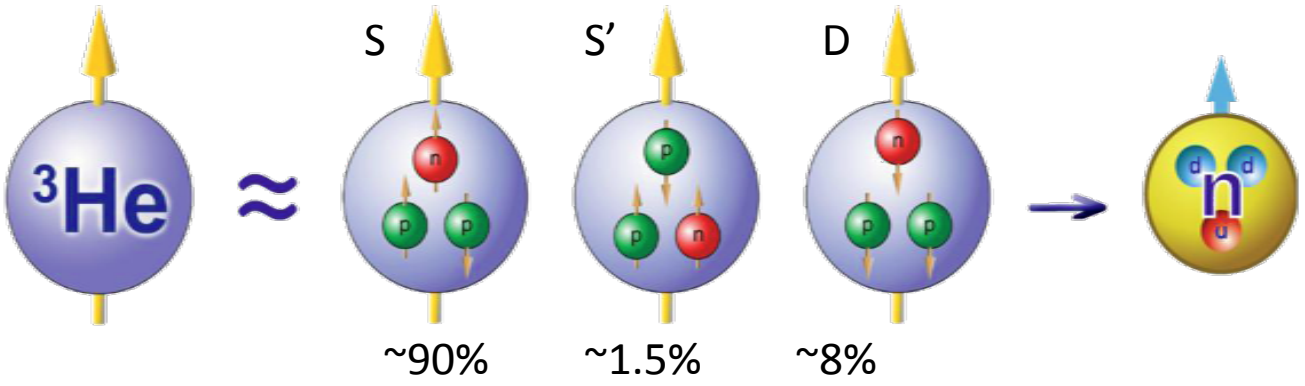
No Stable Free Neutron Targets



Effective neutron targets: Deuterium and ^{3}He used

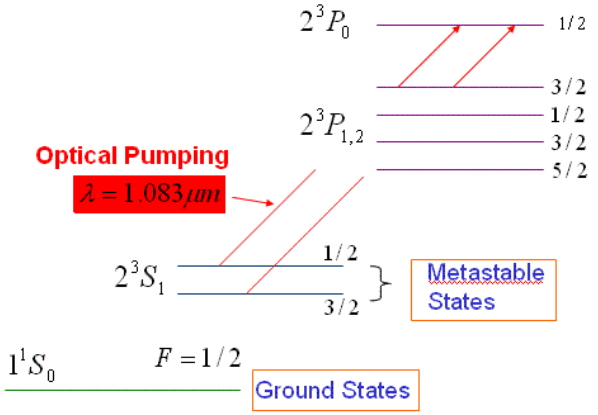
Nuclear corrections needed

State-of-the-art calculations validated by experiments



$^3\vec{He}$ *Targets Pioneered at MIT-Bates in probing the neutron structure (form factors)*

Metastability-exchange optical pumping

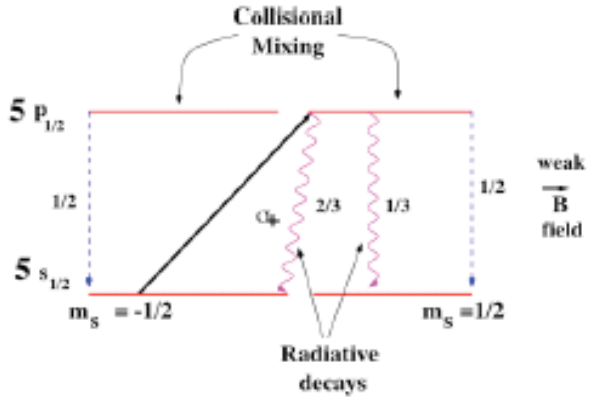


C.E.Woodward *et al.*, PRL **65**, 698 (1990)

H. Gao *et al.*, PRC **50,** R546 (1994)

J.-O. Hansen *et al.*, PRL74, 654 (1995)

Spin-exchange optical pumping

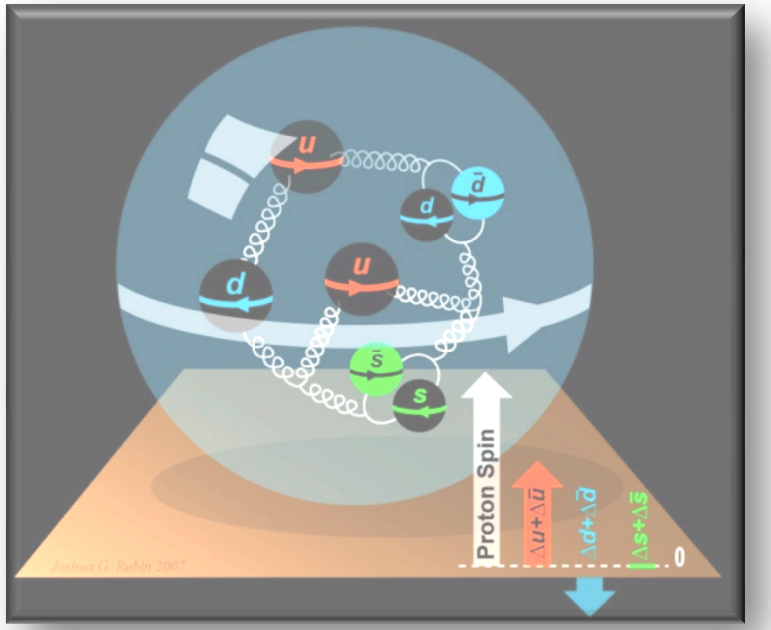


A.K.Thompson *et al.*, PRL**68**, 2901(1992)

MIT-Bates

Taken in June 93

The Incomplete Nucleon: Spin Puzzle



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + L_q(\mu) + J_g(\mu)$$

[X. Ji, 1997]

Jaffe-Manohar 1990

Chen et al. 2008

Wakamatsu 2009,2010

- DIS → $\Delta\Sigma \cong 0.25$
- RHIC + DIS → Δg not small (arXiv:1209.3278)
- L_q

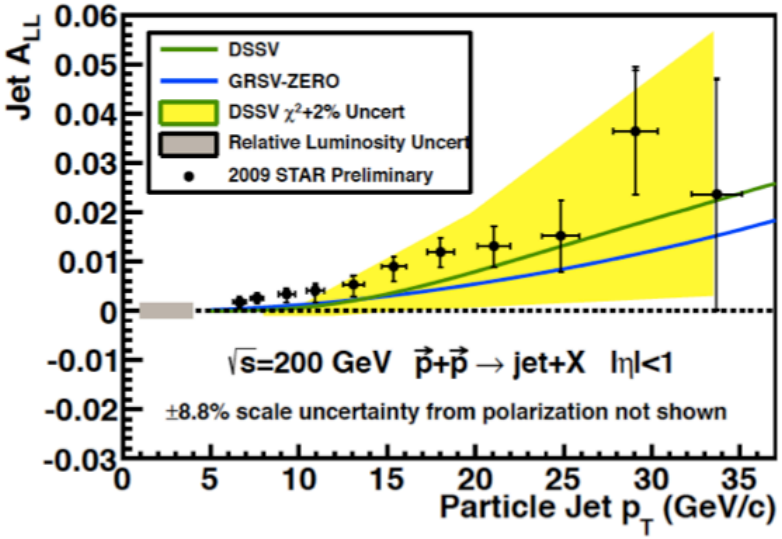


Figure credit to STAR Collaboration

Orbital angular momentum of quarks and gluon likely important

Understanding of spin-orbit correlations (atomic hydrogen, topological insulator…..)

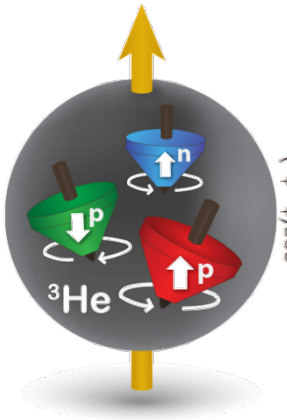
Go beyond collinear to include transverse momentum

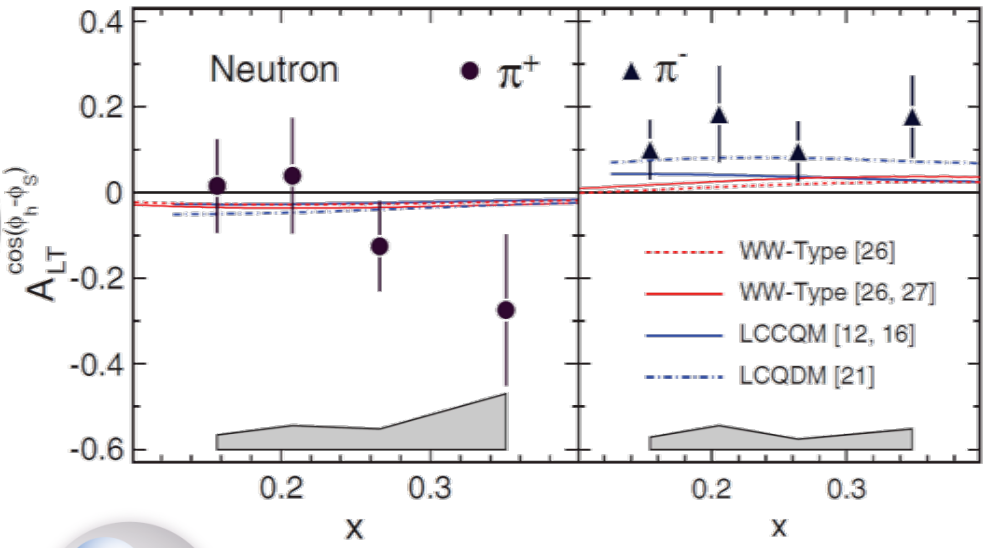
New Observable Reveals Interesting Behaviors of Quarks

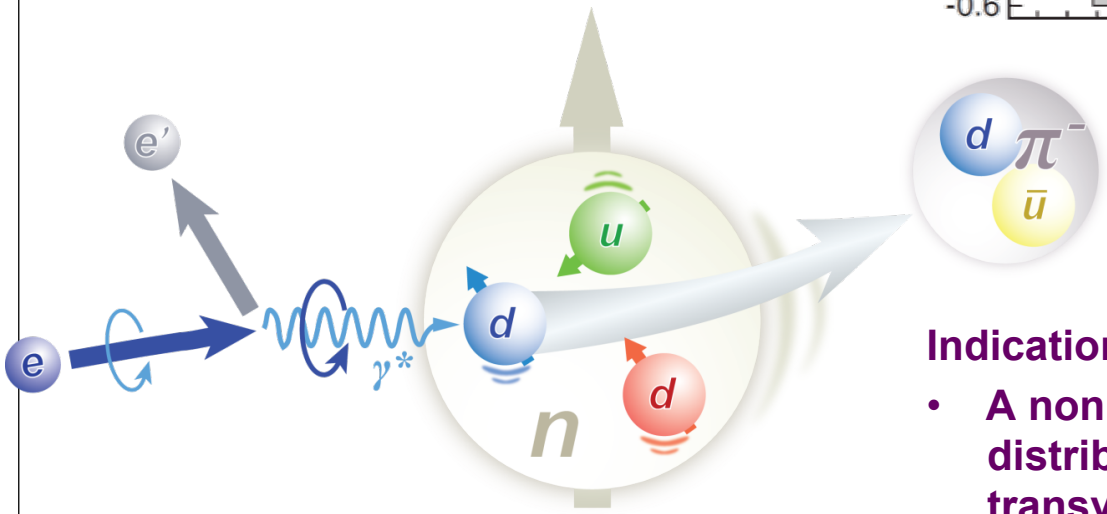
$$A_{\mathrm{LT}}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$$

Huang, *et. al.* PRL. 108, 052001 (2012)

