Polarized Gas Targets

for Nuclear and Particle Physics

J. Maxwell

Jefferson Lab
TARGET Group

20th International Workshop on
Polarized Sources, Targets and Polarimetry
September 22th, 2024

Outline

1. Internal Gas Targets
   - Storage Cell Targets
2. Optical Pumping Targets
   - SEOP
   - MEOP

Gases vs. Solids

Solid polarized targets can provide near 100% polarization at far higher density than can be achieved with any gas.

Why Choose a Polarized Gas Target?

- Available nuclei: different species (^{3}He), nuclear corrections
- Dilution factor: Only 17% of NH_3 is polarizable protons
- Background: Windows, cryogens complicate high-precision measurements
- Spin Reversal: Internal targets flip at up to 100 Hz
- Total luminosity: long cells and higher beam current

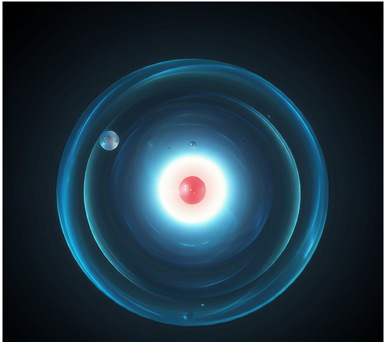
Polarizing Nuclei is Hard

- Take the proton. It has a magnetic moment μ. Why not just line up the spins with a strong magnet?

- Up-down energy different is $2\mu B$, with $\mu_{\text{proton}} = 9 \times 10^{-8} eV/T$
- At 10 T, thermal energy kT at room temperature is 14,000 times larger! Even at 0.3 K, still 14 times.

Electron Spin Is Our Powertool

- The electron's μ is 660 times larger!
- Use hyperfine coupling in atoms to polarize the nucleus



Bad Ai Generated Image

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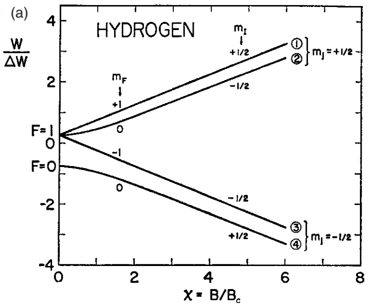
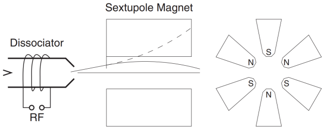
Beginnings of Polarized Gas Targets: Internal Targets

- Remember Stern-Gerlach? Spray atomic H or D through a sextupole.
- 4 spin states for H. To isolate (1):
  - Choose (1) (2)
  - Use RF to flip (2) to (3)
  - Second sextupole to choose (1)
- 100% Vector P (and/or Tensor for D)
- Atomic Beam Source: jets with very low density (10^{16} H/s), good for storage rings
- Storage cells coated with teflon used to increase target density. FILTEX at CERN, and VEPP-3 in Novosibirsk





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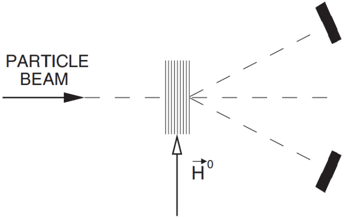
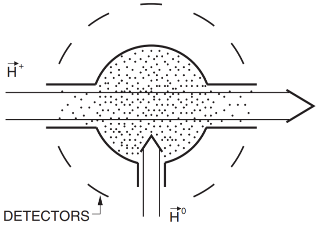
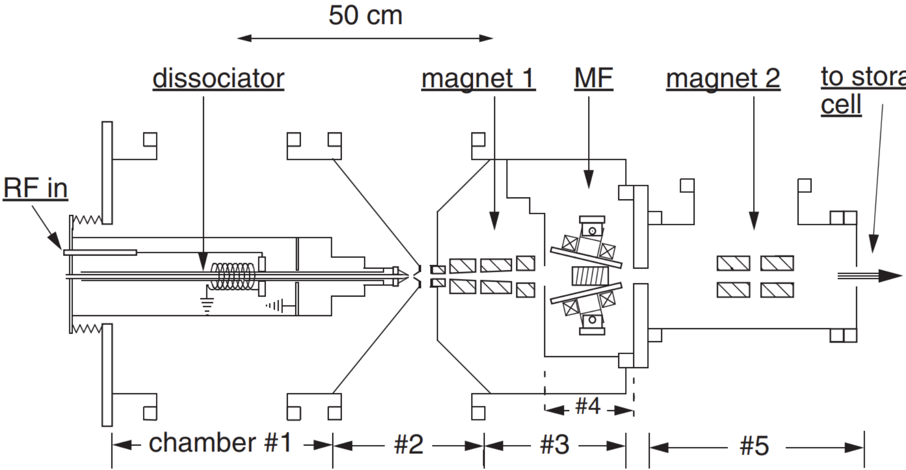




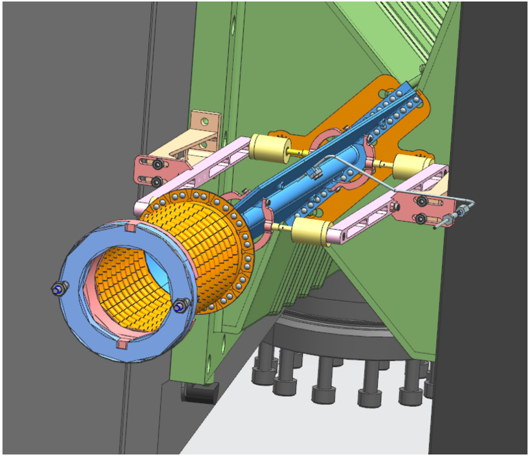
Wisconsin ABS, Polarized H and D Target (CERN, HERMES, IUCF)



Steffens, Haeberli (2003)

SMOG2 Internal Target (LHCspin)

- Bring Spin Physics to the LHC!
- Fixed, internal target at LHCb with storage cell
- Storage ring, so low density is advantageous
- ANKE ABS from COSY, Jülich
- Cell splits in half to accommodate beam, suppress wake field effects
- Already run with unpolarized gases
- Talks Thursday, 11:00 (Lenisa, Engels)



Steffens, PSTP 2022

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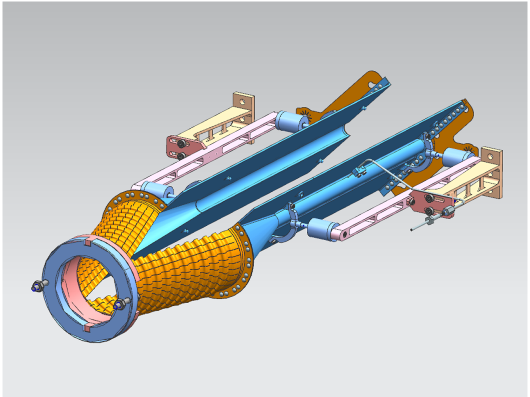

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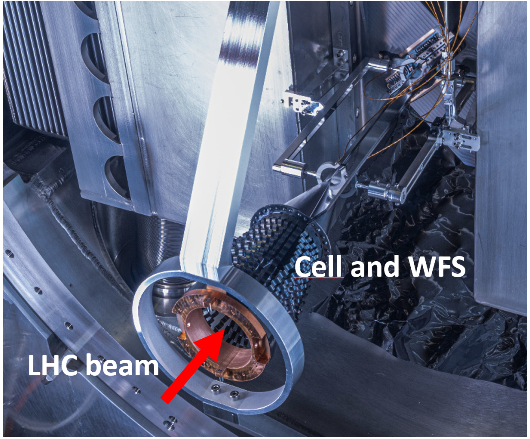

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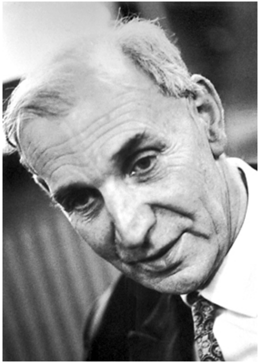
Optical Pumping of Helium



- OP: Kastler in 1952 (Nobel 1966), key to lasers
- Energy to first excited electronic state is 20 eV!
- This corresponds to a wavelength of around 60 nm, not practical for driving polarizing transitions.
- We have to optically pump other electronic states, then transfer to the helium nucleus.

