Spin-Dependent e-^{3}He Polarized DIS Measurements with EIC

Acknowledge discussions with T.W. Donnelly, W. Fischer, R. Jaffe, R. Wiringa

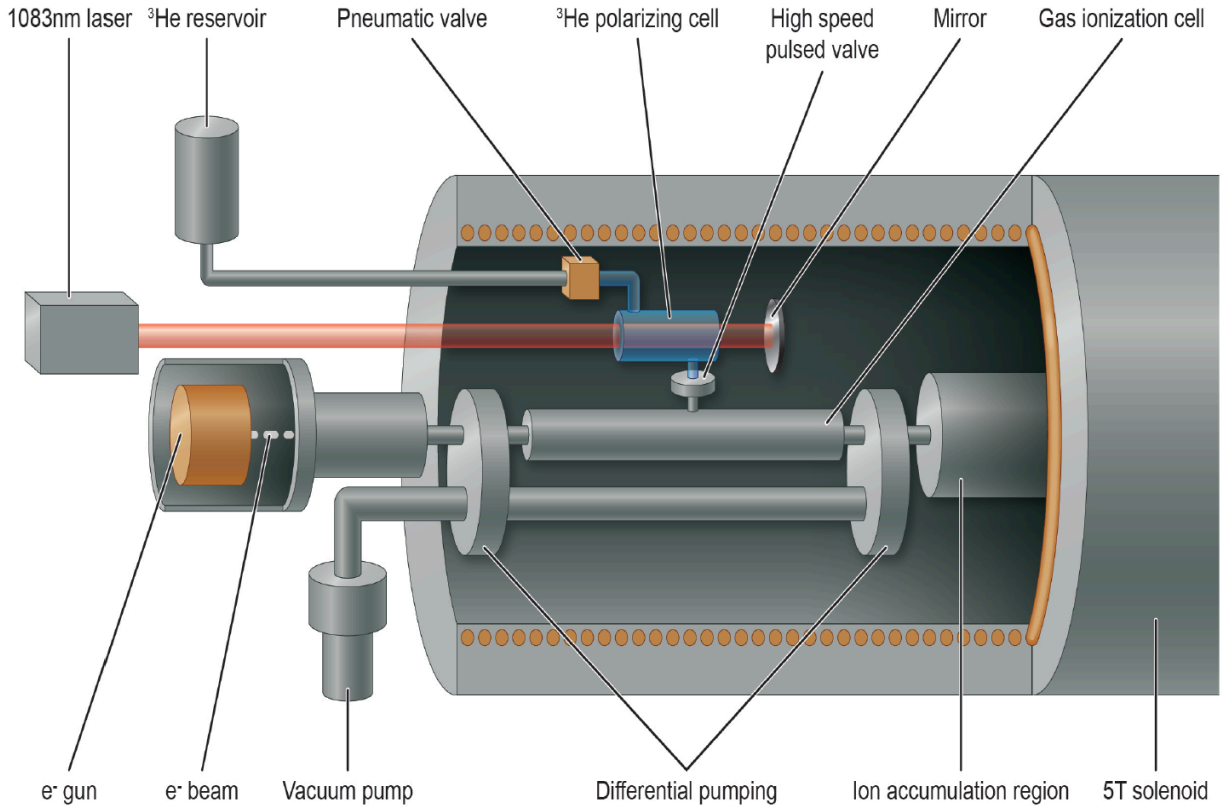


FIG. 5. Schematic layout of polarized ^{3}He ion source under development by a BNL-MIT collaboration using optically pumped polarized ^{3}He atoms directed into the existing Electron Beam Ionization Source.

