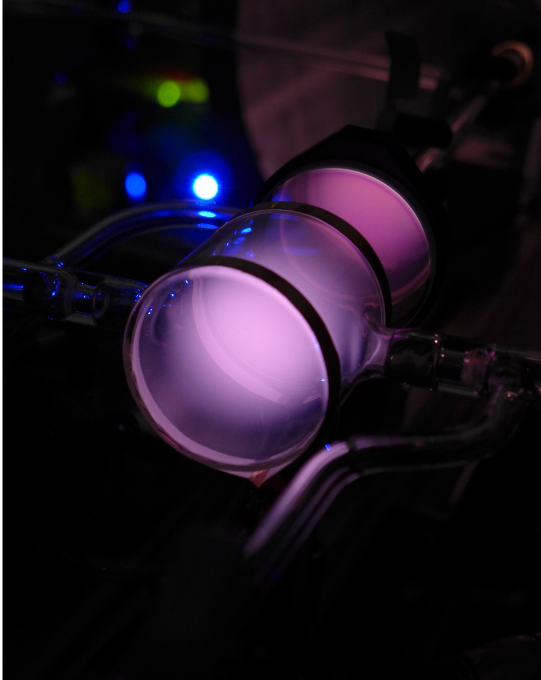
Polarized ^{3}He for Spin Structure Measurements

J. Maxwell

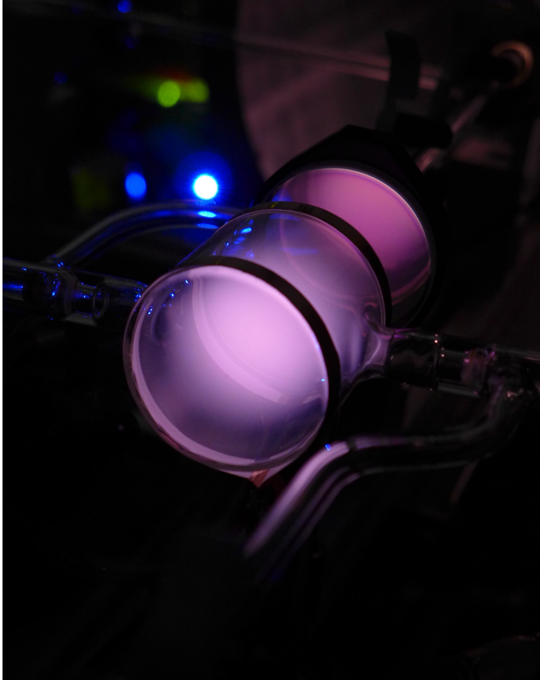
Jefferson Lab
TARGET Group

Exploring QCD with Light Nuclei at EIC
January 21st, 2020



Outline

1. ^{3}He Polarization
   - Optical Pumping Techniques
2. Polarized ^{3}He in Spin Physics
   - Previous Measurements
   - Polarized ^{3}He at JLab 12 GeV
3. New Prospects
   - Polarized ^{3}He for the EIC
   - A High-Field Polarized ^{3}He Target
4. Slight tangent: Nuclear Gluonometry



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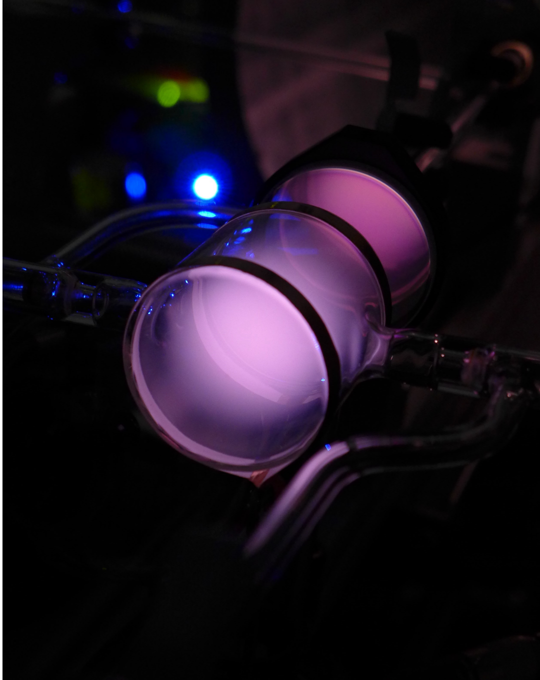
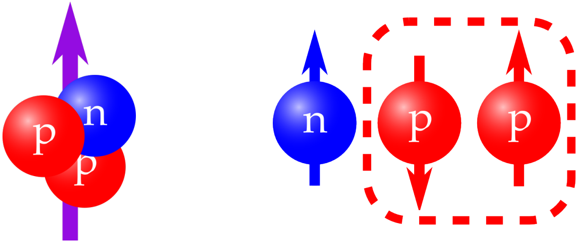


Why Polarized Helium 3?

- Polarized scattering experiments crucial for study of neutron spin structure
    - How do we make polarized neutron targets and beam sources?

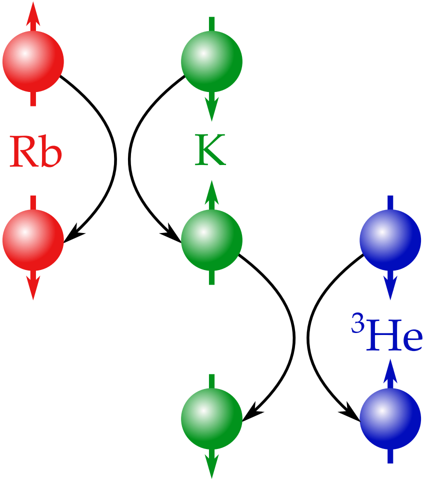


State	Probability
S	88.6%
S’	1.5%
D	8.4%

- 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

Spin Exchange Optical Pumping

- Pump Rb in ∼30 G holding field
  - 795 nm laser light: $5S_{1/2} \rightarrow 5P_{1/2}$
- Spin exchange polarizes K, then ^{3}He
- Pressures 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**
- Wall depolarization ⇒ glass cells
- Improvements: Rb/K hybrid alkali cell, narrow band lasers



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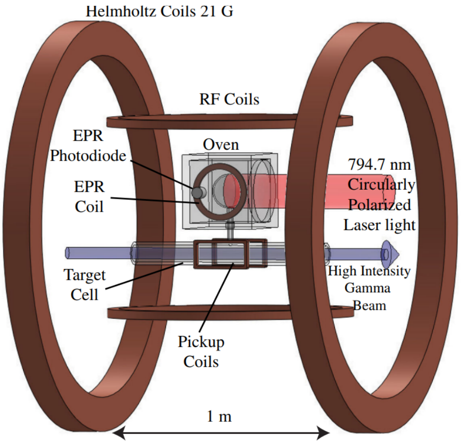

Gentile *et al.* RMP, 2017.

