The JLab Frozen Spin Target

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The g9 Tagged Photon Experiments in CLAS

E02 – 112: Search for Missing Nucleon Resonances in Hyperon Photoproduction
E03 – 105: Pion Photoproduction from a Polarized Target
E04 – 104: Helicity Structure of Pion Photoproduction
E05 – 012: Measurement of Polarization Observables in Eta-Photoproduction with CLAS
E06 – 013: Measurement of $\pi^+ \pi^-$ Photoproduction in Double-Polarization Experiments using CLAS

Common physics goals: Spectroscopy of baryon resonances.

Experimental technique: Measure multiple single- and double-spin observables using all combinations of linearly and circularly polarized photons, incident on longitudinally and transversely polarized protons.

First round of experiments used longitudinally polarized target — completed Feb. 2008

Second round requires transverse target polarization. — scheduled for 2010
g9 Experimental Layout

- CLAS
- Electron beam
- Radiator
- Tagger magnet
- Photon beam
- Polarized target
- Meters
The Existing Hall B Polarized Target

Dynamically polarized NH$_3$/ND$_3$ target
Temperature: 1K
Polarizing Magnet: 5T Helmholtz pair

- longitudinal only
- limits acceptance $\vartheta \leq 55^\circ$

Construct (at JLab) a **Frozen Spin Target** with acceptance up to 135°, and both longitudinal *and* transverse capabilities
The Frozen Spin Technique

Operation is more complicated:

1) Polarize target (DNP) at high field (5 T) and low temperature (~ 0.5 K)
2) “Freeze” the spins at very low temperature (~ 0.05 K)
3) Maintain polarization using a smaller magnet (0.5 T) with beam on target
4) Repeat steps 1 – 3 as needed

Polarization decay time $T_1$ depends on material, field, and temperature.

Goal: $T_1 = 500$ hrs
$\Delta P/P = -5\%$ per day
FROST: Design Specifications

Material: 5 g frozen butanol (C₄H₉OH) + TEMPO (0.5% wt)

Polarizing Conditions: 5 Tesla at 0.3 K
   Cooling requirements: ~ 20 mW

Polarization: ± 85%

Frozen Spin Conditions: 0.5 Tesla at 50 mK
   Cooling requirements: ~ 10 μW

Proton Relaxation Time: $T_1 \geq 500$ hours
   $\Delta P/P = -5\%$ per day
FROST: Equipment List

1 $^3$He/$^4$He dilution refrigerator
1 superconducting polarizing magnet + power supply
1 superconducting holding magnet + power supply
1 microwave generator + waveguide components
2 NMR coils + Q-meter circuits
2 control computers (EPICS + LabView)
2 gas panels + 22 valves
18 vacuum pumps
  7 vacuum gate valves
30 thermometers
18 vacuum/pressure gauges
  1 residual gas analyzer
4 LHe level meters
3 chillers

One Small Problem...

Target must be polarized outside of CLAS and roll forward (while cold!) for data acquisition phase.
The “Frozen Spin Waltz”

Polarizing Mode

- Microwaves ON
- Polarizing magnet ON
- Holding magnet OFF
- Temperature \( \sim 1/2 \) K
- Photon beam OFF
The “Frozen Spin Waltz”

Transition Mode
- Microwaves OFF
- Polarizing magnet OFF
- Holding magnet ON
- Temperature $\leq 0.07$ K
- Photon beam OFF
The “Frozen Spin Waltz”

Transition Mode

- Microwaves OFF
- Polarizing magnet OFF
- Holding magnet ON
- Temperature $\leq 0.07$ K
- Photon beam OFF
The “Frozen Spin Waltz”

Frozen Spin Mode

- Microwaves OFF
- Polarizing magnet OFF
- Holding magnet ON
- Temperature $\leq 0.05$ K
- Photon beam ON
FROST in Hall B, February 2008
FROST Horizontal Dilution Refrigerator

- Mixing Chamber (replaced with single-piece PCTFE)
- Sintered Heat Exchanger: 5 & 20 μm copper
- 1.7 m long
- 4 m² surface area
- Still heater, level probe, & thermometry
- Indium seal
- 3He pump tube flange and umbilical
- Still cover
- Heat exchanger cover
- Indium seal
- Thermometry & heater
- 3He fill tube
Frozen Spin Target: Material
5 g frozen butanol, 1 – 2 mm beads

FROST Zero Heat Load Target Insert

- PCTFE Target Cup
  Ø15 mm x 50 mm
  (5 g butanol)

- Compression nut

- Kapton sealing gasket for Mixing Chamber

- Aluminum beam window

Insert (80 K) is attached to wrench and screwed into M.C. (10 K) via load lock. Wrench is removed after gasket is compressed.
Target material is inserted into mixing chamber.

