Spin Temperature and Dynamic Nuclear Polarization

Latest Results on the Deuteron Polarization

Spin Temperature and Dynamic Nuclear Polarization

A new generation of polarizable deuteron target materials

- **The Quality Factor** of the Material
- **The Components** of a Polarized Target Apparatus
- **A Nice Picture** of the DNP Effect
- **Cornerstones** of the Polarized Solid Target
- **A more Nice Picture** of the DNP Effect
- **What can be done ?** Theoretical & Experimental Hints
- **Results** of the new developments
- **Another Cornerstone** to be added to the target history

The Quality Factor or the Target Figure of Merit

In a simple asymmetry experiment:

$$A_{phys} = \frac{1}{P_T} \cdot \frac{1}{f} \cdot \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow} = \frac{1}{P_T} \cdot \frac{1}{f} \cdot A_{meas}$$

$$f = \frac{\#\,\text{polarizable particles}}{\#\,\text{all particles}}$$

$$\left(\frac{\Delta A}{A}\right)^2 = \left(\frac{\Delta P_T}{P_T}\right)^2 + \left(\frac{\Delta f}{f}\right)^2 + \underbrace{\frac{1}{P_T^{\,2}} \cdot \frac{1}{f^{\,2}} \cdot \frac{1}{N_{tot}}}_{\text{Main contribution to the error}}$$

For a fixed error in A_{phys} :

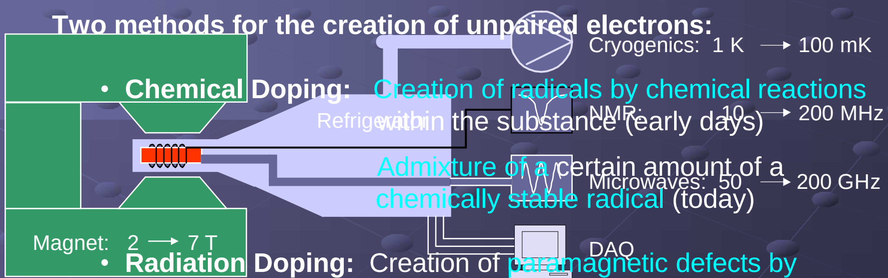
$$F_T \quad \frac{1}{T} \propto \frac{1}{N_{tot}} \approx n_T \cdot \underbrace{P_T^{\,2} \cdot f^{\,2}}_{\text{Optimize !}}$$