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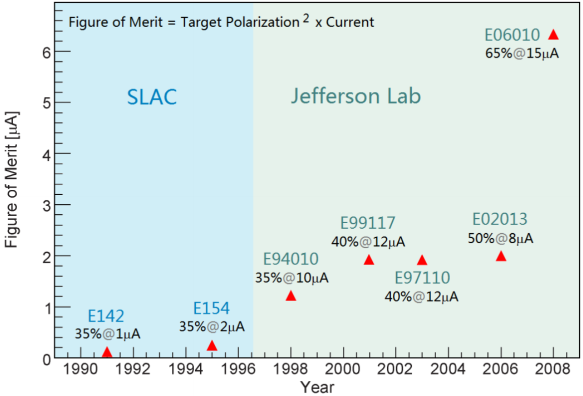
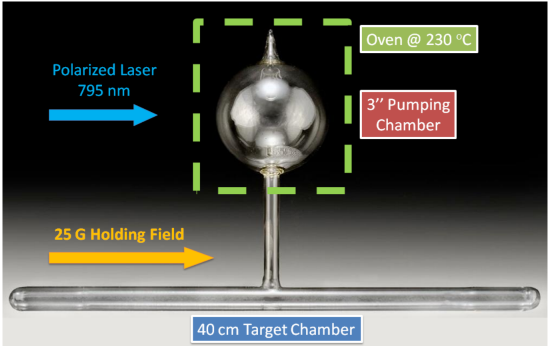


JLab 3He Group

SEOP Improvements

- Legacy cell
  - 10 atm, 40 cm long, 0.1 mm windows
  - 15 μA beam for 10^{36} cm^{-2}s^{-1}
- Stage I cell (currently taking beam)
  - 10 atm, 40 cm long, 0.1 mm windows
  - 30 μA beam for 2.2×10^{36} cm^{-2}s^{-1}
  - Convection reduces polarization gradient
- Stage II cell (under development)
  - 10 atm, 60 cm long, metal foil windows
  - 60 μA beam for 6.6×10^{36} cm^{-2}s^{-1} dfc
- Work by JLab 3He group, UVa, W&M, Kentucky, Temple



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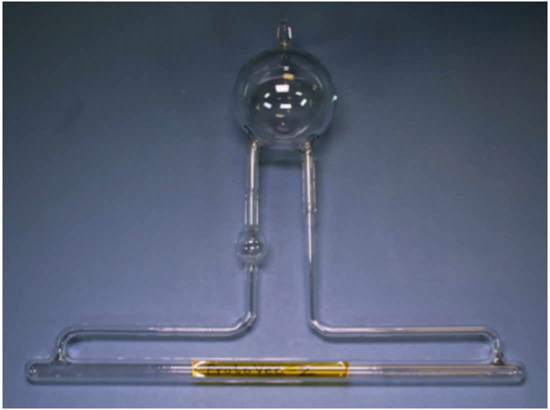

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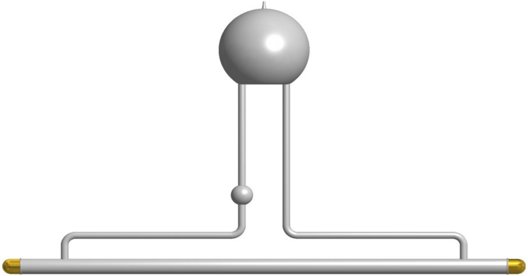

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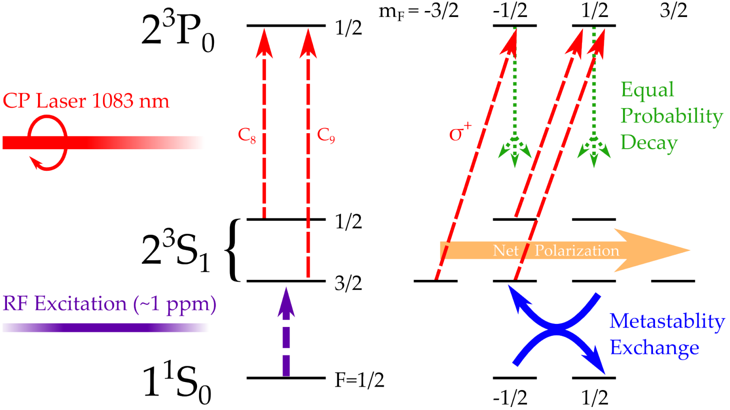
Metastability Exchange Optical Pumping

- 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, >100 K
- Effectively 10^5 faster pump rate (but 10^4 lower pressure)



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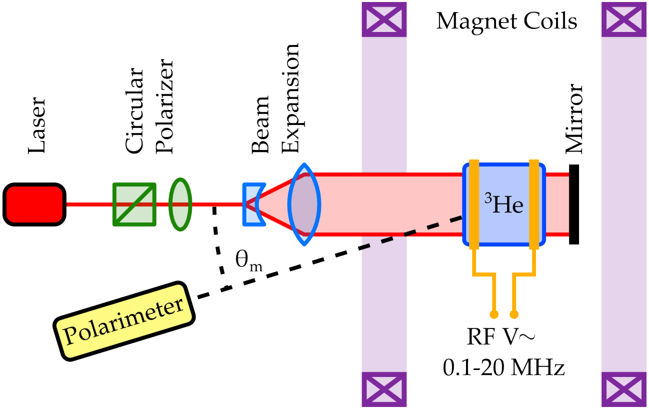
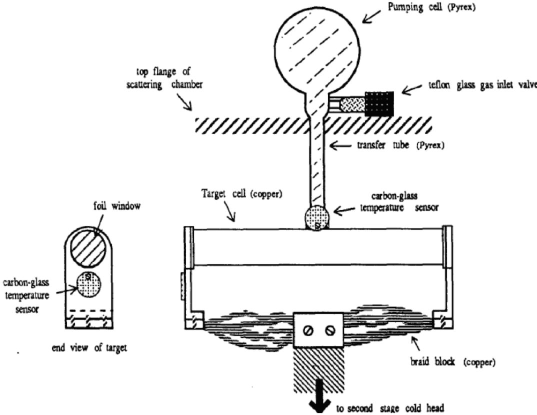


MEOP Double-Cell Cryo Target: Bates 88-02

- Quasi-elastic asymmetries in 1988, 1993
- MEOP pumping cell at 2 mbar, 300 K
- 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
- P measurement performed in pumping cell
- P in target inferred from rate equations: P relaxation and diffusion



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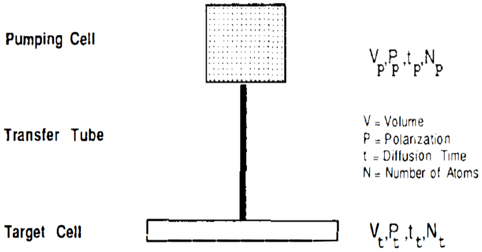

V = Volume
P = Polarization
t = Diffusion Time
N = Number of Atoms

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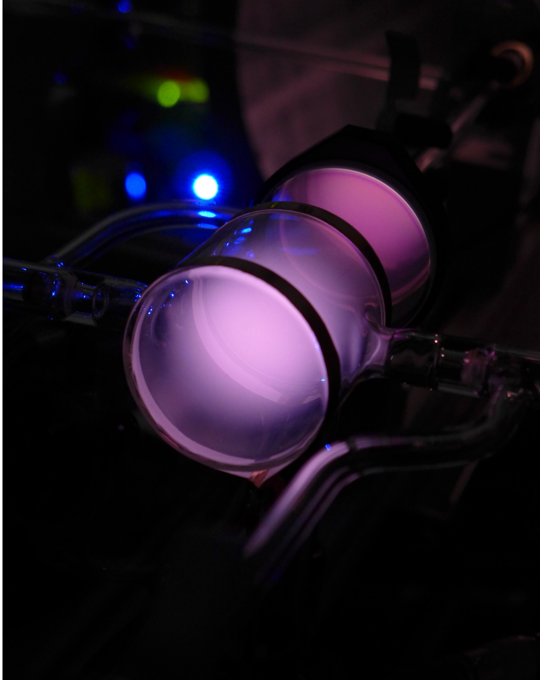


