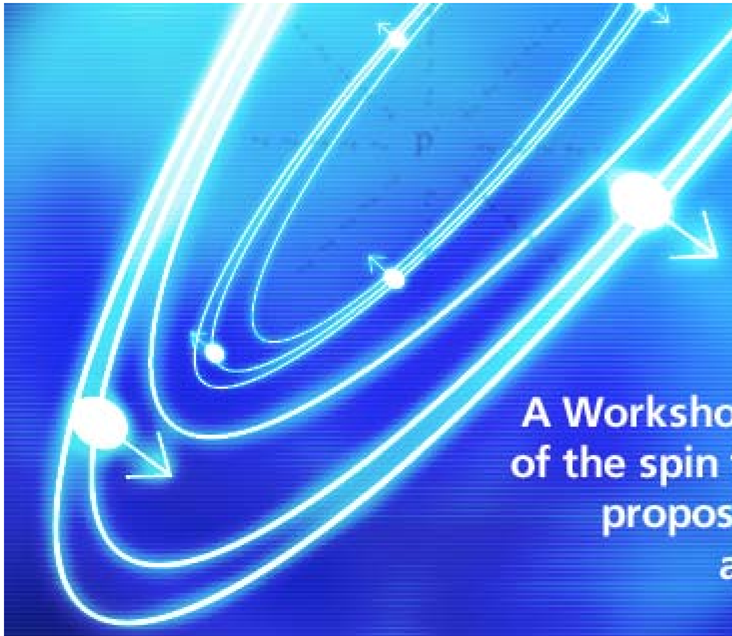


Polarised Antiproton Beams - How?

A Workshop to study the theoretical aspects of the spin filter and spin transfer techniques proposed for the production of polarised antiproton beams in storage rings.

29 - 31 August 2007
e Cockcroft Institute of Accelerator Science and Technology
Daresbury Science and Innovation Campus
Daresbury Laboratory, Warrington WA4 4AD, UK

SUMMARY

Hans-Otto Meyer, Indiana U

- Cockcroft Institute
- www.cockcroft.ac.uk/Polanti-p

The workshop will last for 2½ days, organised as ten nominal 90 minute sessions starting at 09.00 on Wednesday 29 August and finishing at 12.30 on Friday 31 August. Other contributions may b included if time is available.

Wednesday 29 August

Session 1 Introduction

Physics with polarised antiprotons	P. Lenisa
An overview of the physics processes involved in spin transfer	N. Buttimore
Dynamics of polarisation build-up by spin filtering	D. O'Brien

Session 2 Spin filter and spin transfer theory I

Spin filtering of stored protons (antiprotons)	N. Nikolaev
Polarisation build-up in stored proton and antiproton beams interacting with a polarised target	V. Strakhovenko

Session 3 Spin Filter and Spin Transfer Theory II

Polarisation of antiprotons by means of spin-flip interaction with positrons	Th. Walcher
Proton and antiproton beam polarisation due to spin filtering by a polarised hydrogen target	V. Strakhovenko

Sessions 4 Discussion period I - Leader E. Leader

Thursday 30 August

Session 5 Further techniques

Stern-Gerlach forces and spin splitters	D. Barber
Dynamic nuclear polarisation in flight	A. Krisch

Session 6 Storage rings

Relevant storage ring properties and limitations	A. Lehrach
Spin dynamics and simulation of spin motion in storage rings	D. Barber

Session 7 Channelling techniques

How a bent crystal could polarise antiprotons	M.Ukhanov
Experimental study of channelling phenomena	M. Fiorini

Session 8 Discussion period II - Leader E. Steffens

Friday 31 August

Session 9 Current and future experiments

Depolarisation and spin filtering studies at COSY	F. Rathmann
Generation of intense polarised positron beams for spin transfer to antiprotons	K. Aulenbacher
Future Linear Collider Polarised Positron Sources	Ian Bailey

Session 10 Future activities and workshop summary

Workshop summary	H-O. Meyer

Workshop on Polarized Antiprotons

Bodega Bay

April 18 – 21, 1985

Organized by O. Chamberlain and A. Krisch

American Institute of Physics
Conference Proceedings No. 145
AIP New York 1986

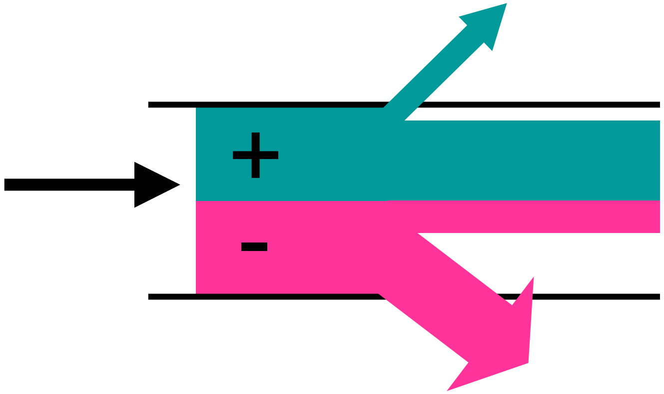
Bodega Bay Area
Salmon Fishing
Marin and Sonoma Counties
Drawn by Dewayne Hight

Fishing Notes

- King Salmon - Fishing is excellent in spring and summer months. Troll Apex lures, Hoochies and anchovies from Russian River mouth to Point Reyes. Mooching is also good for salmon along the same stretch of coast.
- Rockfish and Lingcod - Hit year round on coastal reefs and at Cordell Bank. Use bars, shrimp flies and bait.
- Halibut - Fishing is good in late spring, summer and fall in Tomales Bay. Drift live anchovies and shiners.

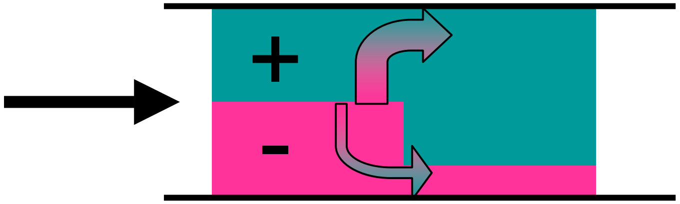
definitions

…we want to polarize a spin-1/2 ensemble (2 magnetic substates, up/down, +/-,…)



selective loss

discard (one) substate
(more than the other)



selective flip

reverse (one) substate
(more than the other)

Conclusions on “How?”

Channeling, dynamic nucl pol	Far out, but worth more attention Intriguing open physics questions
Polarizing beam in a ring by loss	works in principle, but we need Axx+Ayy, and Azz for $\vec{\bar{p}} + \vec{p}$
Polarizing beam in a ring by flip	not the miracle cure that we hoped for

SOLID POLARIZED TARGETS FOR PARTICLE SCATTERING EXPERIMENTS

ADVANCES and SPIN-OFFS

D. G. Crabb
University of Virginia

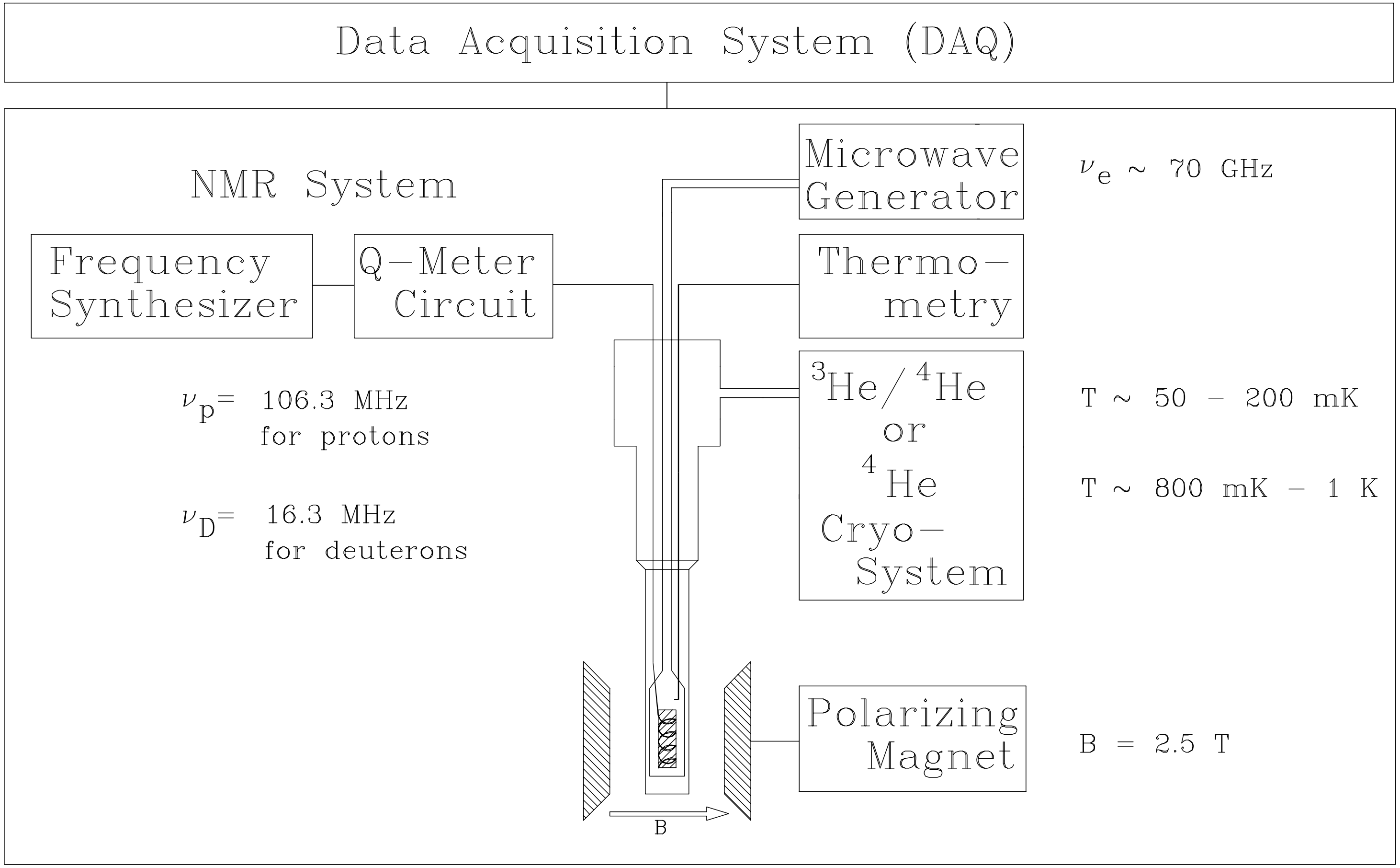
Talk Structure

- Introduction
- Refrigerators
- Materials and Properties
- High Intensity Beams
  - Ammonia
  - ^{6}LiD - Nuclear Effects
  - Radiation Resistance
- Low Intensity and Neutral Beams
- Frozen Spin
  - Conventional
  - HD
- High Temperature
- Medical/Biological
- Thin Targets
- Future

Introduction

- ^{4}He, ^{3}He and ^{3}He/ ^{4}He dilution refrigerators used over ~ 40 years.
- Divergence to using either ^{4}He or dilution fridges
- At same time – improvement in magnets
- DNP process used over range of 2 T to 7 T and 100 mK to ~1 K.
- Modern Systems → High power in high intensity beams
  → Moderate power in low intensity or neutral beams
- Most recent progress in materials

Major Polarized Target Systems



Data Acquisition System (DAQ)

NMR System

Frequency Synthesizer

Q-Meter Circuit

$\nu_p =$ 106.3 MHz
for protons

$\nu_D =$ 16.3 MHz
for deuterons

Microwave Generator

$\nu_e \sim$ 70 GHz

Thermometry

^{3}He/^{4}He or ^{4}He Cryo-System

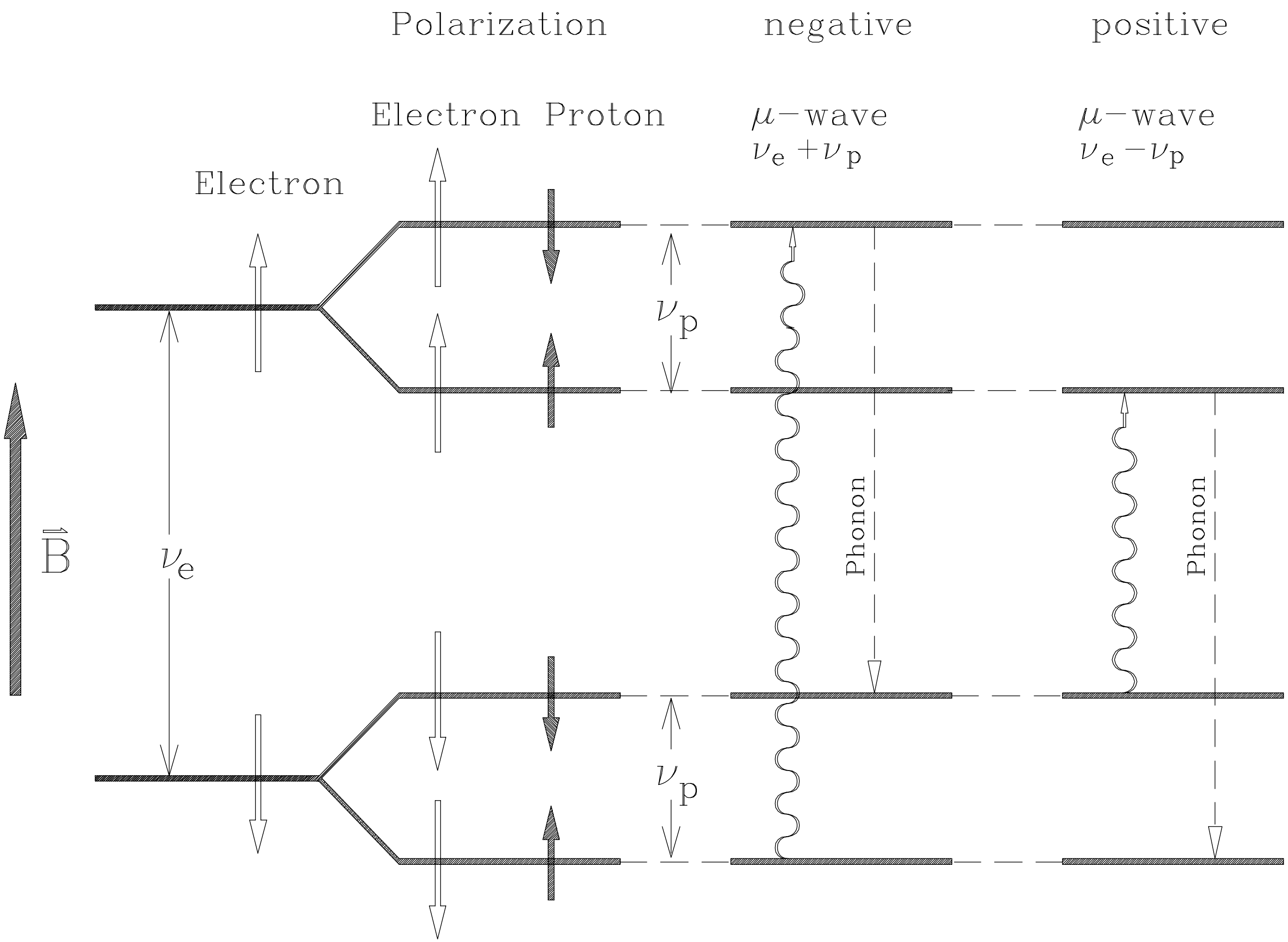
T ~ 50 – 200 mK

T ~ 800 mK – 1 K

Polarizing Magnet

B = 2.5 T

DNP

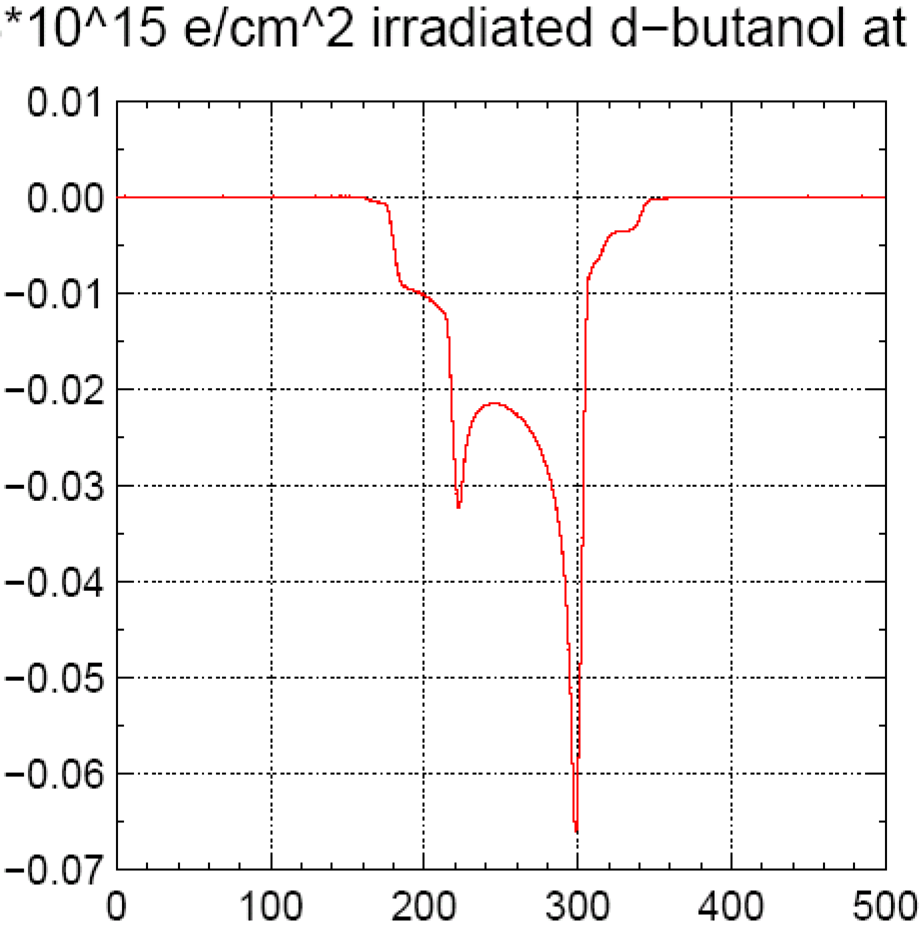

Polarization
negative
positive
Electron
Proton
μ−wave
$\nu_e + \nu_p$
μ−wave
$\nu_e - \nu_p$
Electron
ν_p
$\vec{B}$
ν_e
Phonon
Phonon
ν_p

NMR

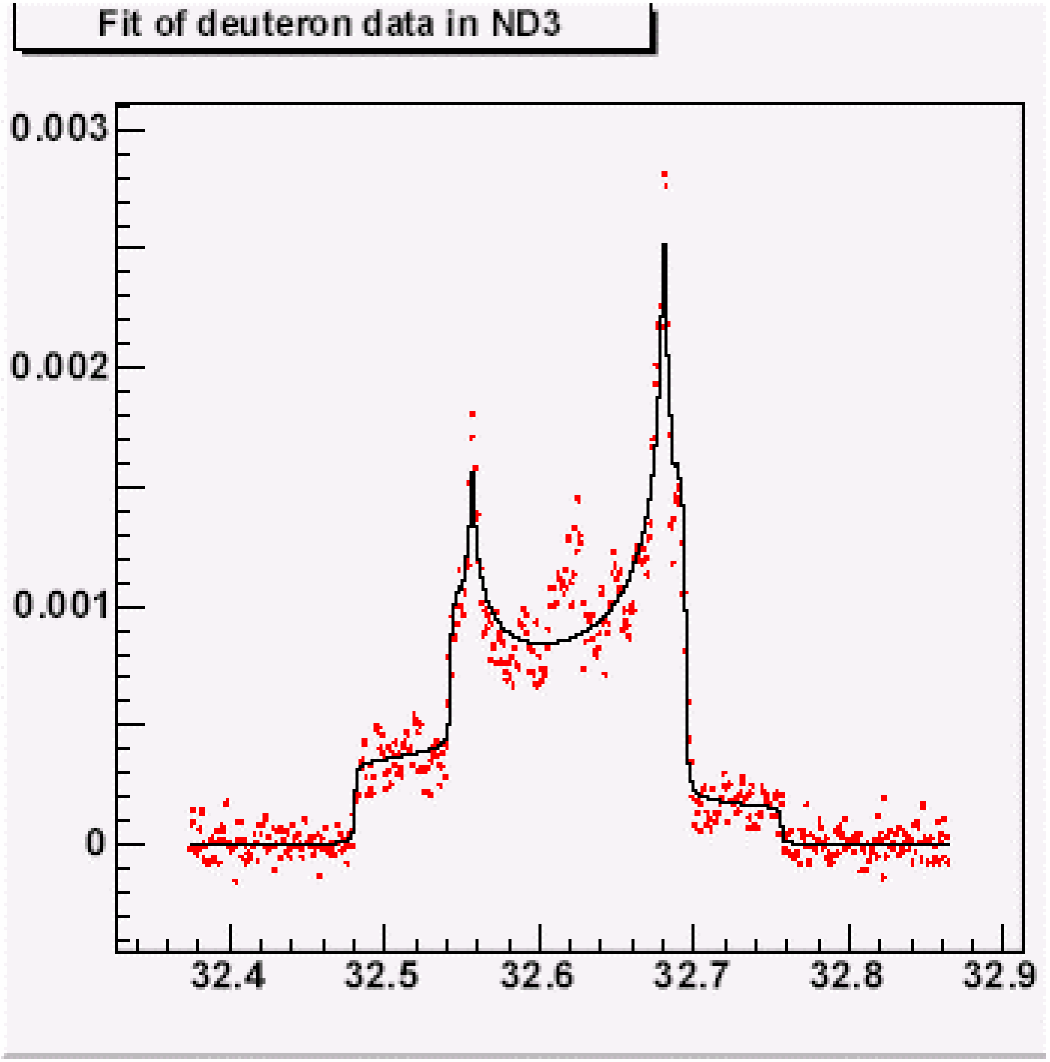
- Liverpool Q-meter - standard for many years.
- Modification - Resonant circuit mounted very near target – reduced noise, increased stability.