The Basic Concept of Dynamic Nuclear Polarization

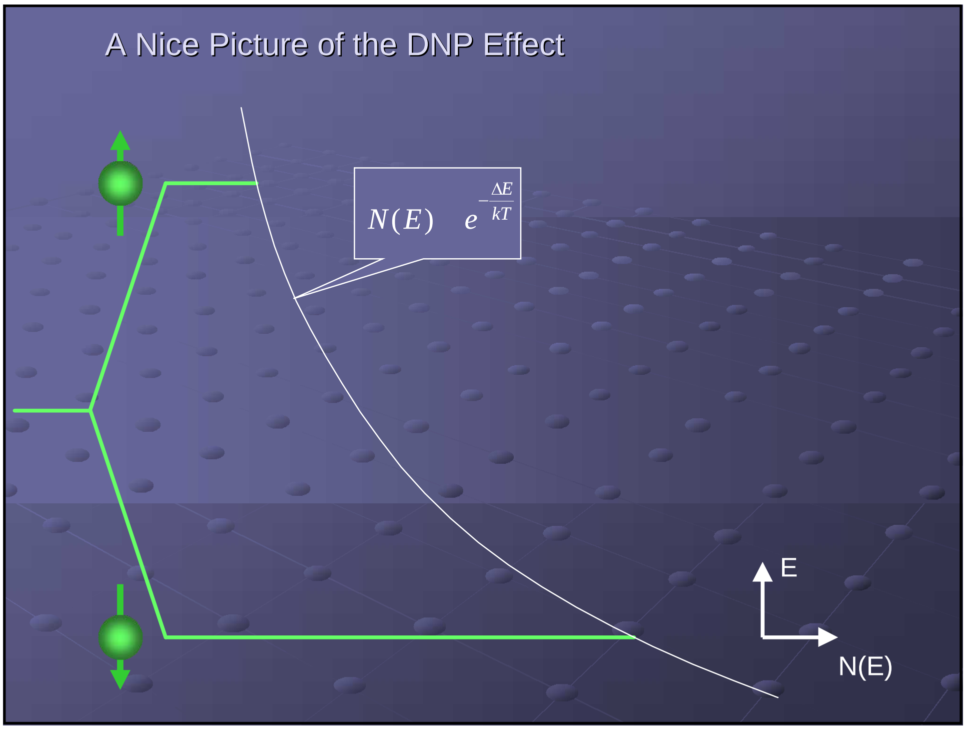
$$P \quad \frac{\mu B}{kT}$$

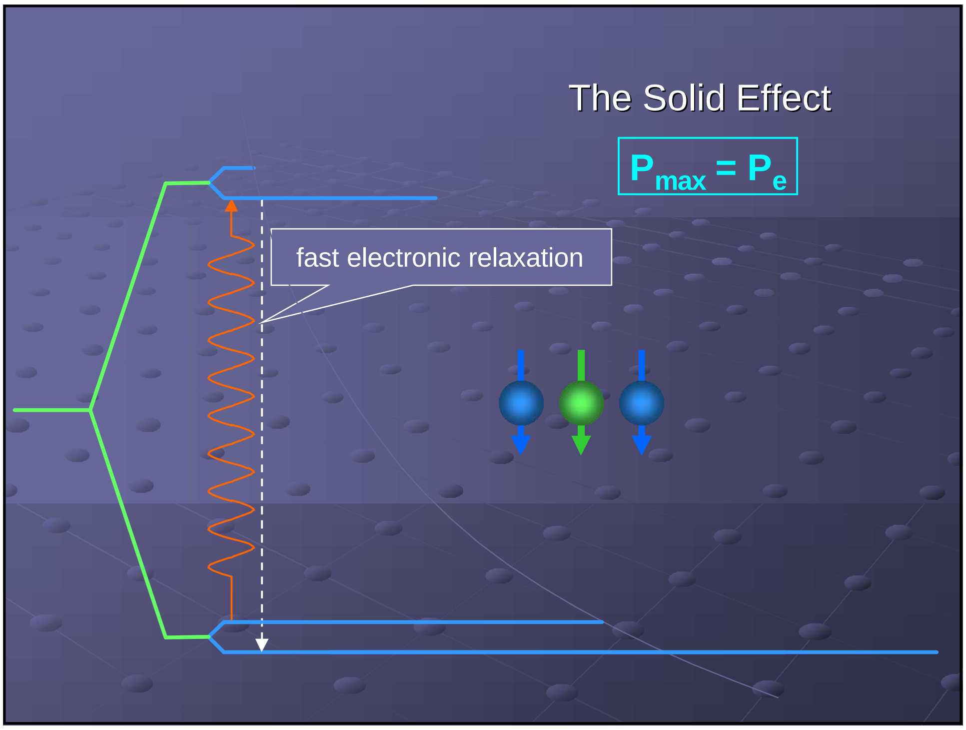
B / T	P_p[%]	P_d [%]	P_e [%]
2.5 T / 1 K	0.25	0.05	93
15 T / 10mK	91	30	100

Two methods for the creation of unpaired electrons:



- **Chemical Doping:** Creation of radicals by chemical reactions within the substance (early days)
  Admixture of a certain amount of a chemically stable radical (today)
- **Radiation Doping:** Creation of paramagnetic defects by ionizing radiation (solid at room temp.)