Polarized ^{3}He expected in RHIC in the early 2020s

Two 5 T Solenoids for Extended EBIS

Polarized ^{3}He ions in RHIC anticipated in early 2020s

Arrived at BNL March 2018

Polarized ^{3}He Ions in RHIC

$$L = \frac{N_p N_{He3} f_{rev} N_c}{2\pi \sqrt{\sigma_{p,x}^2 + \sigma_{He3,x}^2}\sqrt{\sigma_{p,y}^2 + \sigma_{He3,y}^2}} \ .$$

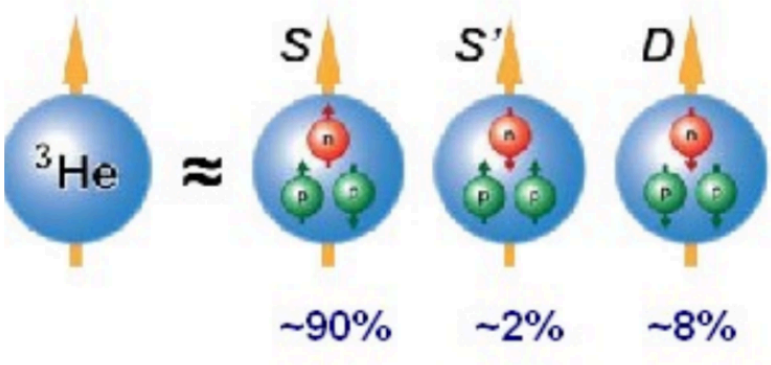
TABLE I. Comparison of $e-p$ vs. $e-^3$He luminosity, maximum center-of-mass energies and minimum x in eRHIC with 20 GeV electrons.

Parameter	Unit	$e-$p	$e-^3$He
Luminosity	$\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	2.5×10^{32}	1.3×10^{32}
Max. Ion Energy	GeV	250	166
$\sqrt{s_{max}}$	GeV	140	115
x_{min}		5×10^{-5}	7.6×10^{-5}

Neutron Spin Structure Function

$g_1^n(x,Q^2)$

Rest frame of the ^{3}He nucleus



Neutron polarization: 87%

Proton polarization: 2.7%

- With successful realization of 70% polarized ^{3}He ion beam in EIC, precision measurement of $g_1^n(x,Q^2)$ should be a goal with a day-1 detector
- Aim should be to test Bjorken Sum Rule with unprecedented precision
- Will require technical development of Siberian Snakes and high energy ^{3}He polarimeter in RHIC
- ***In spin-dependent DIS if one tagged the spectator proton and deuteron, could one access the spin structure functions of the deuteron and proton, respectively?***

RHIC momenta

TABLE II. Magnetic rigidity of incident ^{3}He and final-state spectator ^{2}H and ^{1}H in DIS from polarized ^{3}He at highest energy available in eRHIC with 20 GeV electrons.

Nucleus	Momentum GeV/c	Charge e	Magnetic Rigidity (p/q) GV/c
^{3}He	498	+2	249
^{2}H	332	+1	332
^{1}H	166	+1	166

$$|^3\mathrm{He}\uparrow> = (n\uparrow)\left[(p\uparrow p\downarrow) - (p\downarrow p\uparrow)\right]$$
$$= (n\uparrow p\uparrow)_{(J=1,M=1)}(p\downarrow) - (n\uparrow p\downarrow)_{(\quad ,M=0)}(p\uparrow)\ .$$

For the np system, we have $J = 1, 0$ with

$$|1,1> = (n\uparrow p\uparrow)$$
$$|1,0> = \frac{1}{\sqrt{2}}\left[(n\uparrow p\downarrow + n\downarrow p\uparrow\right]$$
$$|1,-1> = (n\downarrow p\downarrow)$$
$$|0,0> = \frac{1}{\sqrt{2}}\left[(n\uparrow p\downarrow - n\downarrow p\uparrow)\right]\ .$$

We can then write

$$(n\uparrow p\downarrow)_{(J=1,M=0)} = \frac{1}{\sqrt{2}}\left[|1,0> + |0,0>\right]$$
$$(n\downarrow p\uparrow)_{(J=0,M=0)} = \frac{1}{\sqrt{2}}\left[|1,0> - |0,0>\right] \ ,$$

which allows us to express the ^{3}He $\uparrow$ spin- state as

$$|^3\mathrm{He}\uparrow> = |1,1>(p\downarrow) - \frac{1}{\sqrt{2}}\left[|1,0> + |0,0>\right](p\uparrow) \ .$$

When normalized, this becomes

$$|^3\mathrm{He}\uparrow> = \frac{1}{\sqrt{2}}|1,1>(p\downarrow) - \frac{1}{2}\left[|1,0> + |0,0>\right](p\uparrow) \ .$$