- Pulsed NMR ???

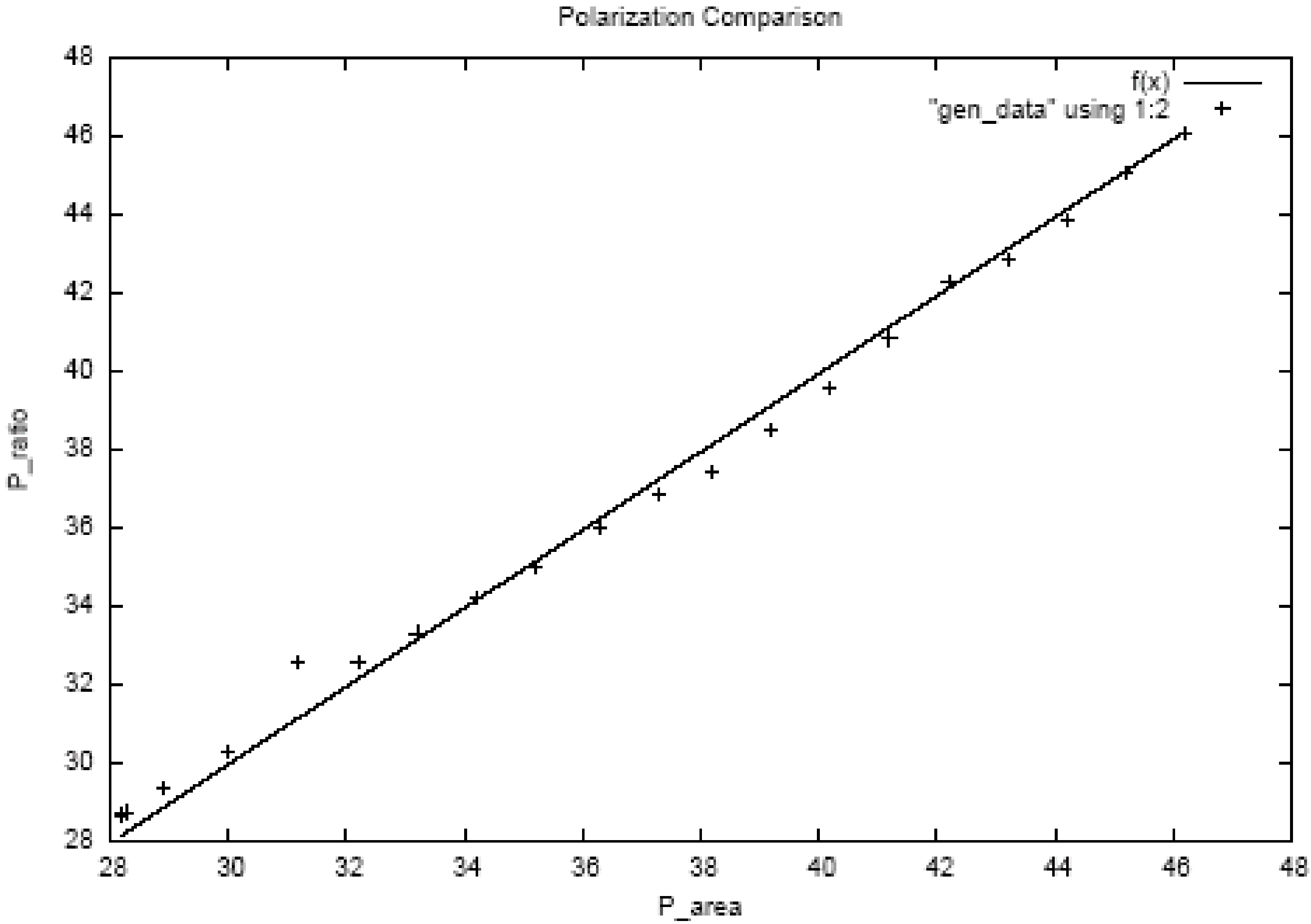
Deuteron Polarization of 63% at 6.5T and 1 K



Deuteron Enhanced Signal in EG4



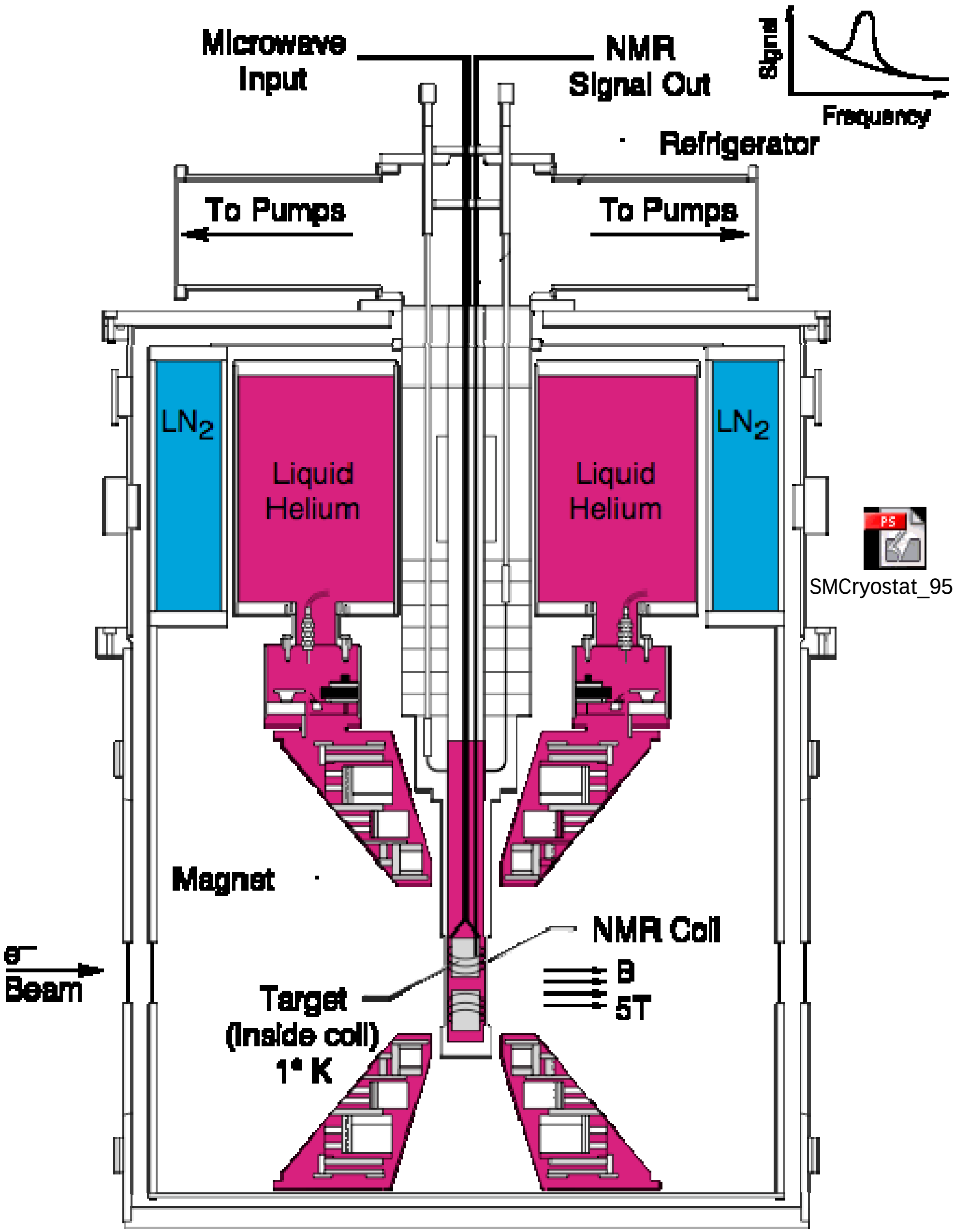
Polarization Comparison between Ratio and Area Method



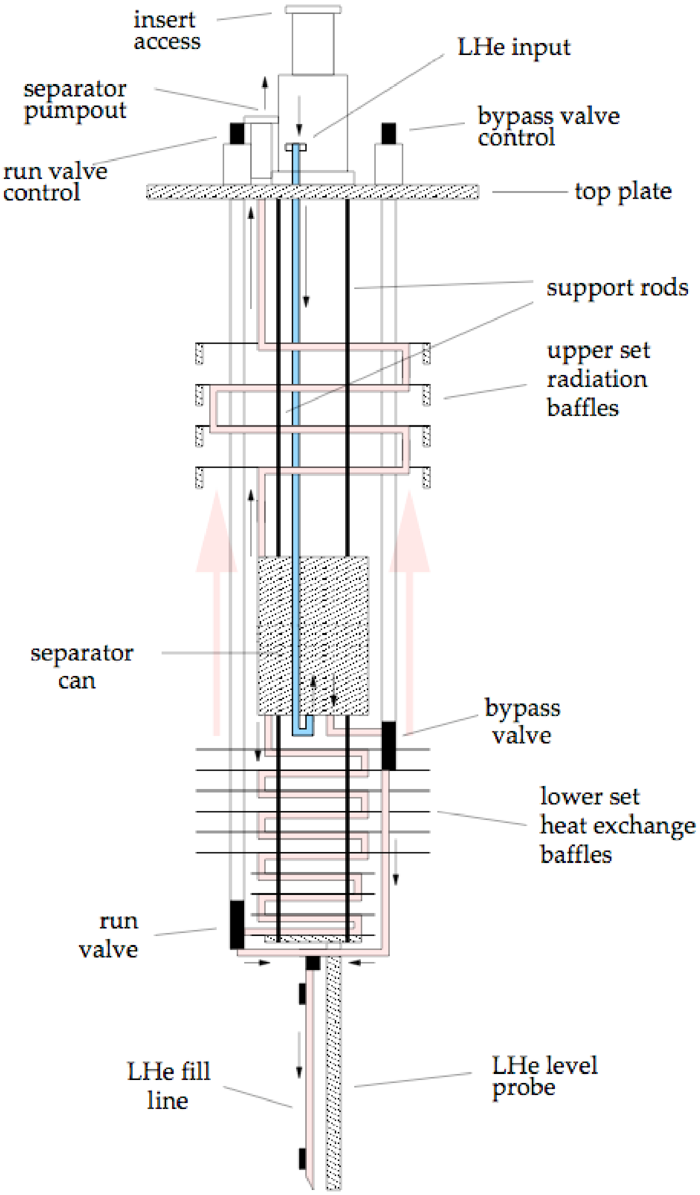
Microwaves

- EIO "standard" especially at higher frequencies – eg. 140 GHz 10 – 15 W
- But can now obtain ~3 to 5 W close to 200GHz ~6W at 183GHz and 2.5 W at 211 GHz
- But no mechanical tuning – electrical tuning range ~200 MHz . Move magnetic field to reach both polarization signs.

