Development of a Frozen Spin Target for CLAS

Chris Keith
Target Group
Jefferson Lab

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Miltenberg
Jefferson Lab Milestones

1976 CEBAF proposed
1983 DOE awards contract to SURA
1987 Groundbreaking for accelerator
1993 1st Experiments commence
1996 Name changed to Th. Jefferson Nat’l Accelerator Facility
1997 5-pass beam (4 GeV) simultaneously delivered to all 3 Halls
2000 6 GeV enhanced design goal met
The Conventional Hall B Polarized Target

Protons (and deuterons) in $^{15}$NH$_3$ ($^{15}$ND$_3$) are continuously polarized by 140 GHz microwaves at 5 Tesla, 1 Kelvin

Used for several experiments (beam current $\sim$ 3 nA) over a 10 month period during 1999, and 2000-2001

Proton polarization: $\sim$75 - 85%
Deuteron polarization: $\sim$25 - 35%
The Current Hall B Polarized Target
Problem: We have a “4π” detector. We need a “4π” target!
Frozen Spin Polarized Targets

Two steps

1. Polarize target material (NH$_3$, C$_4$H$_9$OH, $^6$LiD, ...) at high field (2.5 – 5.0 T) and moderate temperature (.2 - .4 K)

2. Reduce target temperature to ~ 50 mK, and hold polarization with reduced field (0.3 – 0.5 T)

The target polarization then decays exponentially during the data acquisition phase of the experiment. The target must be re-polarized (step 1) every few days.
Specifications for the Hall B Frozen Spin Target

Beam: Tagged photons
Target: Ø15 mm × 50 mm butanol (C₄H₉OH) \( \mathcal{L} \sim 10^{30} - 10^{31}/s\ cm^2 \)
Polarizing Magnet: 5 Tesla warm bore solenoid
Holding Magnet: 0.3 – 0.5 Tesla internal solenoid
Refrigerator: \(^{3}\)He/\(^{4}\)He dilution 'fridge \( Q \sim 20\ mW @ 0.3\ K \)
\( Q \sim 10\ \mu W @ 0.05\ K \)

Ch. Bradtke

Physics Program with Polarized Target and Tagged Photons

Approved Experiments

- E02-112: Missing Resonance Search in Hyperon Photoproduction
- E01-104: Helicity Structure of Pion Photoproduction
- E03-105: Pion Photoproduction from a Polarized Target

Letter of Intent

- LOI-020104: Photoproduction Using Polarized Beam and Target
Polarizing Magnet

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

A. Dzyubak, priv. comm.
Holding Magnet, Longitudinal

Wire: Ø.1 mm multifilament NbTi, three layers
Dimensions: Ø 50 × 110
Max. Field: 0.42 Tesla
Homogeneity: ΔB/B ~ 3 × 10^{-3}
Holding Magnet, Transverse (Prototype)

Wire: Ø.1 mm multifilament NbTi, three layers
Dimensions: Ø 40 × 355 mm
Max. Field: 0.27 Tesla
Homogeneity: ΔB/B ~ 5 10^{-3}
**3He/4He Dilution Refrigeration**

- below 0.8 K, a $^3$He/$^4$He mixture will separate into two phases

- if $^3$He atoms are removed (distilled) from lower phase $^3$He atoms from upper phase will cross the phase boundary to reestablish equilibrium

- $^3$He will absorb energy when it dissolves into the dilute phase.

- heat absorbed by $n$ moles is: $Q = n [H_d(T_m) - H_c(T_m)]$
  
  $= n [94.5 T^2 - 12.5 T^2] = 82 n T^2 \text{ J/mol K}^2$
Continuous Dilution Refrigeration

- $^3$He is “distilled” from the lower, dilute phase of the mixing chamber
- after distillation, the $^3$He is recondensed in a LHe bath at $\sim 1.5\text{K}$ and returned to mixer at elevated temperature $T_c$
- the cooling power and min. temperature depend strongly on heat exchange between the conc. (warm) and dil. (cold) fluid streams

\[
\dot{Q}(T_m) = \dot{n} [H_d(T_m^2) - H_c(T_c^2)] \\
= \dot{n} [94.5 T_m^2 - 12.5 T_c^2]
\]

Performance of HX determines $T_c$
Heat Exchange between Concentrated and Dilute Phases

At low temperatures, the main impediment to heat transfer is the thermal boundary (Kapitza) resistance $R_k$ between the helium and the HX walls.