Target: polarized ^{3}He => polarized neutron







First measurement of A_{LT}

beam-target double-spin asymmetry

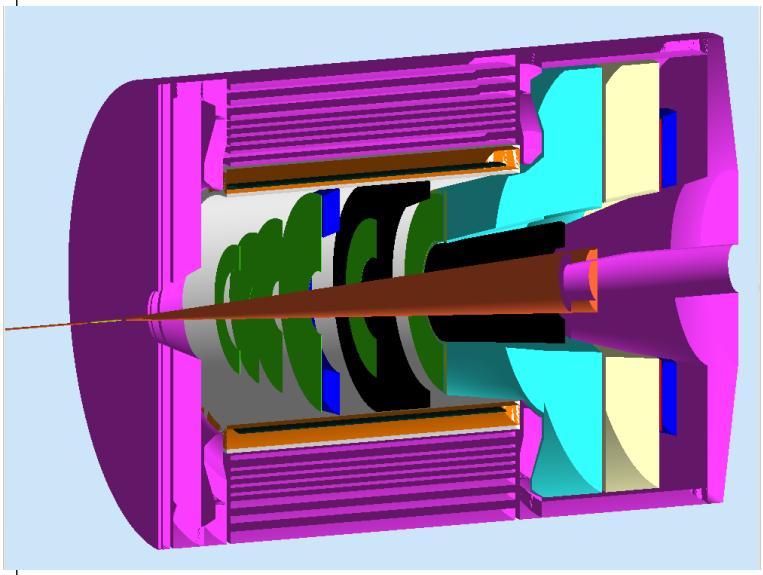
Indications:

- **A non-vanishing quark "transversal helicity" distribution, reveals alignment of quark spin transverse to neutron spin direction**
- **Quark orbital motions**

Hermes showed preliminary results from the proton

J. Huang et al., PRL108, 052001 (2012)

SoLID-Spin: SIDIS on ^{3}He/Proton @ 11 GeV

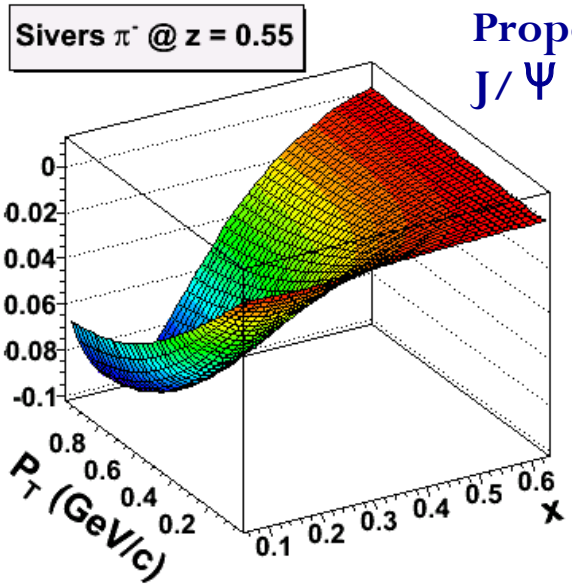


E12-10-006: Single Spin Asymmetry on Transverse ^{3}He @ 90 days, **rating A**

E12-11-007: Single and Double Spin Asymmetry on ^{3}He @ 35 days, **rating A**

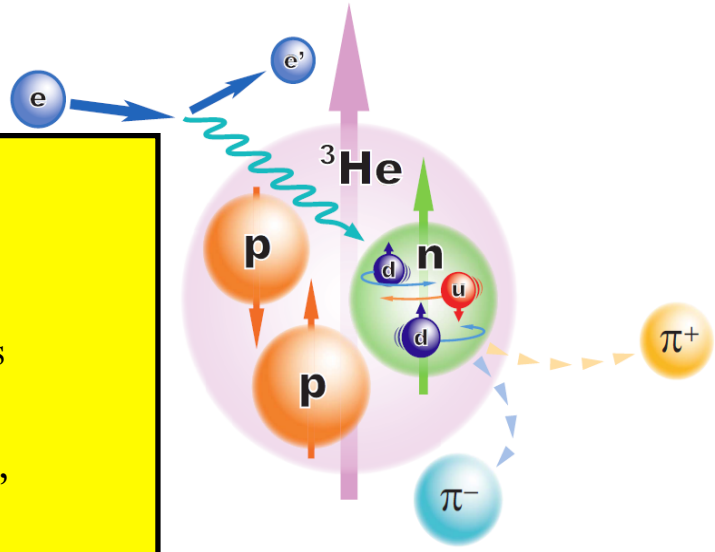
E12-11-108: Single and Double Spin Asymmetries on Transverse Proton @120 days, **rating A**

International collaboration with 180 Collaborators from 8 countries

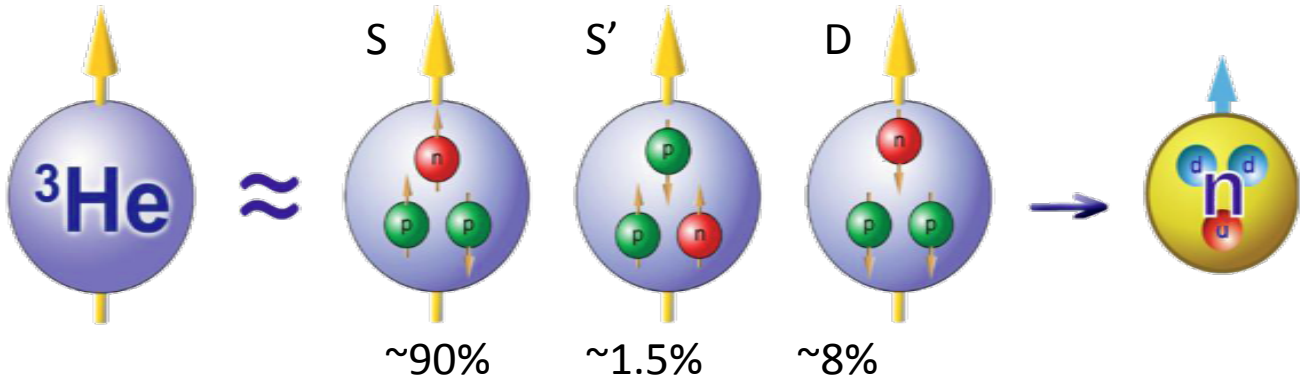


Proposals on PVDIS (A), J/Ψ (A$^-$) approved

Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→ Lattice QCD, QCD Dynamics, Models.



Photodisintegration of ^{3}He with double polarizations at HIγS at TUNL

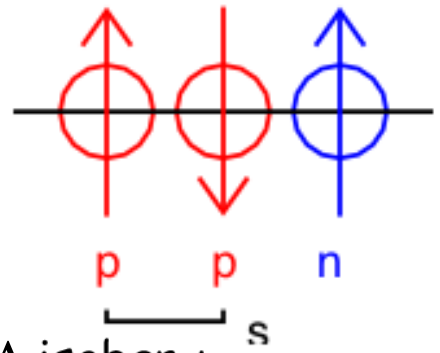


Two-Body Breakup $\gamma + {}^3He \rightarrow p + d$

Three-Body Breakup $\gamma + {}^3He \rightarrow p + p + n$

Test of State-of-the-Art Calculations on ^{3}He

- Three-nucleon system provides an excellent testing ground of few-body theories
  - e.g. Nuclear corrections on effective neutron target



- Three-body calculations
  - **Deltuva *et al.*** : using AGS equations with CD Bonn + Δ-isobar + **Coulomb potential** +...
  - **Skibiński *et al.*** : using Faddeev equations with AV18+UIX+...
  - Chiral EFT: including one- and two- pion exchange of MEC at NLO
- The advance of theories needs more precise experimental data, new observables

$$H = \sum_i \frac{P_i^2}{2m} + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk} + \cdots$$

[1] A.Deltuva *et al.*, Phys. Rev. *C* 71, 054005 (2005); Phys. Rev. *C* 72, 054004 (2005) and Nucl. Phys. *A* 790, 344c (2007)
[2] R.Skibinski *et al.*, Phys. Rev. *C* 67, 054001 (2003); R.Skibinski et al. Phys. Rev. *C* 72, 044002 (2005)
[3] E.O. Alt *et al.* Nucl. Phys. B2, 167 (1967)
[4] L.D. Faddeev, Sov. Phys. JETP 12 1014 (1961)
[5] R. Rozpedzik *et al.* , Phys. Rev. *C* 83, 064004 (2001)

Investigation of the GDH Sum Rule

S.B.Gerasimov, Sov. J. Nucl. Phys. 2 430 (1966)
S.D. Drell et al. Phys. Rev. Lett. 16 908 (1966)

$$I^{GDH} = \int_{\nu_{thr}}^{\infty} \frac{d\nu}{\nu}\left[\sigma_N^P(\nu) - \sigma_N^A(\nu)\right] = \frac{4\pi^2\alpha}{M_N^2}\kappa_N^2 I$$

σ_N^P σ_N^A spin dependent total photon-absorption cross section

κ_N anomalous magnetic moment

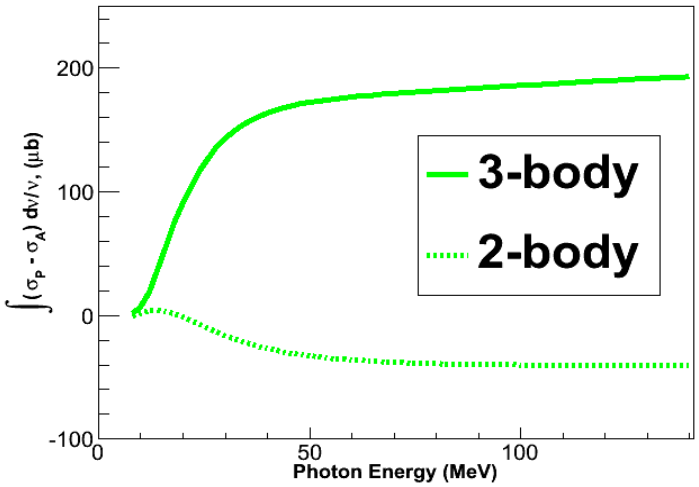
Fundamental Interpretation: any particle with a nonzero anomalous magnetic moment has internal structure and therefore an excitation spectrum

- Based on general principles of physics: **Lorentz and gauge invariance, crossing symmetry, causality and unitarity**
- First measurement on proton up to 800 MeV (Mainz) and up to 3 GeV (Bonn) agree with GDH with assumptions for contributions from un-measured regions (new measurements at Mainz), GDH on deuteron from HIγS

P: target spin parallel to the photon spin
A: spins anti-parallel to the photon spin

GDH Sum Rule on ^3He

$$\int_{\nu_{thr}}^{\infty} \frac{d\nu}{\nu}\left[\sigma_N^P(\nu)-\sigma_N^A(\nu)\right]=\frac{2\pi^2\alpha}{M_N^2}\kappa_N^2$$



$$\int_{\nu_{thr}}^{\infty} GDH_{^3He} = 496\,\mu b$$

$$\int_{\nu_{thr}}^{\nu_\pi} GDH_{^3He} = 217\pm 39\,\mu b$$?? HIγS @ DUKE

$$+\int_{\nu_\pi}^{2-3GeV} GDH_{^3He}$$

$$+\int_{2-3GeV}^{\infty} GDH_{^3He}$$

$\approx 247\pm 38\,\mu b$

Extrapolated from low Q^2 ^3He GDH (E94-010) measurement @ JLab, (**E97-110 much lower Q^2**)

Q^2 (GeV^2)	I_{GDH} (μb)	Statistical (μb)	Systematic (μb)
0.10	187.50	5.23	28.43
0.26	109.92	2.04	13.77
0.42	53.51	1.21	5.48
0.58	31.68	0.74	3.72
0.74	18.27	0.64	2.42
0.90	10.47	0.46	1.52