UVA/SLAC/JLAB Target



SMCryostat_95.ps



SMC Spin Muon Collaboration

Magnet and Refrigerator for the Polarized Target

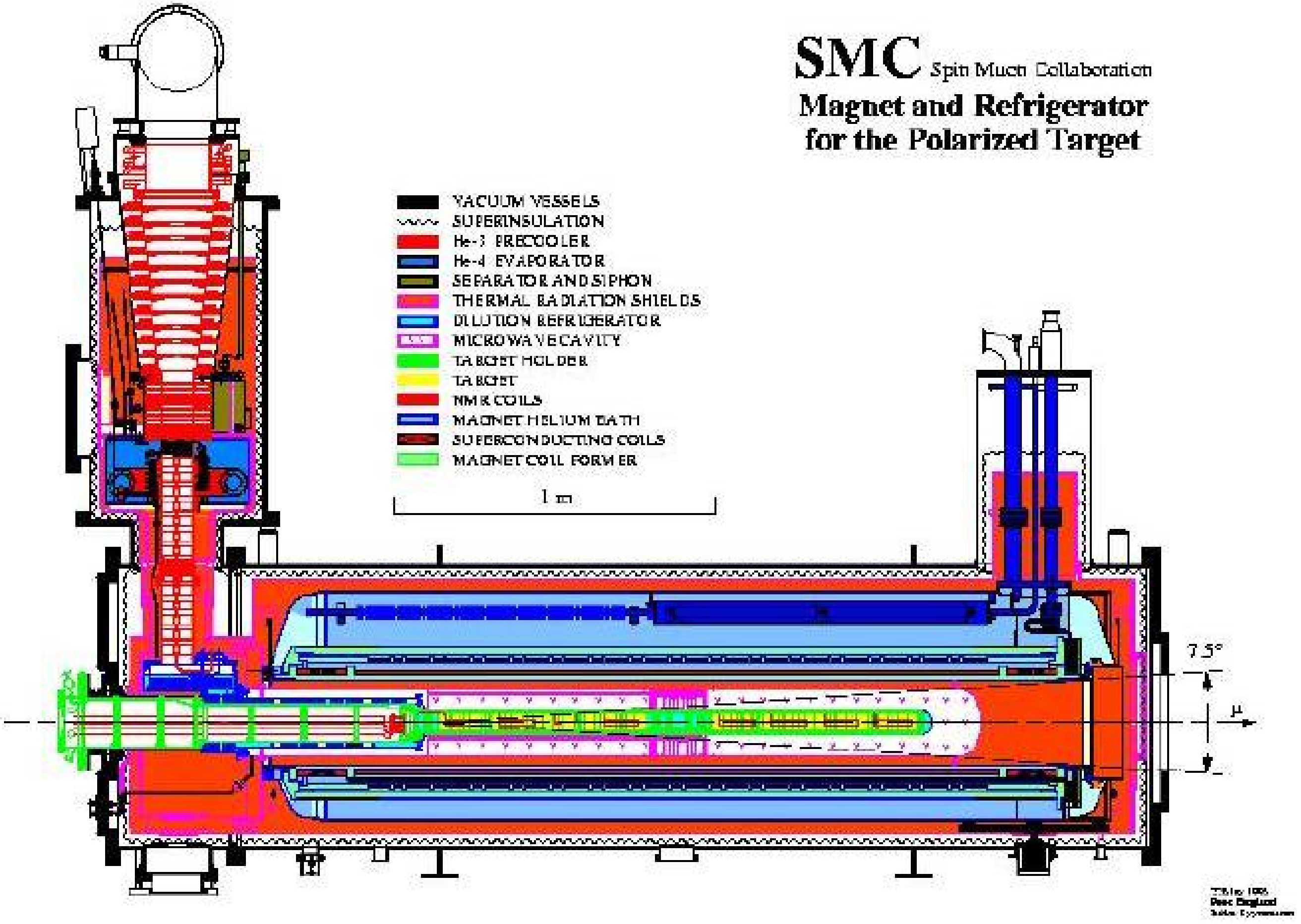


Table of polarized Target Materials

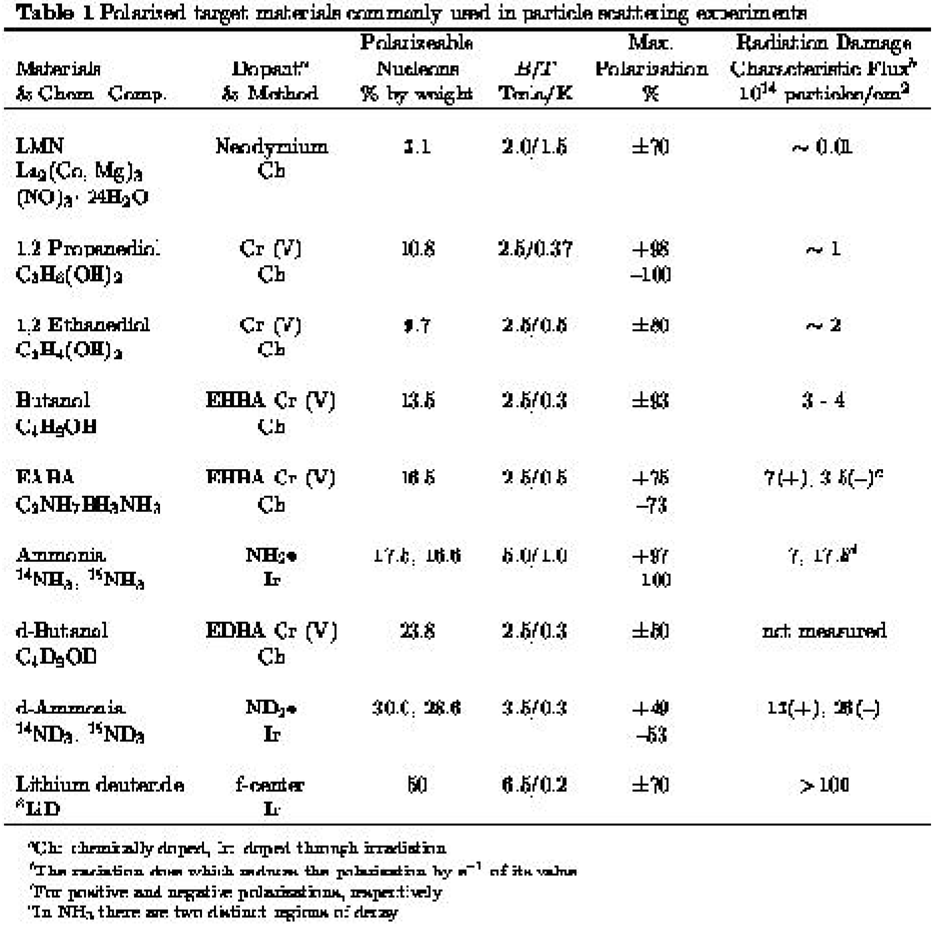
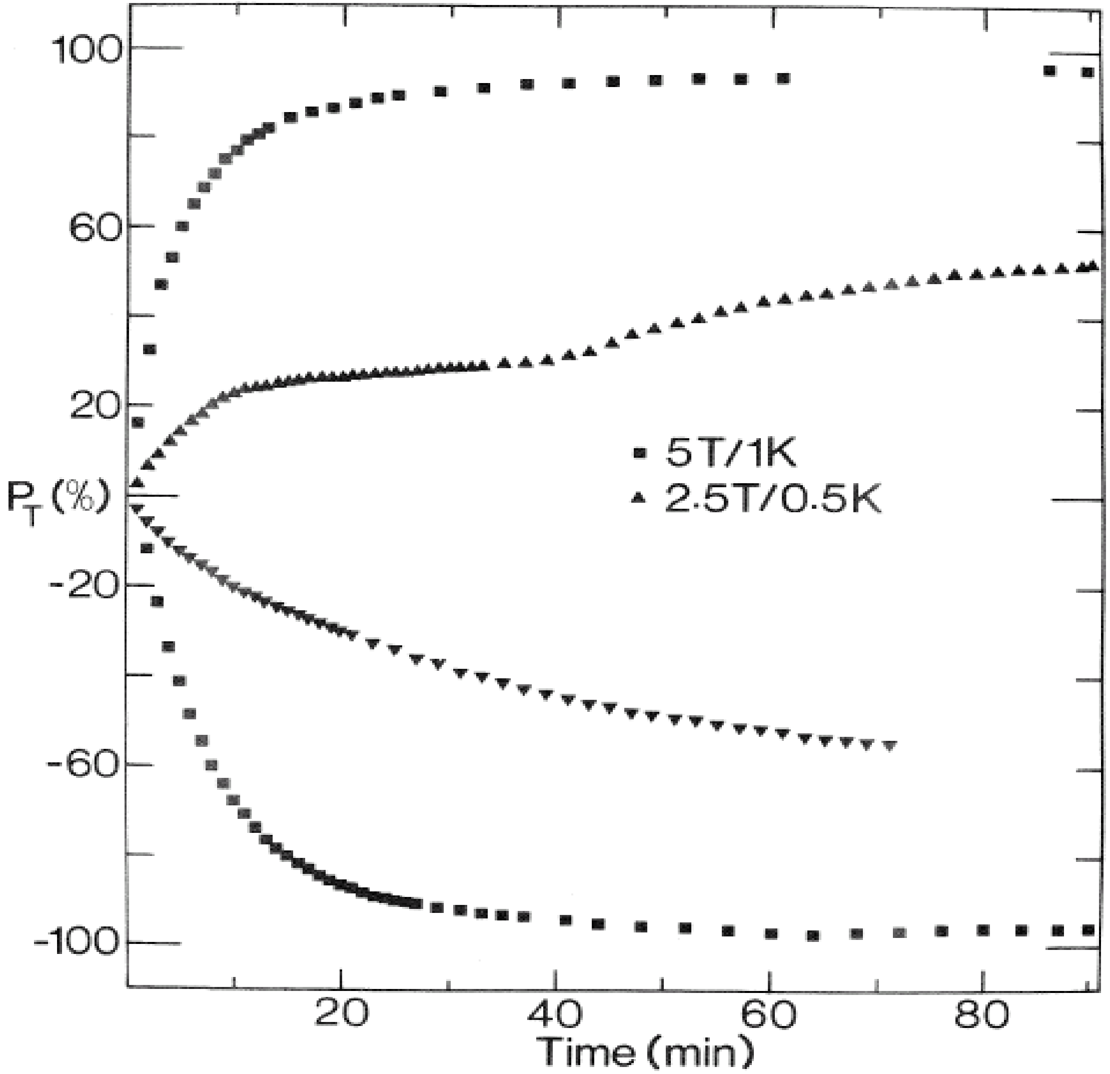


Table 1 Polarized target materials commonly used in particle scattering experiments

Materials & Chem. Comp.	Dopant[a] & Method	Polarizeable Nucleons % by weight	B/T Tmin/K	Max. Polarization %	Radiation Damage Characteristic Flux[b] 10^{14} particles/cm^2
LMN $La_2(Co, Mg)_3$ $(NO)_3 \cdot 24H_2O$	Neodymium Ch	3.1	2.0/1.5	±70	~ 0.01
1.2 Propanediol $C_3H_6(OH)_2$	Cr (V) Ch	10.8	2.5/0.37	+98 −100	~ 1
1.2 Ethanediol $C_2H_4(OH)_2$	Cr (V) Ch	9.7	2.5/0.5	±80	~ 2
Butanol C_4H_9OH	EHBA Cr (V) Ch	13.5	2.5/0.3	±93	3 - 4
EABA $C_2NH_7BH_3NH_3$	EHBA Cr (V) Ch	16.5	2.5/0.5	+75 −73	7(+), 3.5(−)[c]
Ammonia $^{14}NH_3$, $^{15}NH_3$	$NH_2\bullet$ Ir	17.5, 16.6	5.0/1.0	+97 100	7, 17.5[d]
d-Butanol C_4D_9OD	EDBA Cr (V) Ch	23.8	2.5/0.3	±50	not measured
d-Ammonia $^{14}ND_3$, $^{15}ND_3$	$ND_2\bullet$ Ir	30.0, 28.6	3.5/0.3	+49 −53	12(+), 28(−)
Lithium deuteride ^6LiD	f-center Ir	50	6.5/0.2	±70	> 100

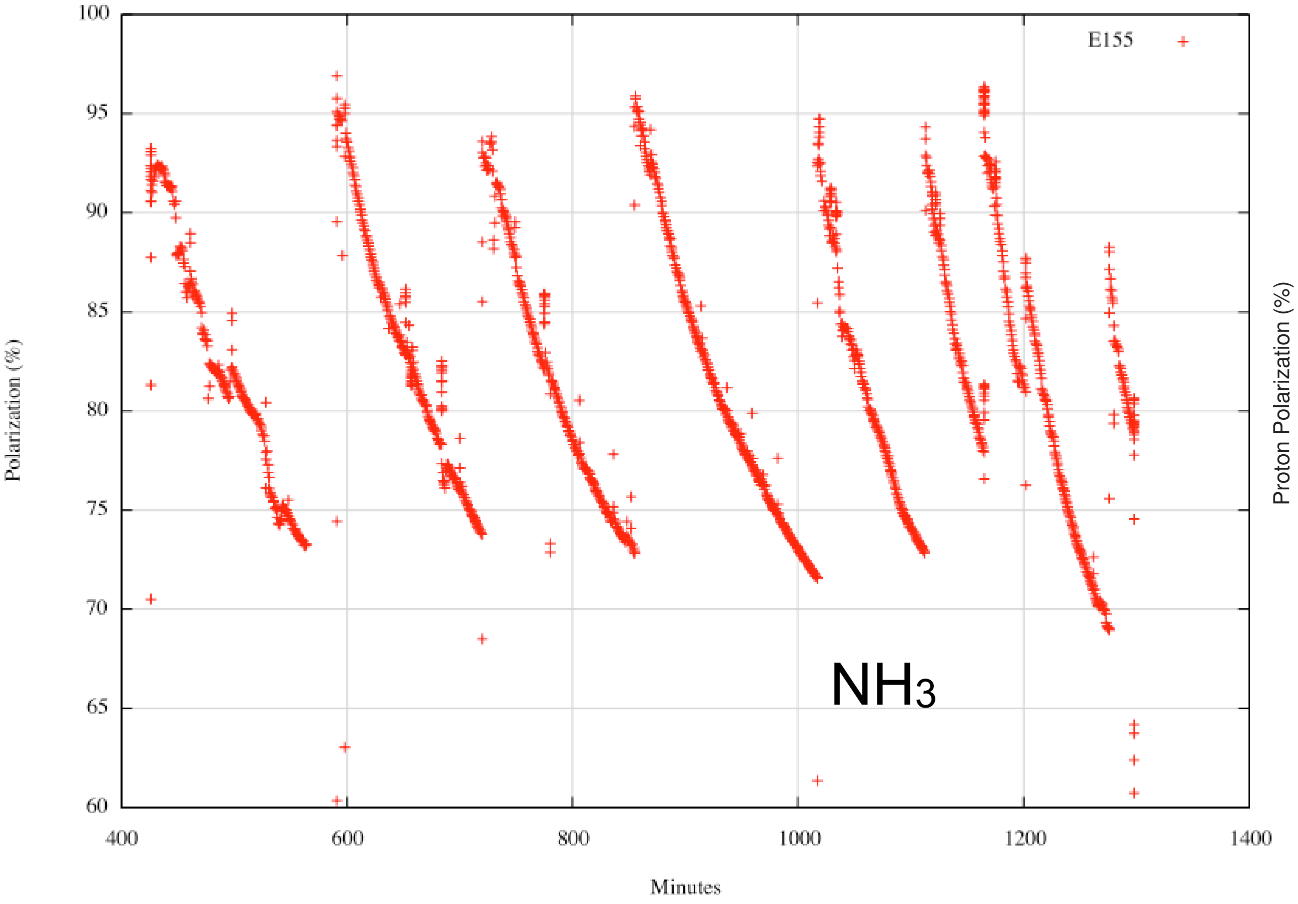
[a] Ch: chemically doped, Ir: doped through irradiation
[b] The radiation dose which reduces the polarization by e^{-1} of its value
[c] For positive and negative polarizations, respectively
[d] In NH_3 there are two distinct regions of decay

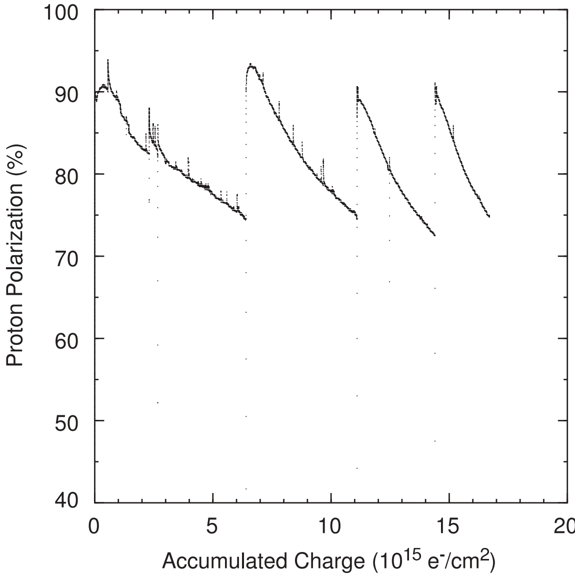
Ammonia Polarization



Target materials

Performance and Experience

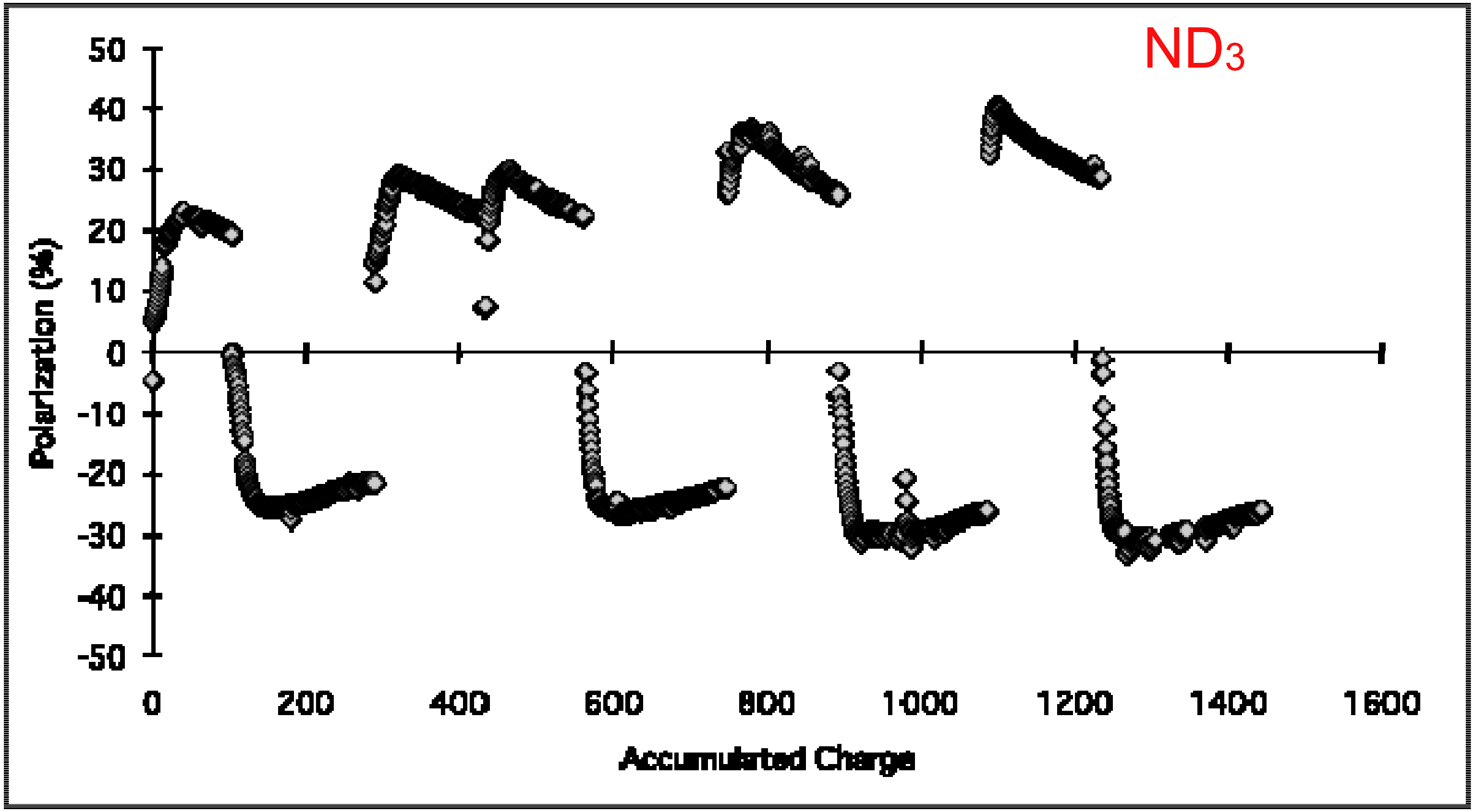




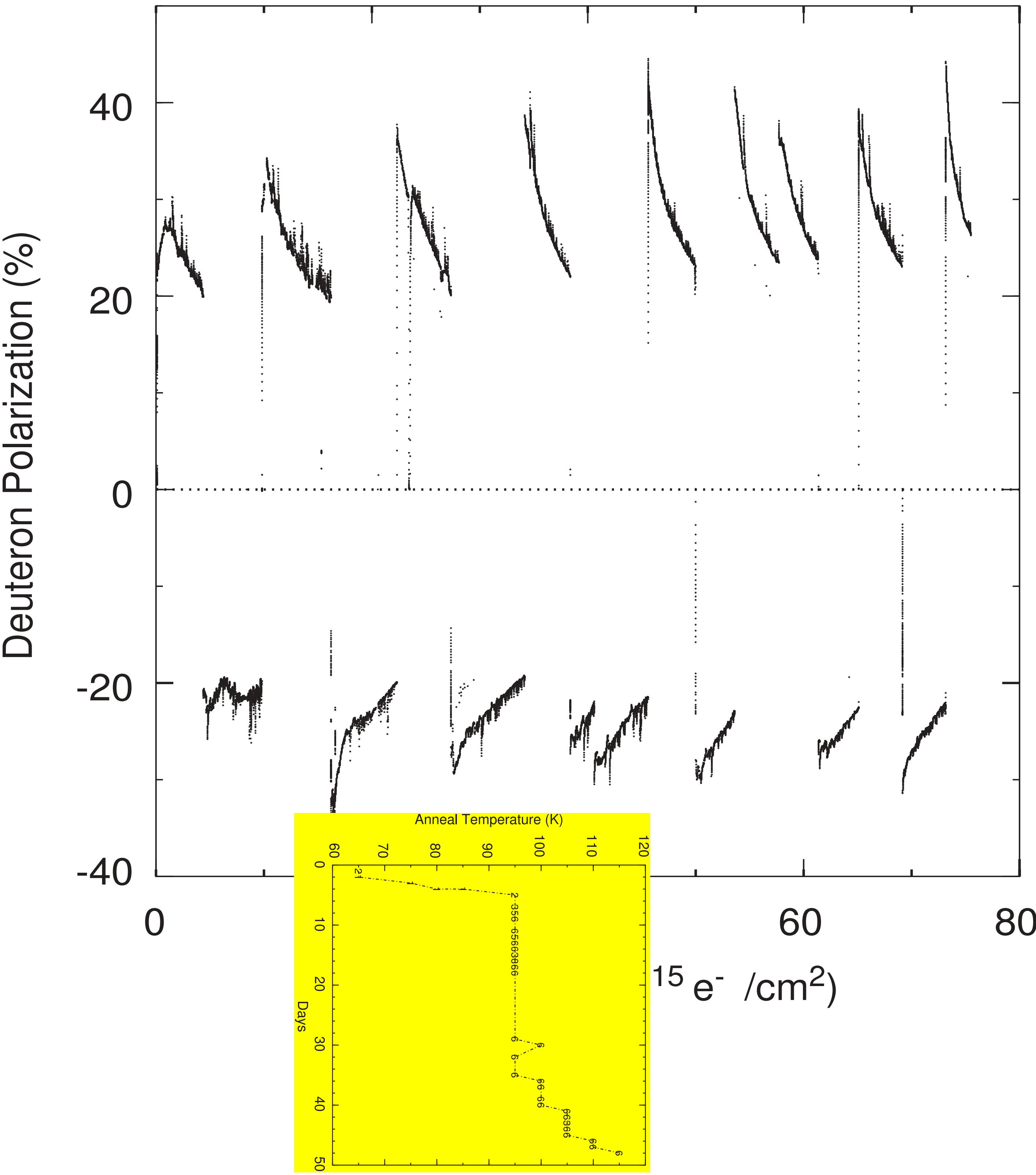
Polarization growth, radiation damage, decay of material