Polarization of Gas via Optical Pumping

- Spin-exchange: Evaporate Alkalis into the Gas, Pump Them
- Metastability-exchange: Excite Electrons to 2S, Pump Them

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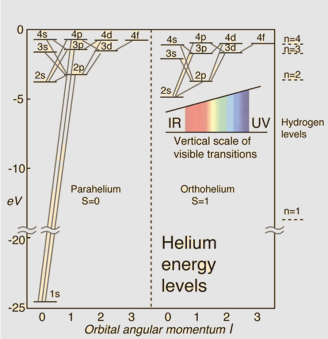

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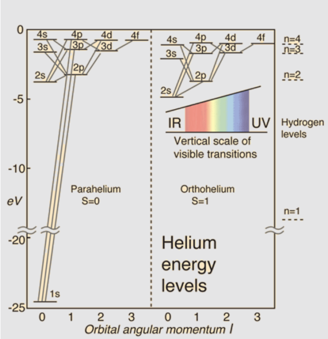

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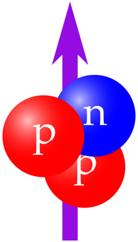
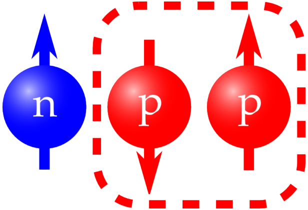
Why Polarized Helium 3?

- How do we make polarized neutron targets and beam sources?





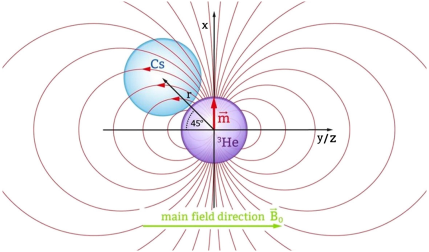
State	Probability
S	88.6%
S'	1.5%
D	8.4%

- S-state ^{3}He: nuclear spin carried by the neutron nearly 90% of the time
- Polarized spin asymmetries: $^3\overrightarrow{\text{He}}$ good surrogate for $\vec{n}$
- ^{3}He's magnetic moment close to n, easier spin manipulation in accelerator
- Crucial cross-check against measurements on "$\vec{n}$" from ND_3

Wider Applications of Gas Polarization

Polarization of gases (^{3}He, ^{129}Xe) important across many fields

- Magnetometers and Co-magnetometers
- NMR and Medical Imaging
- Neutron Spin Filters
- Fuel for polarized fusion efforts



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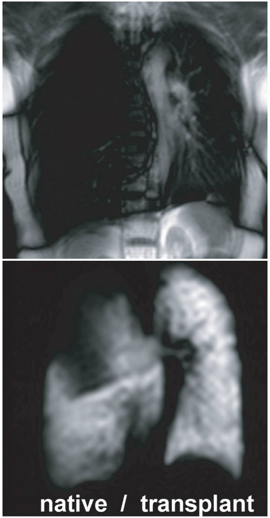

Miller *et al.*, 2010

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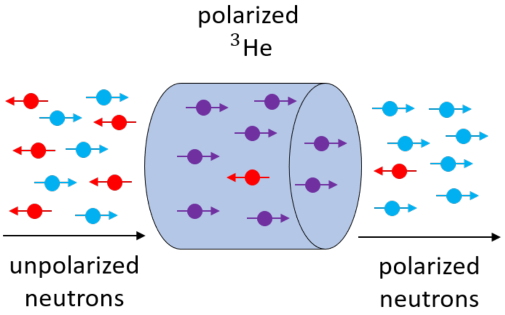

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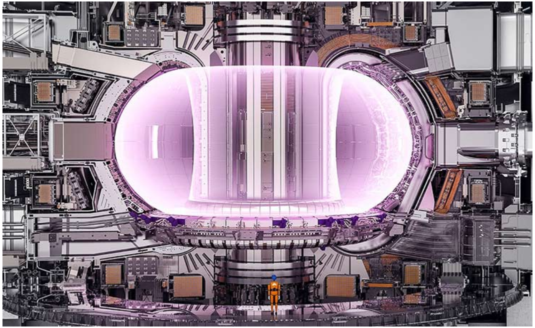
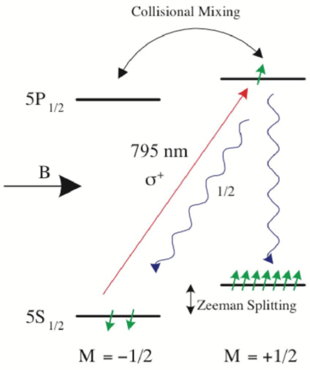


Spin Exchange Optical Pumping

- Done in 1960 with lamps, practical in 1987
  (Chupp *et al.* 1987)
- Pump Rb in ∼30 G holding field
  - 795 nm laser light: $5S_{1/2} \to 5P_{1/2}$
  - N_2 for quench collisions to repopulate the ground state
- Spin exchange polarizes K, then ^{3}He (or Xe)
- Slow, but pressure up to 13 atm
- Polarize in oven, transfer target cell
- $P_{\text{Rb}} \sim 95\%$, $P_{^3\text{He}} \sim 80\%$
  - In-beam reduced to $P_{^3\text{He}} \sim 60\%$
  - Longitudinal or **transverse**



Tadepalli

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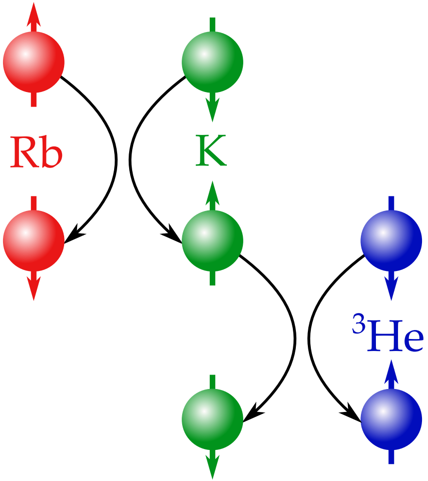

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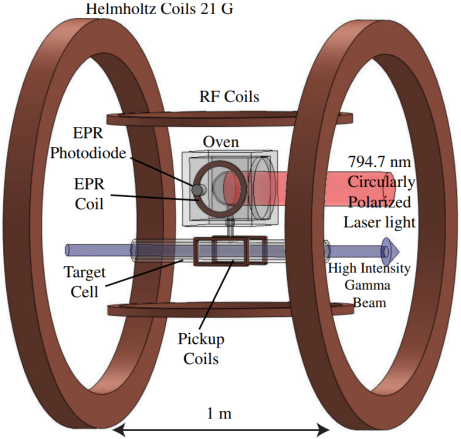

Gentile *et al.* RMP, 2017.

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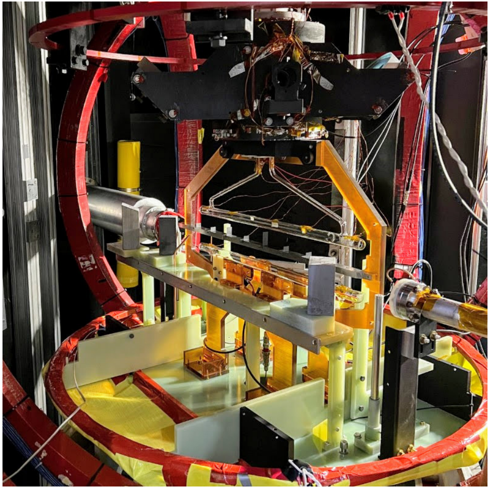

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JLab 6 GeV Polarized ^{3}He: 13 Experiments with SEOP in Hall A

Neutron Spin Structure

- Valence structure: g_1^n, A_1^n
- Higher-twist: g_2^n, d_2^n
- Sum rules (GDH)
- Quark-Hadron duality

SSA, Form Factors, etc.