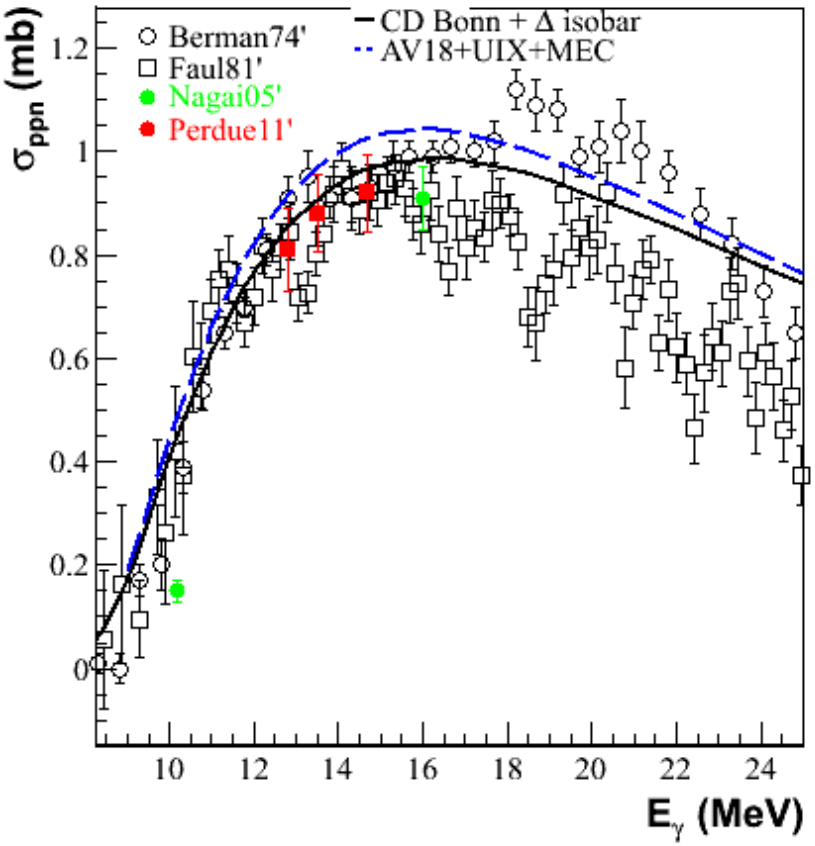
$$\approx 31.9\pm 9.6\,\mu b \int_{2-3GeV}^{\infty} GDH_{^3He} = P_n\times\int_{2-3GeV}^{\infty} GDH_n + 2\times P_p\times\int_{2-3GeV}^{\infty} GDH_p$$
$$= 0.87\times 35 + 2\times(-0.027)\times(-26)$$

M. Amarian, PRL 89, 242301(2002) J.L. Friar et al. PRC 42, 2310 (1990) N. Bianchi, et al. PLB 450, 439 (1999)

Existing three-body calculations

$$\gamma + {}^{3}He \rightarrow p + p + n$$

	Deltuva	Golak
Calculation framework	AGS	Faddeev
NN Potential	CD Bonn	AV18
3 NF	△ isobar	Urbana IX
Nuclear EM current	Siegert theorem for 1body electric current, explict MEC for magnetic multipoles and h.o. terms E	Expliticit MEC: single nucleon current+ two (π ρ) body current
Include Coulomb?	Yes	Only in bound states
Relativistic treatment?	Yes	No



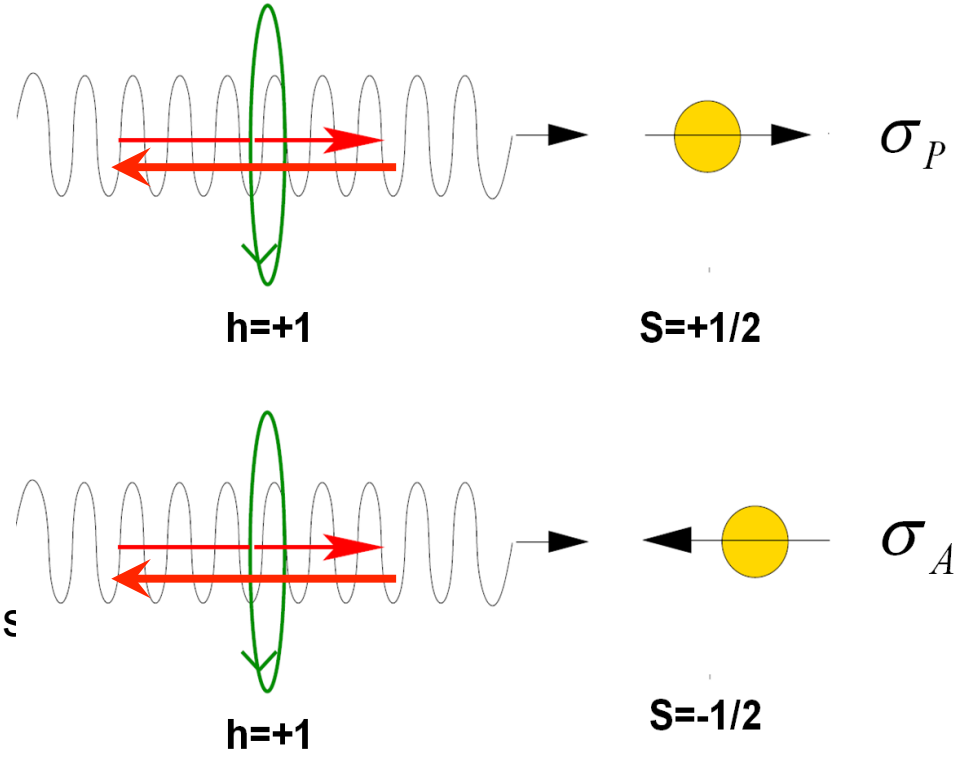
2005 Nagai data @10.2 and 16 MeV (green)

B. A. Perdue et al, Phys. Rev. C 83, 034003 (2011)

Experimental Overview

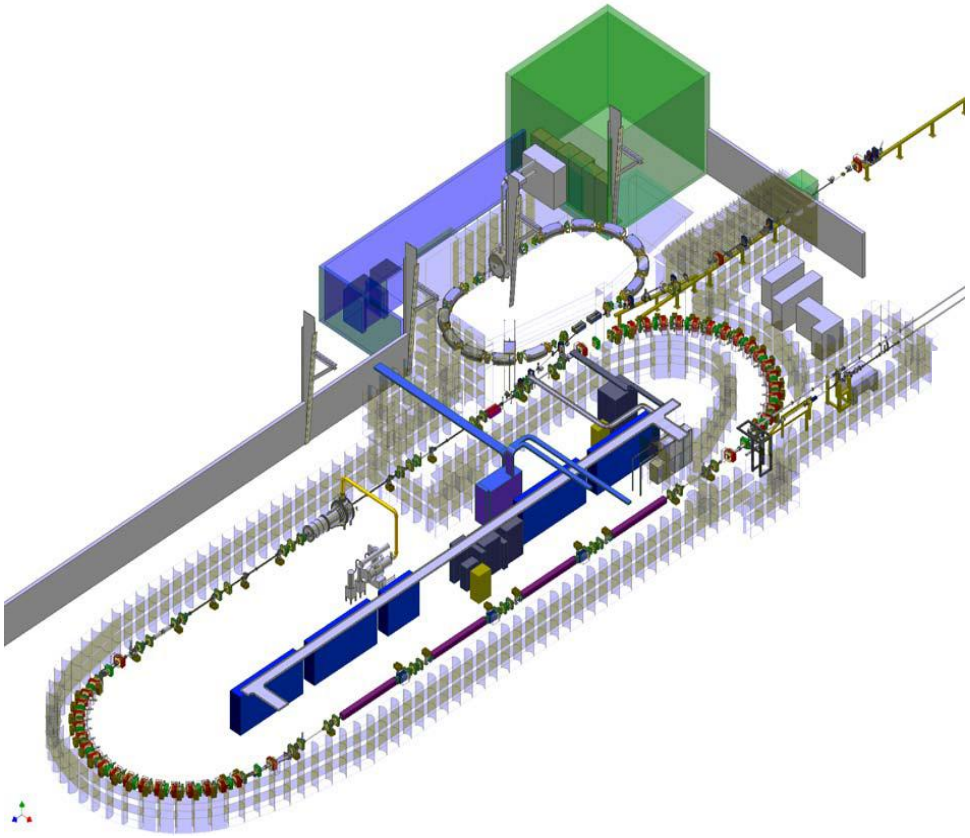
Break up channel $\vec{\gamma} + \overrightarrow{^3He} \rightarrow p + p + n$

- ~100% circularly polarized γ-beam at 12.8 and 14.7 MeV
- Neutrons detected with 16 neutron detectors at different angles
- High pressure hybrid ^{3}He target (~7amgs) polarized longitudinally using Spin Exchange Optical Pumping
- Polarized ^{3}He target spin slip @ 15 mins



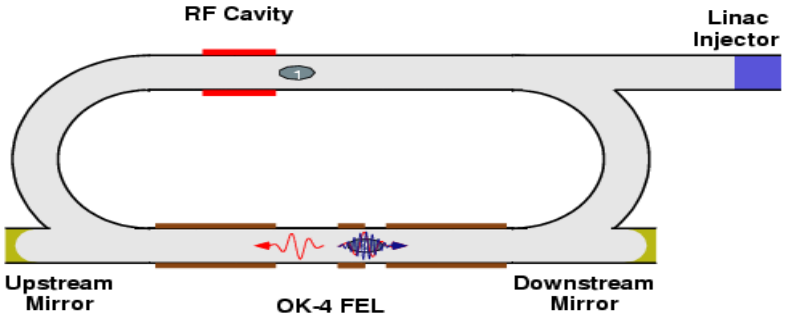
HIγS Facility at TUNL

Schematics of Duke Free Electron Laser



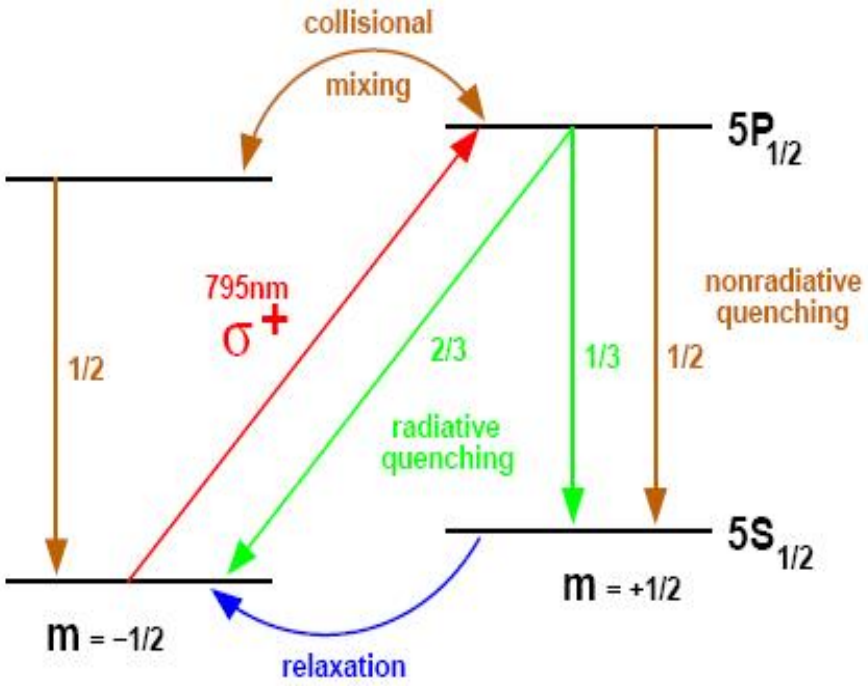
Beam Parameters	Values
Energies (MeV)	12.8 , 14.7
Polarization	~100% (circular)
Flux on target (γ/sec)	$1-2\times10^{8}$
Beam time (hours)	~110
$\Delta E/E$	~3%