Target materials

Performance and Experience

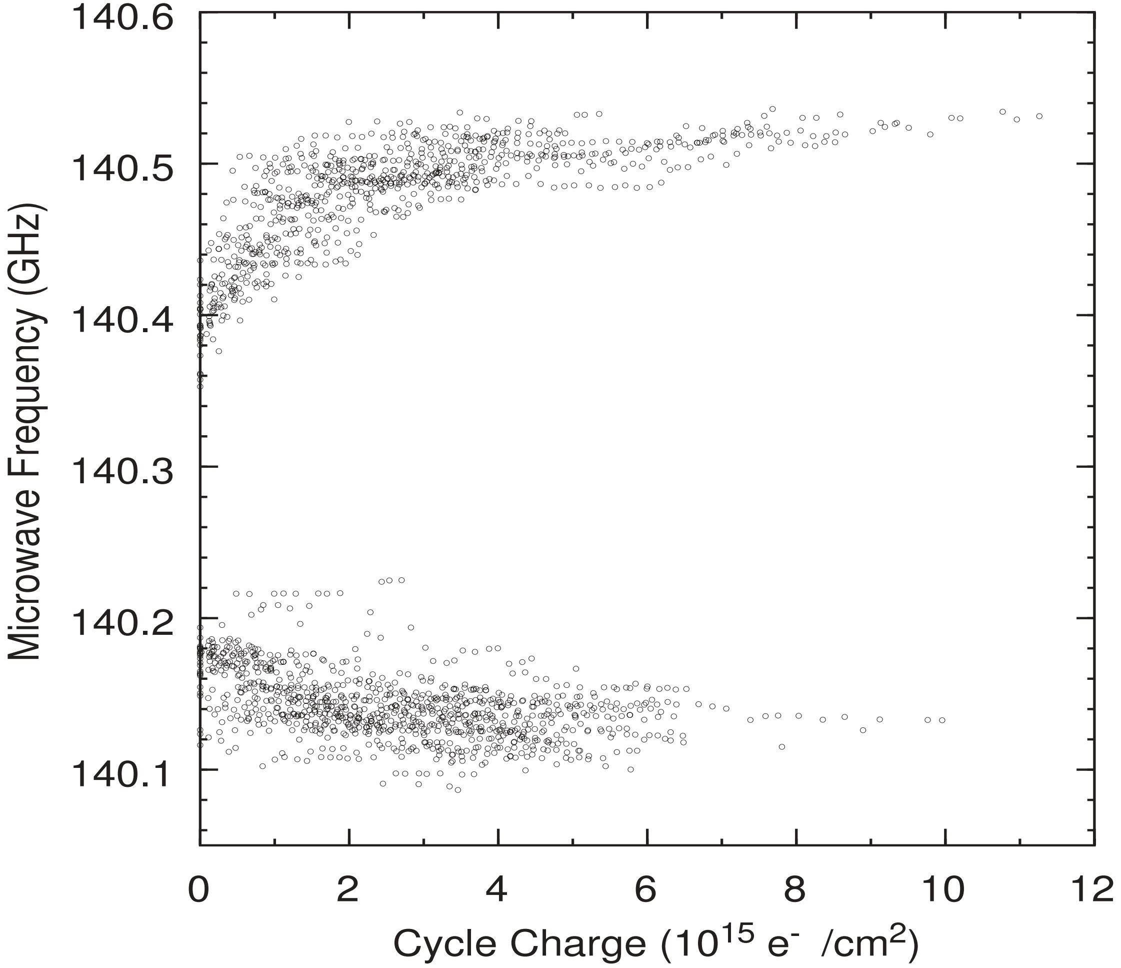


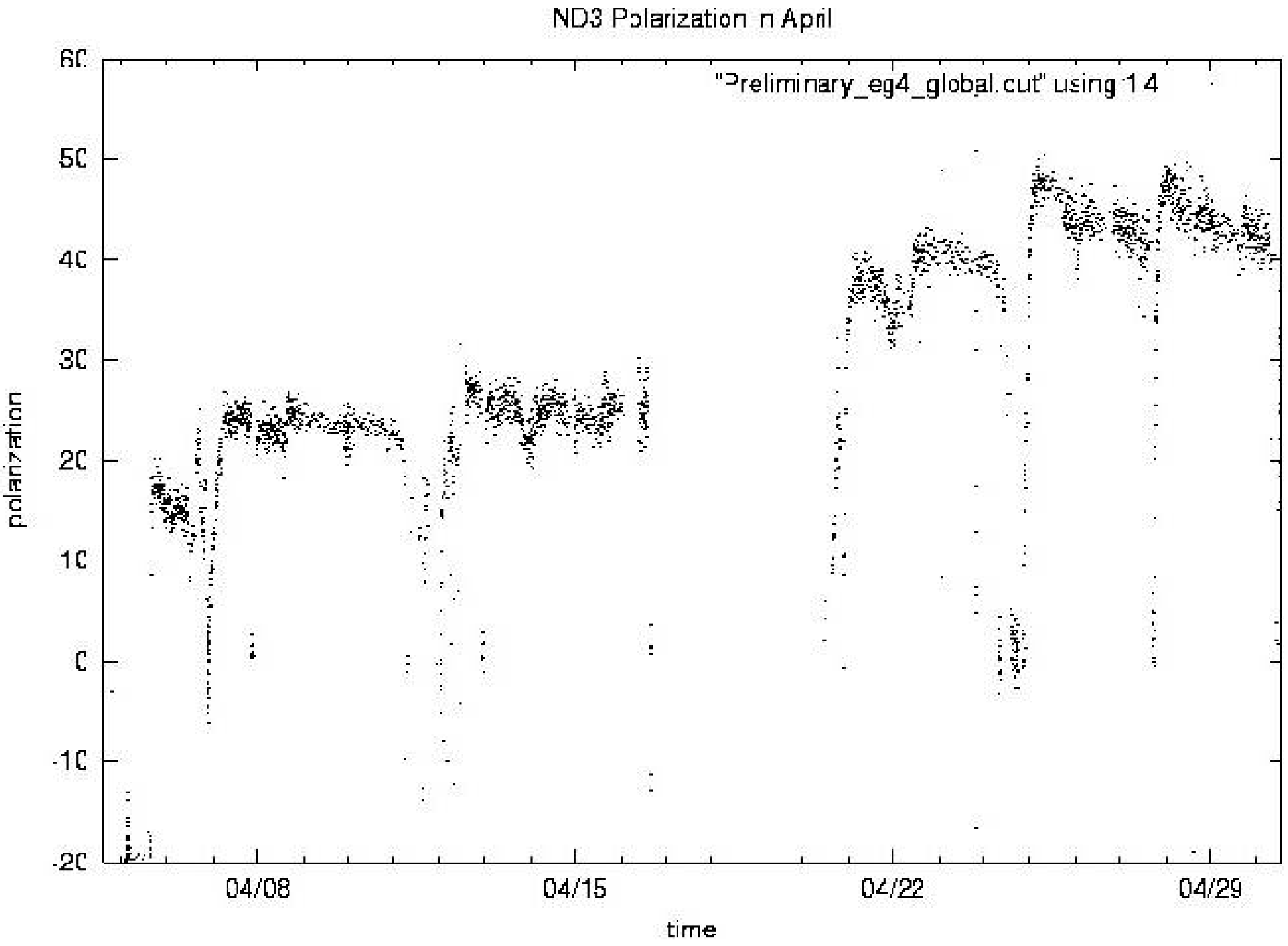
Polarization growth, Radiation damage, anneal, reverse sign

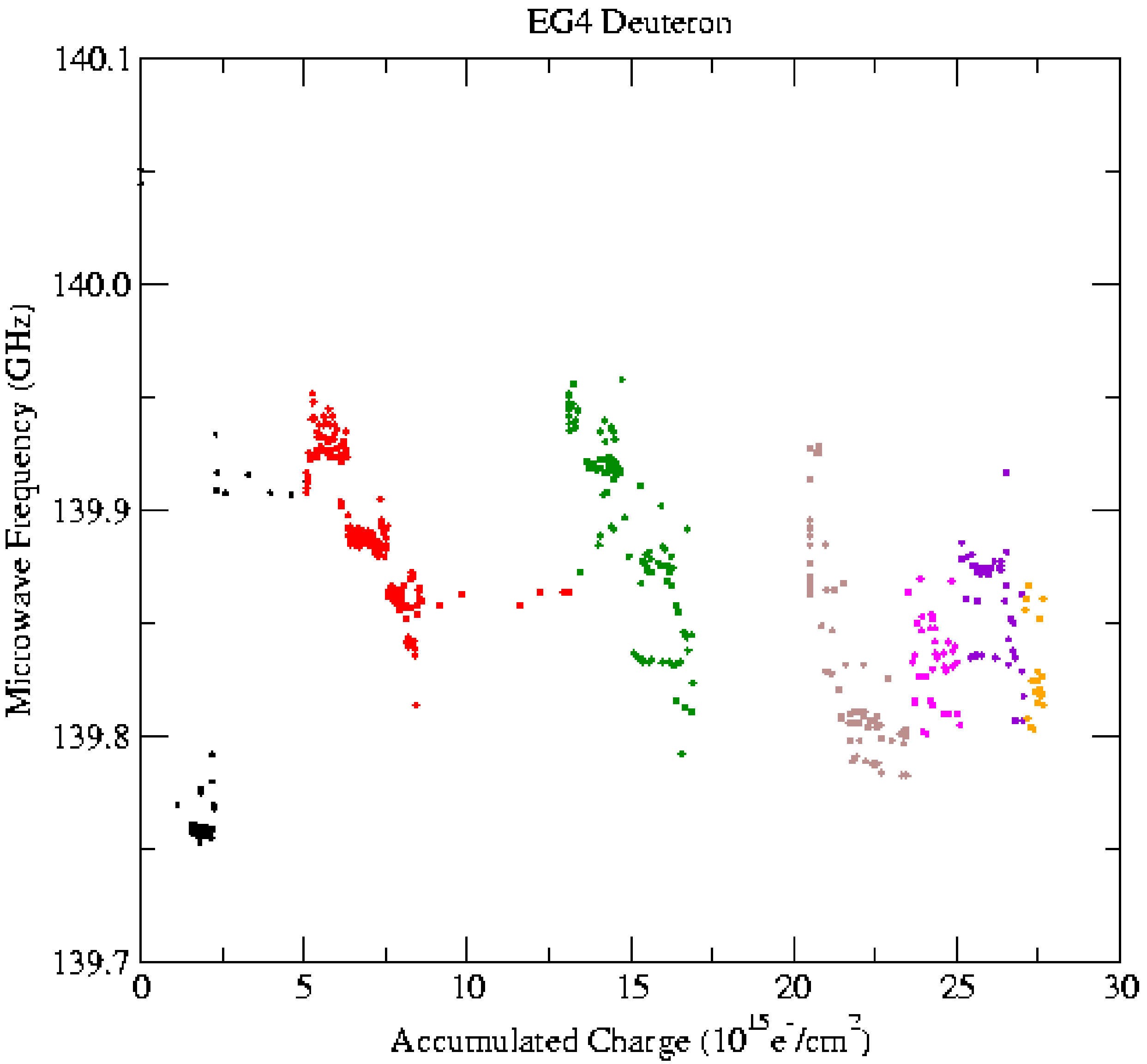


Deuteron Polarization (%)
40
20
0
-20
-40
0
60
80
15 e- /cm2)
Anneal Temperature (K)
60
70
80
90
100
110
120
Days
0
10
20
30
40
50
21
2 356 65663866
6
6
6
6
66 66
66366
66
6

Microwave Frequency Change vs Beam Charge

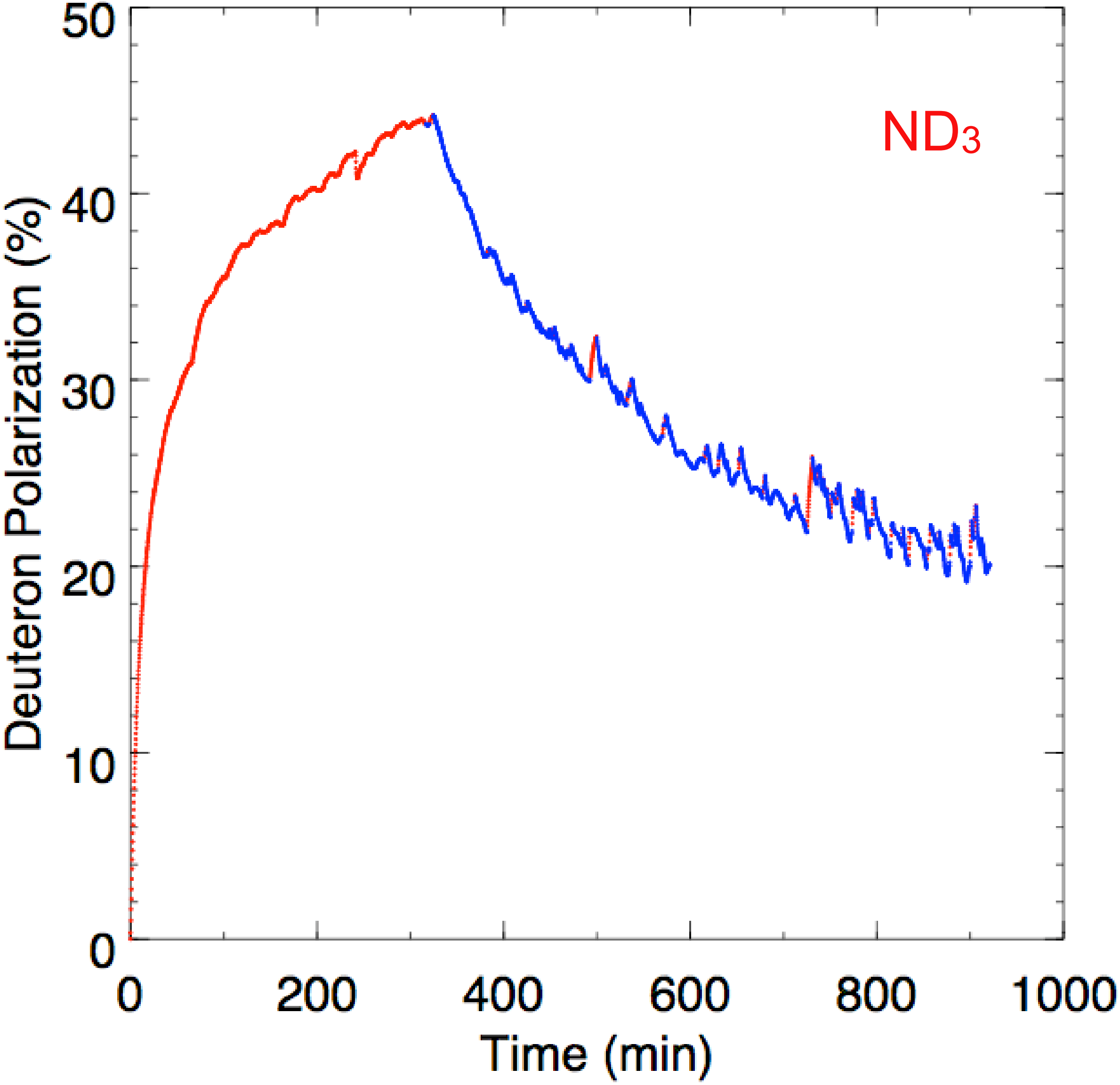



ND3 Polarization in April
"Preliminary_eg4_global.cut" using 1:4
polarization
time
60
50
40
30
20
10
0
-10
-20
04/08
04/15
04/22
04/29


EG4 Deuteron
Microwave Frequency (GHz)
140.1
140.0
139.9
139.8
139.7
0
5
10
15
20
25
30
Accumulated Charge (10^{15} e^-/cm^2)