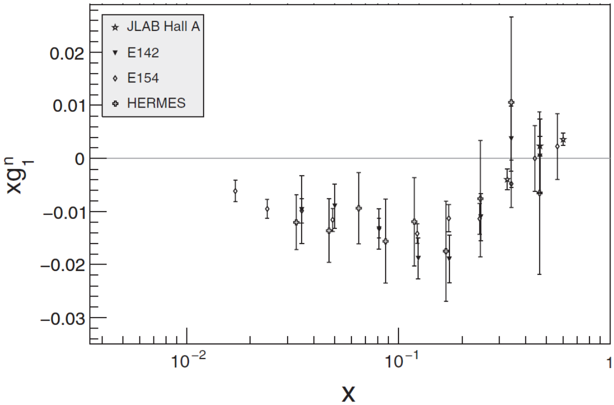
JLab 6 GeV Polarized ^{3}He: 13 Experiments with SEOP in Hall A

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
- Quasi-elastic A_x, A_z



Aidala, 2013

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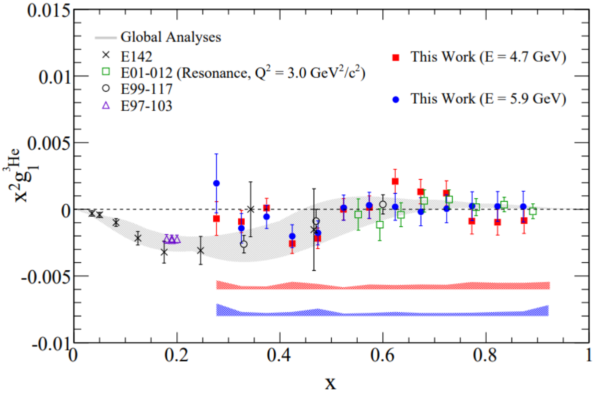

Flay, 2016

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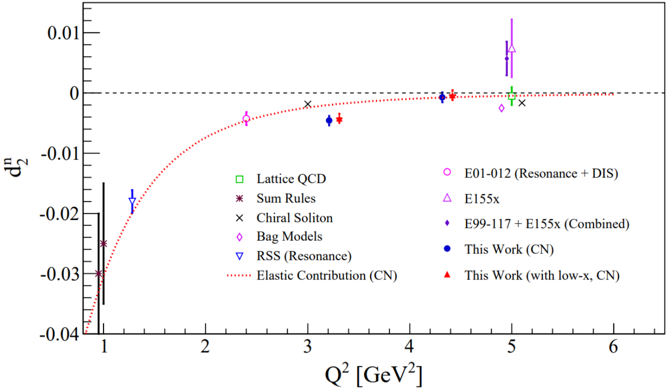

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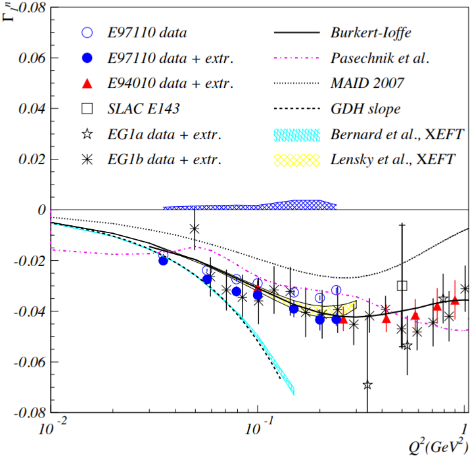

Sulkosky, 2019

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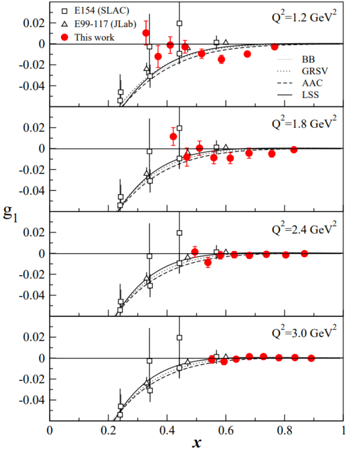

Solvignon, 2008

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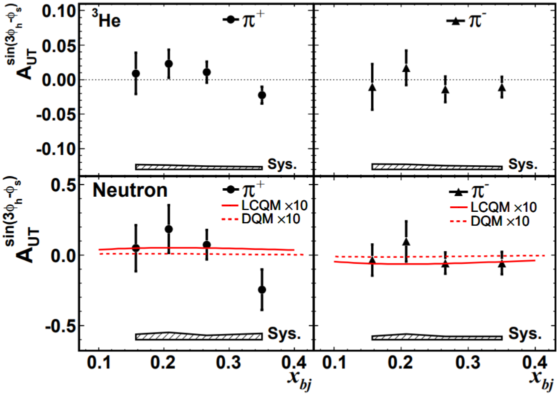

Zhang, 2013

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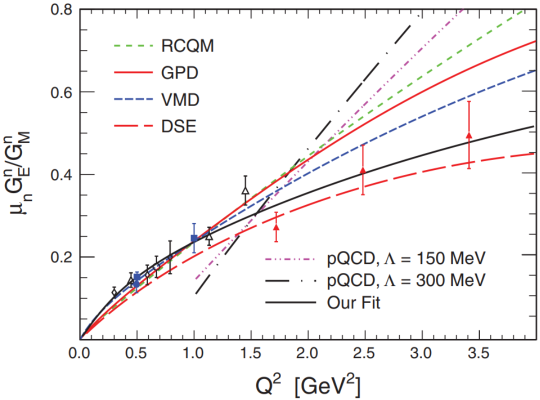

Riordan, 2010

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

Spin Structure in Hall C

- Experiments running now!
- E12-06-110: A_1^n
- E12-06-121: g_2^n, d_2^n

SuperBigBite

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

SoLID SIDIS TMDs

- E12-10-006: Transverse 3He
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Hall C Logbook

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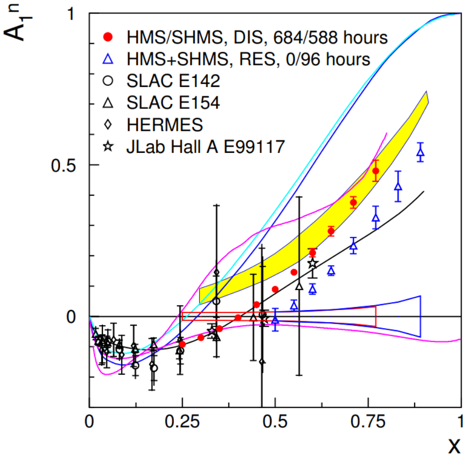

E12-06-110

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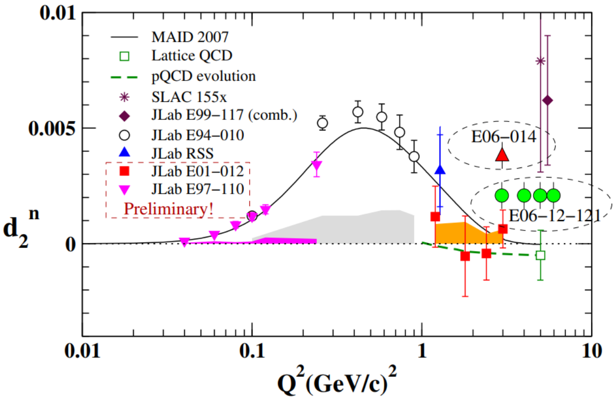

