Spin-exchange polarized $^3\text{He}$ for electron scattering

- Summary of the dramatic progress that has been made, and why.
- Discussion of ongoing limitations to performance.
- Future targets for the JLab 12 GeV era

Special thanks to Jaideep Singh (who was originally invited to give this talk), Peter Dolph, Yunxiao Wang, Yuan Zheng, Maduka Kaluarachchi, Vladimir Nelyubin and Al Tobias. Also to Todd Averett

Spin-exchange optical pumping

Two-step process:

1. alkali vapor is optically pumped.

2. noble-gas nuclei are polarized through spin-exchange collisions.

Collisional mixing

Rb spin relaxation $\gamma_{SD}$

radiationless quenching from $N_2$
The first liter-sized polarized $^3$He targets were developed to study the spin structure of the neutron at SLAC.

With volumes of 150-200 cc's and nearly 10 atmospheres, these targets contained 1-2 STP liters of gas.

To this day, the data from E142 and E154 provide the most accurate data on the spin structure functions of the neutron over the kinematic range studied.

This data on this figure are incomplete, but I believe the statement at left is still true.
The performance of polarized $^3$He targets have increased by roughly a factor of 30 since SLAC E142.

The scales of the FOMs shown have been normalized so that they are of equal height for the target used during E142.

Commercial fiber-coupled high-power diode laser arrays: early JLab
Alkali-hybrid SEOP
Commercial spectrally narrowed high-power diode laser arrays

**Note:**
- $L_{\text{eff}} (10^{34}/\text{cm}^2\text{ sec})$
- $G_E^n$
- Transversity
- $\mathcal{N} (10^{17} \text{ spins/sec})$

**Demonstrated in simulated beam test**
One big step: Hybrid mixtures of Rb and K to greatly improve efficiency of spin transfer

- 1997 - $^3$He-K spin relaxation predicted to be weaker than for $^3$He-Rb: Walker, Thywissen and Happer, PRA vol. 56, pg 2090 (1997).
- 1998 - $^3$He-K spin-exchange shown to be more efficient: Baranga et al. (incl. Romalis), PRL vol 80, 2801 (1998).

Alkali-hybrid SEOP polarized $^3$He targets produce large gains, ~50% polarization, for E02-013, which measured GEn in Hall A.
The alkali-hybrid SEOP polarized $^3\text{He}$ targets were critical to studying the electric form factor of the neutron at high $Q^2$ (JLab E02-013, Hall A, w BigBite).

Has also led to flavor-separated form factors at high $Q^2$ which provide evidence for the importance of diquark degrees of freedom, but that is a different story ....

- More than doubled the $Q^2$ range over which $G_{En}$ was known.
- Provide the first coverage of the regime in which the surprising proton results had been seen.
- The experiment relied critically on high luminosity and the large solid angle provided by the BigBite spectrometer (first developed at NIKEF).
Polarized $^3$He SEOP targets top 70% for the first time using commercial spectrally-narrowed high-power diode-laser arrays

We had purchased four "Comet" lasers for a $^3$He polarizer for medical imaging, and decided to test them on our targets.

From: Gordon D. Cates <cates@virginia.edu>
Subject: Comet lasers
Date: July 10, 2008 9:30:32 PM EDT
To: Xiaodong Jiang <jiang@jlab.org>, Jian-Ping Chen <jpchen@jlab.org>, Todd Averett <tdaver@wm.edu>
Cc: Kees DeJager <kees@jlab.org>, Larry Cardman <cardman@jlab.org>
Bcc: Jaideep Singh <js7uq@mail.phys.virginia.edu>, Vladimir Nelyubin <vvn2c@galileo.phys.virginia.edu>, Al Tobias <wat4y@virginia.edu>, Peter Dolph <pad8c@tetra.mail.virginia.edu>, Karen Mooney <mooney@virginia.edu>

Dear Xiaodong, Jian-Ping and Todd,

Having heard that input is being sought on budget stuff for transversity, I wanted to pass along to you the latest result from our lab. Fortuitously, we had a group meeting earlier today at which we agreed upon numbers that we could release quasi-publicly.

We have just completed measurements on the transversity cell Samantha. Using Comet lasers, which are spectrally narrowed, we achieved a polarization of 70.3 +/- 3.5%. This confirms our belief that a "good" cell would break 70% in polarization. The pump-up time constant was also extremely short, I believe something like around 4 hours, but don't quote me on that. You may recall that a few months ago Simone, a "fair" GEN cell that had never previously broken something like 45% achieved 62% using Comets.

Best regards,
Gordon
Despite polarizations (measured in the pumping chamber) hovering around 65% in beam, the published target polarization was 55.4% +/- 2.8%

Why the big difference?

Diffusion limits mixing between the pumping and target chambers. This problem could be crippling with the high-luminosity experiments planned for 12 GeV
Convection-based target cells

The convection-style cells have two transfer tubes instead of one.

A small heater on one transfer tube creates a buoyancy force that induces convection.

Measuring the gas speed
A “Zapper coil” is used to produce a depolarized slug of gas. Four NMR pickup coils register the passage of the slug of gas as a function of time.

Dolph, Singh, Averett, Kelleher, Mooney, Nelyubin, Tobias Wojtsekhowski and Cates, PRC vol 84, pg 065201 (2011)
Eliminating polarization gradients

With convection-style cells, the velocity of the gas traveling through the target chamber can be easily controlled from a few cm/min up to around 80 cm/min.