Similarly, it follows that

$$|^3\mathrm{He}\downarrow> = \frac{1}{\sqrt{2}}|1,-1>(p\uparrow) - \frac{1}{2}\left[|1,0> - |0,0>\right](p\downarrow) \ .$$

We can then write

$$(n\uparrow p\downarrow)_{(J=1,M=0)} = \frac{1}{\sqrt{2}}\left[|1,0> + |0,0>\right]$$
$$(n\downarrow p\uparrow)_{(J=0,M=0)} = \frac{1}{\sqrt{2}}\left[|1,0> - |0,0>\right] \ ,$$

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When normalized, this becomes

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Similarly, it follows that

$$|^3\mathrm{He}\downarrow> = \frac{1}{\sqrt{2}}|1,-1>(p\uparrow) - \frac{1}{2}\left[|1,0> - |0,0>\right](p\downarrow) \ .$$

- **Tagged deuteron:** Scattering from the $|0,0>$ state cannot contribute. Thus, measurement of $^3\overrightarrow{\mathrm{He}}(\overrightarrow{e}, e' d_{\mathrm{spectator}})$ in DIS kinematics is equivalent to scattering from a negatively polarized proton 66% of the time and 33% of the time from a positively polarized proton. This is equivalent to scattering from the polarized proton in ^{3}He with -33% polarization. This makes polarized ^{3}He an effective polarized proton target.

- **Tagged proton:** 50% of the time, the scattering arises from the $|1,1>$ state, 25% from the $|1,0>$ state and 25% from the $|0,0>$ state. In forming the spin-asymmetry A in the DIS process $^3\overrightarrow{\mathrm{He}}(\overrightarrow{e}, e' p_{\mathrm{spectator}})$ there will be a contribution from scattering from the deuteron A_{ed}, the contribution arising from the $|1,0>$ state will cancel and there will a correction arising from a contribution A_{corr} from scattering from the np pair in the $|0,0>$ state, i.e.

$$A \sim \frac{2}{3} A_{ed} + \frac{1}{3} A_{corr} \ . \tag{29}$$

How large is A_{corr}?

R.B. Wiringa *et al.*, Phys. Rev. C **89**, 024305 (2014)