Target materials

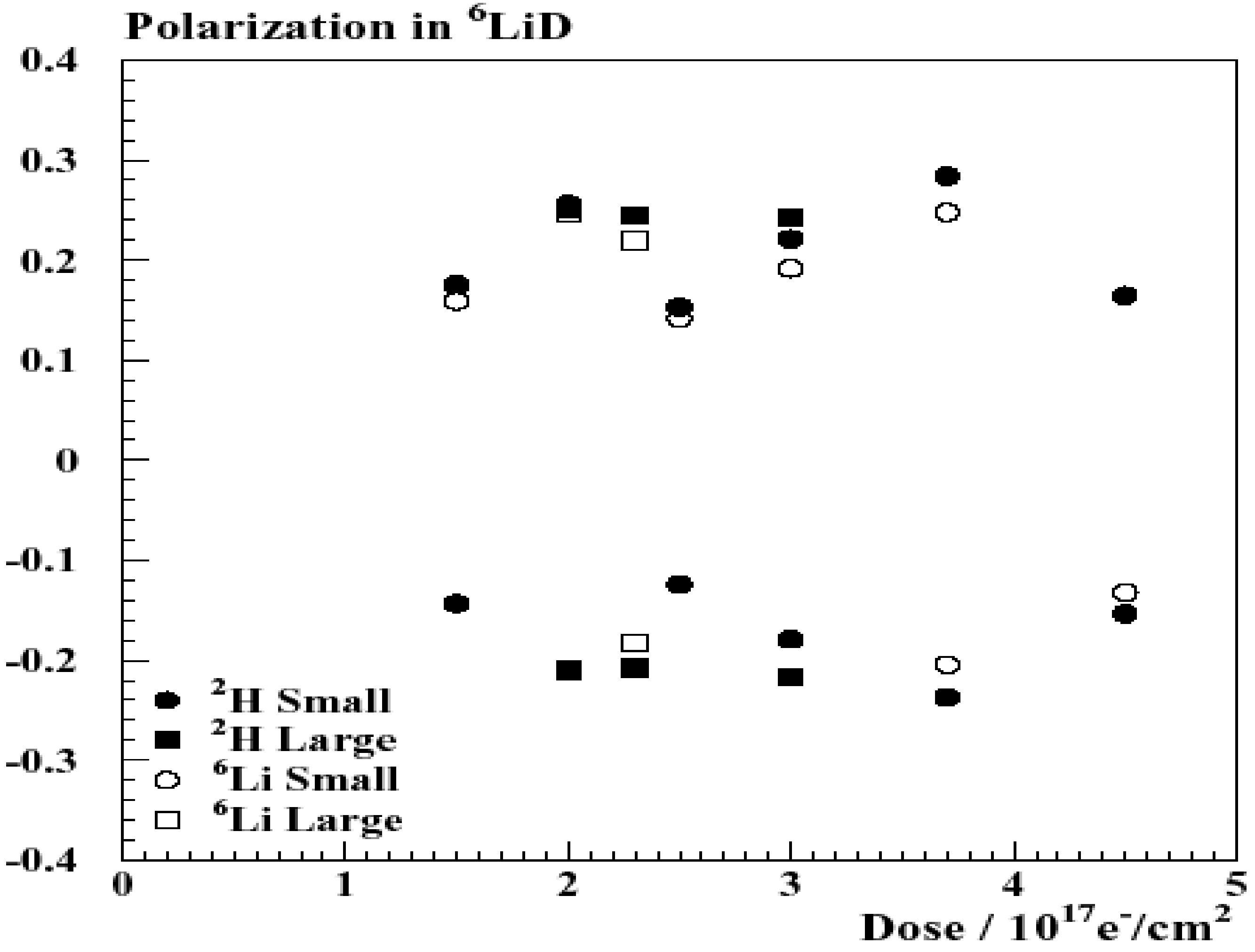
Performance and Experience

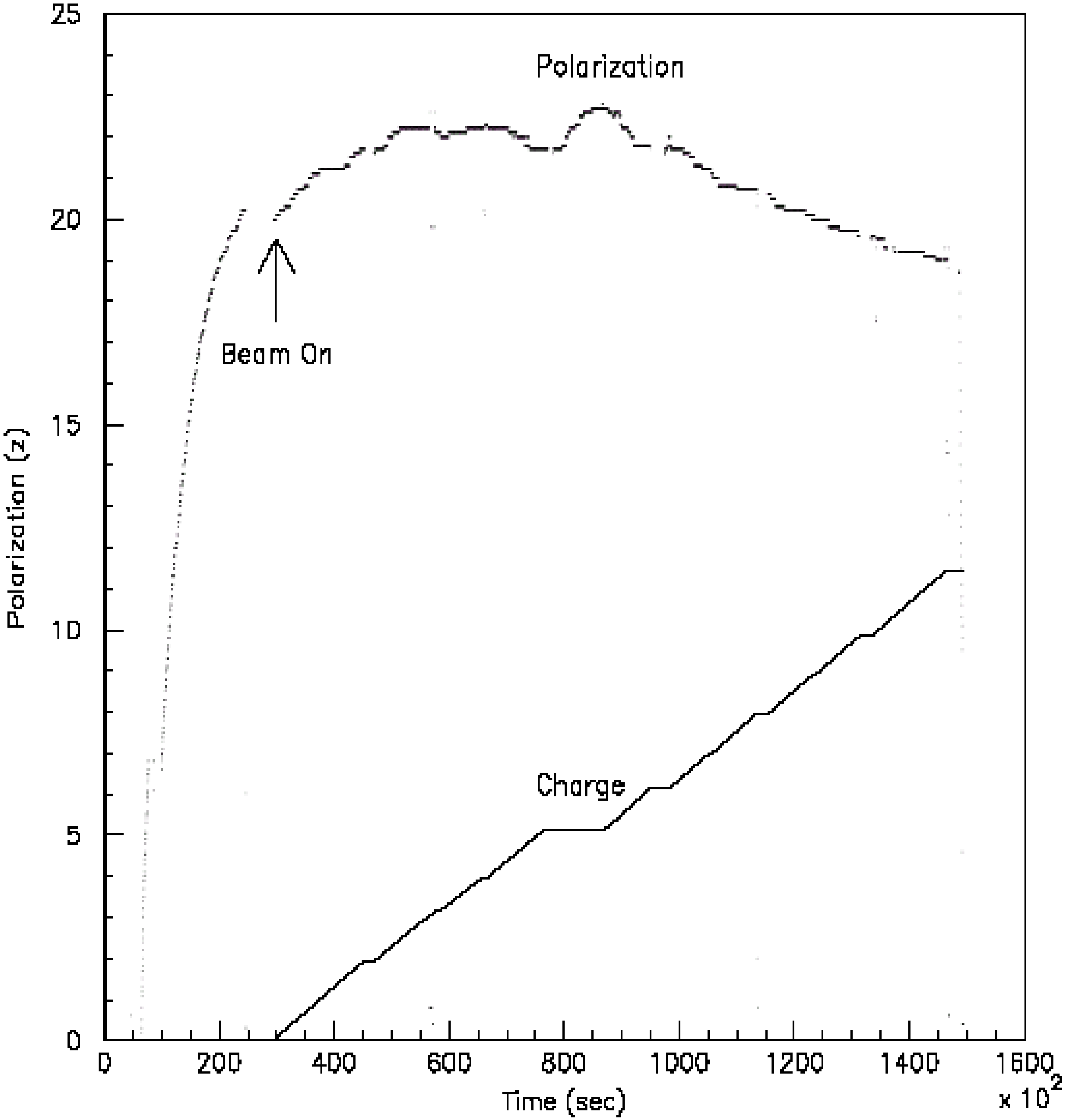


UVA/SLAC/JLAB Target

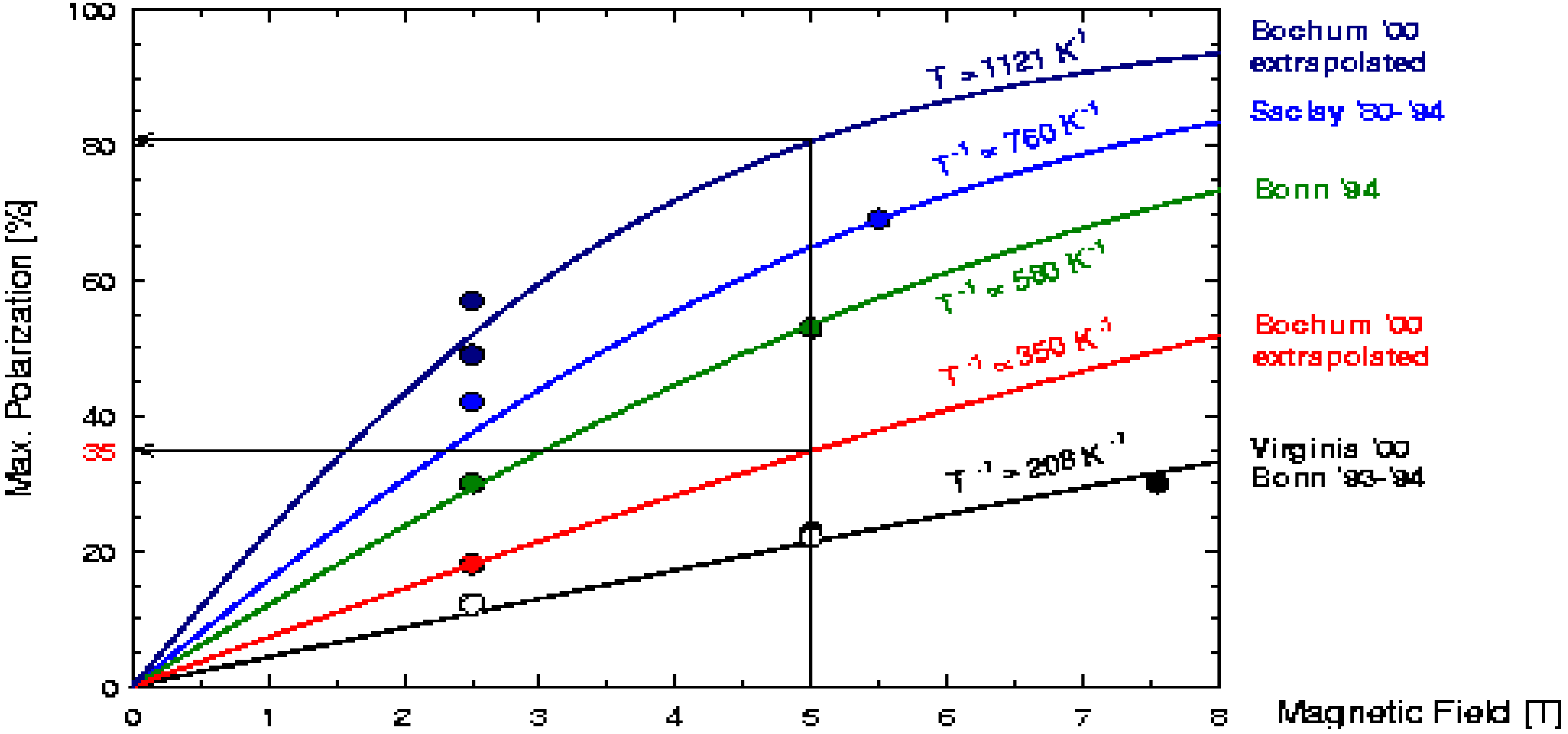
^{6}LiD

- ^{6}Li ~ d + alpha → 50% Dilution Factor
- Actual Dilution factor ~ 40%
- $P_{Li} \sim P_d$
- Irradiation: at 180 K for ~2. 10^{17} e^- cm^{-2}
- Used in SLAC experiments E155 and E155X (g_1 and g_2 for proton and neutron). E143 used $^{15}ND_3$
- Agreement at ~ 5% to 10% level
- JLab experiment ^{6}LiD/ND_3 to ~1%


Polarization in ^{6}LiD
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
0
1
2
3
4
5
Dose / 10^{17}e$^-$/cm^2
● ^{2}H Small
■ ^{2}H Large
○ ^{6}Li Small
□ ^{6}Li Large


Polarization
Beam On
Charge
Polarization (z)
Time (sec)
x 10^2
0
5
10
15
20
25
0
200
400
600
800
1000
1200
1400
1600

Inverse Spin Temperatures of the ^{6}LiD World Pol. Data

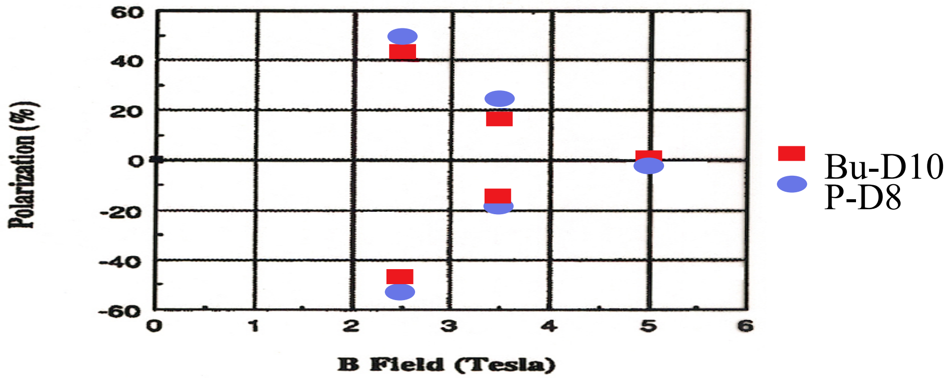


$$P = \frac{4 \tanh(g_d \mu_K B / 2kT)}{3 + \tanh^2(g_d \mu_K B / 2kT)} \sim 4/3\,(g_d \mu_K B / 2kT)$$

Magnetic field dependence of conventionally doped D-Butanol

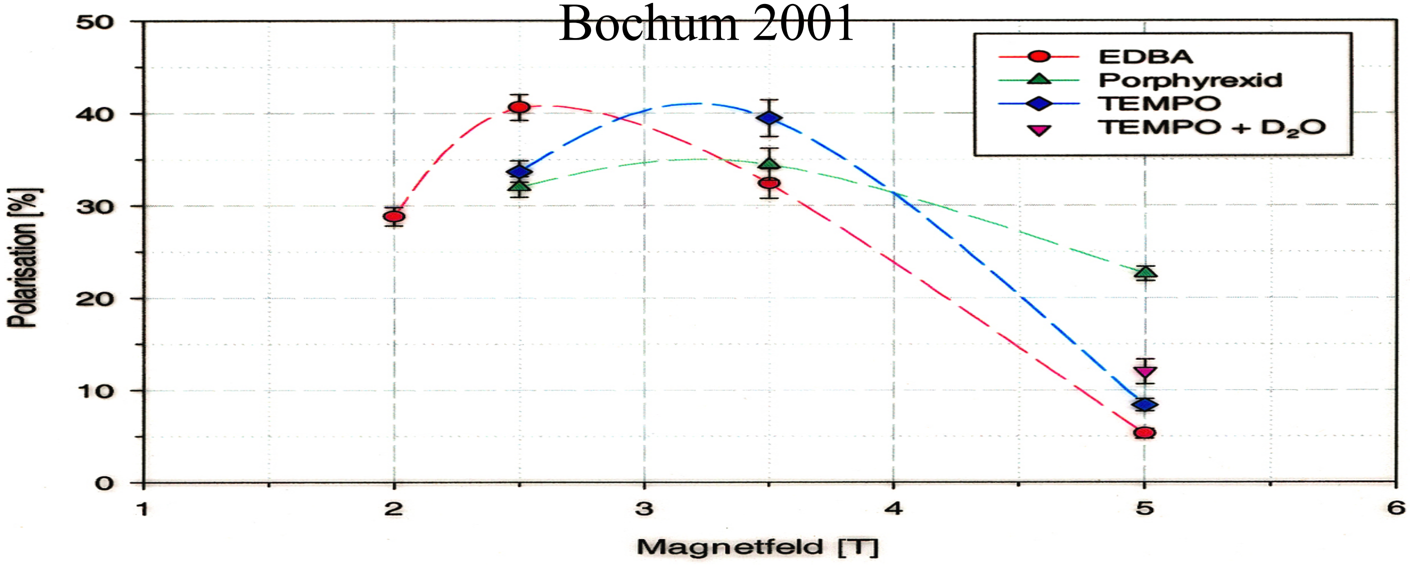
First hint reported by
PSI group
S. Trentalange et al.

Proc. 9th Int. Symposium on
High Energy Spin Physics,
Bonn 1990

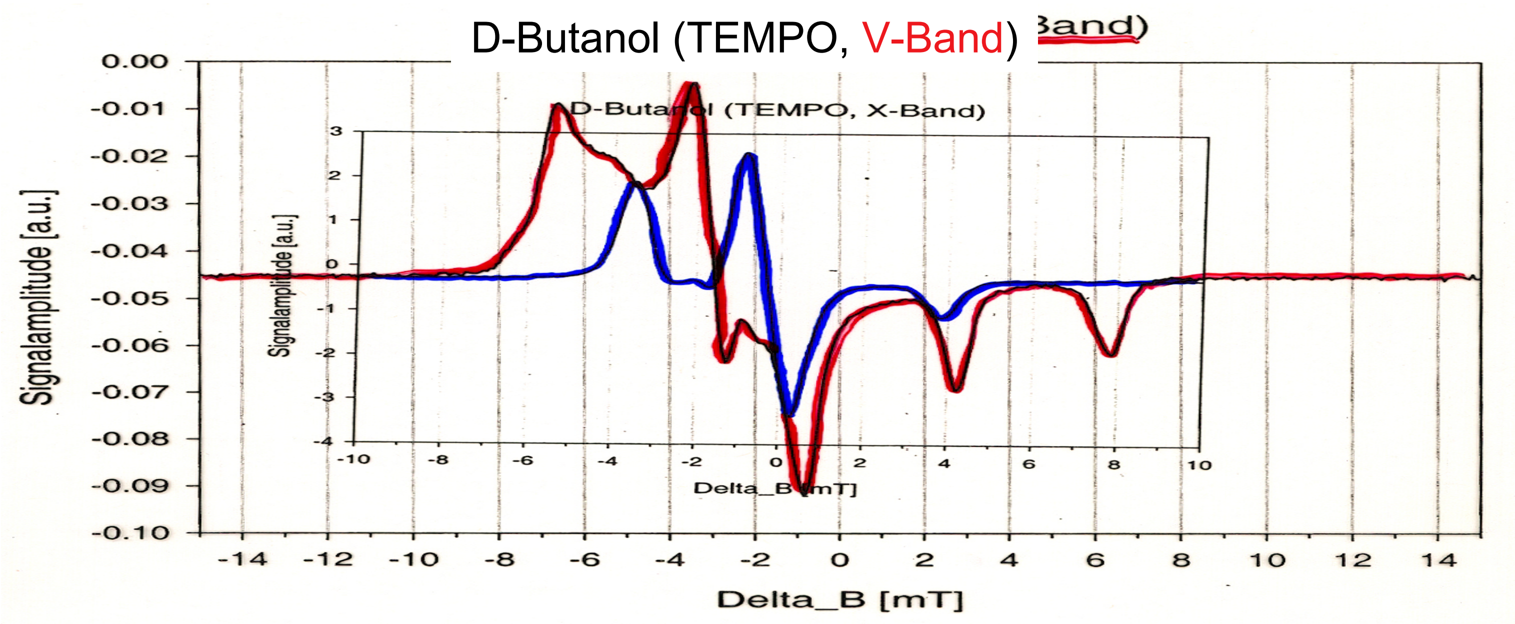


$$P_I = B_I\left(\frac{g_I \mu_K B}{2kT_Z^I}\right) = B_I(\sim B^2) \quad !$$

Systematic investigations on chemically doped D-butanol
Bochum 2001



EPR-LINE WIDTHS : X-band vs. V-Band



Sample	Measured FWHM-Linewidths [mT]	
Material + Dopant	X-band	V-band
D-butanol + Phorphyrexide	2.6	5.20
D-butanol + TEMPO	3.6	5.25
D-butanol + EDBA	2.1	12.30

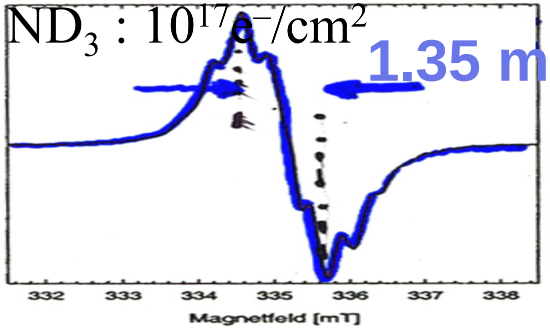
Doping method responsible or material itself ?

