Polarized Solid Targets
9th International Workshop on Polarized Solid Targets and Techniques

October 27 – 29, 2003
Bad Honnef, Germany

Hartmut Dutz – Physikalisches Institut Universität Bonn
Summary given at SPIN04, Trieste 2004
Preceeding workshops:

- 1978: Argonne National Lab, USA
- 1979: Abingdon, UK
- 1982: Brookhaven National Lab, USA
- 1984: Bad Honnfe, Germany
- 1986: Montana, Switzerland
- 1990: Bonn, Germany
- 1994: Bad Honnfe, Germany
- 1996: Vancouver, Canada

Major topics:

- Advances in:
  - Target instrumentation
  - Material doping methods
  - Methods for polarizing HD
  - EPR spectroscopy

- Polarized Targets for new particle- and nuclear physics experiments

- Application of DNP in NMR spectroscopy and MR imaging

- Review talks about the milestones of more than 40 years of polarized solid targets
What is a good Polarized Target?

- Most simple case: Experiment measuring the target asymmetry
  \[ A_{\text{exp}} = \frac{N \uparrow - N \downarrow}{N \uparrow + N \downarrow} = f \cdot \overline{P} \cdot A_{\text{phys}} \]
  \[ f = \frac{\# \text{polarizable nucleons}}{\# \text{all nucleons}} \]

- Relation between error \( \Delta A \) and measuring time \( t \):
  \[ (\Delta A)^2 \approx \frac{1}{\mathcal{L} \sigma (f \cdot \overline{P})^2 t} \iff t \approx \frac{1}{\mathcal{L} \sigma (f \cdot \overline{P})^2} \cdot \frac{1}{(\Delta A)^2} =: \frac{1}{\text{FoM}} \cdot \frac{1}{(\Delta A)^2} \]

Target Material \quad Instrumentation

\[ \text{FoM} = \sigma \ n_T \ f^2 \ \overline{P}^2 \]
Cryogenic Equipment

- H. Dutz (Bonn): Highlights of PST instrumentation
- Y. Usov (Dubna): Frozen spin solid targets at JINR

4He Evaporation Cryostat

3He/4He Dilution Cryostat

Continuous Mode

- Cont. Polarization build-up
- Solid ext. magnet needed

😊 Moderate (high) intensities
😊 Small solid angle

SLAC, JLAB, COMPASS
The COMPASS Polarized Target

K. Kondo: Polarization measurement
J. Koivuniemi: NMR line shapes
Y. Kisselev: Local field in polarized LiD
N. Doshita: Performance of the cryostat
F. Gautheron: Cryogenic control system

$P_{\text{max}} = \pm 55 / -50\%$
$\Delta P / P = \pm 3.5 / \pm 1.9$ for up/down
Cryogenic Equipment

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$^4$He Evaporation Cryostat
$^3$He/$^4$He Dilution Cryostat

Continuous Mode

- Cont. Polarization build-up
- Solid ext. magnet needed

- Moderate (high) intensities
- Small solid angle

SLAC, JLAB, COMPASS

Frozen Spin Mode

- Pol. maintained at low B,T
- Ext. or thin internal magnet

- Low intensities (tagged $\gamma$)
- Large (4$\pi$) solid angle

PSI, Dubna, Mainz, Bonn


‘frozen spin polarized target’
GDH – frozen spin target (internal superconducting ‘holding coil’)

Copper carrier

superconducting coil

current leads

heat exchanger

NbTi-wire: $\varnothing 100\mu m$
$\varnothing 44\, \text{mm}$, $l = 120\, \text{mm}$, $N = 4000$
$d = 0.7\, \text{mm}$

reliable operation at $B_h = 0.44\, \text{T} @ 11.5\, \text{A}, T < 1.2\, \text{K}$

MAGNETS

- H. Dutz (Bonn): Highlights of PST instrumentation
- C. Djalali et al. (U. South Carol.): Design of an int. superconducting holding magnet for the Jlab Hall B frozen spin target.