E12-06-122

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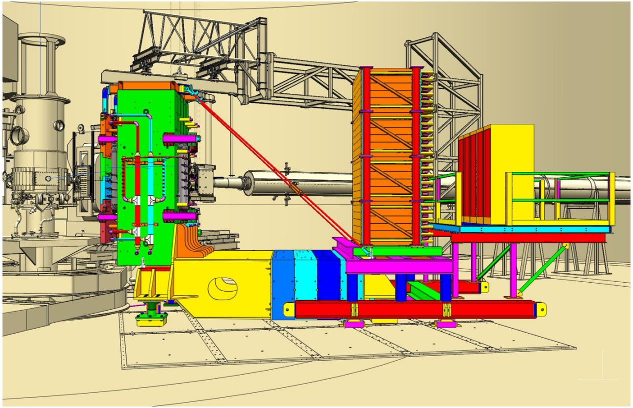

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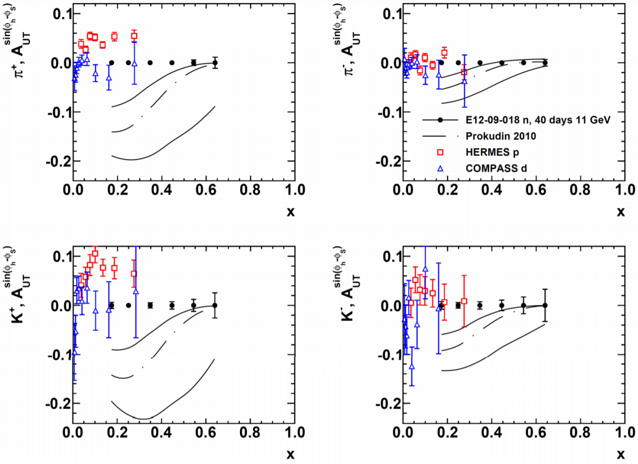

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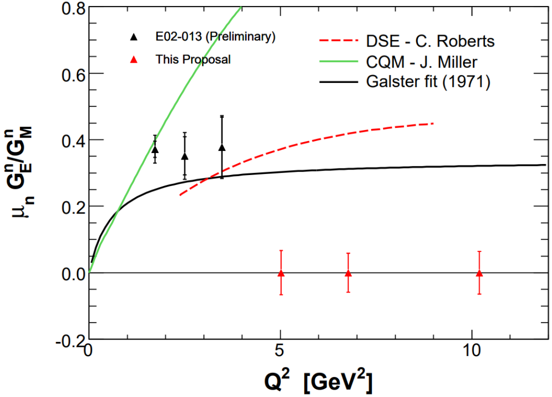

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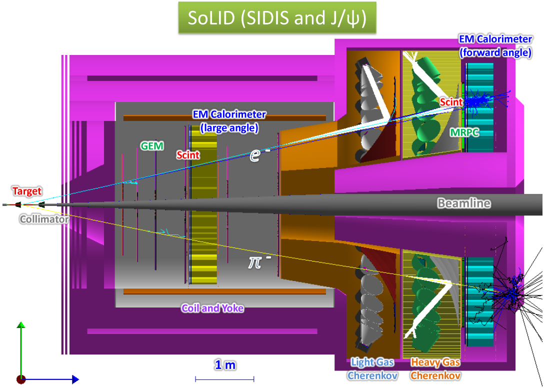

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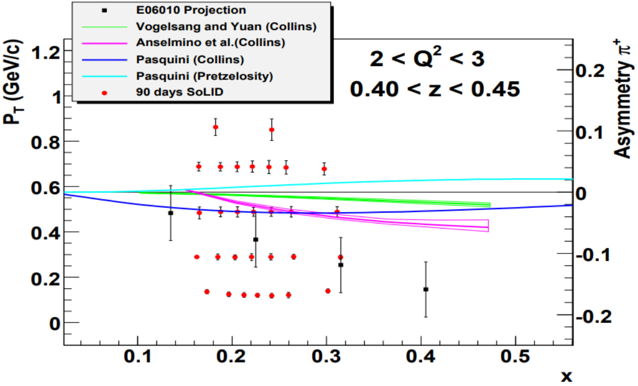

E12-10-006

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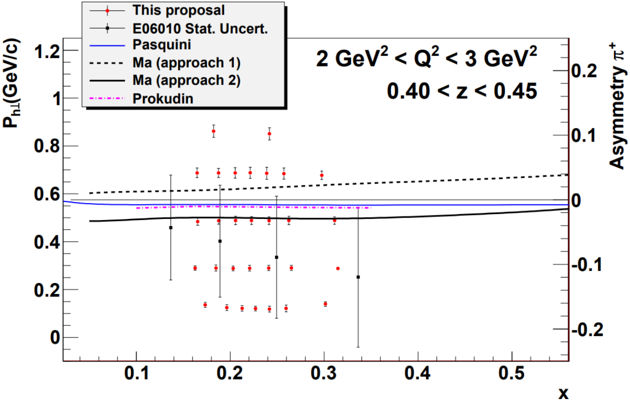

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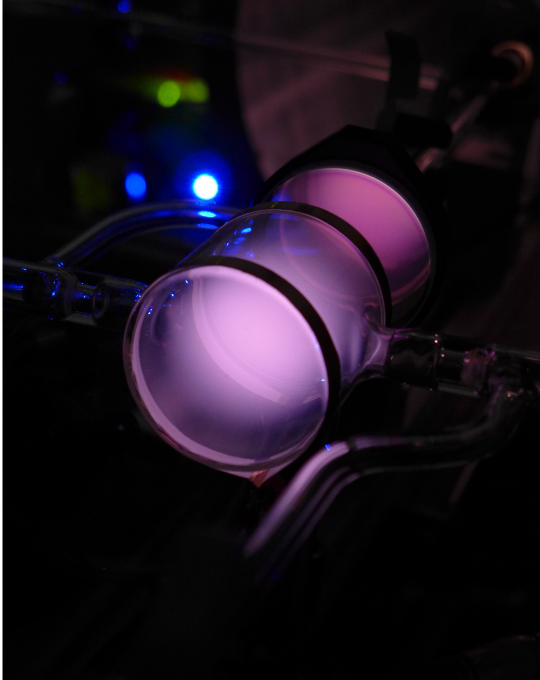

Metastability Exchange and Spin Exchange Optical Pumping

MEOP

- Pure ^{3}He with RF discharge
- High pumping rate
- Less sensitive to wall interactions
- Temperature above 100 K
- 4 W laser typical
- **Limited pressure ($\sim$1 mbar)**

SEOP

- Mixture of Alkali metals with ^{3}He
- Low pumping rate
- Walls carefully selected
- Needs oven (200°C)
- 100 W laser typical
- **Large pressure range (1 to 13 bar)**

- Pressure attainable without pumps has made SEOP the most attractive tool for high luminosity scattering applications

High Magnetic Field MEOP

- Weak hyperfine coupling ⇒ ineffective MEOP?
- Until Courtade *et al* (2000)
- Kastler-Brossel Lab at ENS in Paris found by increasing B_0, MEOP effective at higher pressures!
- ME rates are lower, BUT:
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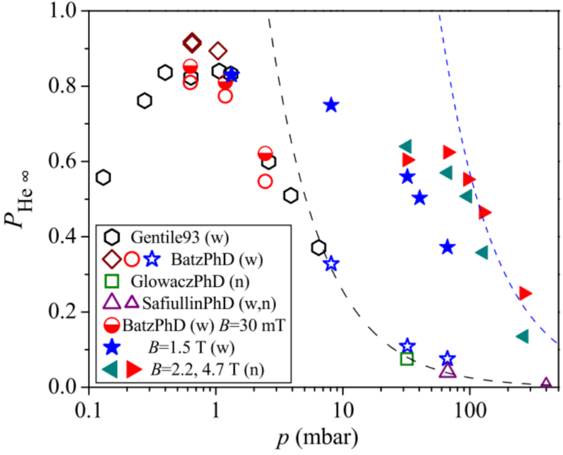