TEST : Paramagnetic doping of D-Butanol
by e$^-$-irradiation at 90K (liq. Ar)

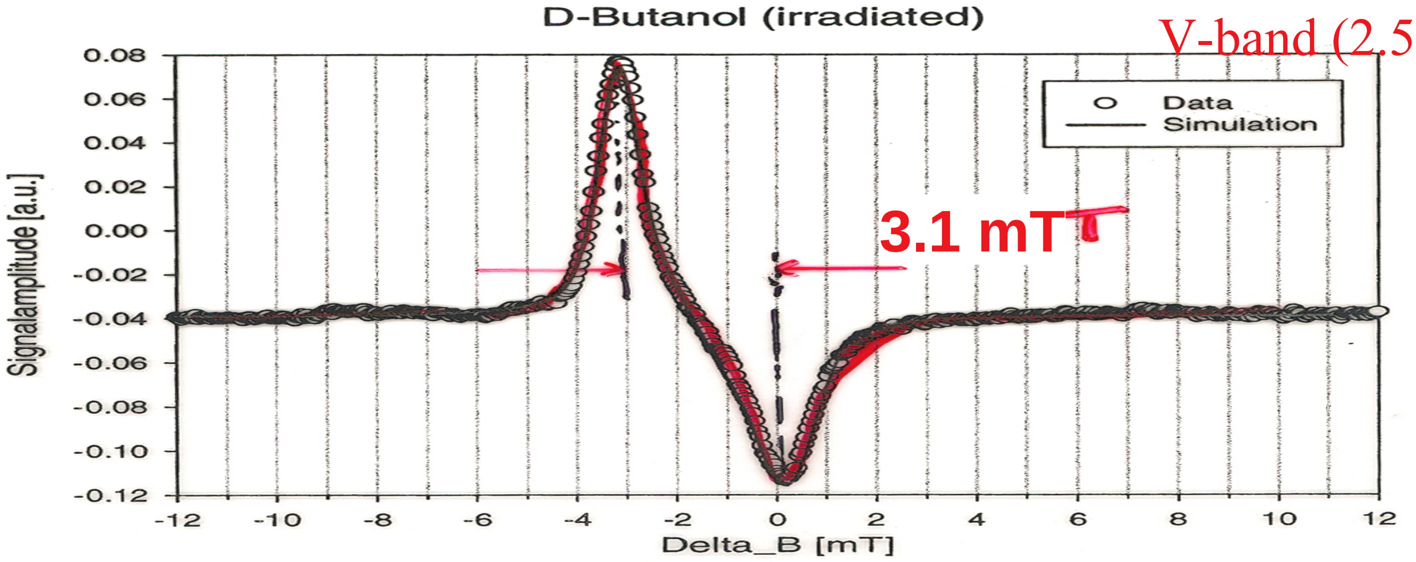
Dose for D-Butanol : some 10^{15}e$^-$/cm^2

For comparison ^{6}LiD; NH$_3$; ND$_3$: 10^{17}e$^-$/cm^2

X-band

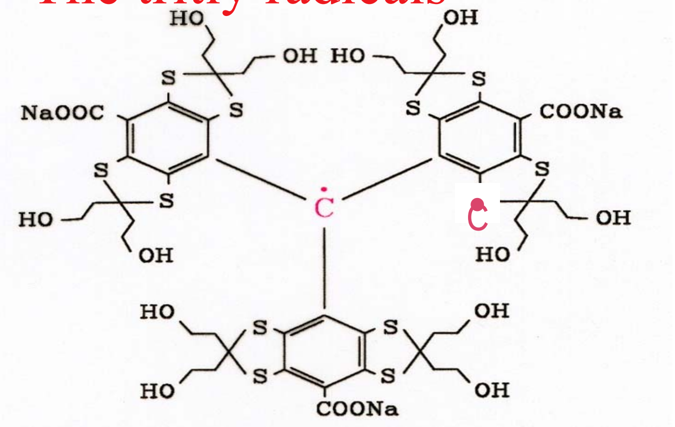

1.35 mT

V-band (2.5T)

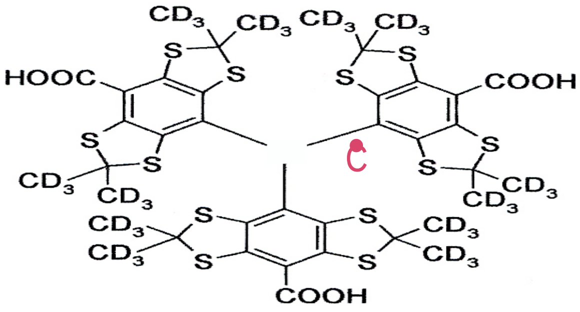

3.1 mT

Goal: Chemically stable radical with a very narrow EPR line

The tritly radicals

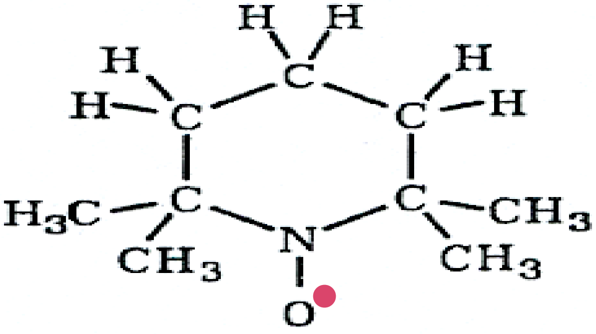


OX 063 M.W.: 1426.78

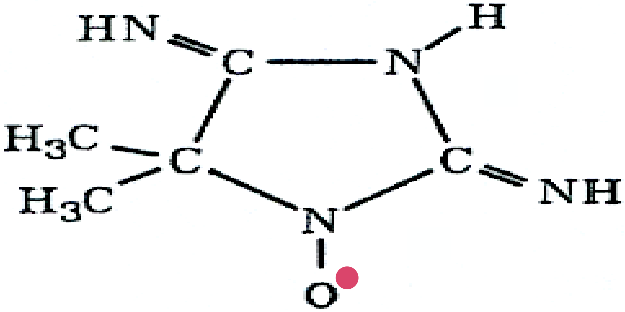


Finland D36 M.W.: 1036.9

The nitroxid radicals



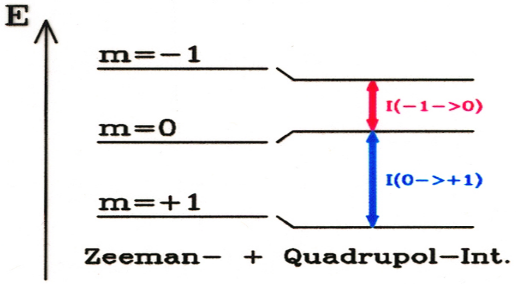
TEMPO M.W.: 144

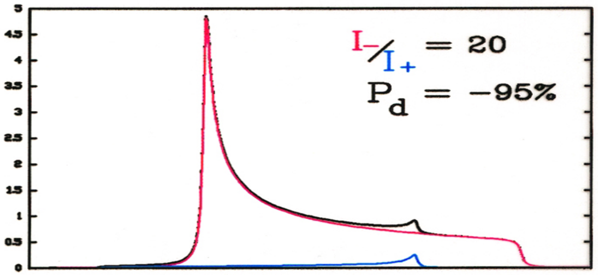


Porphyrexid M.W.: 141

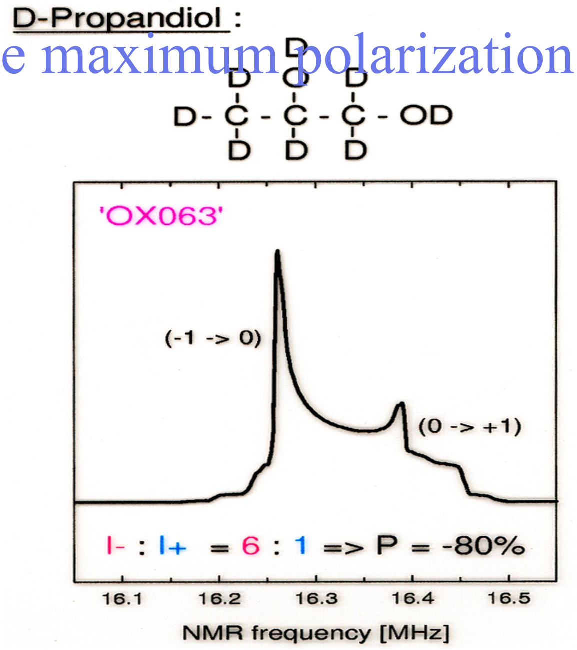
Results on trityl doped hydrocarbons

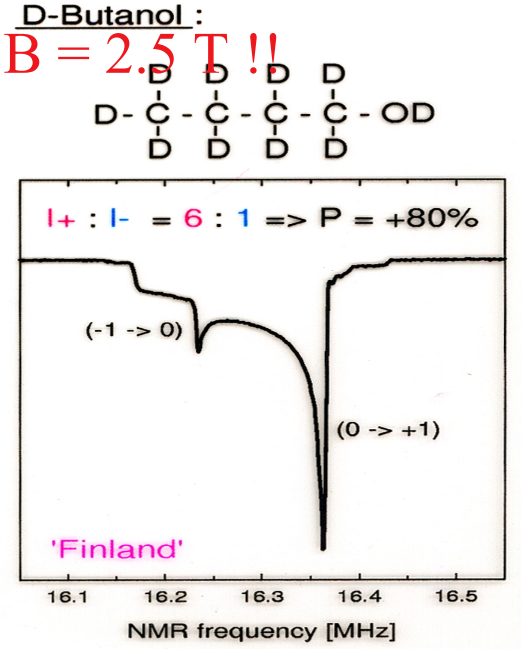
The deuteron NMR signal with quadrupole interaction

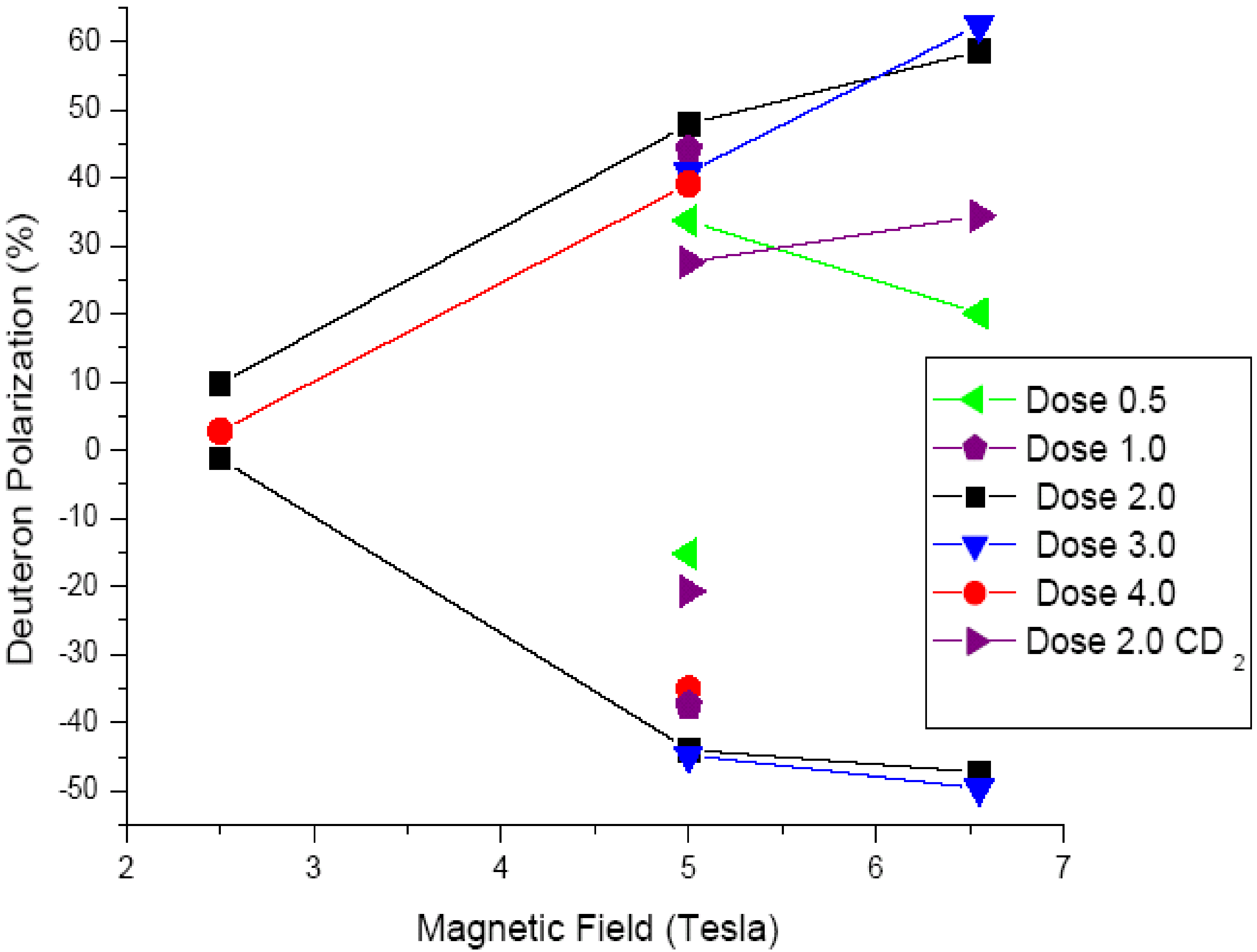


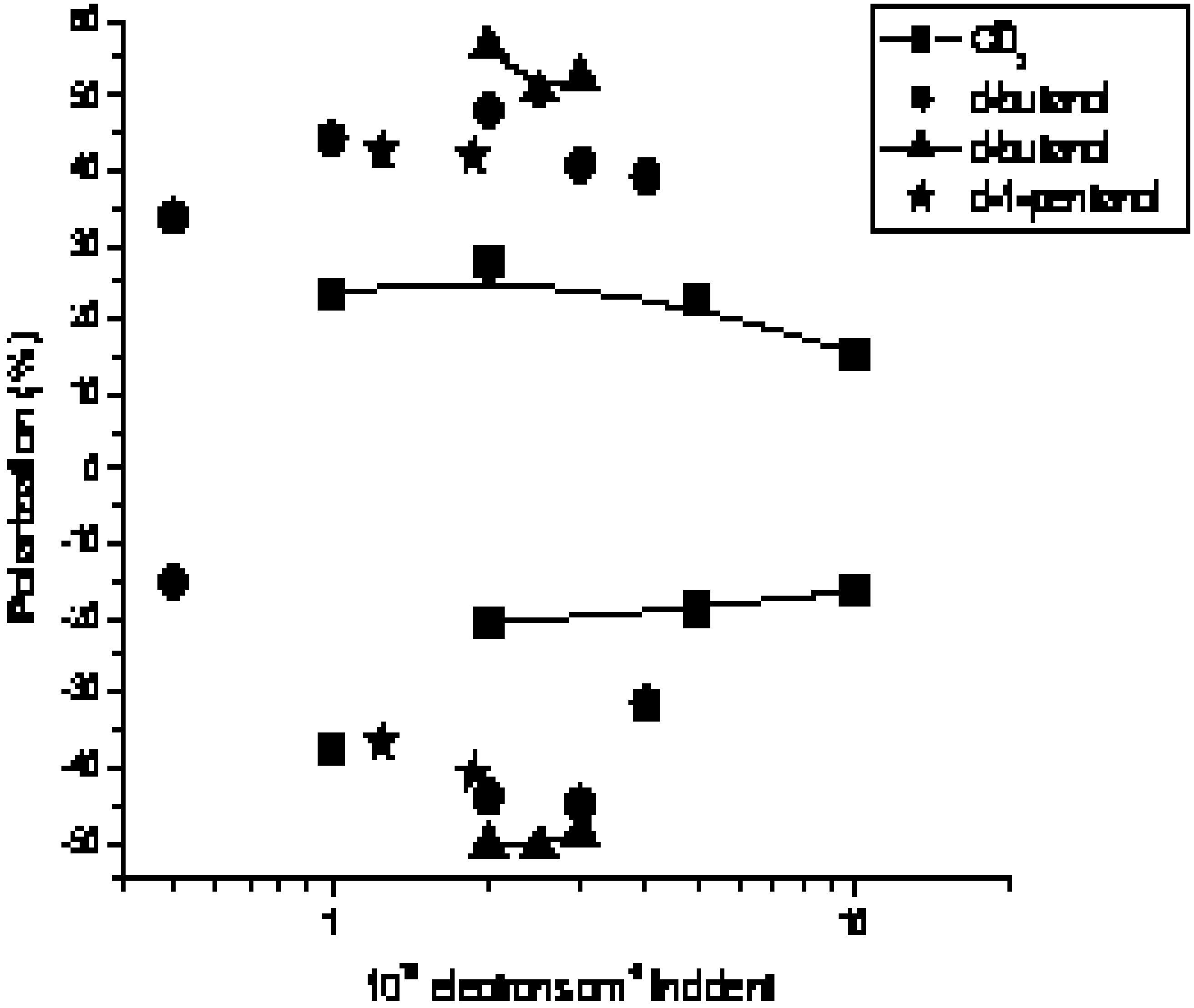


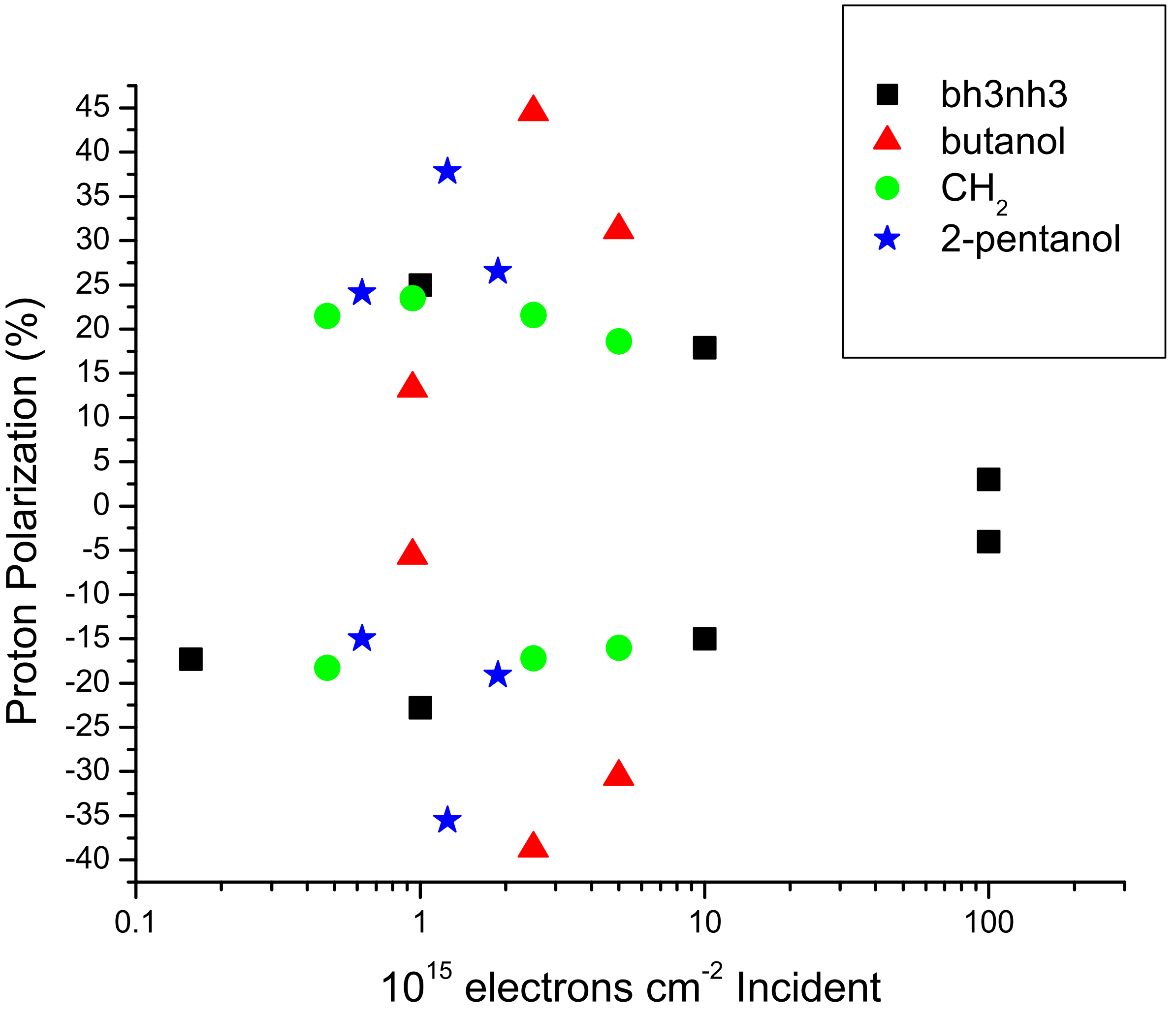
The maximum polarizations at B = 2.5 T !!