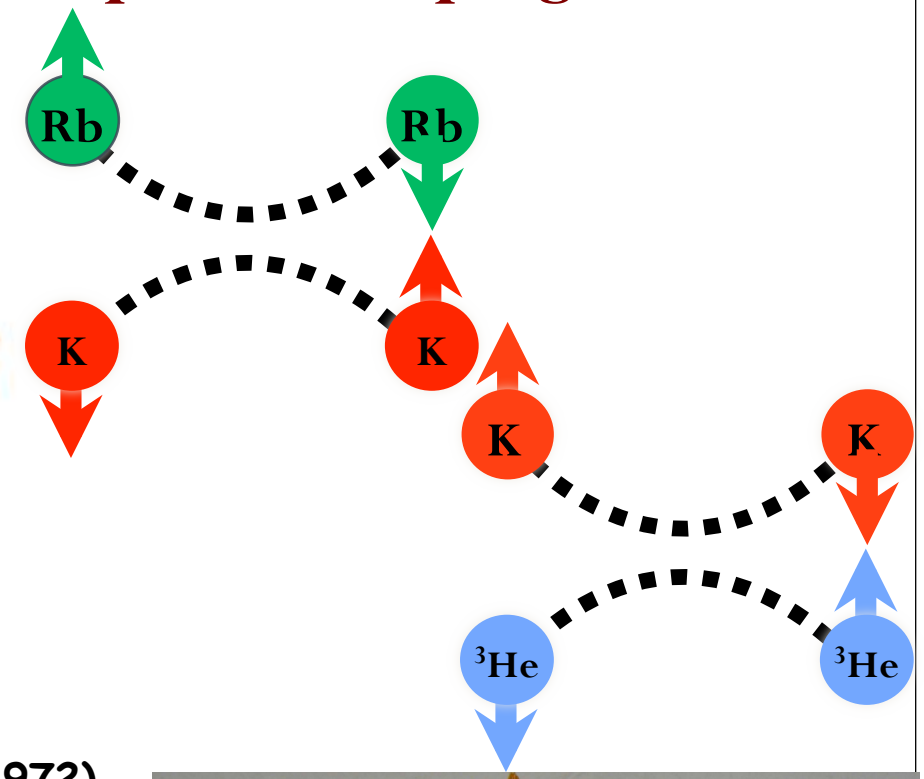
Two Bunch Mode



H.R. Weller *et al.*, Progress in Particle and Nuclear Physics 62, 257 (2009)

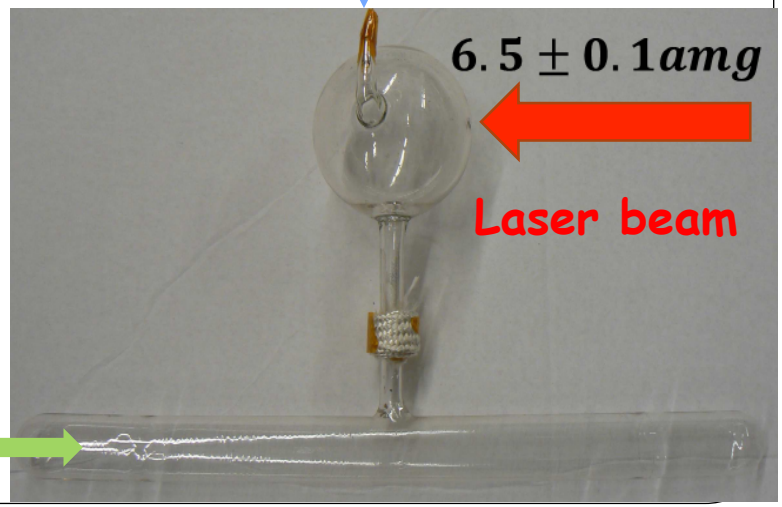
Polarized ^{3}He: Spin Exchange Optical Pumping



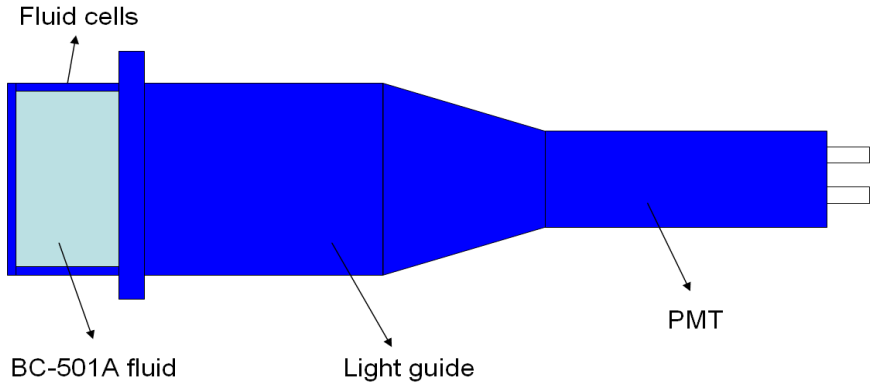


W. Happer, Rev. Mod. Phys. 44, 169 (1972)

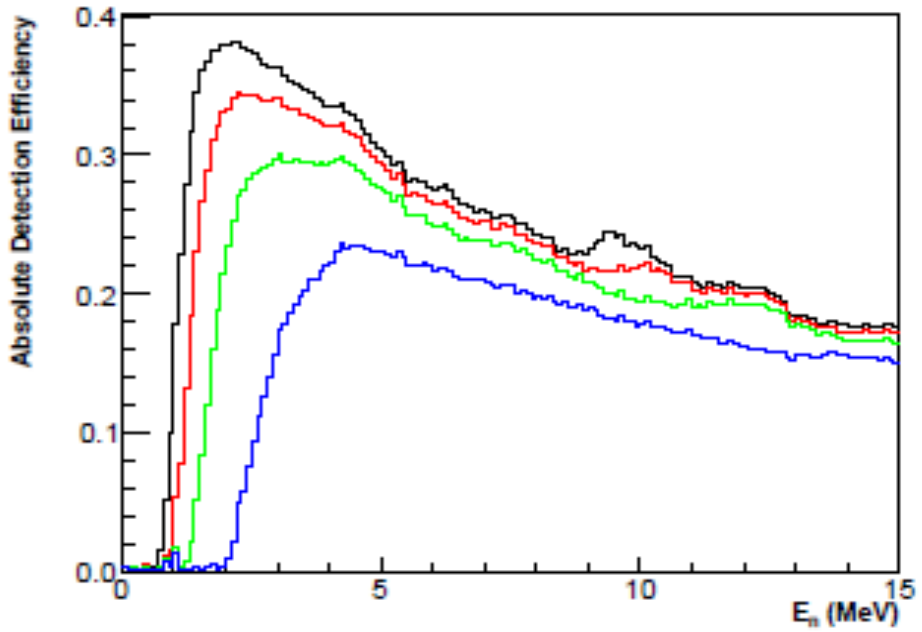
- Polarization measured using NMR and EPR
- Polarization: 38-43%
- Polarization systematic uncertainty 5.5%



Liquid Scintillator Fast Neutron Detector



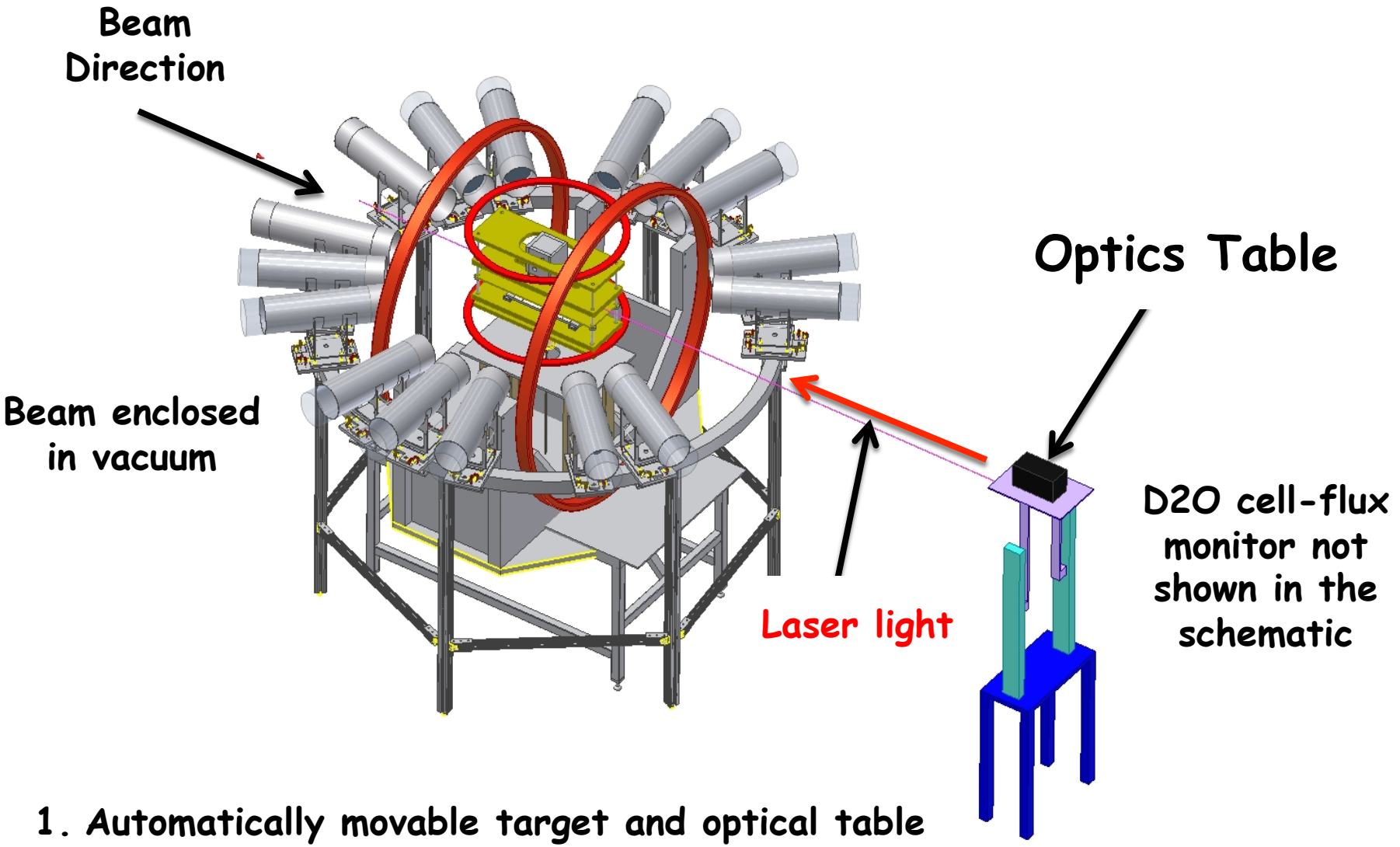
Pulse Shape Discrimination (PSD)
Pulse Height (PH)
Time Of Flight (TOF)