From Gentile, Nacher, Saam, Walker (2017)

High Magnetic Field MEOP

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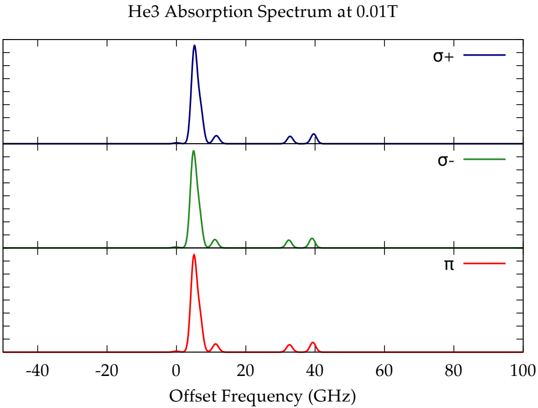

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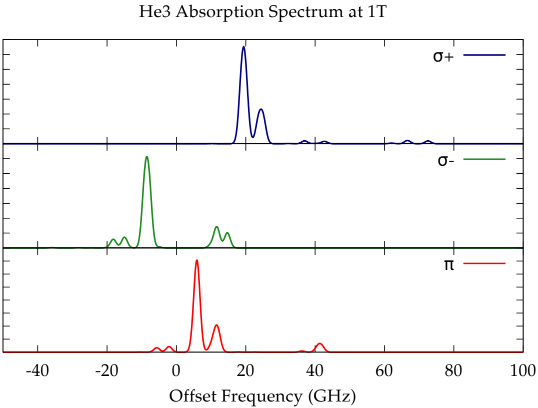
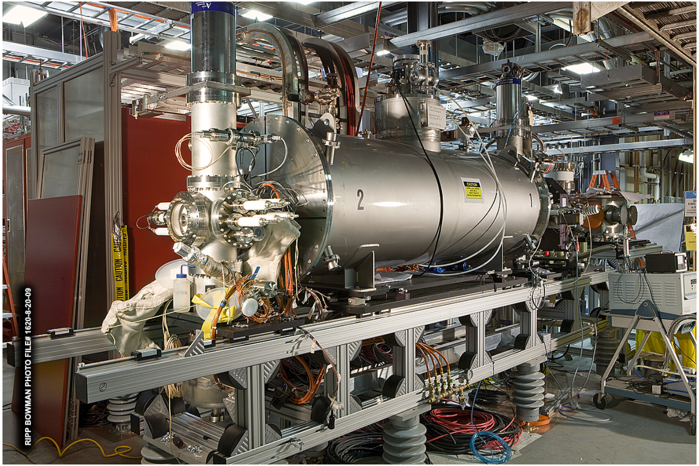


RHIC's Electron Beam Ion Source

- 5 T Solenoid B Field; 1.5 m Ion Trap
- 20 keV electrons up to 10 A, 575 A/cm^2 Current Density
- **Any** species, switch between species in 1 sec
- Very busy with RHIC runs (Au^{32+}), NASA Rad Lab
- Produce ^{3}He^{++} at nearly 100%



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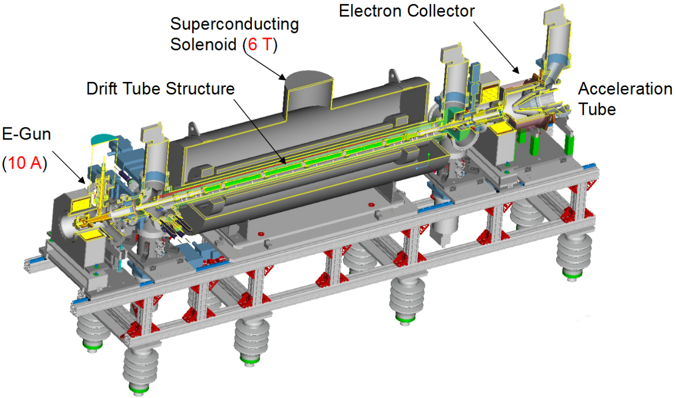

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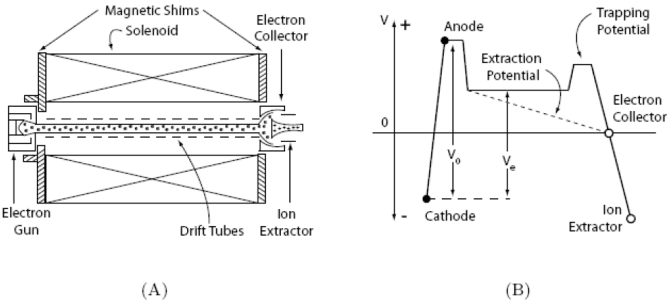
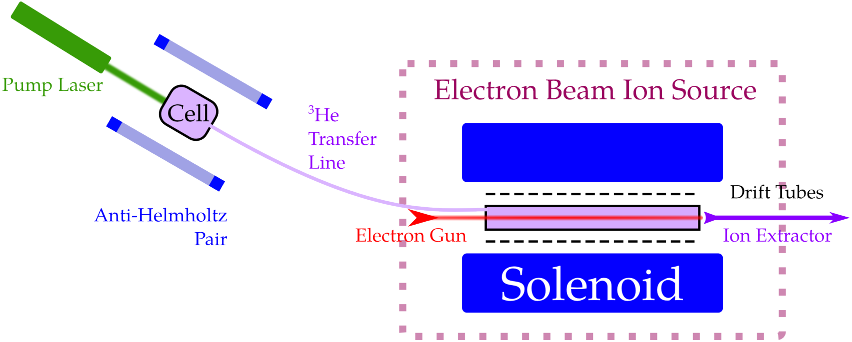


Figure 4. (A) A schematic of the EBIS course. (B) The electric potential along the axis of the source.

Polarized ^{3}He Ion Source

- MEOP inside magnetic shield (30 G), polarize to ∼70% at 1 torr with 10 W laser
- Transfer $\sim 10^{14}$ ^{3}He/s through stray field into EBIS at 5 T & 10^{-7} torr
- Deliver 1.5×10^{11} $^3\text{He}^{++}$ ions per 20 μsec pulse



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- Plot vs "relaxation time," largely dependent on discharge insensity
- Saw great success in steady state polarization >80%
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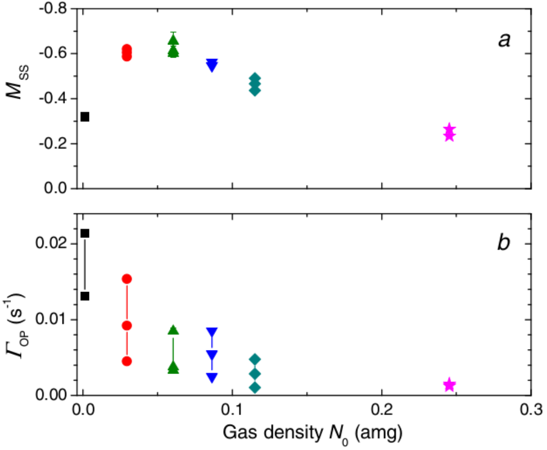