- Transversity, TMDs
- G_M^n, G_E^n
- 2-γ exchange, Inclusive A_y
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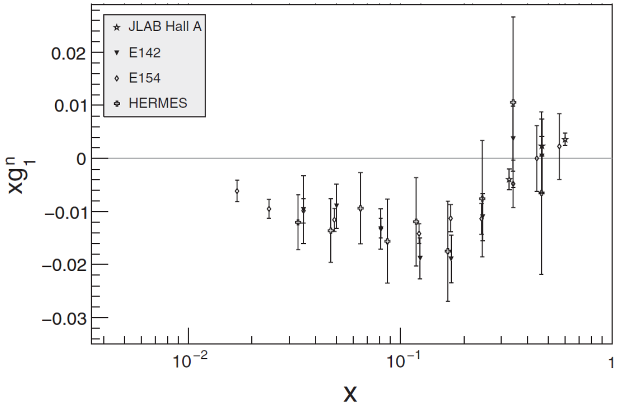

Aidala, 2013

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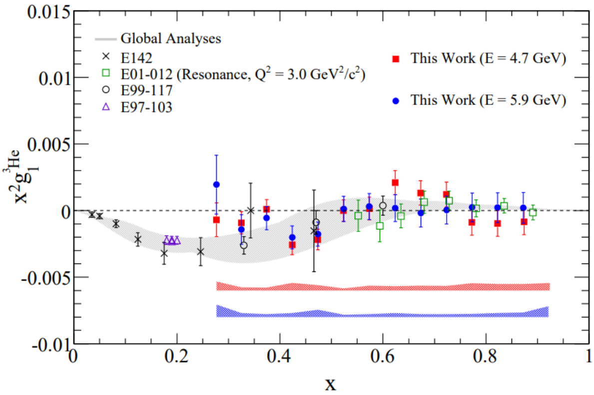

Flay, 2016

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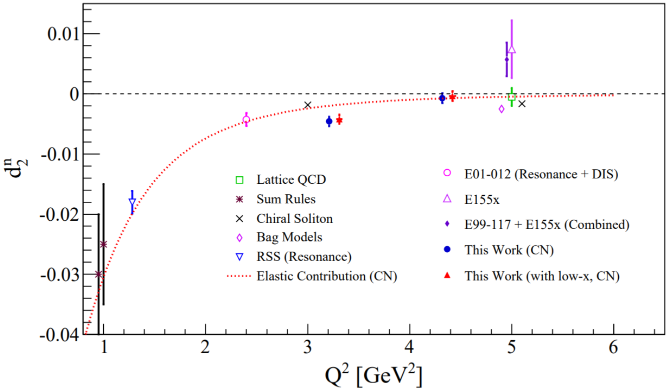

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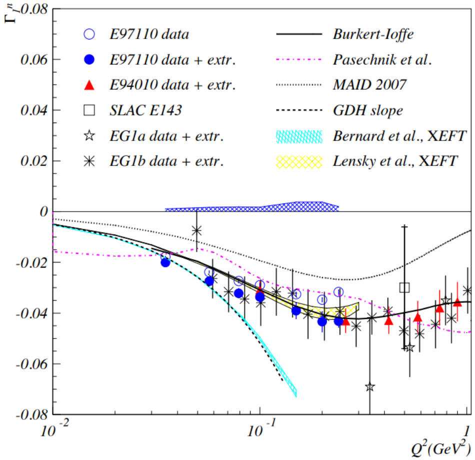

Sulkosky, 2019

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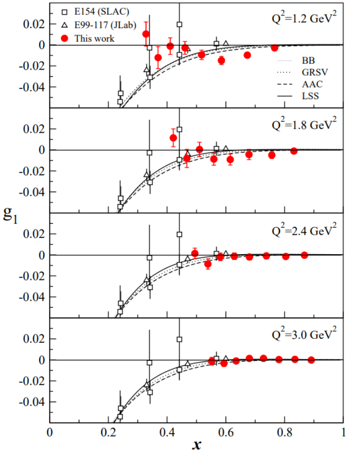

Solvignon, 2008

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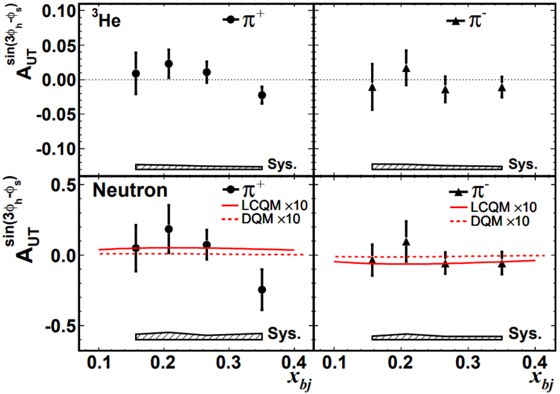

Zhang, 2013

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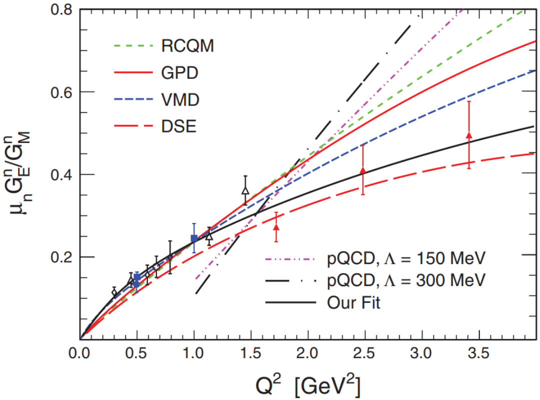

Riordan, 2010

Polarized ^{3}He for 12 GeV: 7 Approved Experiments

Spin Structure in Hall C

- E12-06-110: A_1^n
- E12-06-121: g_2^n, d_2^n

SuperBigBite in Hall A

- E12-09-018: Transverse SIDIS
- E12-09-016: G_E^n, G_M^n

SoLID SIDIS TMDs

- E12-10-006: Transverse 3He
- E12-11-007: Longitudinal 3He
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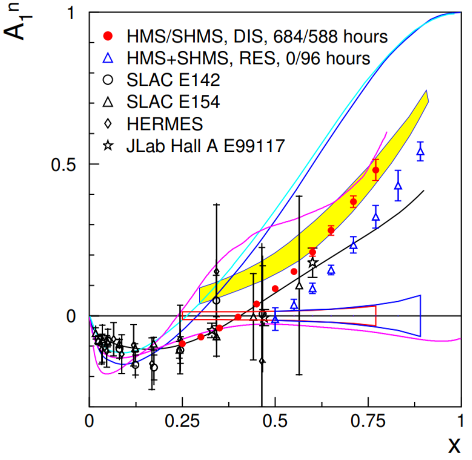

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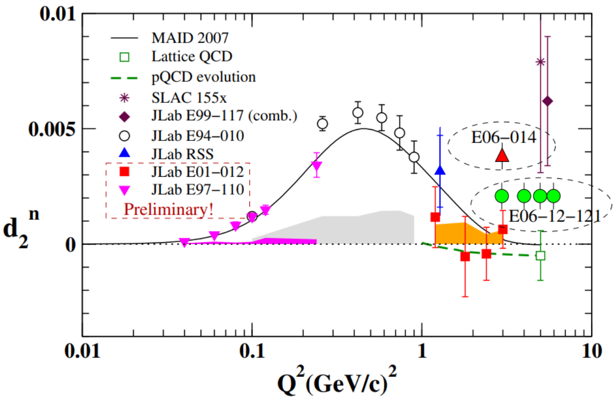

E12-06-122

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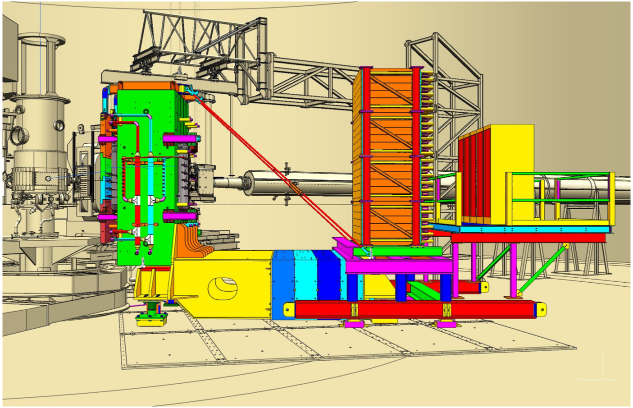