Polarization gradient:

\[
\frac{P_{tc}}{P_{pc}} = \frac{1}{1 + \Gamma_{tc}/d_{tc}}
\]

With \( V_{gas} = 6 \text{ cm/min} \),
\( P_{tc}/P_{pc} > 0.98 \) with beam, and
\( P_{tc}/P_{pc} > 0.99 \) with no beam.

With \( V_{gas} = 60 \text{ cm/min} \), \( P_{tc}/P_{pc} > 0.999!!! \)

Thus, convection also has implications for polarimetry.
Why isn’t $P_{\text{He}} > 70\%$? -- The “X-factor”

The so-called X-factor characterizes a poorly understood temperature-dependent spin-relaxation mechanism that limits the maximum polarization of the target.

Babcock, Chann, Walker, Chen and Gentile
PRL vol. 96, pg. 083003 (2006)

$$\lim_{\gamma_{se} \to \infty} P_{\text{He}} = \lim_{\gamma_{se} \to \infty} \frac{\langle P_A \rangle \langle \gamma_{se} \rangle}{\langle \gamma_{se} \rangle (1 + X) + \langle \Gamma_{\text{He}} \rangle} = \frac{\langle P_A \rangle}{1 + X}$$

The new relaxation mechanism has been observed to be roughly proportional to the spin-exchange rate, so it cannot be overwhelmed by running the target “harder”.

Indeed, the highest polarization reported in the PRL mentioned above is 79%, and there are VERY few examples in the literature claiming anything higher.
The X-factor

One way of measuring X-factors is by looking at spin-relaxation rates at different temperatures (and thus alkali densities).

These quantities are determined by looking at “spin-ups” and cold “spin downs”

The expected spin-exchange rate is determined by measuring the alkali densities and using known spin-exchange coefficients

\[
\langle \gamma_{se} \rangle = \frac{\Gamma_s - \langle \Gamma \rangle + \delta \Gamma}{(1 + X)}
\]

\[
\gamma_{se} = k_{se}^{Rb} [Rb] + k_{se}^{K} [K]
\]
X-factors can also be measured at a single temperature. We did so in a manner that overdetermined the X-factors, allowing both a better determination, as well as a check of internal consistency.

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The X-factor

We see evidence suggesting there may be temperature dependence in the X-factor, a possibility explicitly mentioned by Babcock et al.

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If true, X factors may represent an even more limiting ceiling on the polarization of SEOP ³He targets.
The first prototype quasi-next-generation polarized $^3$He target

Spin-up while inducing spin relaxation equivalent to beam current of 50 - 63 $\mu$A, and convection speed of 6 cm/min.

Saturation polarization = 49%

- Simulated beam test: $P_{^3\text{He}} > 49\%$ with 45 $\mu$A beam current.
- $P_{^3\text{He}} \sim 67\%$ with no convection (and no simulated beam).
- $P_{^3\text{He}} \sim 61\%$ with convection (and no simulated beam).

- $P_{^3\text{He}}$ likely around 55-60%, with 30 $\mu$A beam current for actual target cell under full operating conditions.
In the QCD DSE approach, it is the diquark that causes such a different behavior for the u and d quarks.

True next-generation polarized $^3$He target

- Capable of Luminosity $\sim 1 \times 10^{37} \text{ cm}^{-2}\text{s}^{-1}$ (more than four times higher than Transversity).
- Double pumping chamber
- Target chamber 60 cm instead of 40 cm.
- $P_{He}$ 60-65%
- Would probably need metal end windows.
One design is ready to roll

- Beryllium window mounted on OFHC copper frame
- Inner surface of OFHC copper coated with gold
- Glass-to-aluminosilicate glass seal
- Gold shown at Mainz to have $\sim 22$ spin-relaxation time for $^3$He target, more than good enough.
- Mainz tests involved NO ALKALI metals .....
In the QCD DSE approach, it is the diquark that causes such a different behavior for the u and d quarks.

Tests show two surfaces get worse with exposure to Rb.

Conclusion - metal parts may need to be protected against exposure to alkali vapor.
In the QCD DSE approach, it is the diquark that causes such a different behavior for the u and d quarks.

Summary

- SEOP Polarized $^3$He targets have figures of merit that have climbed by x30 since E142 and E154 at SLAC
- We expect the improvement to be X120 (compared to E142) with the next generation of targets.
- Even larger gains are almost certainly possible.
- Polarized $^3$He continues to broaden our reach in terms of physics.
In the QCD DSE approach, it is the diquark that causes such a different behavior for the u and d quarks.
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Several features to notice in measurement:

- Large shifts in baseline
- Very large apparent losses.
- Asymmetric line shape.
- Regardless of messed-up signal, excellent signal-to-noise. Made us wonder if the cell was better when we first started our tests.
Next test: valved gold-coated cell

• If gold is a good surface before being exposed to Rb, we should get good lifetimes if we never allow the gold to see any Rb.
• With a valve, we can isolate the gold portion of the cell until the pumping chamber is cold.
• If the results are favorable, we may well be able to design a target in which the Rb reaching the gold is minimized.

We also have cells in the pipeline with both titanium as well as non-magnetic stainless steel.
In the QCD DSE approach, it is the diquark that causes such a different behavior for the u and d quarks.

Currently, our magnetic-field studies are of option a).

Our design of choice would probably be option b).

The current plan is option c). This is essentially the design of Protovec-I, which has already been bench tested.
In the QCD DSE approach, it is the diquark that causes such a different behavior for the u and d quarks.
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