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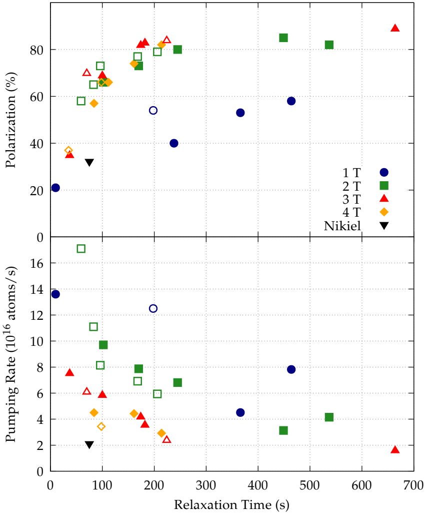
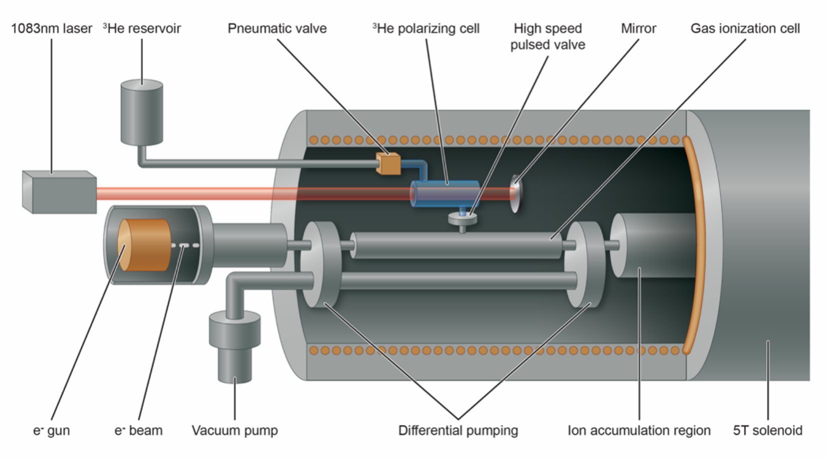


Polarized ^{3}He Source via High Field MEOP



Polarized ^{3}He Source via High Field MEOP

Polarized ^{3}He Ion Source Outlook

- Demonstrated >80% polarization above 4 T, allowing polarization **within** EBIS
- This prompted a design change, which accelerated plan to **extend** EBIS
- Other benefits of revamped system. Extended trap allow 40% more Au intensity: easy sell.
- Extended EBIS to be installed summer of 2020, first tests of ^{3}He injection
- Polarization measurement of extracted beam at 6 MeV in 2021
- See slides from 2019 PSTP Workshop, Knoxville by Musgrave, Atoian
- **^{3}He Source Collaboration**: G. Atoian , E. Beebe, S. Ikeda, S. Kondrashev , J. Maxwell, R. Milner, M. Musgrave, M. Okamura, A. Poblaguev , D. Raparia, J. Ritter, S. Trabocchi , A. Zelenski

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Opportunities with Polarized ^{3}He in CLAS12

- CLAS12 a crucial tool for nuclear physics, designed to observe complete response for nuclei inelastic, resonance, quasi-elastic and deep-inelastic
  - Large acceptance
  - Excellent particle ID ($e/p/\pi/K/\gamma, ...$)
  - Neutron detection and tagged particle detection
- Even considering existing plans for the 12 GeV era, a polarized ^{3}He target in CLAS12 would offer unexplored observables, complementary measurements with different systematics
  - Multi-hadron SIDIS
  - P_T, k_T dependence for TMDs
  - Overlap of JLab 12 GeV and EIC crucial in the valence region
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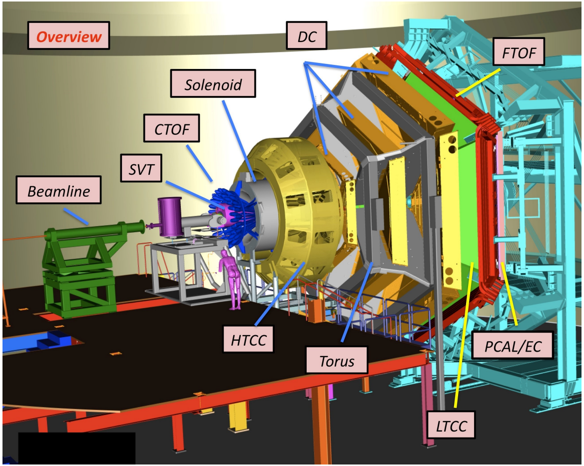
CLAS12 Target Constraints

- Getting a conventional polarized ^{3}He target in CLAS12 is tricky:
    - Remove solenoid, OR
    - Put target upstream of solenoid, OR
    - Transfer polarized gas into solenoid
- To operate in the standard configuration:
    - Fit inside solenoid (10 cm diameter space to work with)
    - Operate at 5 T



The Idea

Double-Cell Cryo Target

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

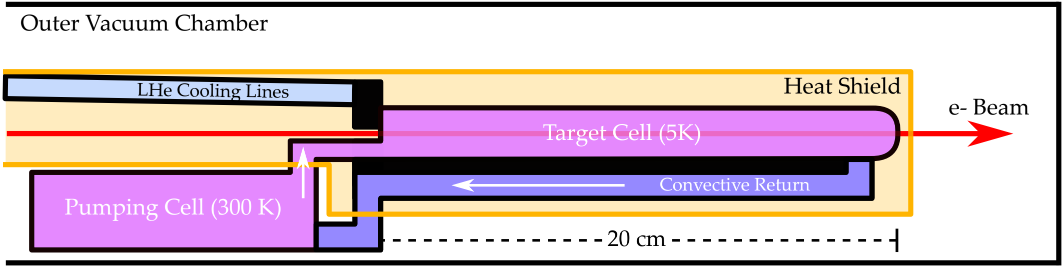
\+

High Field MEOP

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

- MEOP at 1 mbar offers 10,000× less density than SEOP at 10 bar
- This scheme increases MEOP density by 6,000×
- Reaches CLAS12 max luminosity with 4.5×10^{34} ^{3}He/cm^2/s at 2.5 μA

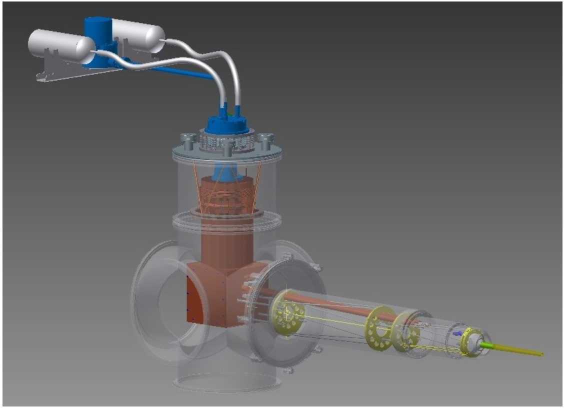
Proposed Target



- Cell volumes: 100 cm^3, Cell pressure: 100 mbar, Polarization: 60%
- Beam Current: 2.5 μA, Luminosity: 4.5×10^{34} ^{3}He/cm^2/s at 2.5 μA
- Must fit in tight space constraint of CLAS12 ($\sim$10 cm)