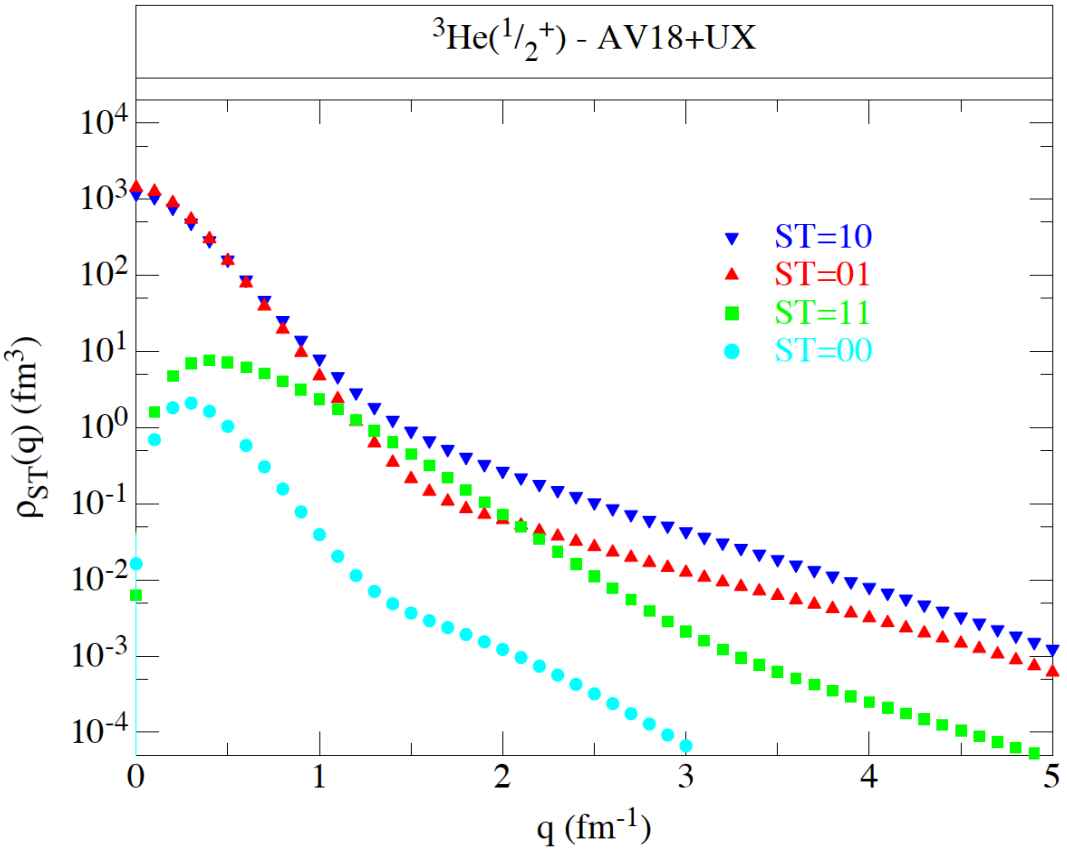

FIG. 8. Momentum distributions of nucleon-nucleon pairs by spin (S) and isospin (T) in ^{3}He in fm^3 calculated using variational Monte-Carlo techniques from [9].

Questions

- What is the probability of detecting a spectator deuteron or proton when the partner proton or deuteron, respectively, suffers a DIS scattering from a polarized high-energy electron?

- How large are the corrections in extracting $A_1^p(x, Q^2)$ and $A_1^d(x, Q^2)$ from electron scattering from polarized ^{3}He? Is it even tractable?

- In spin-dependent scattering from the polarized ^{2}H nucleus, can one extract $A_1^p(x, Q^2)$ and $A_1^n(x, Q^2)$ by tagging on the spectator neutron and proton?