A Nice Picture of the DNP Effect
$N(E) \quad e^{-\frac{\Delta E}{kT}}$
E
N(E)


The Solid Effect
$P_{max} = P_e$
fast electronic relaxation

Cornerstones of the Polarized Solid State Target

1957 **Abragam / Jeffries:** **DNP ⟶ ´Solid Effect´**
(Overhauser-Effect 1953)

- DNP by forbidden transitions of electron - nucleon pairs
  - **1958:** First demonstration in **^{6}LiF**
  - **1959:** Many substances with **P ~ O(%)**

1962 **Jeffries / Schmugge:** **First high polarization observed**

- **Nd:LMN(·24H_2O)** (Lanthanium Magnesium Nitrate with Nd Ions)
- **P_p ~ 70 %**
- **Very narrow EPR line** ⟹ Resolved Solid Effect

1962 **Abragam et al.:** **First Polarized Target**

- Measurement of the spin correlation parameter C_{nn} at the 20 MeV proton beam (Saclay)
- **Ce:LMN(·24H_2O)**

  P ~ 20 % at ν_e = 35 GHz / T = 1.6 K

1963 **Chamberlain et al.:** **First Pol. ´High Energy´ Target**

- $\pi^+ \vec{p}$ – Scattering at 246 MeV (Berkeley)
- **Nd:LMN(·24$H_2$0)**

  P ~ 70 % at ν_e = 70 GHz / T = 1.1 K

Until 1968 **Nd:LMN targets used in more than 40 experiments**

- with **Polarizations** $\longrightarrow$ **70 %**
- at Temperatures 0.95 $\longrightarrow$ 1.35 K and fields 1.7 $\longrightarrow$ 2.0 T
- but: **Content of free protons only 3.1 %**

  Radiation damage already after 10^{10} – 10^{11} /cm^2

Since 1966 **Borghini / Mango et al.: The alcoholes und dioles**

- Doping: Free radicals **Porphyrexide / Cr(V)-Complexes**
- **P ~ 40 %** (T ~ 1 K) and **70 – 80 %** (T ~ 0.5 K)
- Free protons: **~ 13 %**
- Radiation Hardness: **10^{13} – 10^{14} particles / cm^2**

1970s **Measurement of electromagnetic processes**

- Photoproduction with **beam intensities up to 10^{10} γ/s**

  z.B.: $\gamma \vec{d} \longrightarrow pn$ (Bonn 1972 – 74)

  (SLAC, DESY, INS (Tokyo), Yerevan)

1976 **SLAC: First pol. deep inelastic $\vec{e}\,\vec{p}$ – Streuung**

- For sufficient statistics: Some 10 nA needed !
- **Alcohols need very frequent annealing (every hour !)**

1974 de Boer / Niinikoski: ^3He / ^4He – dilution cryostat

- **Temperatures lower than 100 mK possible !**
- **Nearly complete polarization** e.g. in **Cr(V):Propanediol**

1979 – 1980 Niinikoski / Meyer: NH_3 / ND_3

- Dilution factor: **17 % (NH_3) and 30 % (ND_3)**
- Radiation hardness: **~ 10^{15} particles / cm^2**

Late 1980s 2^{nd} **Generation of pol. deep inelastic scattering**

CERN EMC:

- 190 GeV $\vec{\mu}$ from pp $\rightarrow \pi^+ \rightarrow \mu^+$ (P_μ ~ 80 %)
- Double cell dilution refrigerator (2.5 T / 150 mK)
- NH_3 (P = 80 – 90 %) because of the dilution factor

⇓

Spin carried by quarks only contribute to a minor extent, $\Delta S \neq 0$

! Spin Crisis !