NMR coils (2) and microwave waveguide are fixed outside the mixing chamber.

Holding coil, longitudinal or transverse, attaches to 1 K heat shield.

Also serves as a microwave cavity.
Field: 0.56 Tesla @ 22.3 A
$\Delta B/B: < 3 \times 10^{-3}$
Bore: $\Ø$ 50 mm
Thickness: 0.1 mm NbTi wire (3 layers)

Longitudinal Holding Coil and NMR Spectra
Field: 0.54 Tesla @ 38.5 A
ΔB/B: < 8 \times 10^{-3}
Bore: \( \Ø \) 50 mm
Thickness: 0.1 mm NbTi wire (4 layers)

Transverse Holding Coil and NMR Spectra
5 Tesla Polarizing Magnet
and NMR spectra

Max. Field: 5.1 T @ 82.5 A
ΔB/B: < 3×10^{-5}
Bore: Ø127 mm

Cryomagnetics, Inc.
Oak Ridge, TN
Frozen Spin Target: Base Temperature

- 26 mK (EEL Bldg)
- 28/30 mK (Hall B, no beam)
- 32 mK (Hall B, ~10^7 γ s^{-1})
Frozen Spin Target: Cooling Power

300 mK: 60 mW
100 mK: 10 mW
50 mK: 800 μW

Refrigerator ran continuously Oct. 29 '07 thru Feb. 12 '08 (~1100 hours of beam time)
Frozen Spin Target: Polarization

Positive Polarization
7 times (1 unscheduled)
~ 80%

Negative Polarization
10 times (3 unscheduled)
~ -85%

All unscheduled polarizations due to failure of holding coil power supply.
**Frozen Spin Target: Relaxation Time**

**Positive Polarization**

~ 3500 hours, w/o beam  
~ 2700, w/ beam  

**Negative Polarization**

~ 1800 hours, w/o beam  
~ 1400, w/ beam  

Polarization loss ~1 - 1.5% per day.

Re-polarize every 5 – 7 days.
Frozen Spin Target: Relaxation Time of Butanol

JLab
0.56 Tesla
28 – 150 mK

Bonn
0.42 Tesla
56 – 100 mK

“Semi-empirical” $T_1$ equation

$$T_{1p}^{-1} = [AT_{1e} H^2 \cosh^2 \left( \frac{h \nu_e}{2kT} \right)]^{-1} + \left[ a \frac{H^b}{T^c} \right]^{-1}$$

$$AT_{1e} = 225 \left[ H^5 \coth \left( \frac{h \nu_e}{2kT} \right) + 6.75 \times 10^5 e^{-0.5/T} \right]^{-1}$$

Fit with 3 adj. parameters
a = $3.1 \times 10^{-4}$
b = 4.3
c = 2.5
**Frozen Spin Target: Summary**

- A Frozen Spin Target of polarized protons has been built for tagged photon experiments inside CLAS.

- In its first use (2007), FROST met or exceeded all design goals.

- FROST utilizes an internal, superconducting holding coil (H > 0.5 T) while in Frozen Spin mode.

- Coils have been fabricated to provide either longitudinal or transverse holding fields.

- With a base temperature < 30 mK, extraordinarily long (> 3000 hours) relaxation times were measured for the butanol target.
Additional Slides
Frozen Spin Target: Collaboration

**JLab Target Group** (*past member, +unofficial member*)
- Dr. Chris Keith (project leader, DR design, day-to-day operation)
- Dr. Mike Seely (holding magnets)
- Dr. David Meekins (target material preparation)
- James Brock, Mark Hoegerl (fabrication & assembly)
- David Griffiths (electrical)
- Chris Carlin, +Sue Witherspoon (software)
- Paul Hood, *Rusty Salmons, *Steve Knight (vacuum & plumbing)
- +Amy Comer (heat exchanger R&D)
- +Jim Rohrbach (machinist extraordinaire)

**Hall B**
- Dr. Volker Burkert (signed the checks)
- David Kashy & Pete Hemler (target cart design)
- Mike Zarecky (draftsman)
- Doug, Tom, Jill, Dennie, Calvin & rest of technical staff

Dr. Eugene Pasyuk (Arizona State U.) - liaison w/ g9 collaboration