Deuteron Polarization (%)
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
2
3
4
5
6
7
Magnetic Field (Tesla)
Dose 0.5
Dose 1.0
Dose 2.0
Dose 3.0
Dose 4.0
Dose 2.0 CD 2


CO$_2$
d-butanol
d-butanol
d-1-pentanol
Polarization (%)
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
1
10
10 electrons cm incident


Proton Polarization (%)
45
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
0.1
1
10
100
10^15 electrons cm^-2 Incident
■ bh3nh3
▲ butanol
● CH2
★ 2-pentanol

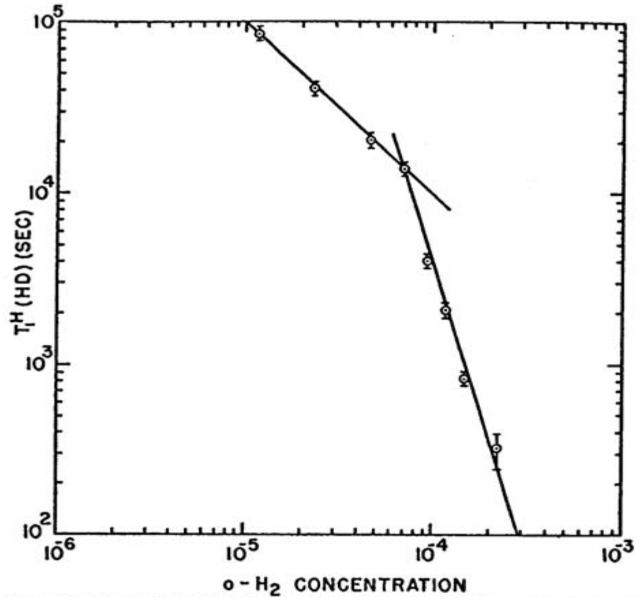
Hydrogen Deuteride (HD)

- W. N. Hardy (1966) and A. Honig (1967) proposed the HD polarization
- by a brute force method. **(Static Polarization)**

- They measured the relaxation properties of proton and deuteron at 0.5 K, which depend on the ortho-para and para-ortho conversions of H_2 and D_2, respectively .

- Honig pointed out that p's and d's can be polarized with a little ortho H_2 at 0.5 K, then polarization is kept for long time at ^{4}He temperature after ortho H_2 converts to para H_2 in 2 months **(relaxation switch).**

- H. M. Bozer and E. H. Graf measured T_{1n} in a dilution refrigerator.



Proton spin relaxation time vs. ortho-H_2 consentration at 0.5 K (Honig)*

Actual Hydrogen Deuteride (HD) Targets

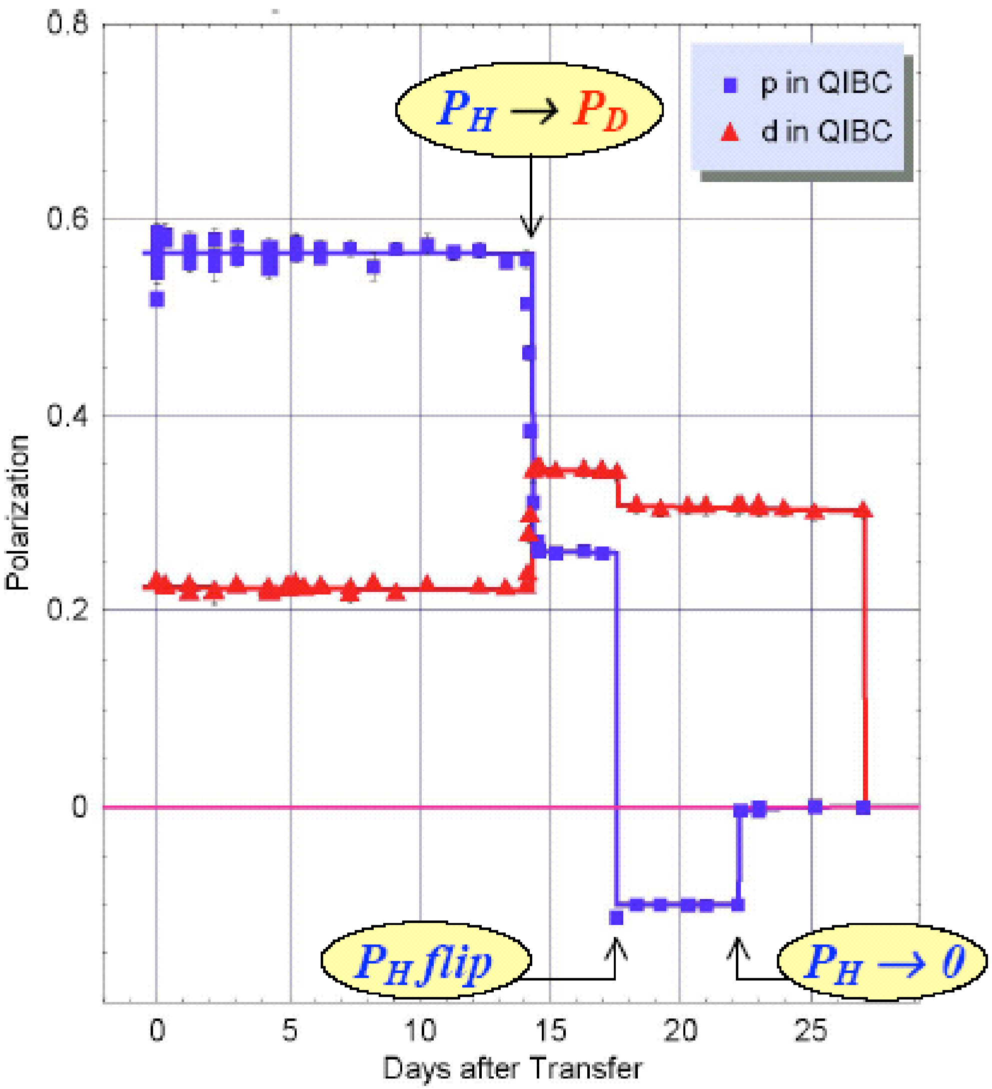
~ 2000: Grenoble - Orsay:

- ♦ Static Polarization at 10 mK and 13.5 T
    - Proton polarization : $\geq$ 60 %
    - □□□□□ Deuteron Polarization : $\geq$ 14 %
    - Small concentration of ortho H_2 and para D_2

~2000: BNL (LEGS): Polarizing proton to 70% and deuteron to 17% at 17mK and 15T, and holding at 1.25K and 0.7T

~2002: (Bochum): Trial of DNP with free radicals of ~10^{18} spins/cm^3 produced by ^{90}Sr.

BNL – Fall'2006



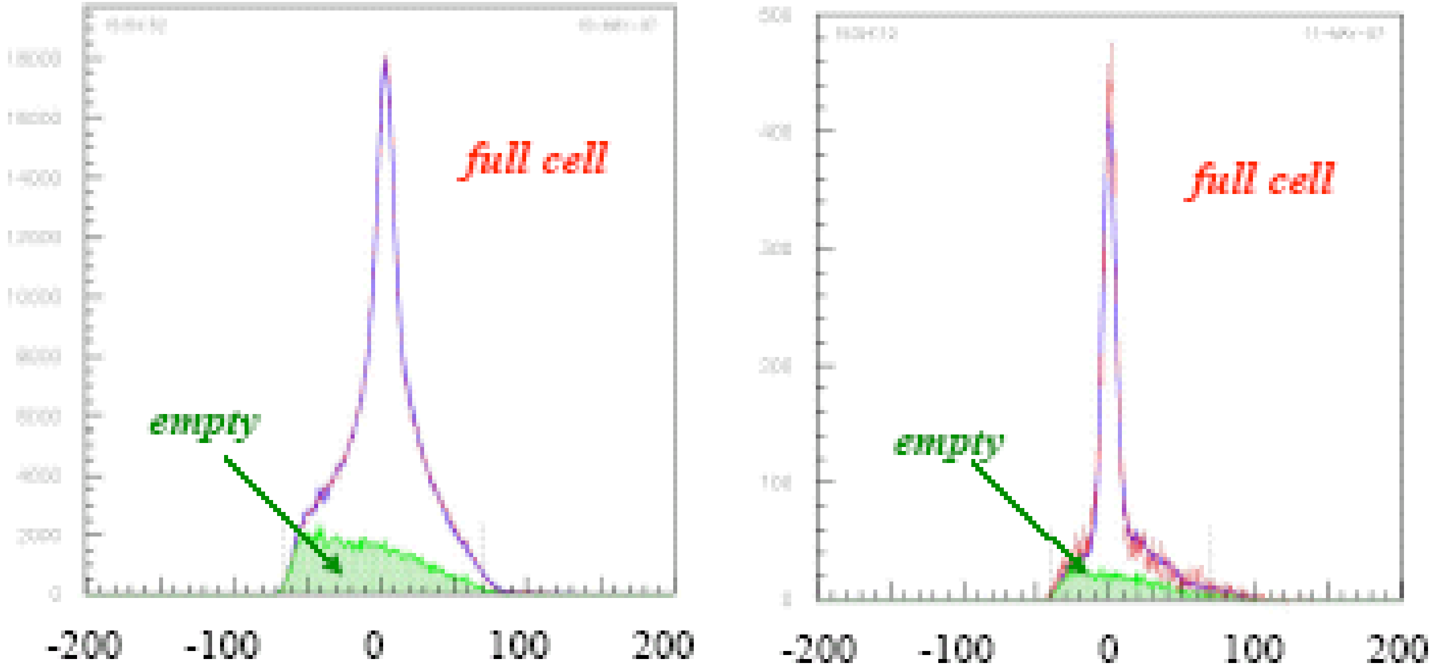
T6 P & D pol in QIBC

- *target cell contribution can be measured and subtracted*

$E_\gamma = 300\ MeV$

$\gamma + HD \rightarrow \pi^{\pm}\ X$

$\gamma + H_2 \rightarrow \pi^{+}\ n$



missing 2 - body energy (MeV)

the nd-experiment

a high-accuracy measurement of the spin-dependent neutron-deuteron scattering length $b_{i,d}$

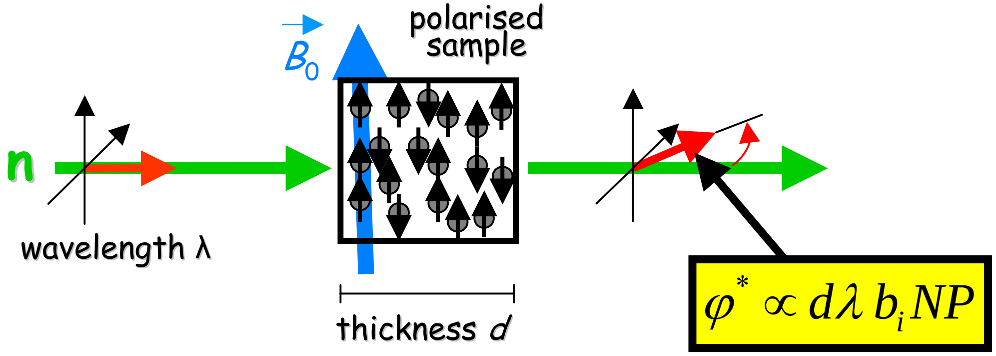
contact: florian.piegsa @ psi.ch

Motivation: Effective field theories (EFT's) need well known experimental input parameters to make accurate predictions.

Most important for the 3 nucleon system is the nd doublet scattering length $b_{2,d}$, which is known with only 6% accuracy.

It is accessable via a linear combination of $b_{i,d}$ and $b_{c,d}$.

Method: Measure the pseudomagnetic precession of neutron spins, which is proportional to $b_{i,d}$, in a polarised solid deuterated plastic target.



$$\varphi^* \propto d\lambda\, b_i N P$$

[A. Abragam et al., PRL **31** (1973) 776]

B. van den Brandt, H. Glättli, P. Hautle,
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the nd-experiment

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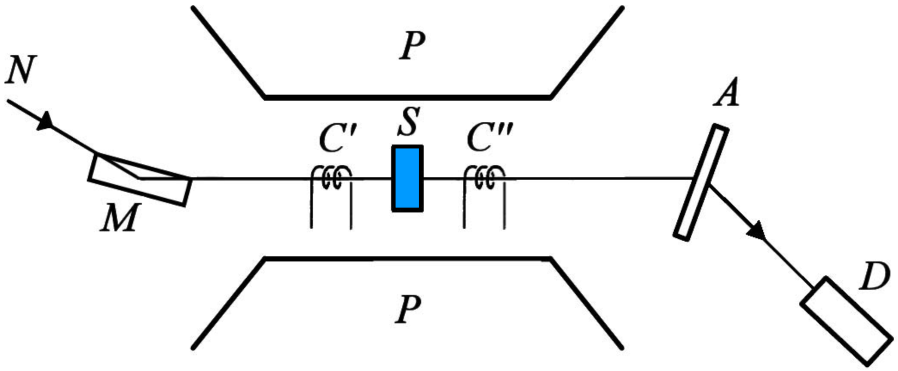
Used Technique:

Ramsey's atomic beam method
adapted to cold neutrons:

N: polarised cold neutron beam (FUNSPIN – SINQ @ PSI)
M: wavelength monochromator
C',C'': $\pi/2$ rf-spin flipper
S: polarised sample
P: pole pieces of 2.5 Tesla magnet
A: spin analyser
D: detector



The goal is to perform the first direct measurement of $b_{i,d}$ and to improve its present accuracy.

present data: [W. Dilg et al., Phys. Letters B 36 (1971) 208]

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the nd-experiment

a high-accuracy measurement of the spin-dependent neutron-deuteron scattering length $b_{i,d}$

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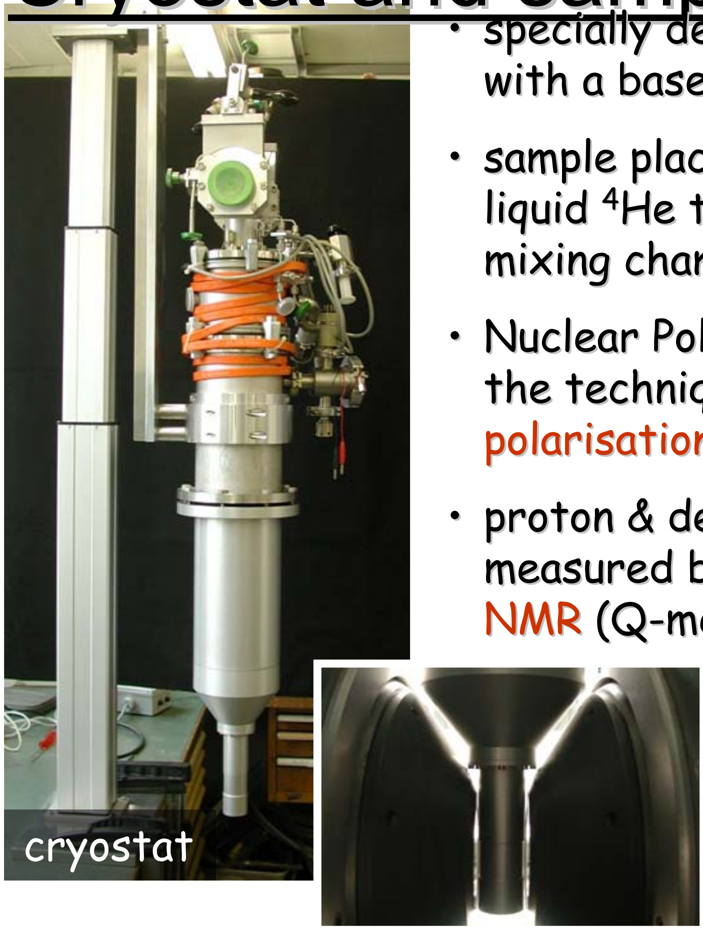
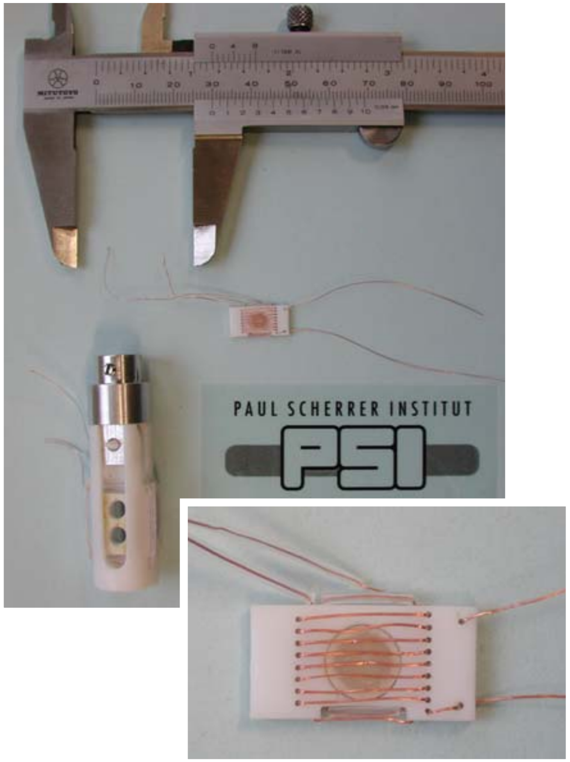
Cryostat and sample:



- specially designed dilution cryostat with a base temperature below 100 mK.
- sample placed in target cell filled with liquid ^{4}He thermally anchored to the mixing chamber
- Nuclear Polarisation is achieved using the technique of dynamic nuclear polarisation (DNP)
- proton & deuteron polarisation is measured by a low temperature NMR (Q-meter)



Sample: d-polystyrene doped with d-TEMPO

(size: Ø 5 mm x 1.2 mm)

B. van den Brandt, H. Glättli, P. Hautle,
J. Kohlbrecher, J.A. Konter, F.M. Piegsa & O. Zimmer

Polarized Proton Solid Target for RI beam experiments

Developed at CNS, University of Tokyo

Takashi Wakui
CYRIC, Tohoku University

M. Hatano	University of Tokyo
H. Sakai	University of Tokyo
T. Uesaka	CNS, University of Tokyo
S. Sakaguchi	CNS, University of Tokyo
T. Kawahara	Toho University
A. Tamii	RCNP, Osaka University

Experiments with radioactive ^{6}He beam at RIKEN

Structure study of unstable nuclei

Polarize nuclei of interest

- Optical pumping in superfluid helium **[T. Furukawa]**
- Collinear optical pumping technique **[T. Shimoda]**
- Projectile-fragmentation reaction **[H. Ueno]**
- Tilted-foil technique **[G. Goldring]**
- Pick-up reaction **[M. Mihara]**

Polarized target + RI beam

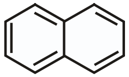
- Polarized target using thin foil **[P. Hautle]**
- ○ **Polarized target in a lower B and at a higher T**

(< 0.3 T) **(> 100 K)**

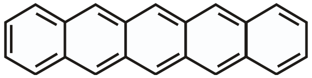
Target material

Target material a crystal of aromatic molecules

Host material naphthalene ($C_{10}H_8$)



Guest material pentacene ($C_{22}H_{14}$)



Polarizable protons	6.3% by weight
Density	4.2×10^{22} cm^{-3}
Concentration	0.01 mol%
Target size	1 mm x 14 mmϕ