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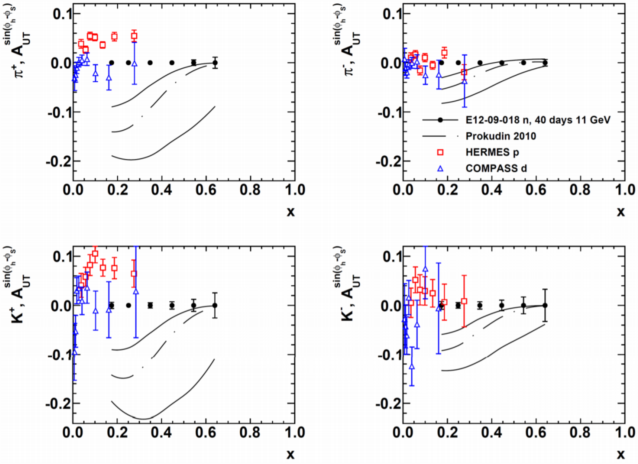

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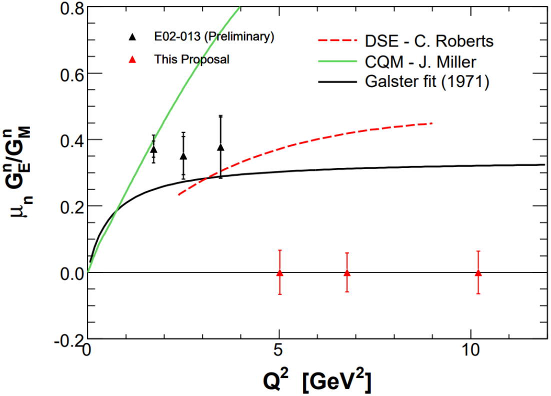

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SuperBigBite in Hall A

- E12-09-018: Transverse SIDIS
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SoLID SIDIS TMDs

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- E12-11-007: Longitudinal 3He
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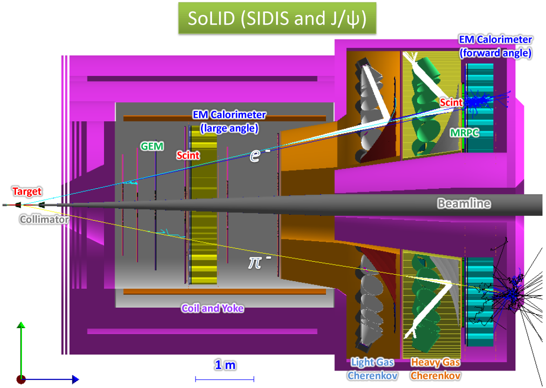

Polarized ^{3}He for 12 GeV: 7 Approved Experiments

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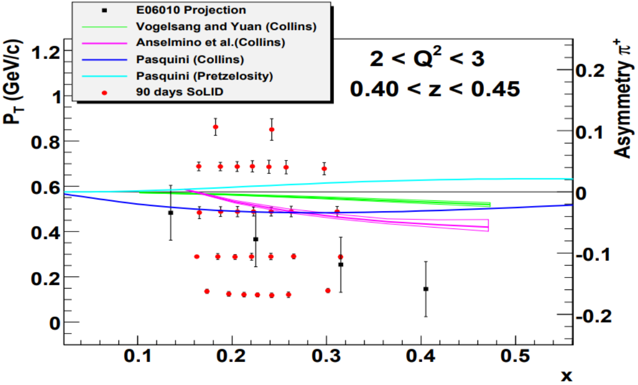

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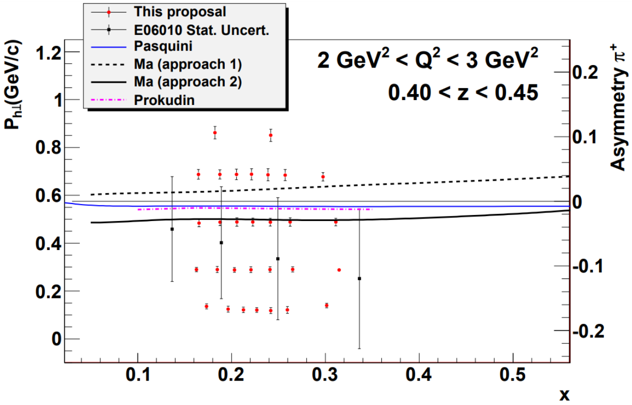
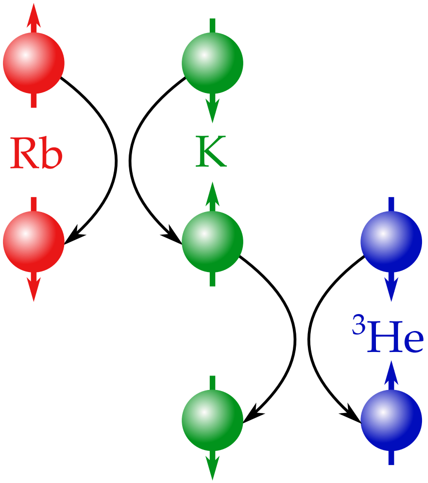


E12-11-007

SEOP Improvements

- Hybrid cell in the 2000's, Rb to K to He, faster spin exchange
- Narrow line-width lasers
- Cell Improvements
  - 40 cm to 60 cm long
  - Increase to 45 μA beam
  - Added convection to reduce polarization gradient from beam
  - Added air cooling to glass windows (metal windows to come)
- Work by JLab 3He group, UVa, W&M, Kentucky, Temple



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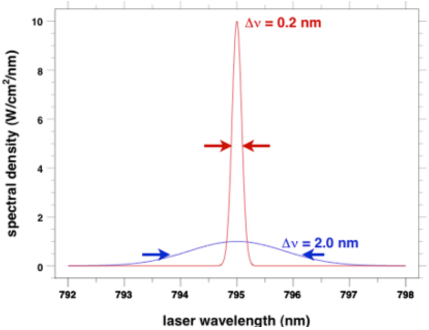

JLab 3He Group

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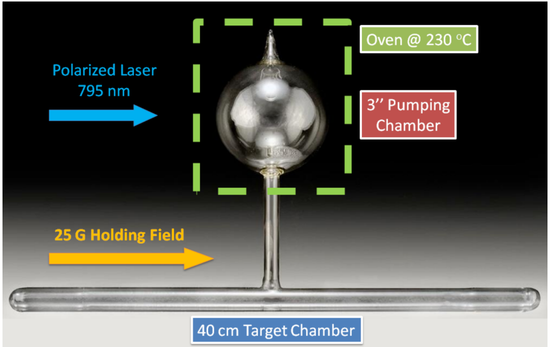

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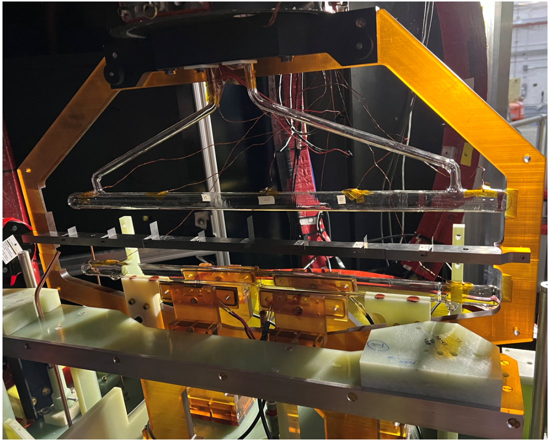