CRYOGENIC EQUIPMENT

- H. Dutz (Bonn): Highlights of PST instrumentation
- Y. Usov (Dubna): Frozen spin solid targets at JINR

4\textsuperscript{He} Evaporation Cryostat

3\textsuperscript{He}/4\textsuperscript{He} Dilution Cryostat

Continuous Mode

- Cont. Polarization build-up
- Solid ext. magnet needed

\small{MODERATE} \ (\texttt{HIGH}) intensities
\small{SMALL} solid angle

SLAC, JLAB, COMPASS

Frozen Spin Mode

- Pol. maintained at low B,T
- Ext. or thin internal magnet

\small{LOW} intensities (tagged $\gamma$)
\small{LARGE} (4$\pi$) solid angle

PSI, Dubna, Mainz, Bonn

4$\pi$ Continuous Mode

- Cont. Polarization build-up
- Thin high field int. magnet

\small{MODERATE} beam currents
\small{LARGE} (4$\pi$) solid angle
New concepts

‘$4\pi$ – continuous mode target’

minimize and integrate the large polarizing magnet in the d-cryostat

Prinzip : Reduktion des magnetischen Volumen

$\phi$ 44 mm, $l$ = 125 mm, $N$ = 2560, 5 Lagen NbTi/CuNi $\phi$200$\mu$m

$B_p = 2.54$ Tesla , $I_N = 100$ A , Dicke : 1.5 mm, $\Delta B/B \approx 10^{-4}$
Cryogenic Equipment
- H. Dutz (Bonn): Highlights of PST instrumentation
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Magnets
- H. Dutz (Bonn): Highlights of PST instrumentation
- C. Djalali et al. (U. South Carol.): Design of an int. superconducting holding magnet for the Jlab Hall B frozen spin target.

Polarization Measurement
- G.R. Court (University of Liverpool): Development of NMR techniques for high precision pol. Measurement
- P. Hautle (PSI): Comparison of different NMR concepts
- G. Reicherz (Bochum): Pulsed NMR for pol. measurement

4He Evaporation Cryostat

3He/4He Dilution Cryostat

Continuous Mode
- Cont. Polarization build-up
- Solid ext. magnet needed

Frozen Spin Mode
- Pol. maintained at low B,T
- Ext. or thin internal magnet

4π Continuous Mode
- Cont. Polarization build-up
- Thin high field int. magnet

Choices:
- Moderate (high) intensities
- Small solid angle
- Low intensities (tagged γ)
- Large (4π) solid angle
- Moderate beam currents
- Large (4π) solid angle

SLAC, JLAB, COMPASS

PSI, Dubna, Mainz, Bonn
**Target Material**

- **Material Properties**
  - Dilution factor
  - Radiation hardness
  - Polarized background
  - Handling

- **Chemical Doping**
  - Chemical reaction
  - Dissolution of free radicals

- **Radiation Doping**
  - Point Defects by ionizing radiation

**Organic Materials**
- Alcohols
- Diols
- Plastics

- Experiments in hadron physics with low to moderate currents
  - PSI, Dubna, GDH@Bonn/Mainz

**Inorganic Materials**
- Ammonia
- Lithium Hydrides
- HD

- Experiments at high energies with moderate to high intensities
  - COMPASS, SLAC, JLAB

**E.I. Bunyatova (Dubna)**
Static and Dynamic Nuclear Polarization

\[ P_{TE} = B_I \left( \frac{\mu_I B}{2kT_L} \right) \]

Doping with unpaired electrons

\[ P_{dyn} = B_I \left( \frac{\mu_I B}{2kT_{SS}} \right) \]

Off-resonance \( \mu \)-wave saturation

\[
\frac{1}{T_{SS}^{\min}} = \frac{\omega_e}{2\sqrt{(\tau_Z/\tau_D)D}} \cdot \frac{1}{T_L}
\]

\[
\frac{1}{T_{SS}} \approx \frac{\omega_e \Delta}{\Delta^2 + (\tau_Z/\tau_D)D^2} \cdot \frac{1}{T_L}
\]

<table>
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<tr>
<th>B[T]</th>
<th>T[mK]</th>
<th>P(p)[%]</th>
<th>P(d)[%]</th>
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<td>2.5</td>
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<td>0.25</td>
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<tr>
<td>15</td>
<td>12</td>
<td>90</td>
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\[ D^2 = D_{hom}^2 + D_{inhom}^2 \]

Minimize to minimize the spin temperature

S. Goertz et al., Bochum
Novel doping methods for organic deuterated materials

- Radiation doping of d-butanol and deuterated polyethylene
- Chemical doping of d-butanol and d-propanediol with the trityl-radical

New standard tool:
- Low and high field EPR measurements
- EPR spectroscopy at DNP conditions
nGDH @ MAMI 2003

Highest deuteron polarization in a polarization experiment

![Graph showing deuteron polarization over time with two lines representing different butanols: D-butanol (trityl-complex) and D-butanol (porphyrexide). The graph inset shows a detailed view of the D-butanol (trityl-complex) line with a peak at 81% polarization.]
E. Radtke (Bochum): Efforts towards a dynamically polarized HD-target
Further new achievements in polarized target material research