Polarizing process

1. Optical excitation (Laser)

   Electron alignment

2. Cross polarization (Microwave)

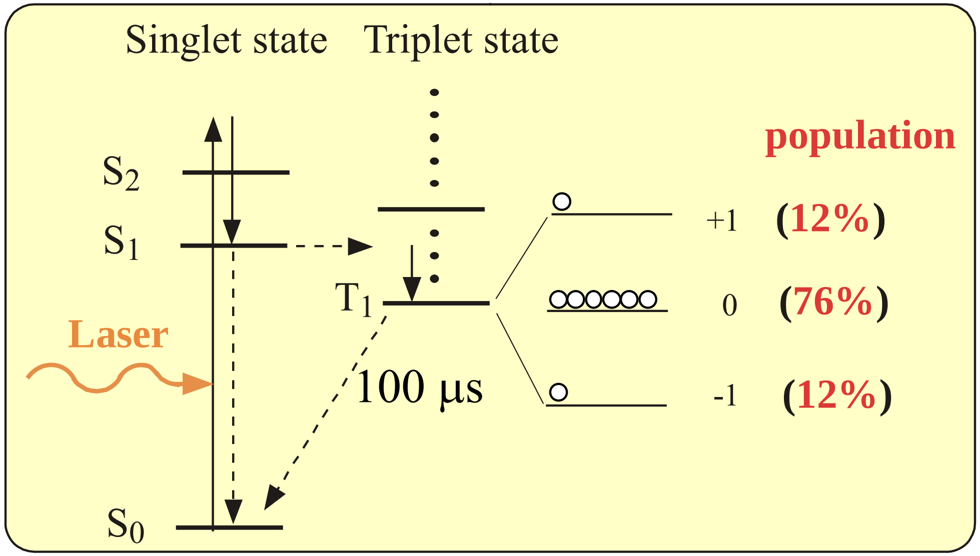
   Electron alignment → Proton polarization

3. Diffusion of polarization

   $\vec{p}$ in guest → p in host

Optical excitation

Energy levels of pentacene (guest molecule)



Singlet state Triplet state

population

S_2

S_1

T_1

Laser

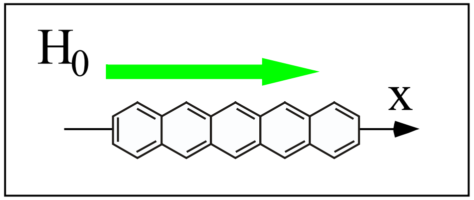
100 μs

S_0

+1 **(12%)**

0 **(76%)**

-1 **(12%)**



- Decay to T_1 state (intersystem crossing)

$$|\mathrm{T}'\rangle = |\mathrm{T}\rangle + \sum_k \frac{\langle \mathrm{T}|\, H_{so} \,|\mathrm{sk}\rangle}{W_{sk} - W_T} |\mathrm{sk}\rangle$$

- Electron alignment

depend on the angle between H and x-axis

$$Pe = \frac{N(0) - N(-1)}{N(0) + N(-1)} = 73\%$$

Polarizing process

① Optical excitation

electron alignment

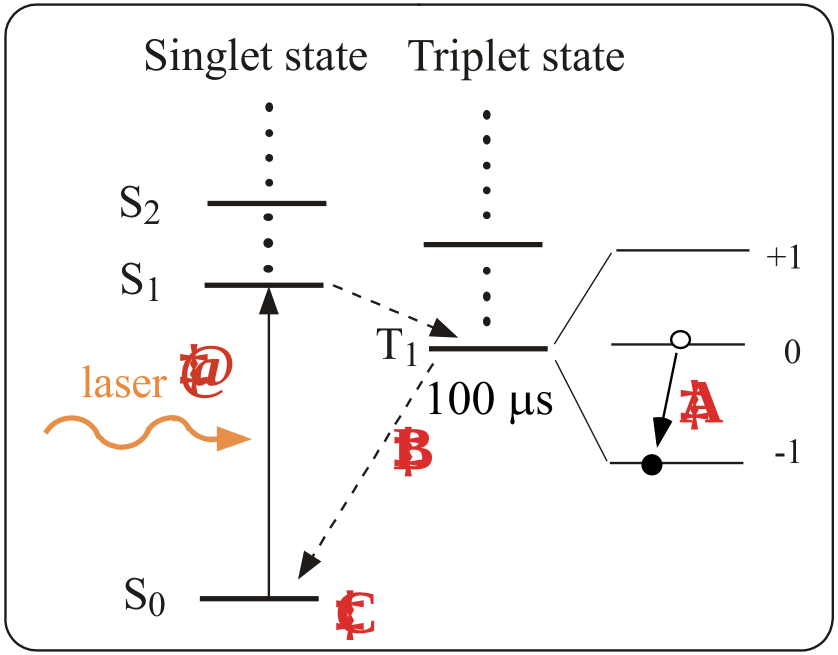
② Cross polarization

polarization transfer

③ Decay to the ground state

④ Diffuse the polarization

to protons in host molecules
by dipolar interaction

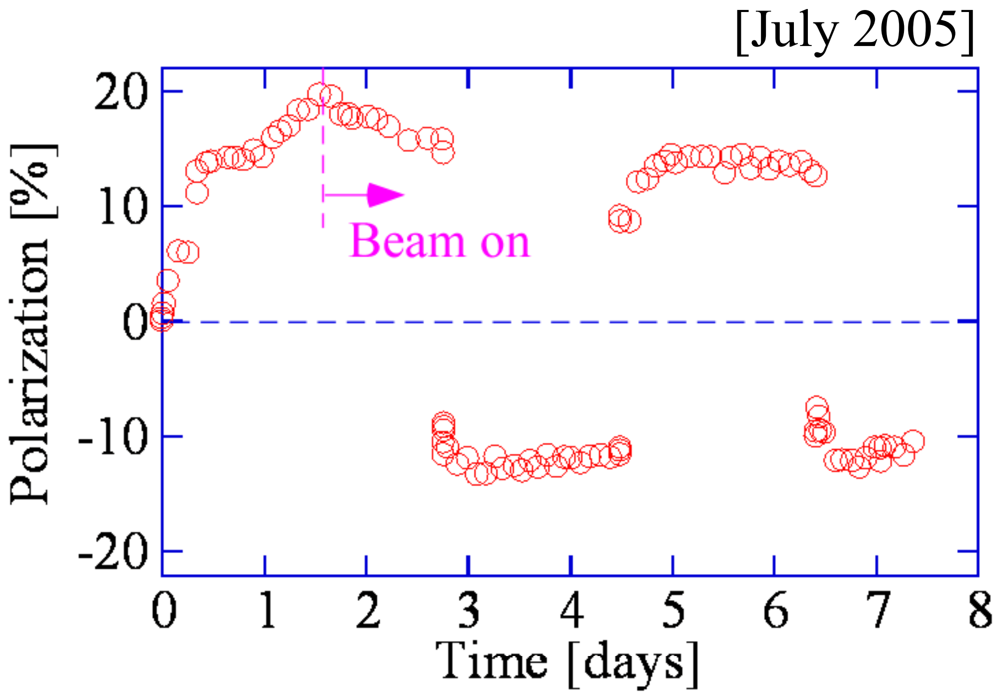


ground state is diamagnetic

➡ long relaxation time

Repeating 1 → 4 ➡ Protons are polarized

Polarization during Experiment



Magnetic field : 90 mT
Temperature : 100 K

- Relative polarization

  pulsed NMR

- Polarization calibration

  $\vec{p}+{}^4$He elastic scattering

P_{max} = 19.7 (56)%

P_{av} = 13.5 (39)%

- Polarization reversal

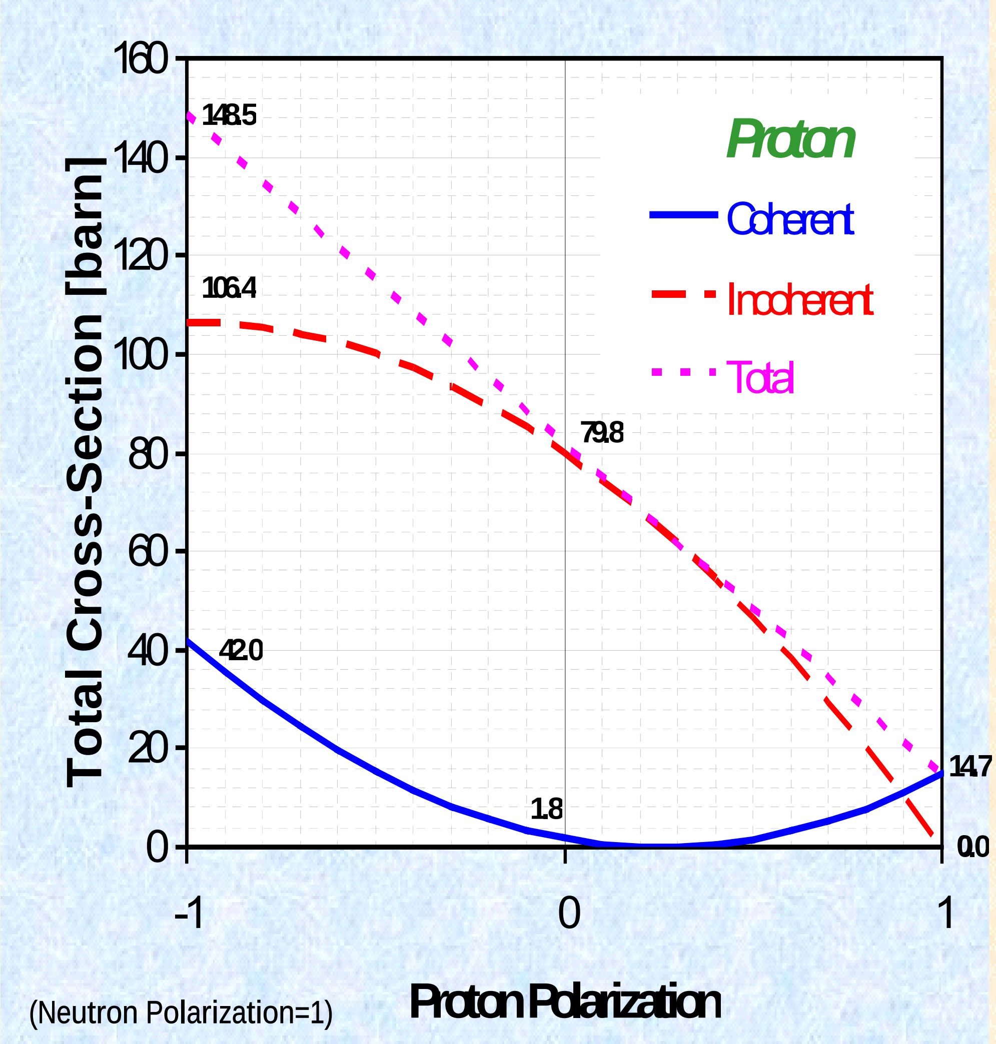
  to reduce systematic uncertainties

  pulsed NMR

- Radiation damage

Polarized Neutron Scattering

- **Hydrogen is the most abundant element in living matter (~50%) as well as many other soft materials.**
- **Hydrogen has very strong polarization dependent scattering cross-section.**
- **Without polarization, the huge hydrogen incoherent cros-section(79.8 barns) puts a severe limit on experiments, which are almost always flux limited.**
- **At polarization =1, the hydrogen coherent cross-section increases from 1.8 to 14.7 barns, while its incoherent signal drops to 0 – a huge signal-to-noise gain.**
- **The difference in cross-section between polarization =+1 and -1 can be exploited to polarize shorter wavelength neutrons (<1A), which are difficult to polarize with other techniques.**
- **Polarization on nuclei other than hydrogen can be exploited as well.**

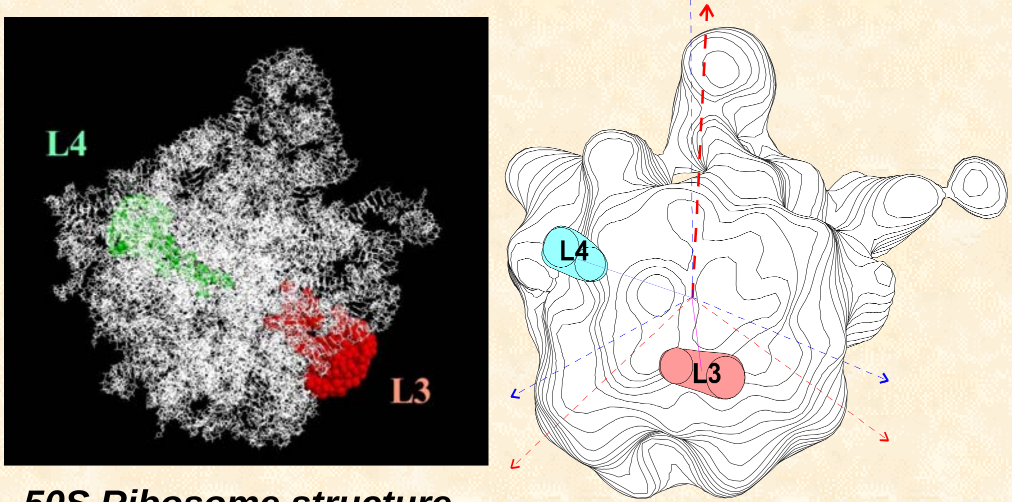


Experiments with polarized targets

- **Past neutron scattering experiments with polarized target have been confirmed by crystallography and proven to be very powerful.**

- **There are many situations where crystallography is not yet possible.**

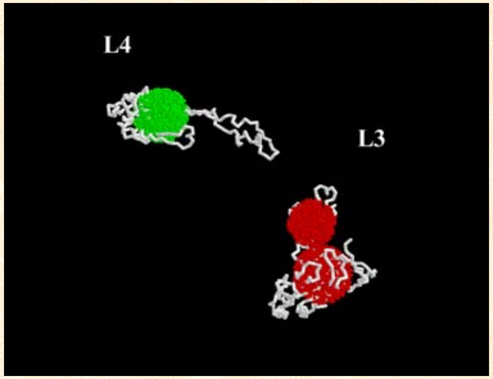
- **Polarized neutron can enhance neutron protein crystallography!**



50S Ribosome structure

Left: Crystal structure (Nissen et al2000).

Right: Low resolution neutron scattering with polarized target (Zhao et al 1992). The experiment was carried out at the 5MW reactor. Similar result was NOT possible without polarized neutrons even at the best research reactor(60MW).



Comparison of two proteins (L3 and L4) within the 50S Ribosome as studied by polarized neutrons (color) and *crystallography (ribbons)*

Plans at SNS

- **First Stage: Quick and portable (between neutron beam lines) setup.**
  - **Using existing, 5T compensated magnet.**
  - **Using helium-4 cryostat for simplicity.**
  - **Major Components (Magnet, Microwave generators & counters, rf-generator for NMR, helium pumping system) have been bought.**
- **Second Stage: Custom and optimized setup for specific instruments, such as *neutron protein crystallography*:**
  - **Neutron protein crystallography is severely flux-limited.**
  - **Samples are very small (<< 1x1x1 mm^3).**
  - **Compact apparatus needed.**
  - **Frozen spin mode desired.**
- **Other Applications: Polarization filter for <1A neutorns.**

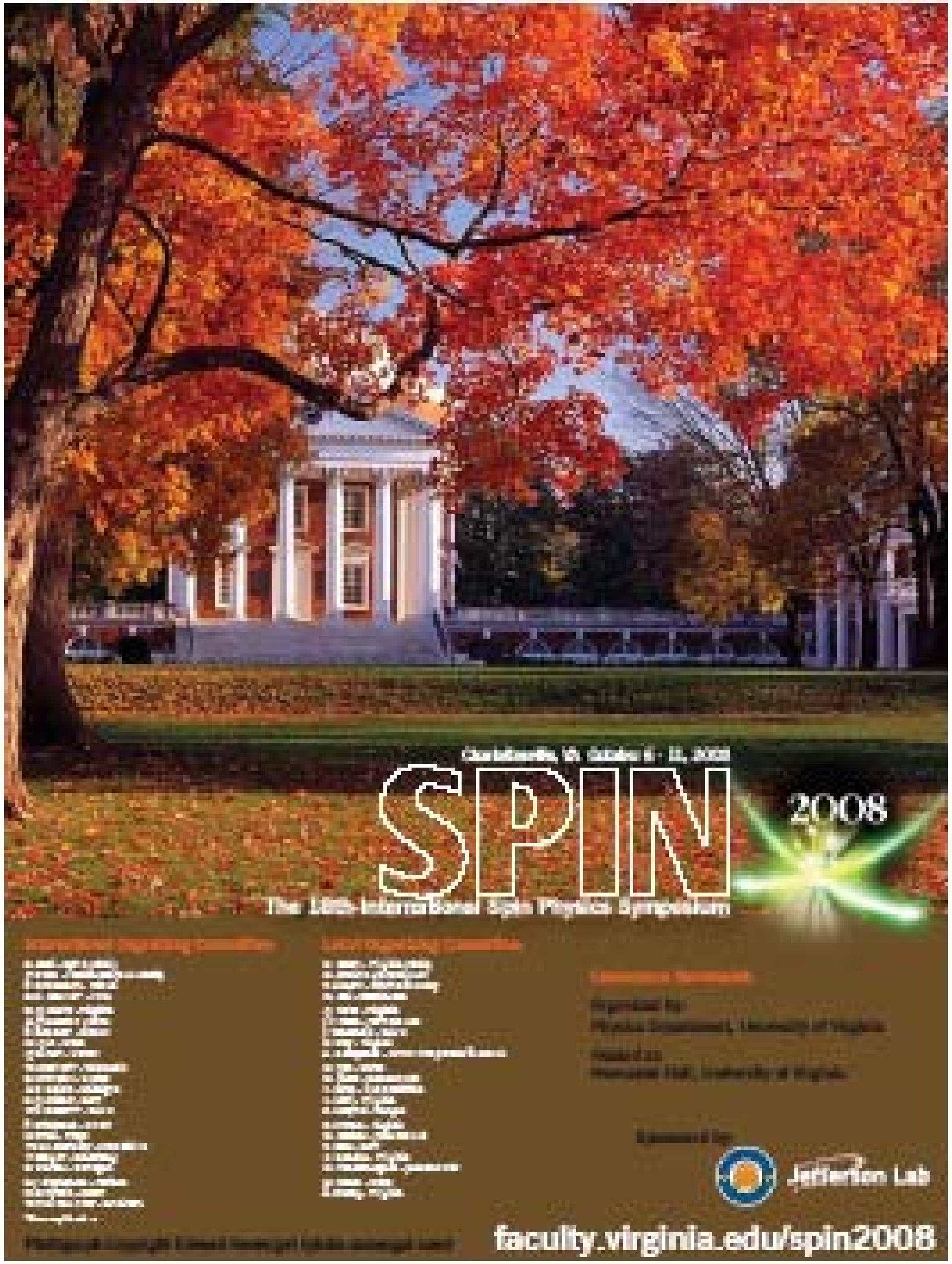
MRI with ^{13}C

- Normal MRI on hydrogen at room temperature in a field of ~2 T.
- Polarization $\sim 10^{-6}$, but lots of protons.
- Signal/noise issues
- Instead polarize ^{13}C enhanced material and inject into patient. Very good signal to noise.

- Polarization at 1 K and 5 T using Trityl radicals.
- P(^{13}C) ~40% - 45%
- BUT:
- Rapid warm up for injection. Rapid fall in polarization. Can make measurements (in rat) for ~ 1 – 2 minutes (Amersham, Sweden)
- Now Proprietary (especially radical)

NEAR FUTURE

- Programs of physics which require transverse polarization.
- Dilution refrigerators with internal saddle coils for transverse frozen spin operation.
- Large field (~4 T) magnets with 1 K refrigerator. Difficult tomeet transverse requirements at 5 T.
- HD target operation in transverse mode, but for operation in CLAS in Hall B at JLab must be able to withstand ~ 1 nA????
- Other materials (CH_3 and CH_4)
- Other applications (eg medical)



Charlottesville, VA October 6 - 11, 2008

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