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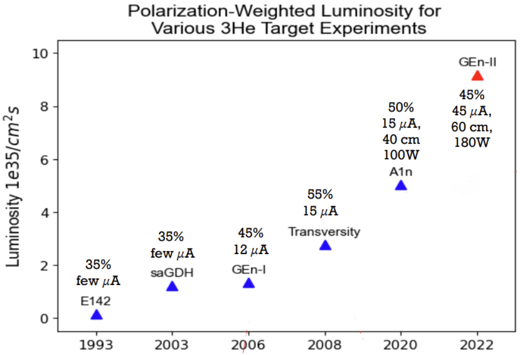
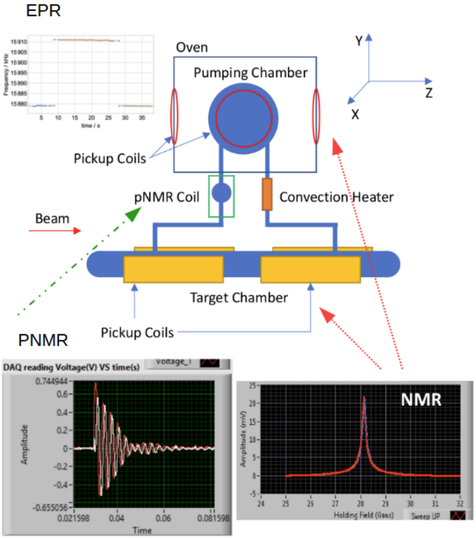


JLab 3He Group

SEOP Polarimetry

- AFP-NMR
  - Sweep transverse RF (or holding field) through Larmor ν to flip spins
  - Watch with pickup coils
  - Relative measure needs calibration, but "non-invasive" during experiment
- Pulse-NMR
  - Use pulse of RF at Larmor ν to tilt spins
  - Watch precession and decay
- EPR
  - Watch resonance of alkali atoms
  - Flip ^{3}He spins, alkali resonance frequency difference gives absolute measure
  - Used to calibrate NMR



JLab 3He Group

No Pain, No Gain: SEOP Challenges

- Glass choice crucial to reduce relaxation: Need very low permeability (GE-180)
- Very high laser power: 200 W means arrays and complicated optics
- Cell preparation/variation
- Hot, explodey cells in beam
- Larger cells bring complications: microfissures reduce polarization & integrity
- Talks Friday 11:00 (Presley, Jackson)

T. Gentile with a Neutron Spin Filter Cell

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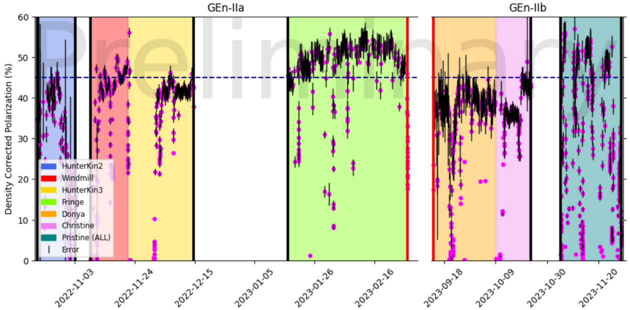

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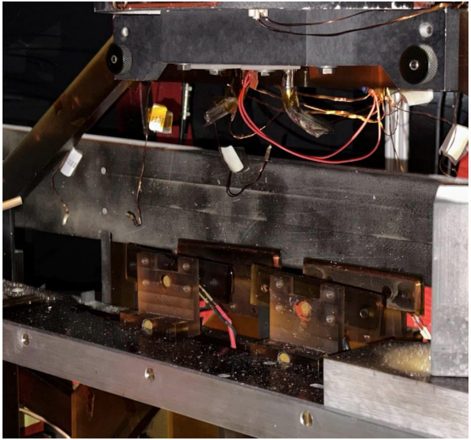

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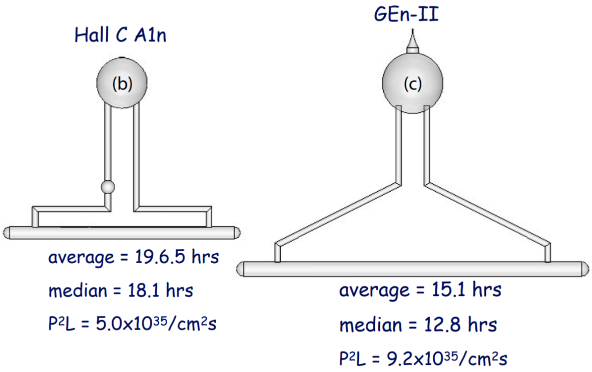
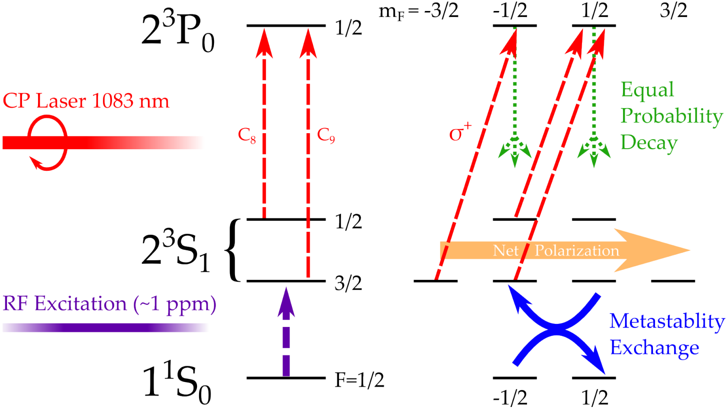


Metastability Exchange Optical Pumping

- 1963, Colgrove *et al* (TI)
- Pure ^{3}He, ~30 G field
- Discharge promotes states to 2^3S_1
- Laser drives polarization
- Collisions between 2^3S_1 and ground state polarize nuclei
- Requires ~2 mbar
- Rate drops with temperature



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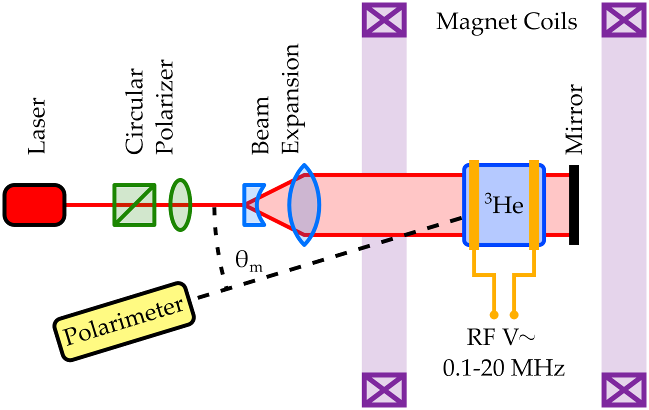

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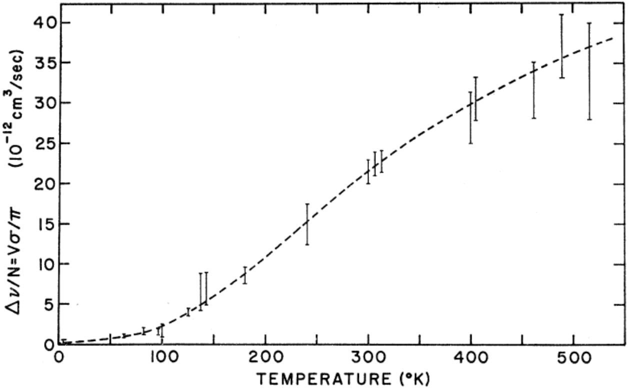

Colgrove, Schearer, Walters, 1964

Overcoming the Pressure Limitation of MEOP

- Increasing the gas pressure crucial for scattering, medical imaging
- Toepler pump at MAMI
- Titanium piston pumps
- Peristaltic pumps used in a system to ship polarized gas
- Cryogenic cooling of gas to increase density

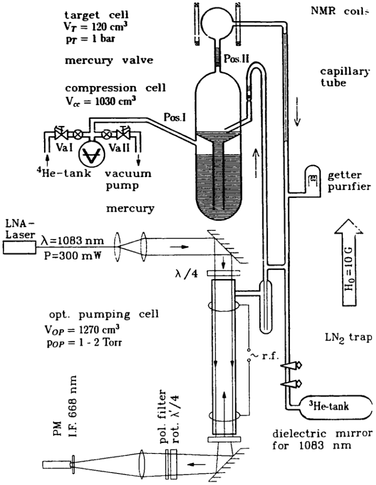

Fig. 6. Scheme of the Toepler-compressor.