Black to blue: ¼*Cs to 1 Cs, Cs edge 0.47 MeVee

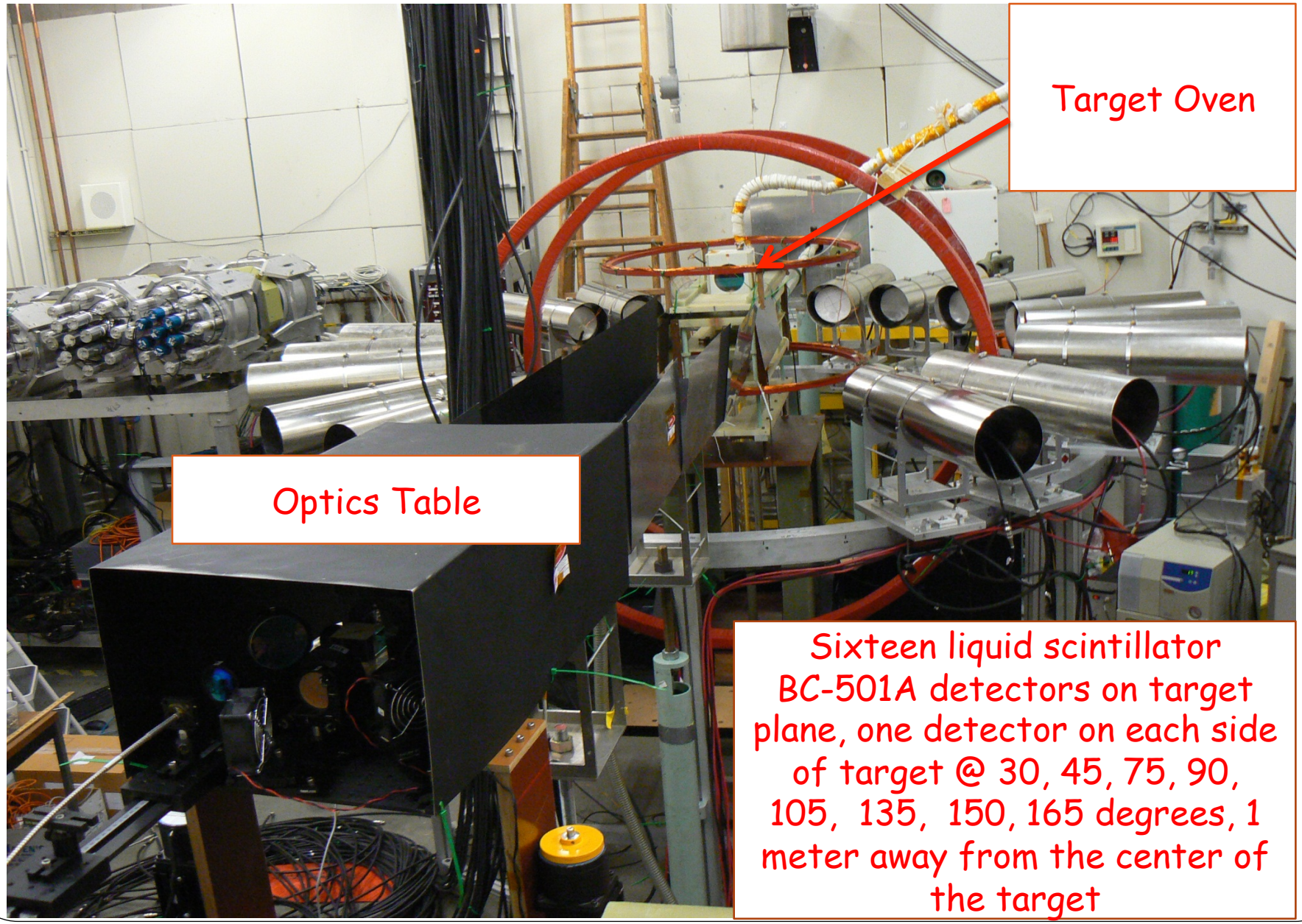
Property of BC-501A	Value
Density	0.874 gr/cm^3
Ref. Index	1.530
Wavelength	425 nm
Light output % Anthracene	78
Decay constant	3.2 nsec, 32.3 nsec, 270 nsec
H/C Ratio	1.212
Scintillating Materials	Xylene (C_8H_{10}) Naphtalene ($C_{10}H_8$)

Three-body Photodisintegration Experiment

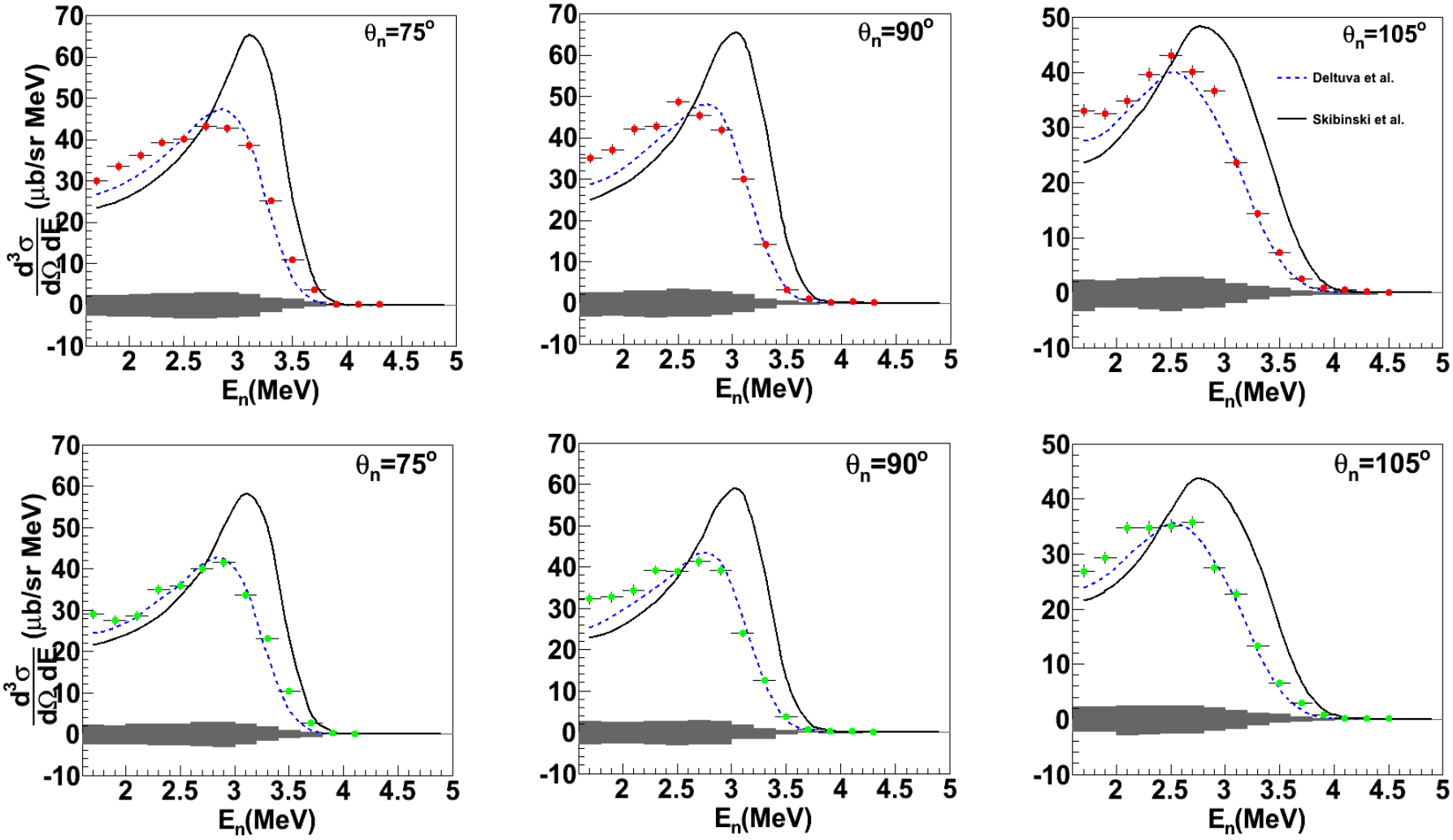


1. Automatically movable target and optical table
2. Detectors in mu-metal shielding tubes

Experiment

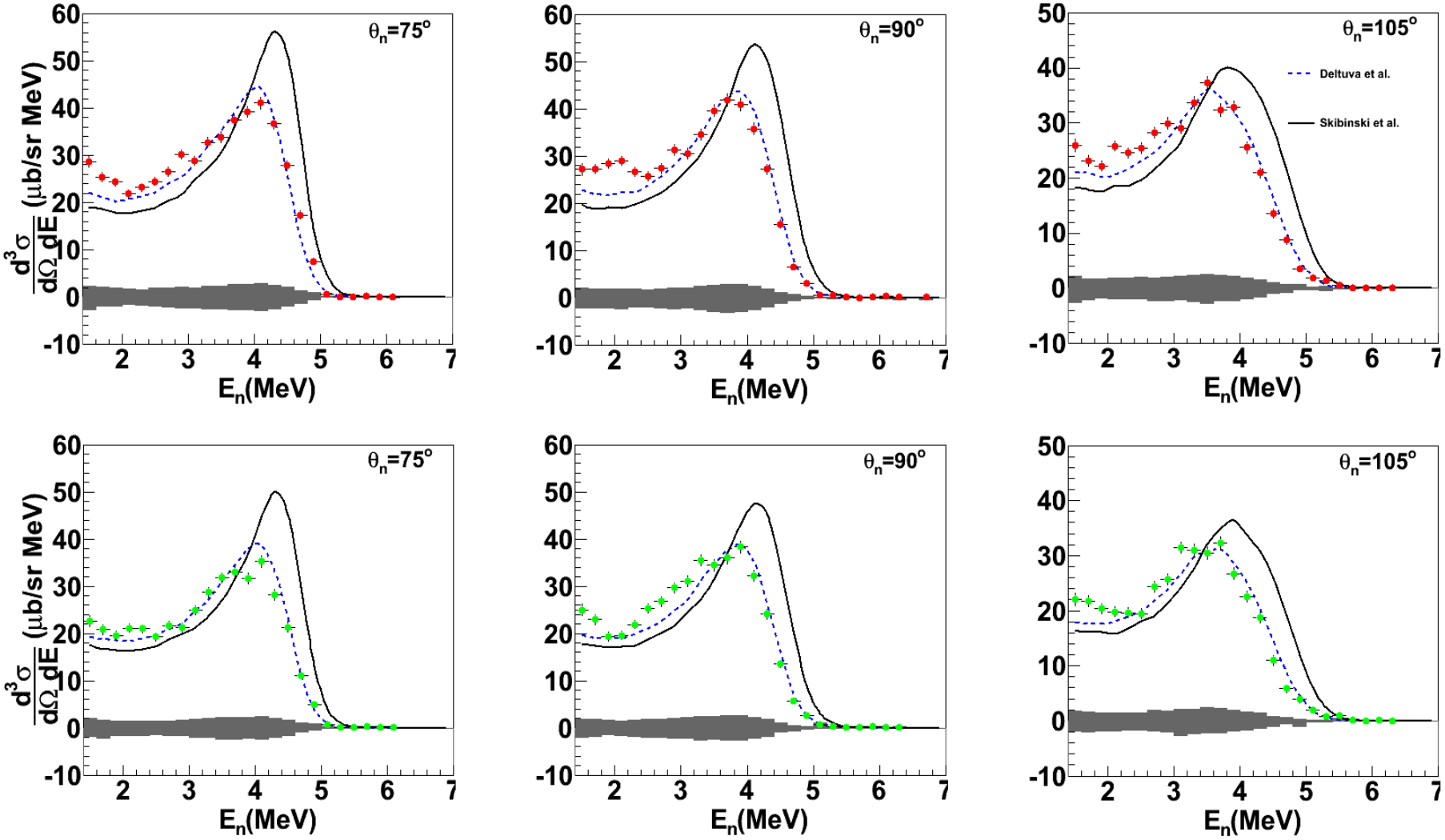

Target Oven
Optics Table
Sixteen liquid scintillator BC-501A detectors on target plane, one detector on each side of target @ 30, 45, 75, 90, 105, 135, 150, 165 degrees, 1 meter away from the center of the target