Path to CLAS12 Polarized ^{3}He

- Cryogenics: Pulse Tube for 2 W at 4.2 K
- Heat load looks to be less than 500 mW
- Al cells, 200μm windows
- Coating of H_2 prevents wall depolarization below 6 K
- Field depolarization no problem
- Beam depolarization should be studied: balance with flow between cells with convection
- Heat load tests coming soon, prototype construction as soon as I find money



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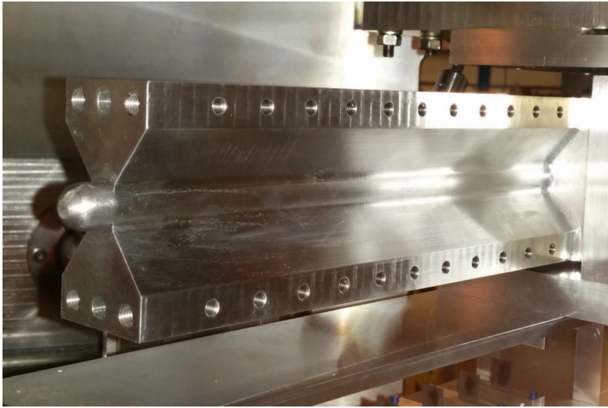

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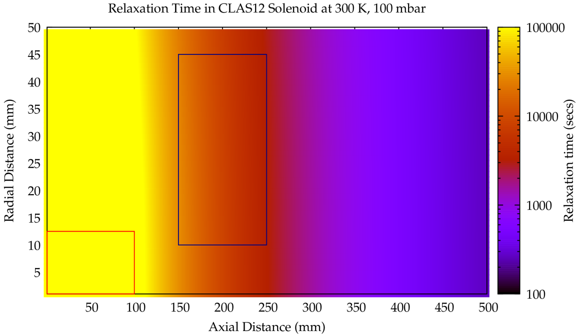

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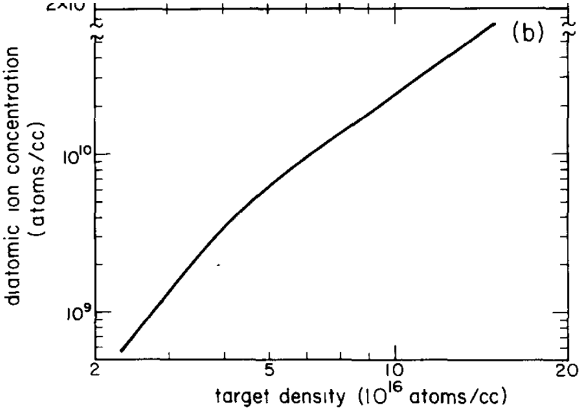

Milner (1987)

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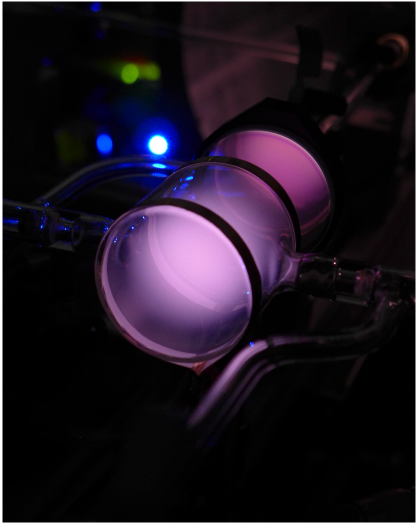
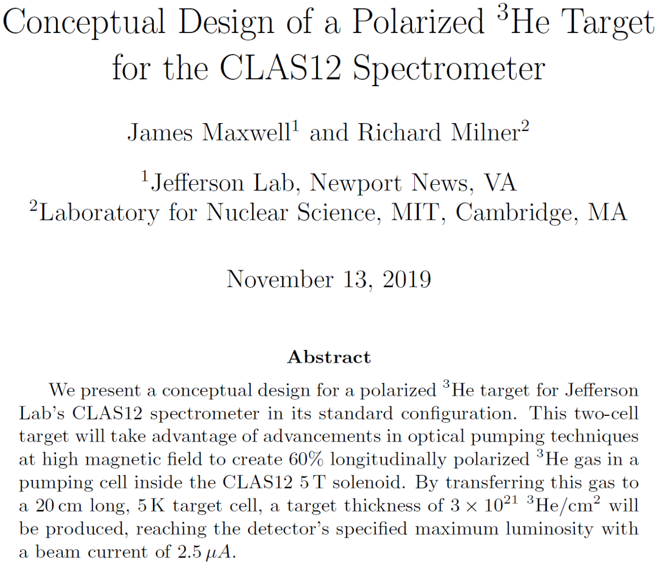


Transverse Polarized ^{3}He in CLAS12?

- Transverse target offers tantalizing physics opportunities
- Very tricky in a longitudinal 5 T solenoid
- HD-Ice has a plan involving bulk superconductor to cancel 5 T and create a transverse holding field
- Scheme could involve bulk superconductor to block field and create 30 G holding field
- Rotate spin adiabatically in transit to target cell
- Warrants exploration with tempered expectations

A High-Field Polarized ^{3}He Target

- Conceptual design report on arXiv:1911.06650
- Idea shown at CLAS collaboration meeting in November
- First meeting of study group on Dec 17th, 13 attended
- Volunteers to begin simulations on SIDIS, DVCS, Inclusive DIS
- Workshop for physics case at CLAS meeting in March



Conceptual Design of a Polarized ^{3}He Target for the CLAS12 Spectrometer

James Maxwell[1] and Richard Milner[2]

[1]Jefferson Lab, Newport News, VA
[2]Laboratory for Nuclear Science, MIT, Cambridge, MA

November 13, 2019

Abstract

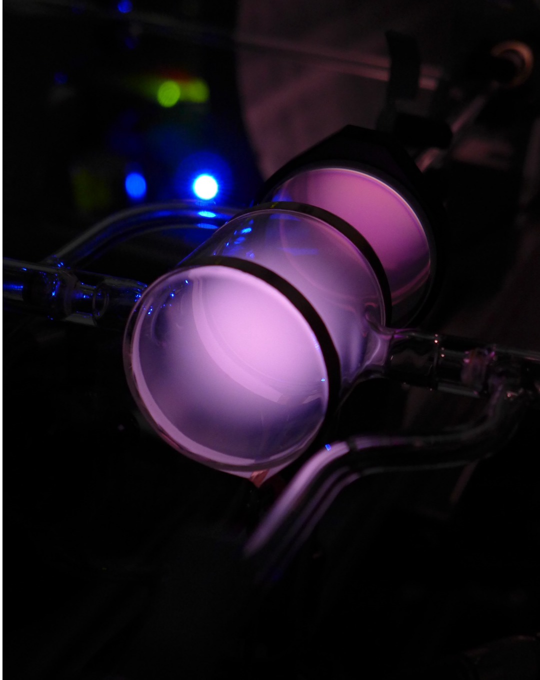
We present a conceptual design for a polarized ^{3}He target for Jefferson Lab's CLAS12 spectrometer in its standard configuration. This two-cell target will take advantage of advancements in optical pumping techniques at high magnetic field to create 60% longitudinally polarized ^{3}He gas in a pumping cell inside the CLAS12 5 T solenoid. By transferring this gas to a 20 cm long, 5 K target cell, a target thickness of 3×10^{21} ^{3}He/cm^2 will be produced, reaching the detector's specified maximum luminosity with a beam current of 2.5 μA.