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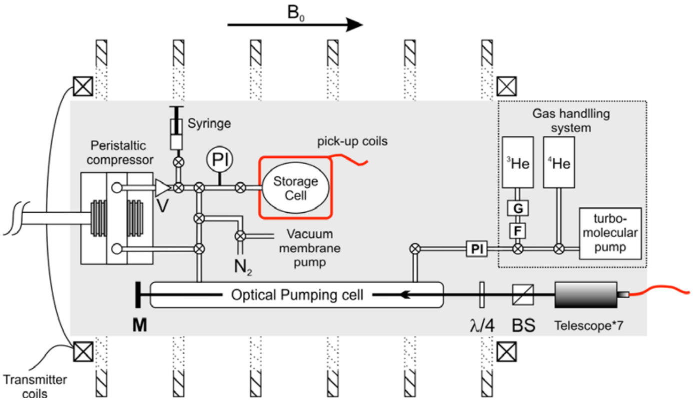

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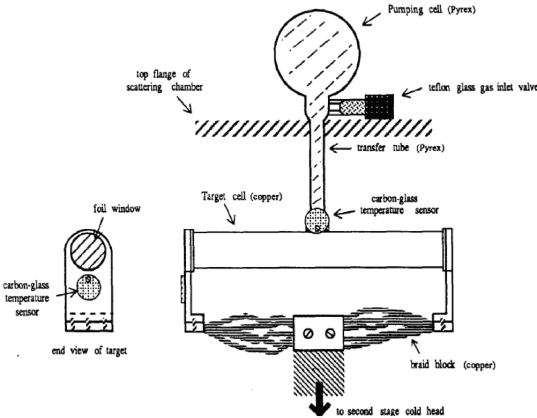
MEOP Double-Cell Cryo Target: Bates 88-02

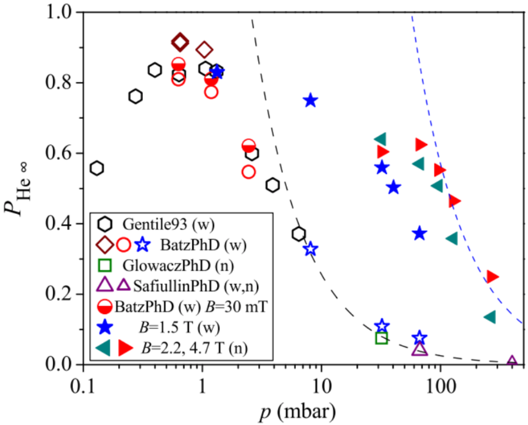
- Quasi-elastic asymmetries in 1988, 1993
- MEOP pumping cell at 2 mbar, 300 K, 30 G: 40% in-beam polarization
- Cu target cell at 2 mbar, 17 k
- Cu foil beam windows (4.6 μm)
- Cold surfaces coated with N_2 to reduce depolarization from wall interactions
- 7.2×10^{32} ^{3}He/cm^2/s Luminosity w/ 10μA



High Magnetic Field Optical Pumping

- OP not historically done at high B
  - SEOP: Increasing wall relaxation
  - MEOP: Weak hyperfine coupling...?
- Kastler-Brossel Lab at ENS in Paris found by increasing B_0, MEOP effective at higher pressures

  (Nikiel-Osuchowska *et al*, Eur. Phys. J.D., 2013.)
- 5 T: near 60% at 100 mbar!
- Zeeman splitting separates states for laser pumping
  - Decouples relaxation paths
  - Creates probe peaks (Suchanek *et al.*, Euro Phys JST, 2007.)



Solid points above 1 T

From Gentile, Nacher, Saam, Walker (2017.)

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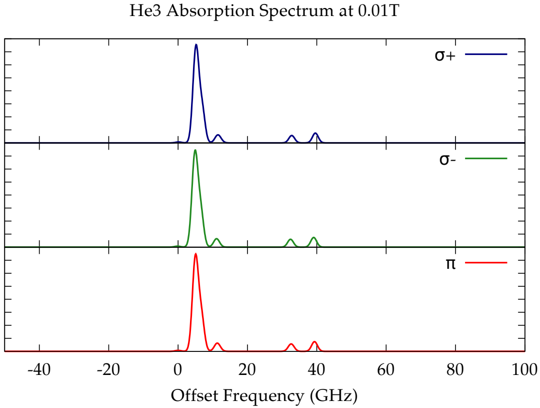

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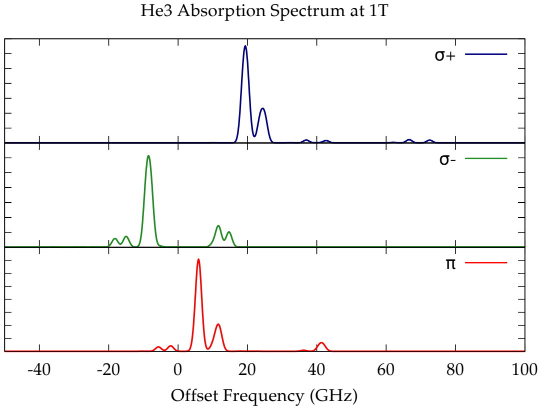
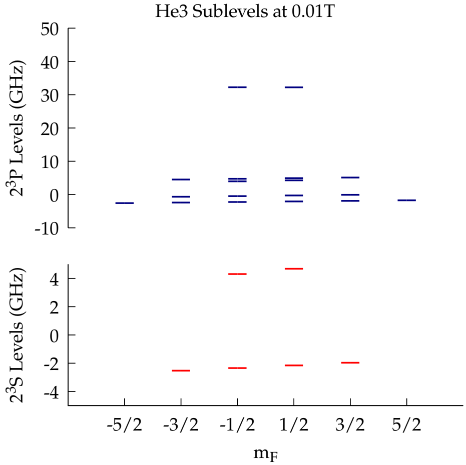
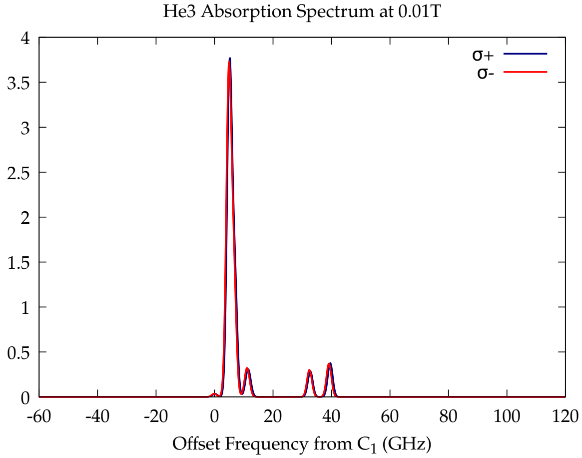


^{3}He Transitions at Low Field





Figures based on Courtade (2002), Nikiel (2013), from calculation by Nacher.

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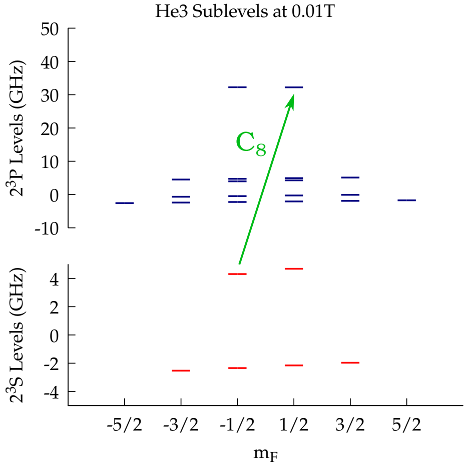