Spin-Dependent Double Differential Cross Sections at 12.8 MeV



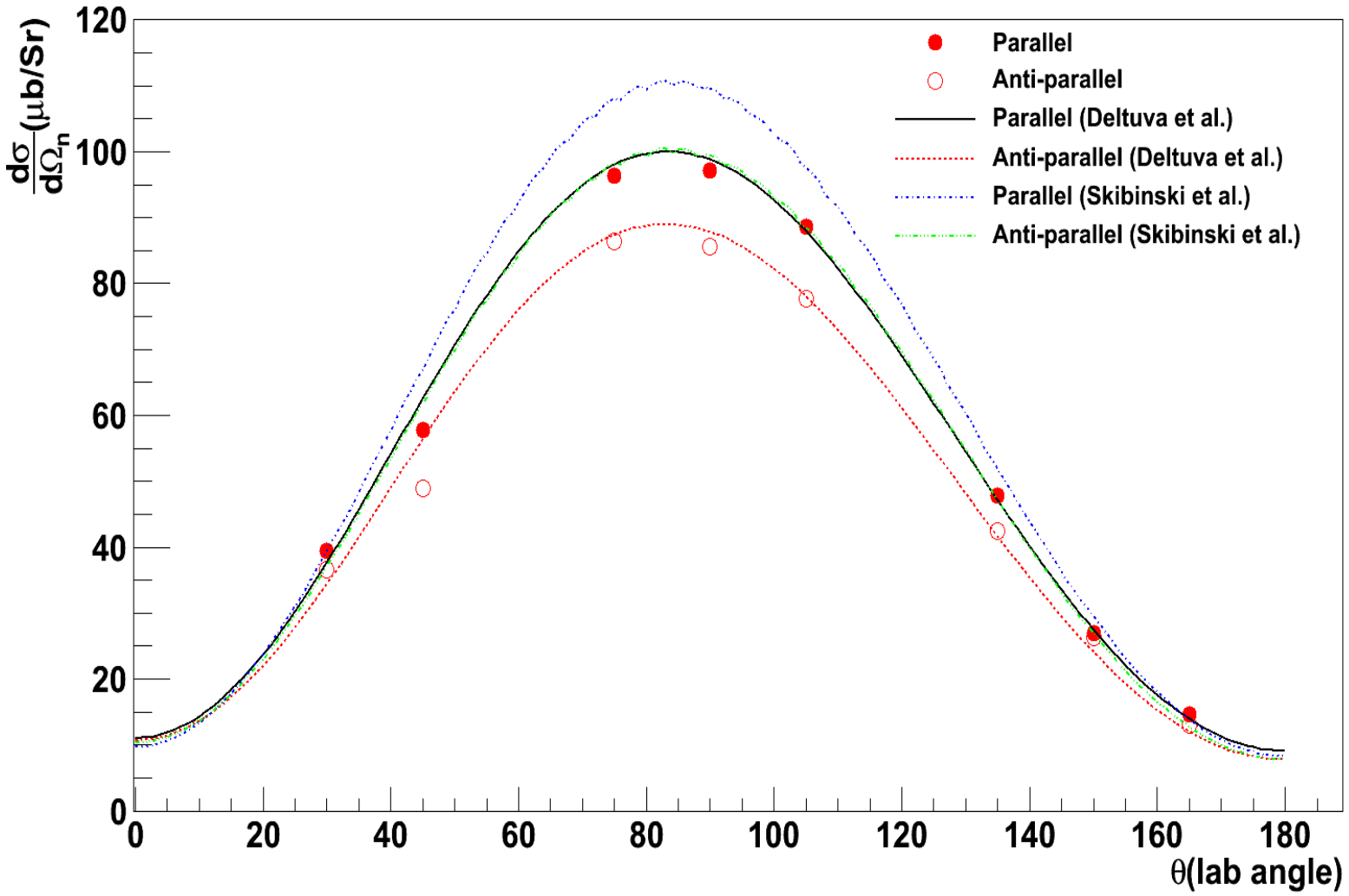
G. Laskaris *et al.*, Phys. Rev. Lett. 110, 202501 (2013)

Spin-Dependent Double Differential Cross Sections at 14.7 MeV

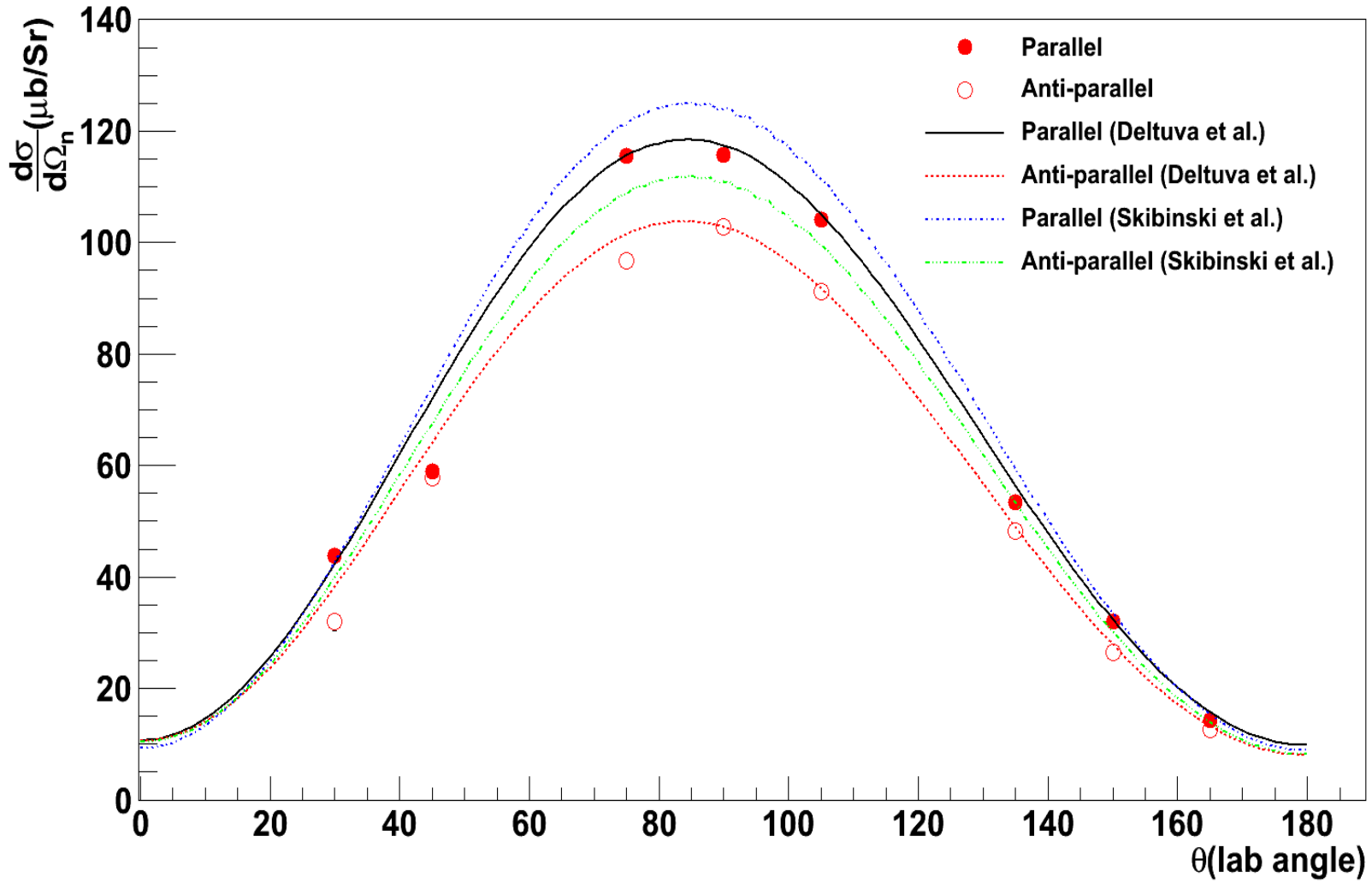


G. Laskaris *et al.*, Phys. Rev. Lett. 110, 202501 (2013)

Spin-Dependent Single Differential Cross Sections at 12.8 MeV (Preliminary)

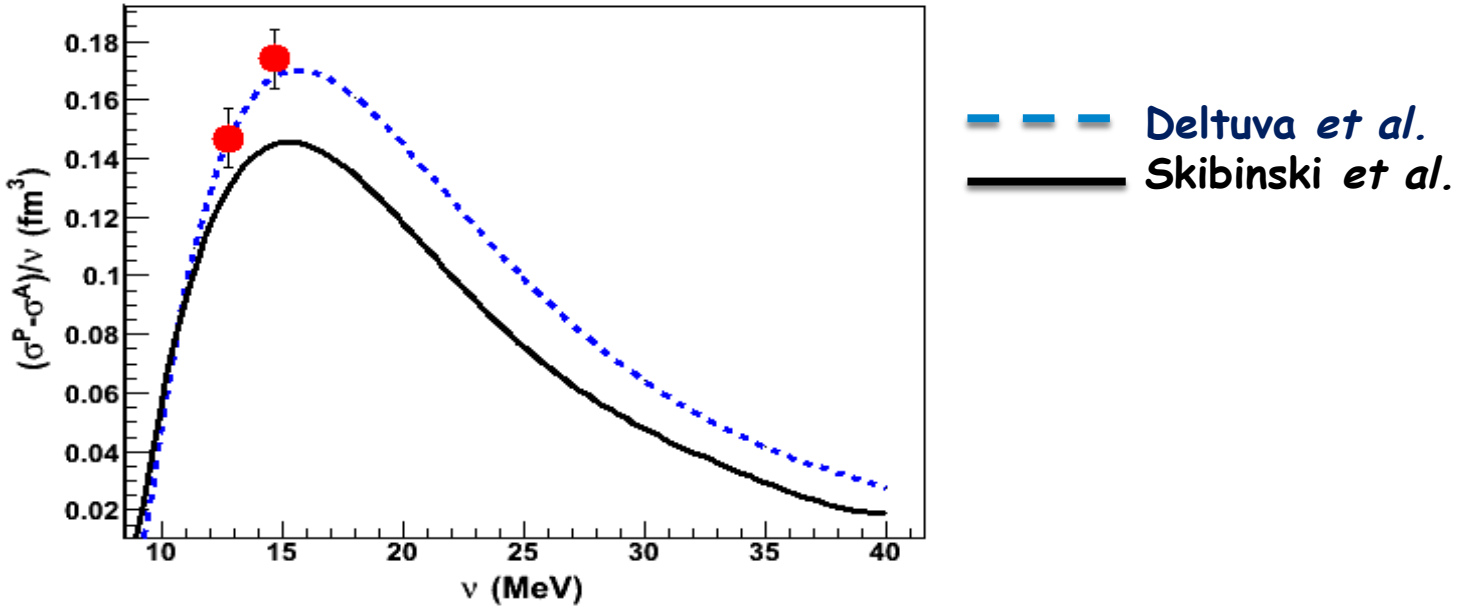


Spin-Dependent Single Differential Cross Sections at 14.7 MeV (Preliminary)



Spin-Dependent Total Cross Sections and the GDH Integrand

ν	$\sigma^P(\mu b)$	$\sigma^A(\mu b)$	$(\sigma^P-\sigma^A)/\nu\ (fm^3)$
This work 12.8	$861 \pm 5 \pm 81$	$765 \pm 5 \pm 71$	$0.147 \pm 0.010 \pm 0.018$
Deltuva *et al.*	872	777	0.146
Skibiński *et al.*	956	872	0.131
This work 14.7	$999 \pm 5 \pm 89$	$869 \pm 5 \pm 78$	$0.174 \pm 0.011 \pm 0.020$
Deltuva *et al.*	1026	900	0.168
Skibiński *et al.*	1079	970	0.146