Until today **`Spin Crisis´ confirmed in a wide kinematical region**

SLAC: E143, E154 (with ^3He gas target), E155

- **High current target** at 5 T / 1 K / 1 W !
- **NH_3 / ND_3 / ^6LiD**

CERN SMC: Protonated und deuterated alcohols
NH_3 (Bonn ´96)

DESY Hermes: $\vec{H}$ / $\vec{D}$ / $^3\vec{He}$ storage cells

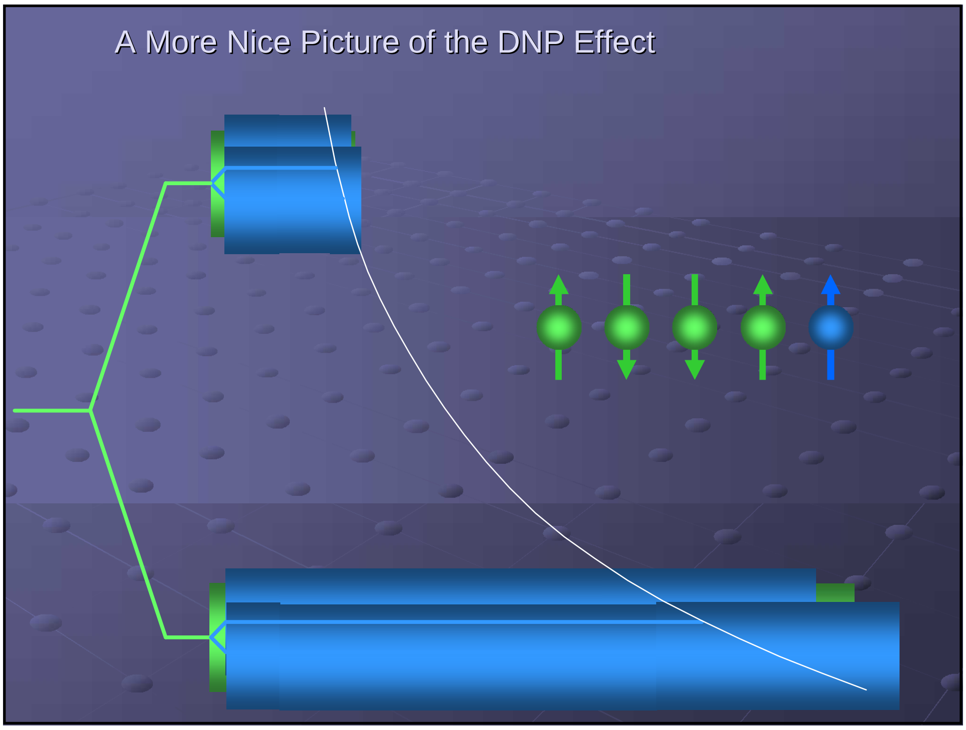
Since 2001 **Contribution of the gluon ΔG = ?**