B. Van den Brandt et al. (PSI): **DNP with the free radicals deuterated TEMPO and deuterated oxo-TEMPO**

- New record polarization in d-polystyrene doped with \(2 \times 10^{19}\) spins/cm\(^3\) TEMPO-d18

\[ P_{\text{max}} = +34\% / -40\% (+10\%) \text{ at } 2.5T / 100\text{mK} \]

P.M. McKee (Virginia): **Observation of radiation damage and recovery in ammonia**

- \(\text{NH}_3\) is still THE polarized proton material for intense particle beams!
- \(\text{ND}_3\) shares the leading role with \(^6\text{LiD}\) depending on physics demands.

- Essentially no un-annealable radiation damage in ND3 ↔ NH3

<table>
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<tr>
<th>EXP.</th>
<th>Lab</th>
<th>Year</th>
<th>Proton</th>
<th>Deuteron</th>
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Polarized Targets for new particle- and nuclear physics experiments

T. Uesaka et al. (CNS Tokyo, RCNP Osaka):

**The CNS polarized proton target for radioactive isotope beam experiments**
- First successful application of the CNS PT at the RI beam at RIKEN:
  Vector analysing power for the proton-6He elastic scattering

T. Wakui et al. (Tokyo, Osaka):

**Optimization of laser parameters for polarizing protons in naphtalene crystal**

M. Iio et al. (Miyazaki, Osaka, Nagoya, Chubu, Tsukuba, Yamagata, Tokyo):

**Development of a polarized target for nuclear fusion experiments**
- Measurement of D(d,p)T using the 20 MeV beam of the UTTAC tandem accelerator

O. Zimmer et al. (München, PSI, Saclay):

**The spin-dependent $nd$ scattering length – a proposed high accuracy measurement**
- Measurement of the ‘incoherent’ $nd$ scattering length $b_{i,d}$ ($a_{i,d}$)
- **High accuracy** ($10^{-3}$) relative to the well known $b_{i,p}$ of the proton

**Equipment:** Cold neutron beam at PSI
- **Ramsay apparatus** for pseudomagnetic precession
- **Proton and deuteron polarized target**

**Allows extraction of important parameters for effective field theories**
J.H. Ardenkjaer-Larsen et al. (Amersham Health, Malmö, Sweden): Generating highly polarized nuclear spins in solution using dynamic nuclear polarization

- NMR spectroscopy, analytical technique
- MRI, non-invasive clinical imaging method
- Low sensitivity at room temperature

Is it possible to generate dynamically polarized nuclei in a solvent at room temperature? **YES!**

1 min...

13C-urea in glycerol + OX063

13C-coronal projection image of a rat

1s

3s

Vascular tree of the lung

Heart

Aorta

Kidneys
48 participants from 10 countries and
23 universities and institutions all over the world:

Amersham Health R&D, Malmø, Sweden
Laboratoire Saturne LNS/SAP, Gif-sur-Yvette, France
CEA Sackay, Gif-sur-Yvette, France
University of Bielefeld, Germany
Joint Institute of Nuclear Research, Moscow, Russia
University of Liverpool, UK
University of Virginia, Charlottesville, USA
Institut de Physique Nucléaire, Orsay, France
University of South Carolina, Columbia, USA
CERN, Switzerland
University of Bonn, Germany
Charles University Prague, Czech Republic
Ruhr-University Bochum, Germany
Paul Scherrer Institut, Villigen, Switzerland
Miyazaki University, Japan
University of Michigan, Ann Arbor, USA
University of Mainz, Germany
Czech Technical University, Prag, Czech Republic
Institut de Biologie, Grenoble, France
University of Tokyo, Japan
RIKEN, Japan
Brookhaven National Lab, New York, USA
Technical University München, Germany
The Process of Dynamic Nuclear Polarization

The Microscopic Picture

Degrees of freedom of the electron and nuclear spin system

The Macroscopic Picture

Observation of spin diffusion by SANS at PSI, at ILL Grenoble and at Saclay

P. Hautle / J. Kohlbrecher et al. (PSI)

\[ P_{\text{dyn}} = B_i \left( \frac{\mu_i B}{2kT_{SS}} \right) = B_i \left( \omega_i \alpha_i \right) \]

Nuclear Zeeman

\( C^2 \sim N_1 \omega_i^2 \)

Degree of freedom

Zeeman

\( C^2 \sim N_3 \Delta_i^2 \)

Lattice

Dipol

\( C^2 \sim N_2 D_i^2 \)