G. Laskaris *et al.*, Phys. Rev. Lett. 110, 202501 (2013)

Two-body Photodisintegration: April 2013 Beam Test

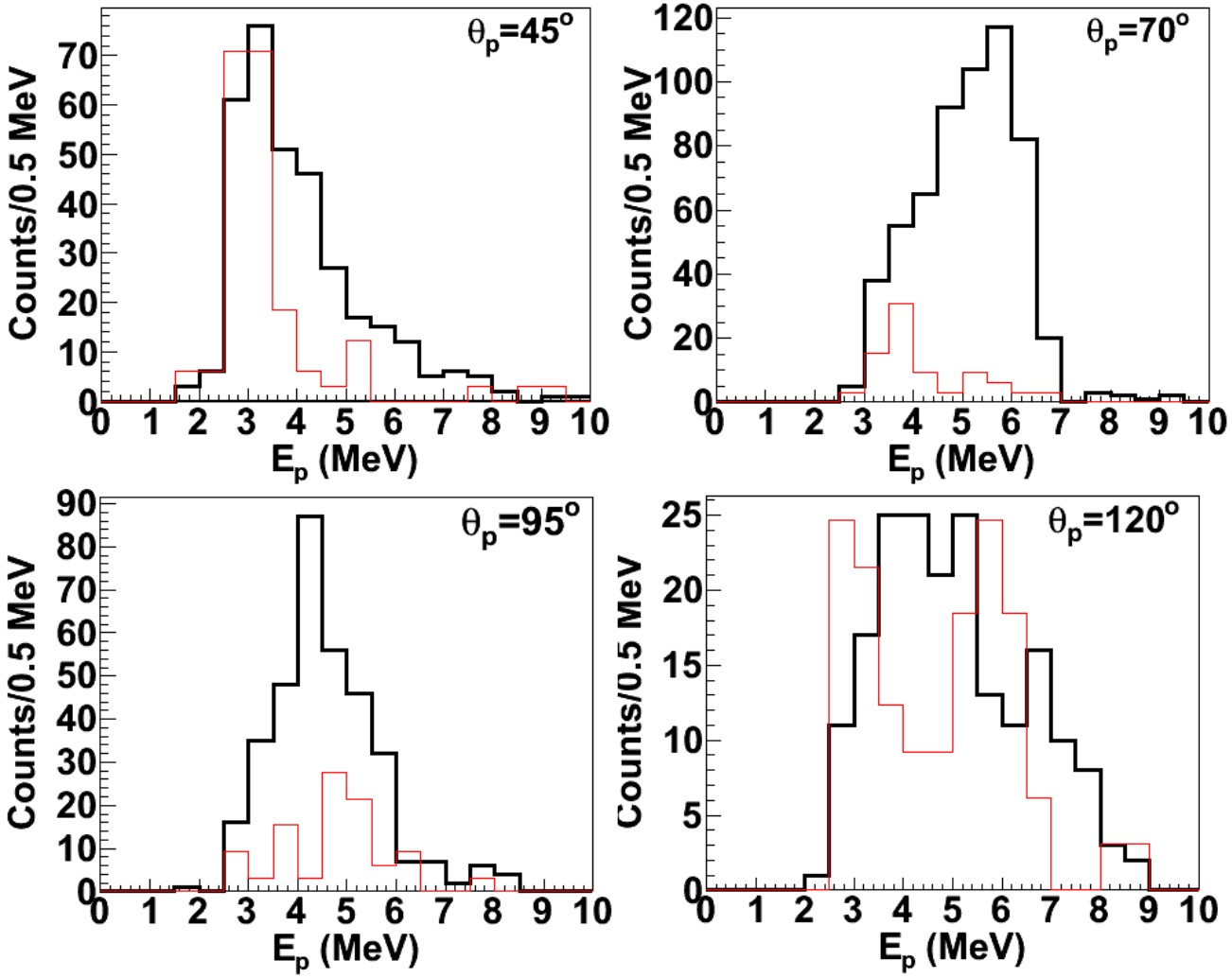
- ~100% circularly polarized γ-ray beam at 30 MeV (flux during the run 3×10^7 γ/sec)
- High pressure hybrid ^{3}He target (6.48±0.1 amg, ~1mm wall thickness)
- 16 Silicon Surface Barrier (SSB)
- detectors at 45°, 70°, 95° and 120° (4 detectors at each angle)

60 hours of beam time (total)
30 hours on ^{3}He cell
10 hours on N_2 reference cell
20 hours on the optimization of setup

Two-body Photodisintegration: April 2013 Beam Test

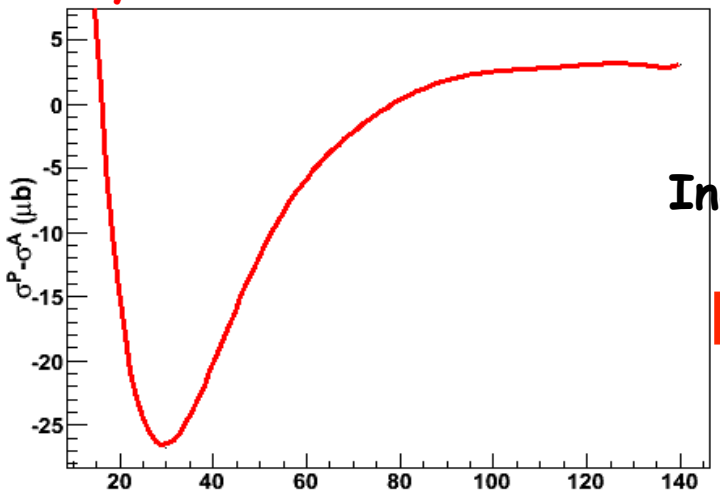
Protons from the ^{3}He cell

Protons from the N_2 cell

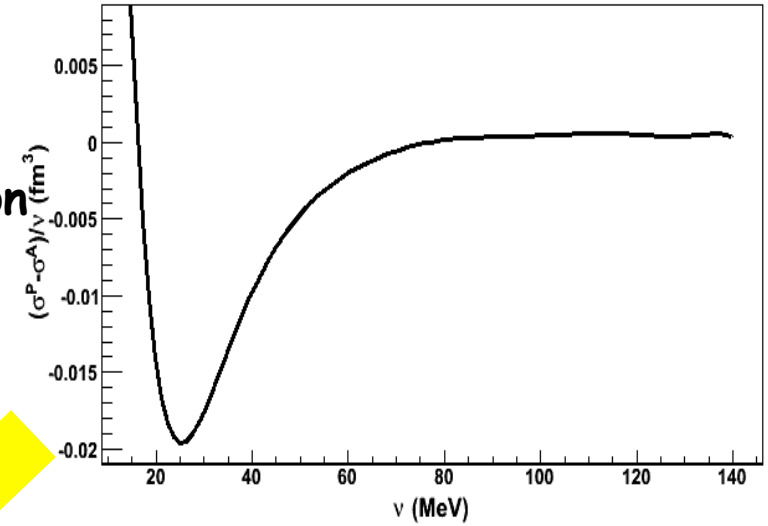


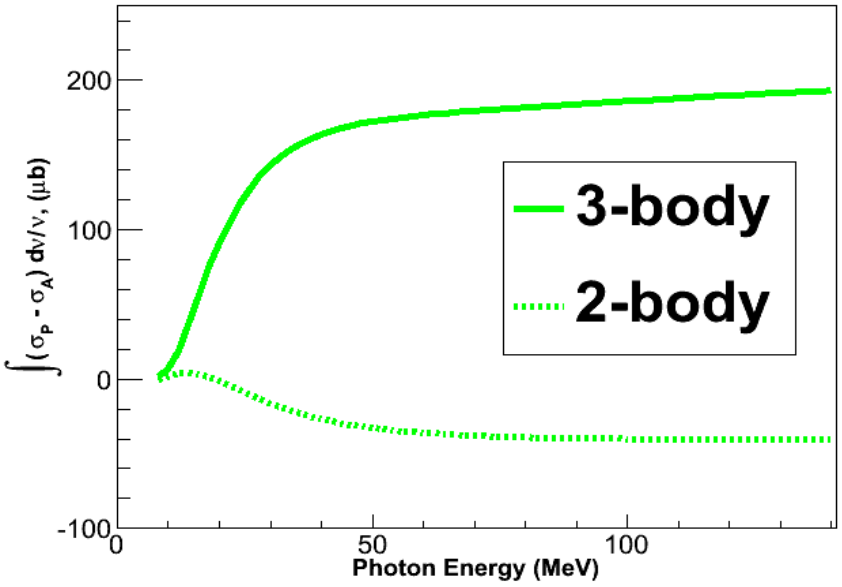
First Measurement of $\overrightarrow{^3He}(\vec{\gamma}, p)d$ at Incident Photon Energies of 25 and 30 MeV

- **Why 25 and 30 MeV?**



Divide by Incident Photon energy

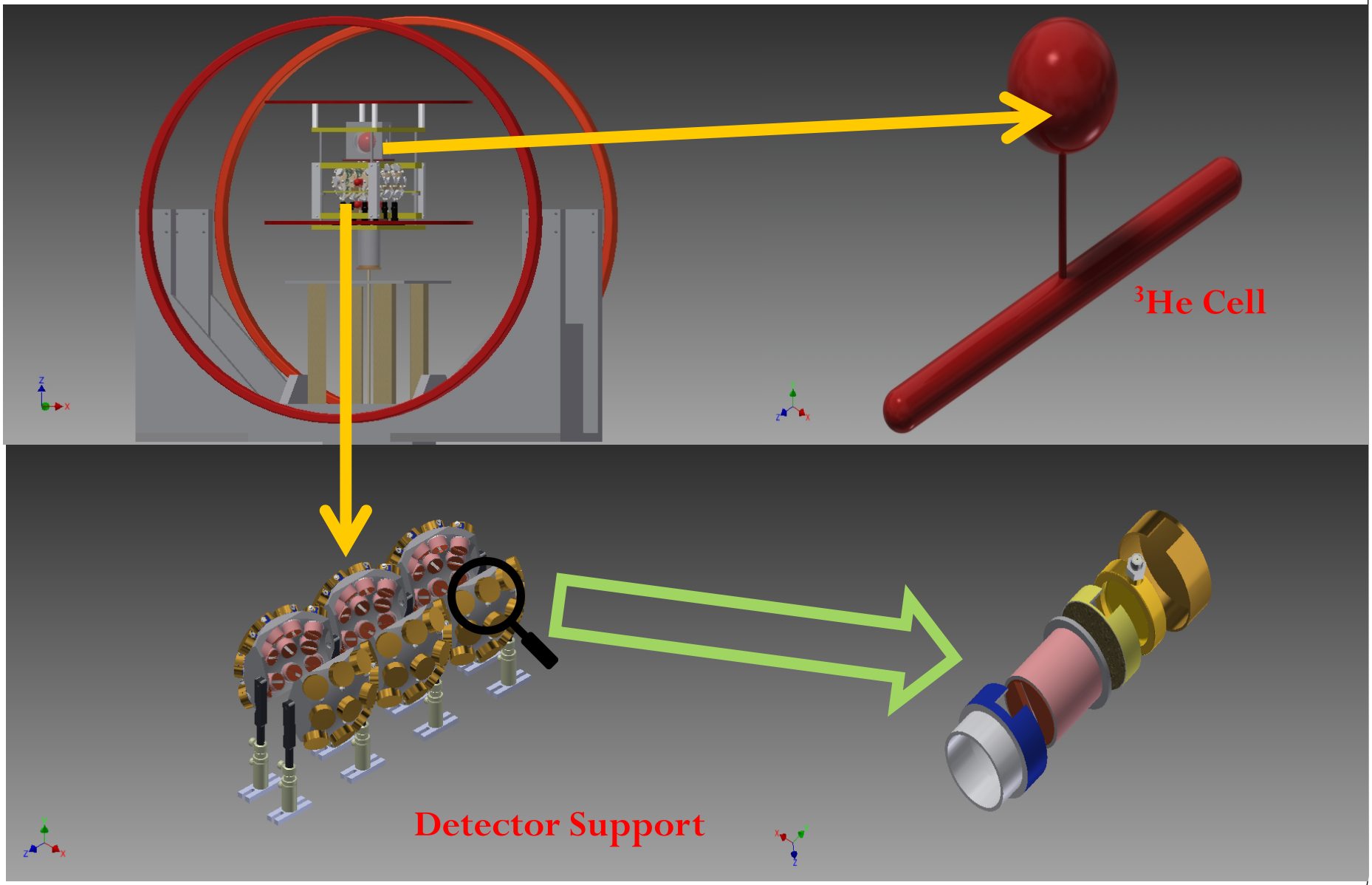




- Main Contribution to the GDH integral from the three-body break up
- Two-body contribution non negligible
- $\sigma^p - \sigma^A$ maximizes at ~30 MeV
- $(\sigma^p - \sigma^A)/\nu$ maximizes at ~25 MeV