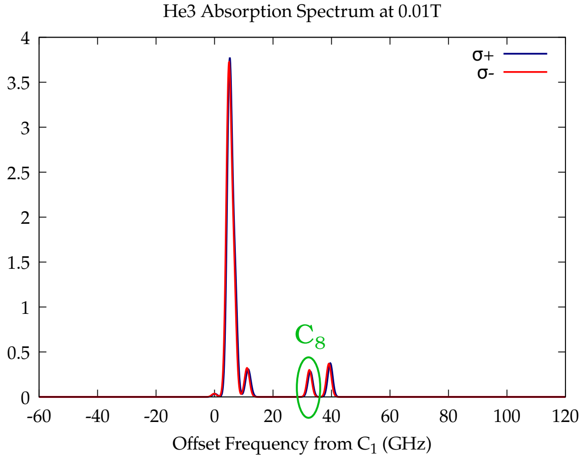

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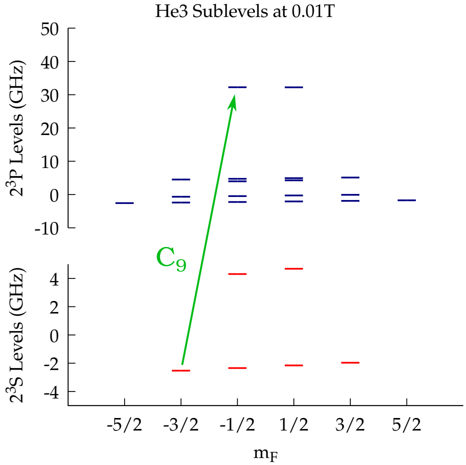

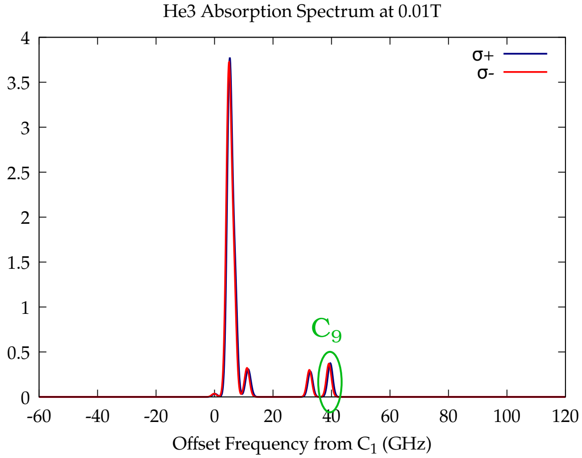

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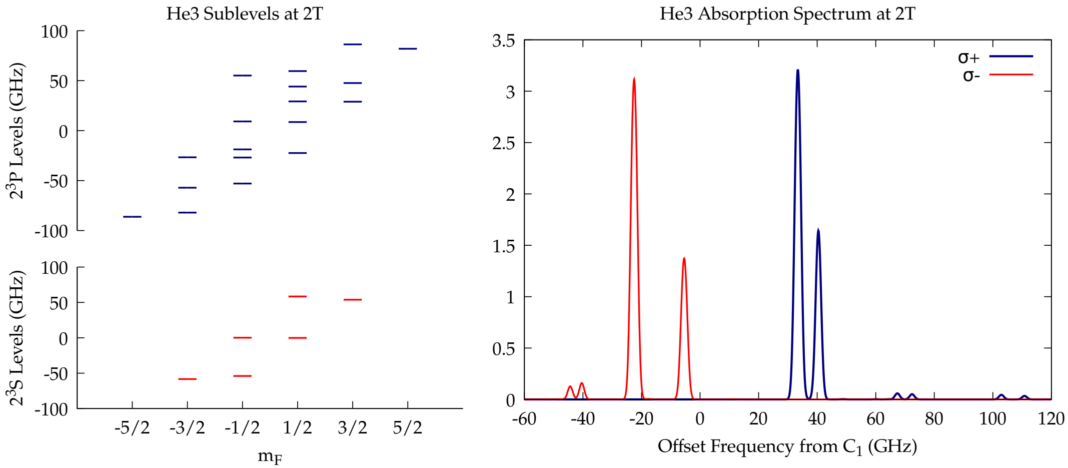

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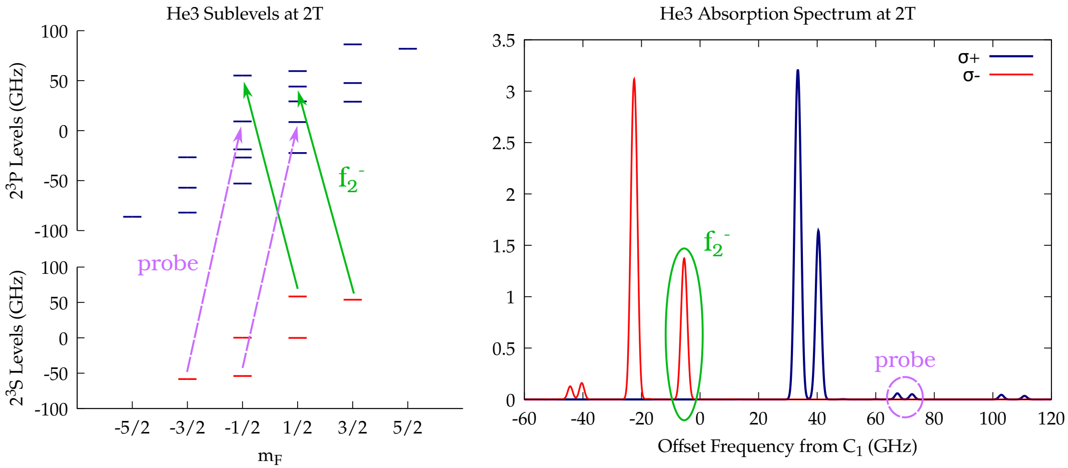

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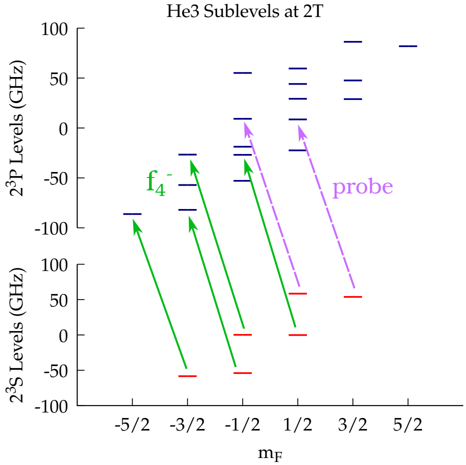

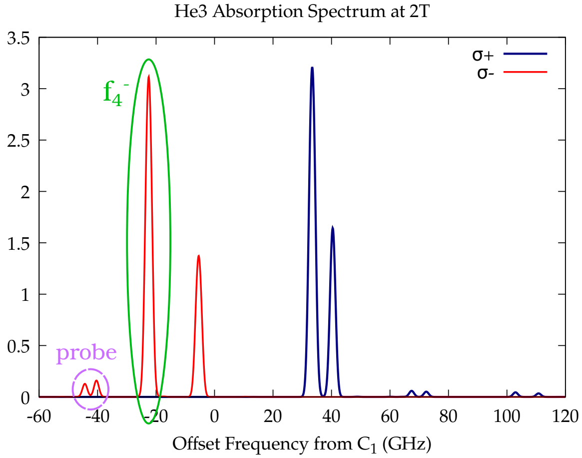

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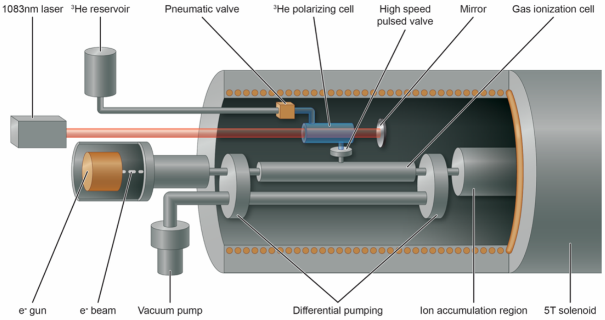
High Magnetic Field MEOP for EIC

- High field MEOP techniques already being applied for nuclear physics
- BNL-MIT: Polarized ^{3}He Ion Source for EIC

- BNL's Electron Beam Ion Source operates at 5 T
- MEOP within 5 T field, transfer into EBIS for ionization and extraction
- Tests between 2 to 4 T gave nearly 90% at 1.3 mbar (Maxwell *et al.*, NIM A **959**, 2020)
- Talk Monday 11:00 (Wuerfel)