Physics from Polarized ^{3}He in Hall B

- Inclusive DIS: $g_1^n(x, Q^2)$, Bjorken sum rule
- **Tagged** Inclusive DIS: spin-dependent EMC effect
- SIDIS: flavor decomposition, Δu, Δd, Δs
- TMDs, exploration in P_T, k_T
- DVCS: Neutron GPDs
- Quasielastic nucleon knockout: ground state spin-isospin structure, high-momentum correlated pairs
- $(e, e'\pi^{\pm})$: Search for pre-existing Δs
- **Suggestions and collaborators are welcome!**

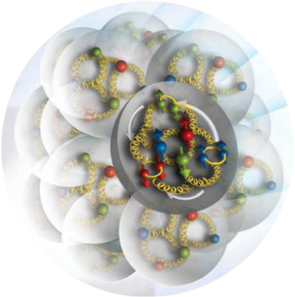
Outline

1. ^{3}He Polarization
   - Optical Pumping Techniques
2. Polarized ^{3}He in Spin Physics
   - Previous Measurements
   - Polarized ^{3}He at JLab 12 GeV
3. New Prospects
   - Polarized ^{3}He for the EIC
   - A High-Field Polarized ^{3}He Target
4. **Slight tangent: Nuclear Gluonometry**



Gluon Structure of Nuclei

- Understanding glue is a key challenge of NP and central goal of EIC



Studying gluons is tricky

- Gluon does not couple to photon
- Probed indirectly by electron scattering from nuclei

- A nuclear glue effect, free from contributions of any nucleon, could offer invaluable view of nuclear structure
- "Nuclear Gluonometry" (Jaffe, Manohar, 1989) offers a probe sensitive **only** to gluonic states in the nucleus: $\Delta(x, Q^2)$

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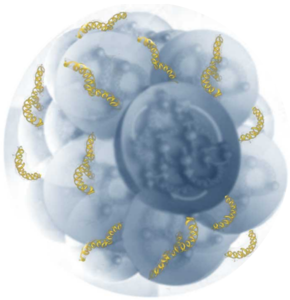

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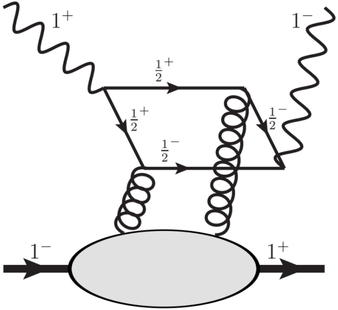
Double Helicity-Flip Structure Function $\Delta(x, Q^2)$

- $\Delta(x, Q^2) \Rightarrow$ helicity amplitude $A_{+-,-+}$
  - Photon helicity flip of two
  - Unavailable to bound nucleons or pions
  - Purely gluonic observable
- Hadrons: Gluonic Transversity
- Nuclei: Exotic Glue
  - Gluons not associated with a nucleon
- Unpolarized e beam on transversely polarized nuclei, spin ≥ 1



- Lattice QCD signal seen in non-physical d: NPLQCD Collab, P.Rev.D 96, 2017
- JLab Letter of Intent 12-16-006: Transversely polarized ^{14}N target
- Very interesting for EIC; need light ions! d, ^{6}Li, ^{7}Li, ^{23}Na?

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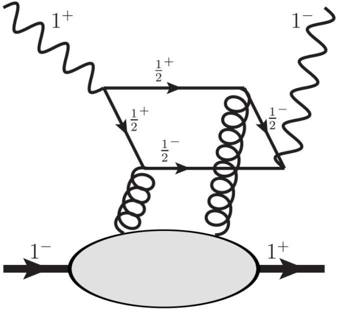

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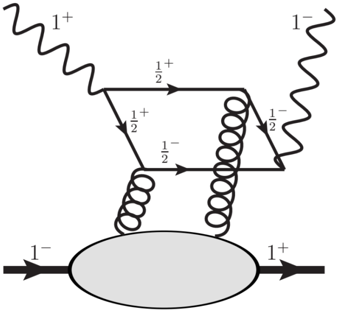

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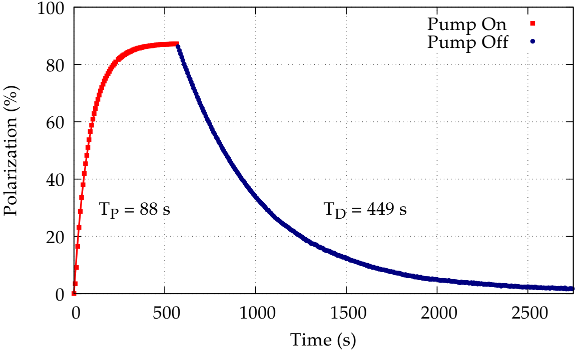
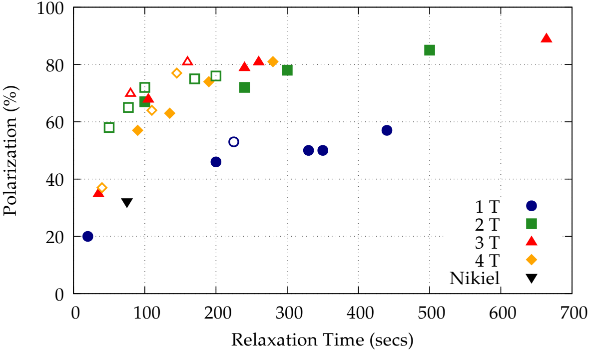
Thanks to BNL-MIT ^{3}He Collaboration, JLab ^{3}He Group (JP Chen), H. Avakian, Nuclear Gluonometry Collaboration

Thank you for your attention!

Parameter	Bates 88-02 Target Achieved	CLAS12 Target Proposed
Pumping cell pressure (mbar)	2.6	100
Pumping cell volume (cm^3)	200	120
Target cell volume (cm^3)	79	100
Target cell length (cm)	16	20
Number of atoms in pumping cell	1.2×10^{19}	3×10^{20}
Number of atoms in target cell	6×10^{19}	1.5×10^{22}
Holding field (T)	0.003	5
Polarization	40%	60%
Incident electron beam energy (GeV)	0.574	10
Cell temperature (K)	17	5
Target thickness ($^3He/cm^2$)	1.2×10^{19}	3×10^{21}
Beam current (μA)	10	2.5
Luminosity ($^3He/cm^2/s$)	7.2×10^{32}	4.5×10^{34}

High Field MEOP at 1 mbar





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- Initial calculations for first moment of Δ on spin-1 ϕ $(s\bar{s})$
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  - Gave definitive signal[1]
- Following year, first moment of Δ calculated on non-physical d
  - $m_\pi = 806$ MeV
  - Again definitive signal was seen[2]
- Results have generated significant interest in an observable mostly ignored since 1989
- Calculation with physical d underway

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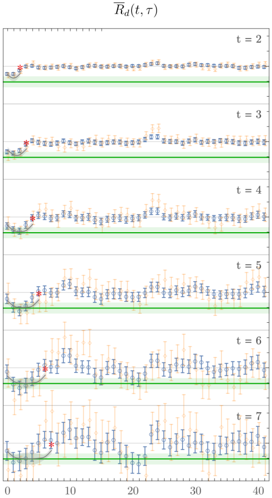

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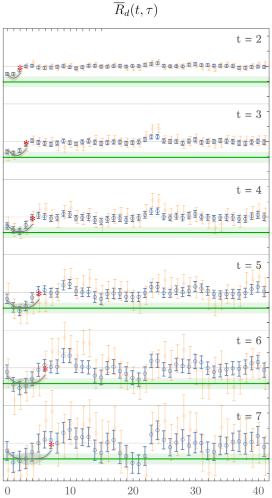

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