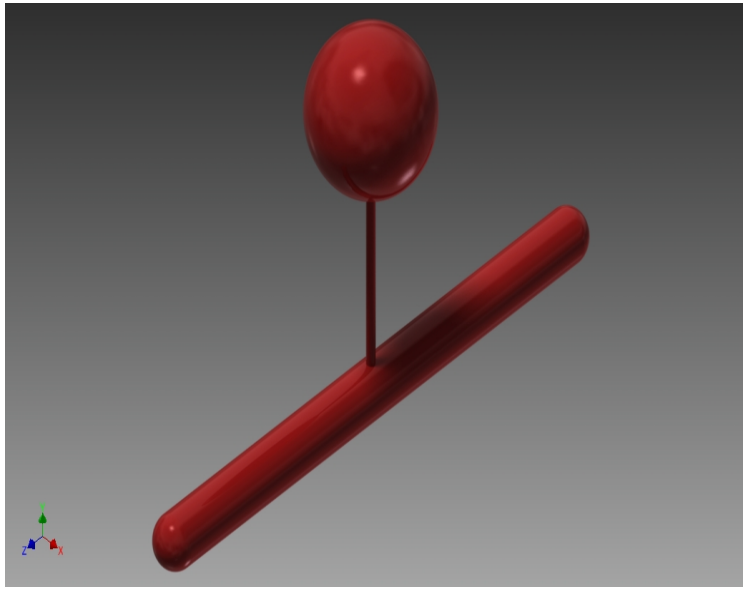
(PAC: Approved P-06-2013, 250 hrs awarded, M.W Ahmed, H. Gao)

New Target and Detector Array Support for $\overrightarrow{^3He}(\vec{\gamma}, p)d$



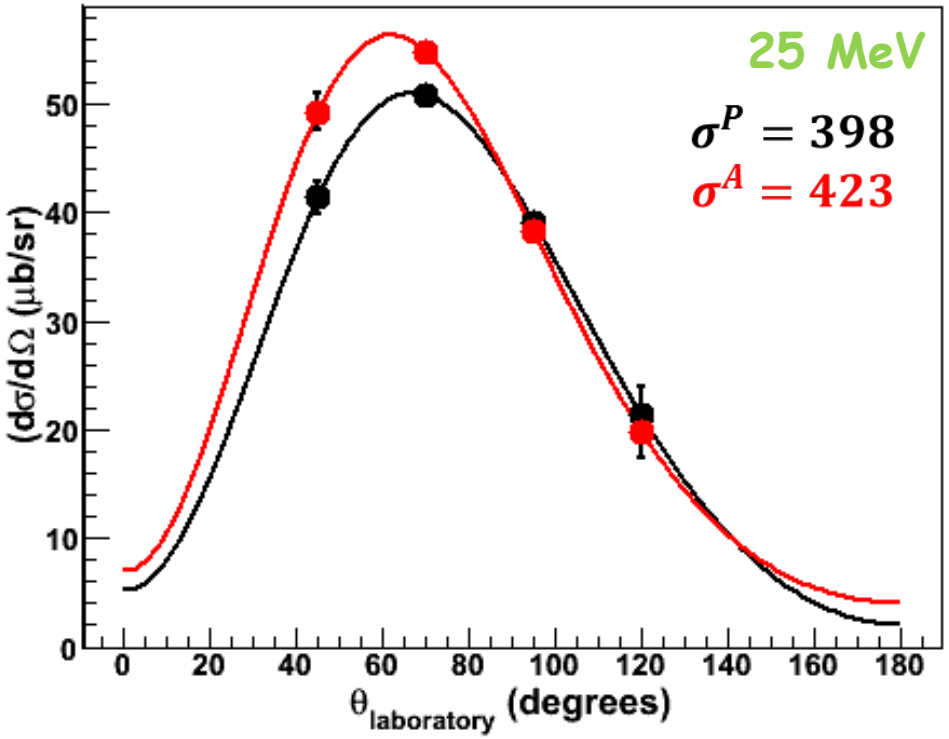
^{3}He Target Cells for $\overrightarrow{^3\mathrm{He}}(\vec{\gamma}, \mathrm{p})\mathrm{d}$

- Two different cells for the measurements at 25 and 30 MeV
- Make possible for protons to "escape" from the target chamber of the ^{3}He cell
- Typical cell have three volumes: pumping and target chambers (P.C. and T.C.) connected with transfer tube
- Both cells will have the same P.C. (8 cm in diameter) and transfer tube (1 cm in diameter and 9 cm long)



Technical Characteristics	Cell at 25 MeV	Cell at 30 MeV
Target Chamber diameter	3 cm	3 cm
Target Chamber wall thickness	700 μm	1 mm
^{3}He Filling Density	4.5 amg	6.5 amg

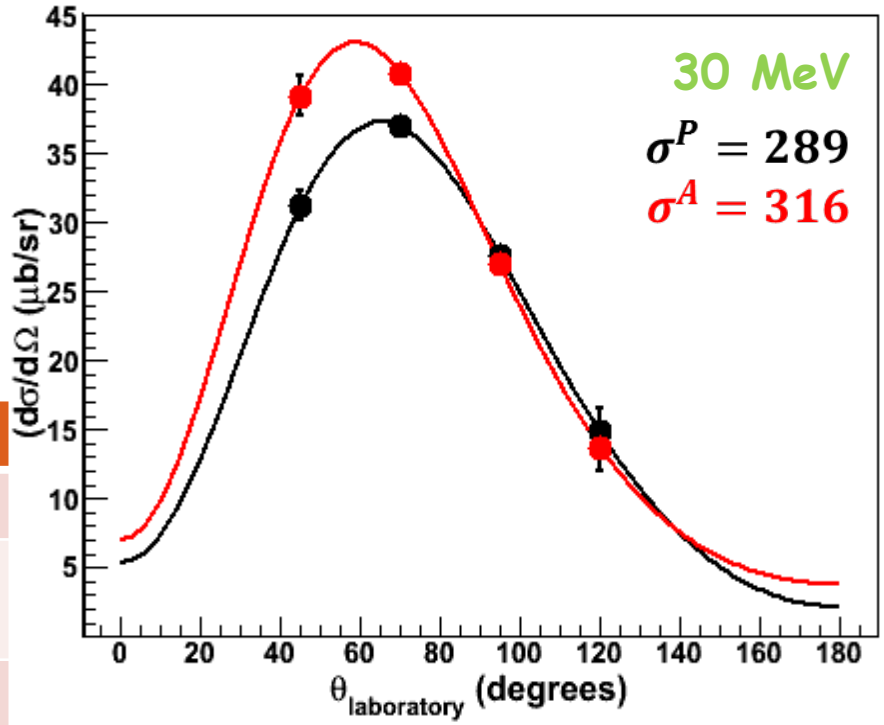
Projections for $\overrightarrow{^3He}(\vec{\gamma}, p)d$



Parameters	Values
Flux	3×10^7 γ/sec
^{3}He cell at 25 MeV	80 hrs
N_2 cell at 25 MeV	40 hrs
^{3}He cell at 30 MeV	80 hrs
N_2 cell at 30 MeV	40 hrs

Systematic Uncertainties

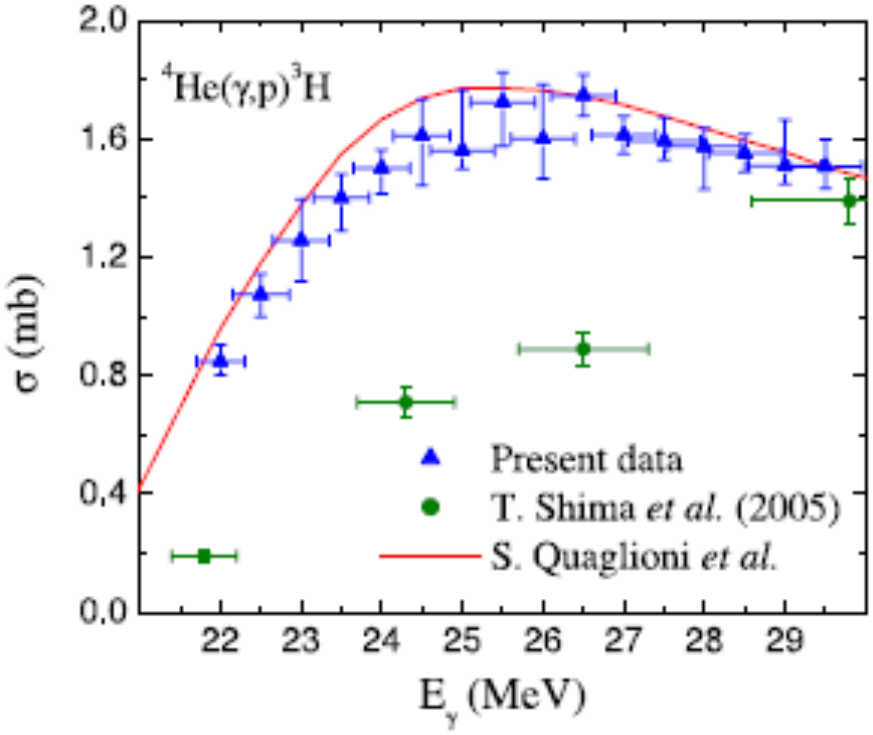
Sources	Uncertainties (%)
D_2O Flux Monitor	6
γ-ray beam polarization	5
Target Polarization	5
Target Thickness	2



Deltuva *et al.*, private communication

Photodisintegration of the Reaction $^4He(\gamma,p)^3H$ between 22 and 30 MeV

Recent results from Shima et al. had put into question the validity of theoretical calculation.



- new data are in good agreement with the calculation of the Trento group.
- providing confidence in the related calculations of core-collapse supernova explosions and big-bang nucleon-synthesis abundances of certain light nuclei.

R. Raut et al., Phys.Rev. Lett.108 042502 (2012)

Collaborations

Three-body

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Two-body

M.W. Ahmed (co-spokesperson), T. Averett, P.-H. Chu, D. Dutta, H. Gao (co-spokesperson), C.R. Howell, M. Huang, S.S Jawalkar, A. Kafkarkou, H.J. Karwowski, D. Kendellen, **G. Laskaris**, J. Manfredi, M. Meziane, J.M. Mueller, L.S. Myers, C. Peng, M.H. Sikora, B. Tsang, H.R. Weller, Y.K. Wu, X. Yan, Q. Ye, Q. J. Ye, Y. Zhang

Summary

- The first experiment on $\overrightarrow{^3\mathrm{He}}(\vec{\gamma},\mathrm{n})\mathrm{pp}$ took place at HIγS/TUNL facility
- The spin-dependent double/single differential, total cross sections and GDH integrand were extracted at 12.8 and 14.7 MeV
- The Coulomb force should be included in the calculations for the three-body photodisintegration of ^{3}He
- A new experiment on the two-body photodisintegration of ^{3}He with double polarizations will take place on the spring of 2014
- Pion-less/-full EFT calculations make good progress concerning the two-body break up of ^{3}He

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