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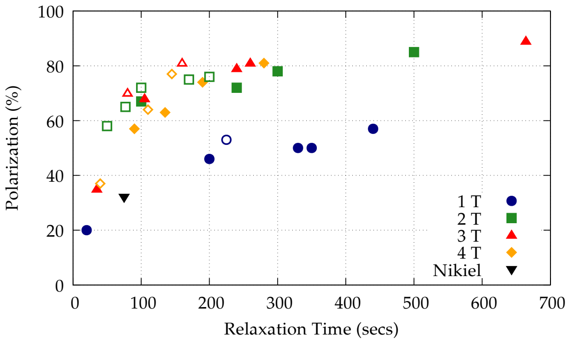
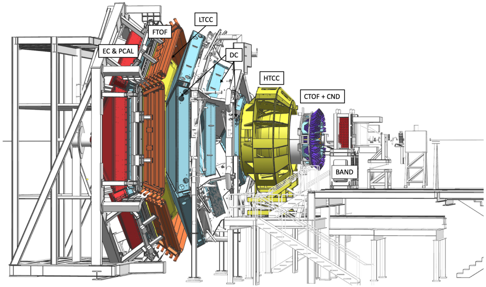


Results at 1.3 mbar

An Opportunity in Hall B's CLAS12

- CEBAF Large Acceptance Spectrometer for Jefferson Lab's 12 GeV upgrade
  - High luminosity electron scattering
  - Multi-particle final state response
- PR12-20-002: A program of spin-dependent electron scattering using a polarized ^{3}He target in CLAS12
  - P_T-dependence of n longitudinal spin structure
  - Nuclear corrections to SIDIS
  - Conditionally approved with A- rating
  - Spokespeople: Avakian, Maxwell, Milner, Nguyen
- 5 T solenoid in interaction region
- Novel target needed for standard config



Creating a New Target for CLAS12

Double-Cell Cryo Target

- Polarize at 300 K
- Transfer to 5 K target cell
- Density increase 60×

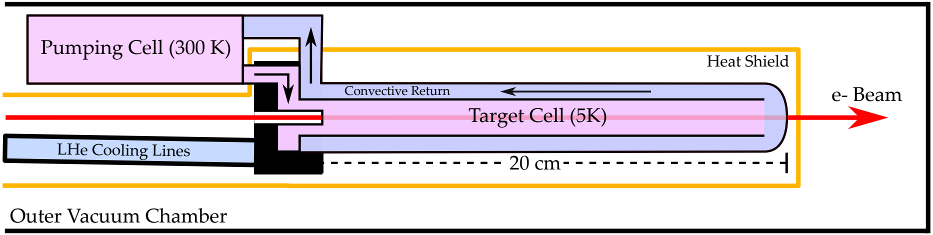
+

High Field MEOP

- High Polarization (∼60%)
- High magnetic fields (5 T)
- Pressure increase 100×

- By combining established technologies: a new polarized target (Maxwell, Milner, NIM A, 2021.)
- Achieve 5.4 amg, roughly half JLab SEOP target gas density
- Polarize within 5 T solenoid: CLAS12 standard configuration
- Talks on Thursday, 11:00 (Pandey, Lu)

Proposed Target



293 K Pumping Cell

- 200 cm^3 borosilicate glass
- MEOP to 60% polarization
- Annular cylindrical volume

5 K Target Cell

- 100 cm^3, 20 cm long aluminum cell
- Cooled by LHe heat exchanger
- Luminosity of 2.7×10^{34} nuc/cm^2/s at 0.5 μA

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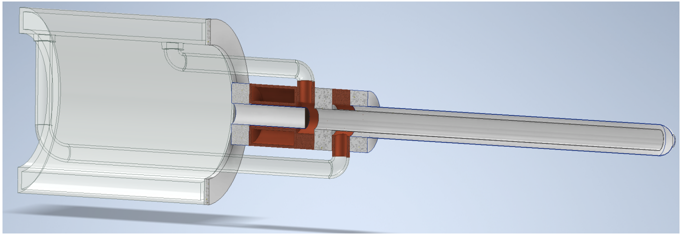

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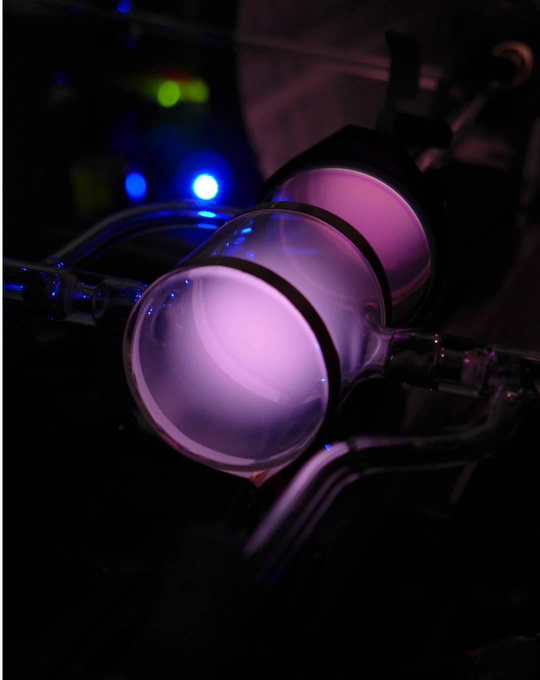
Overview

- Polarized gas targets are crucial tools for spin physics, and important counterparts to polarized solid targets
- Development furthers technologies with wide and increasing use in other fields
- For further reading, excellent review articles:
  - Steffens, Haeberli. Rep. Prog. Phys. **66** (2003)
  - Gentile, Nacher, Saam, Walker. Rev. Mod. Phys. **89** (2017)

Special thanks to those whose papers and slides I’ve mined to make this talk, including:

- Steffens, Haeberli, Cates, Tadepalli, Jackson, Henry, Gentile, Nacher, Milner

Thank you for your attention!



Metastability Exchange and Spin Exchange Optical Pumping

SEOP

- Pump: alkali metals in mixture
- Transfer: spin exchange
- Low pumping rate
- Walls carefully selected
- Needs oven (473 K)
- 100 W laser typical
- **Large pressure range (1 to 13 bar)**

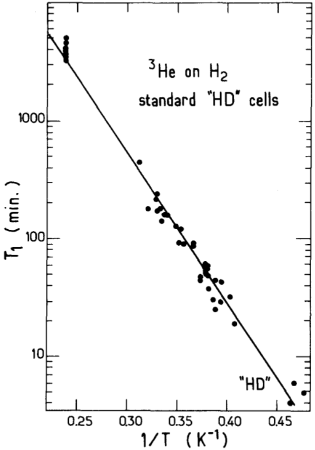
MEOP

- Pump: metastable population
- Transfer: metastability exchange
- High pumping rate
- Less sensitive to wall interactions
- Temperature above 100 K
- 4 W laser typical
- **Limited pressure ($\sim$1 mbar)**

- MEOP pumping rate starts 9 orders faster, minus 4 for higher alkali density, and minus 4 for lower pressure $\Rightarrow$ MEOP about 1 order of magnitude faster

Depolarization Mechanisms

- Wall relaxation on Al: H_2 coatings yield days long relaxation at 4 K (Lefevre-Seguin, Low Temp. P. 1988.)
- Depolarization from transverse magnetic field gradients, dependent on pressure, temperature
- Beam produces $^3He_2^+$ ions: increase with density, but decrease with higher field. (Bonin, PRA, 1988)



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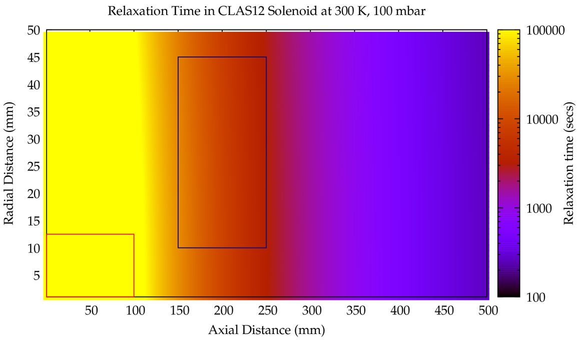

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