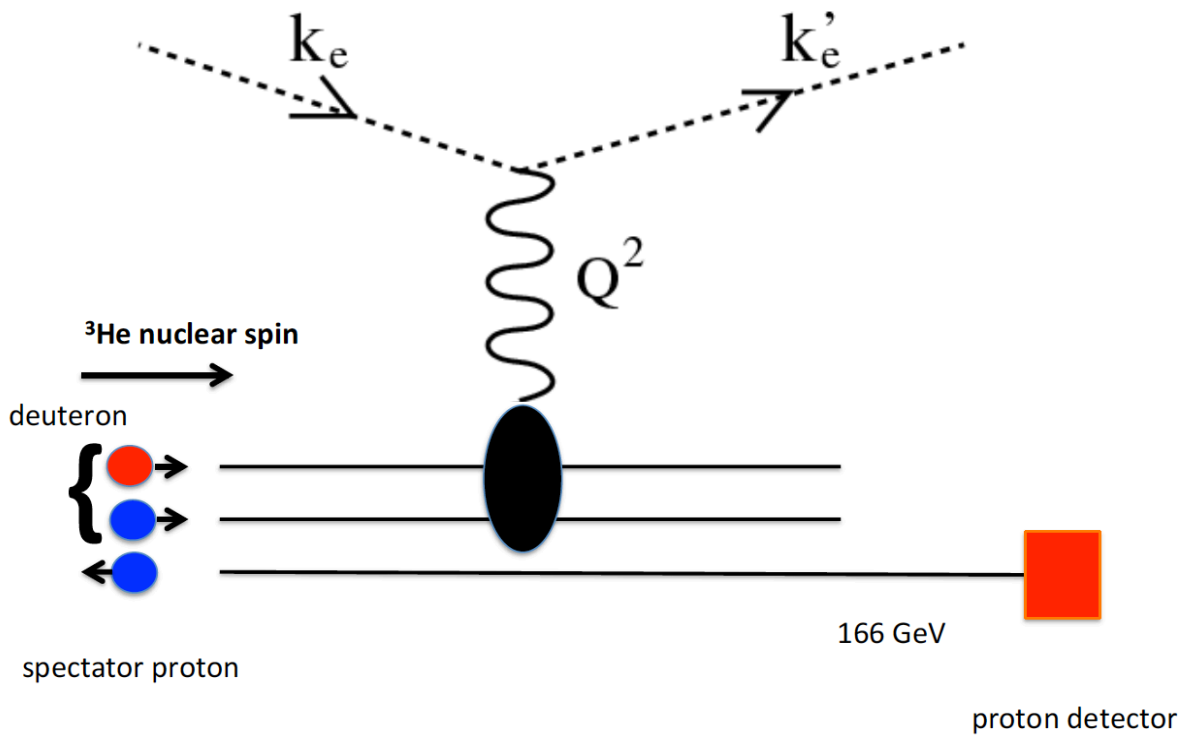

FIG. 7. Spin-dependent DIS from the deuteron in ^{3}He at maximum energy in RHIC by tagging the spectator proton. The deuteron is predominantly polarized in the direction of the ^{3}He nuclear spin.

Tagged protons and deuterons

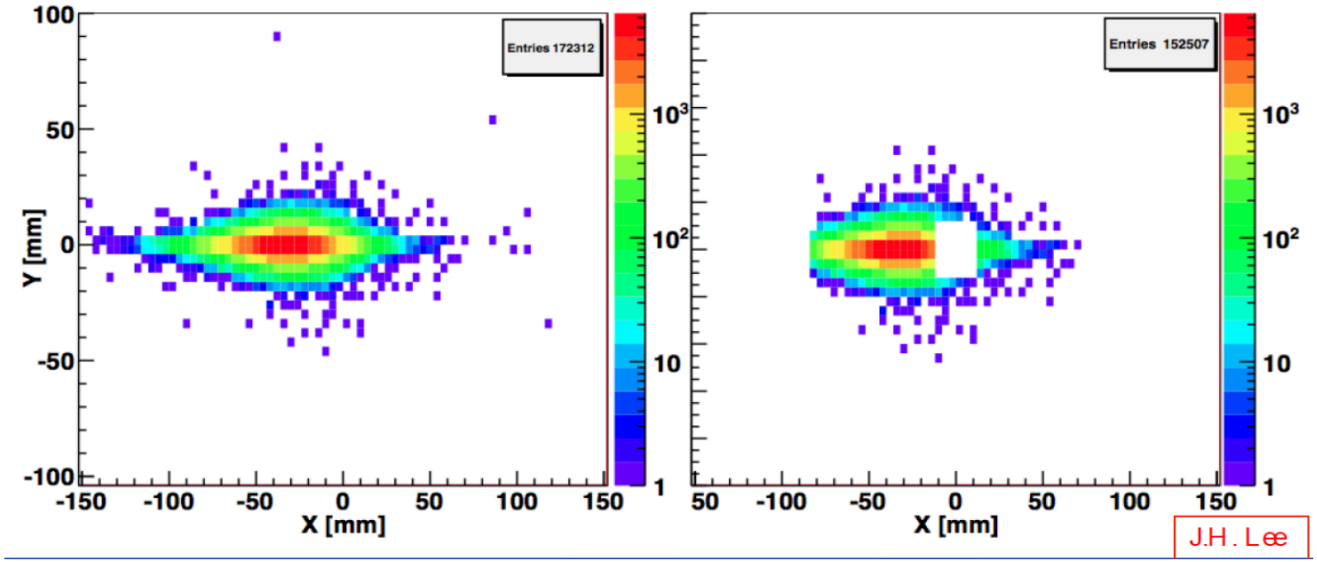

FIG. 9. Acceptance at the Roman Pot detector located 20 m from the IP for spectator protons in 5 GeV electrons incident on 100 GeV/nucleon ^{3}He as determined in a simulation for eRHIC using DPMJET III by J.H. Lee (BNL) as reported in [12].

Summary

- Our perspective on spin-dependent DIS from few-body nuclei is all based on these targets being in their rest frame.
- Calculations of spin-dependent DIS in the EIC frame are needed.
- T.W. Donnelly: approach is to calculate spin-dependent interaction in nuclear rest-frame and boost to EIC frame.
- Donnelly and Sofiatti have done this for e-p elastic:

  Phys. Rev. C **84**, 14606 (2011)
- Sizable effects on spin when boosting.
- If needed, boosted ^{3}He spin structure in collider frame could be measured at RHIC once polarized ^{3}He become available.