Only a small fraction of phonons from liquid will enter the HX walls:

$$\frac{\rho_1 v_1^3}{\rho_2 v_2^3} \propto 10^{-5} \quad \dot{Q}_k = \frac{A}{2R_k} [T_2^4 - T_1^4]$$

Or a more familiar form:

$$\dot{Q}_k = \frac{\Delta T}{R} = \frac{A T^3}{R_k} \Delta T$$  

Heat transfer drops fast at low $T$!
Performance of an “Ideal” Heat Exchanger

(Giorgio Frossati, 1986)

\[
d_{d} \frac{d}{dx} \left[ \kappa_d(T) \frac{dT_d}{dx} \right] + \eta_d V_d^2 \frac{dZ_d}{dx} + \frac{dA}{dx} \left( \frac{T_c^4 - T_d^4}{4 R_{kT}} \right) = \dot{n} C_d \frac{dT_d}{dx}
\]

\[
d_{c} \frac{d}{dx} \left[ \kappa_c(T) \frac{dT_c}{dx} \right] + \eta_c V_c^2 \frac{dZ_c}{dx} + \frac{dA}{dx} \left( \frac{T_c^4 - T_d^4}{4 R_{kT}} \right) = -\dot{n} C_c \frac{dT_d}{dx}
\]

Axial conduction
Frictional heat
Kapitza conduction
Enthalpy change

\[ s = \text{sectional area} \]
\[ \eta = \text{viscosity} \]
\[ Z = \text{flow impedance} \]
\[ V = \text{molar volume} \]
\[ \kappa = \text{thermal cond.} \]
\[ \kappa_c(T) = \text{thermal cond.} \]
\[ \eta_c = \text{viscosity} \]
\[ V_c = \text{molar volume} \]
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\[ \kappa_c(T) = \text{thermal cond.} \]
\[ \eta_c = \text{viscosity} \]
\[ V_c = \text{molar volume} \]
\[ Z_c = \text{flow impedance} \]

Frossati: design HX so that 1st and 2nd terms are small compared to the 3rd

\[
T_c^2 = \frac{2 \cdot 25}{(1-(25/107)^2)} \frac{R_{kT}}{A} \dot{n} \approx 50 \frac{R_{kT}}{A} \dot{n}
\]

Temperature of $^3\text{He}_c$
entering mixing chamber
Cooling Power with Ideal Heat Exchanger

(Giorgio Frossati, 1986)

Cooling power, assuming “ideal” heat exchange is determined by molar flow rate and $R_k/A$ of heat exchanger

\[
\dot{Q}(T_m) = \dot{n} \left[94.5T_m^2 - 12.5T_c^2\right]
\]

\[
= \dot{n} \left[94.5T_m^2 - 625\frac{R_{kT}}{A}\dot{n}\right]
\]

Build HX with low $R_{kT}$
OR, large Area
Optimization of Heat Exchanger Geometry

To optimize heat exchangers, must consider heat leaks due to both axial conduction and frictional heating

\[ Q_{\text{cond}} = \frac{\pi D^2}{4L} \int \kappa(T) dT = aD^2 \]

\[ Q_{\text{fric}} = \eta \left( \frac{128L}{\pi D^4} \right) (\dot{V})^2 = bD^{-4} \]

Minimize \( Q_{\text{con}} + Q_{\text{fric}} \):

\[ \frac{d}{dD} (aD^2 + bD^{-4}) = 0 \quad \Rightarrow \quad D_{\text{opt}} = \left( \frac{2b}{a} \right)^{1/6} \]
Intrinsic heat leak as a function of tube diameter

HX Length: 1.5 m
Flow rate: 1 mmol/s
Inlet temperature: 200 mK
Outlet temperature: 20 mK
Sintered Silver Heat Exchangers

- large surface areas are necessary to overcome Kapitza resistance
- use sinters of ultra-fine silver powder to provide several m² of area

JLab: Use 5 identical segments (in series) between Still and Mixer
1 micron Ag powder
Sinter at 250 °C ➞ 0.5 m²/g

each segment:
Dil. = 15 g = 7.5 m²
Conc. = 8.5 g = 4.2 m²

5 segments:
Dil. = 37.5 m²
Conc. = 21 m²
Cooling Power, "Ideal" Heat Exchanger

$^3$He circ. rate: 1 - 6 mmol/s
An example of a commercial, vertical dilution refrigerator

Very nice, but it won't fit inside CLAS...
Horizontal Dilution Refrigerator for Frozen Spin Target

T.O. Niinikoski, CERN 1971
Dilution Unit

- Sintered HX
- Tube-in-Shell HX
- 3He Pump Tube
- Mixer
- Target Cup
- Still
- Waveguide
- Target Insert
- Holding Magnet
Outer Vacuum Jacket
Distillation Chamber

$^4$He Precooling Stages

Gas/Gas HX

4K Pot

1K Pot

Tube-in-Shell HX

Distillation Chamber
The Frozen Spin Waltz

Step 1: Polarizing
- Target is fully retracted, magnet is lifted to beam height
- Target is inserted into magnet, magnet energized, microwaves on

Step 2: Beam On
- Microwaves off, magnet off, holding coil on
- Target is fully retracted, magnet is lowered
- Target is fully inserted into CLAS
Summary

- A frozen spin polarized target for tagged photon experiments is under development at Jefferson Lab.

- 5 Tesla polarizing magnet is in house.

- Superconducting holding coils (~1mm thick) are under development.
  - longitudinal solenoid (0.4 Tesla) constructed and tested
  - prototype of transverse dipole has been tested (0.3 Tesla)

- Horizontal dilution refrigerator is under construction.

- Positioning system for Hall B is still in conceptual design stage.