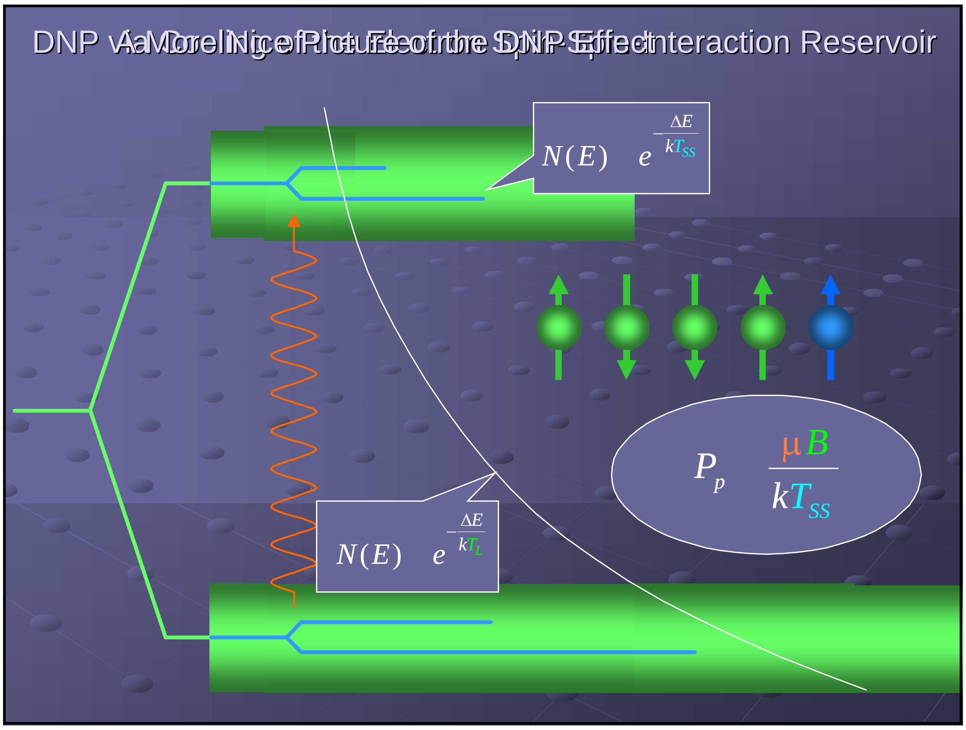
CERN COMPASS

- Target apparatus of SMC (1 Liter of **^6LiD** !!!)
- Bochum 1996 – 2000: **P_d = 55 %**
- Alcohole target of the newest generation: **P_d ~ 90 %**

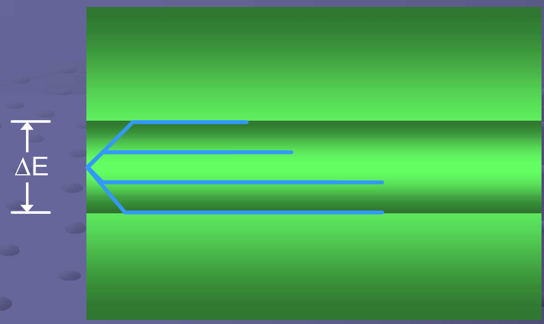
Status of the Polarized Solid Target End of 2000

- **Proton target materials can be polarized almost completely**
  - under nearly all conditions
    - ✓ Low intensity beams ⇨ dilution refridgerator at 2.5 (or 5.0 T)
    - ✓ High intensity beams ⇨ ^4He evaporator preferably at 5.0 T
  - independently of the actual material
    - ✓ H-butanol, H-propanediol, NH_3, LiH, …
- **This is not the case for the deuterated (neutron) materials**
  - P_{max} ~ 30 – 40 % on average (exception ^6LiD)
    - ✗ Low magnetic moment of the deuteron
    - ✗ Radicals insufficient to cool the low μ nuclei


A More Nice Picture of the DNP Effect


DNP via Cooling of the Spin-Spin Interaction Reservoir
A More Nice Picture of the DNP Effect
$N(E)\ e^{\frac{\Delta E}{kT_{SS}}}$
$P_p\ \frac{\mu B}{kT_{SS}}$
$N(E)\ e^{\frac{\Delta E}{kT_L}}$

The special problem of low μ nuclei (e.g. deuterons)



$$P \quad \mu \cdot \frac{1}{T_{SS}}$$

$$|T_{SS}|_{min} \quad \frac{\Delta E}{E_Z} T_L$$

⇨ Try to minimize the energy spread ΔE

- Find a suitable doping method / radical such that

$$\Delta E \sim O(\nu_D)$$

- Try radiation doping if only low μ nuclei present

Contributions to the Electron Zeeman Line Width

Zeeman Energy of a free electron

$$E_Z = -g_e \mu_B \vec{S} \cdot \vec{B}$$

Solid state: Presence of

- other electrons ⇨ Dipol-Dipol Interaction ✓ (weak, necessary)
- magnetic nuclei ⇨ Hyperfine Interaction (indep. of B_0)
- a crystal field ⇨ g-factor anisotropy (~ B_0)

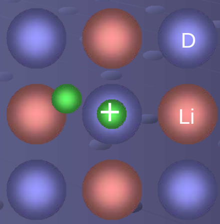
$$\Delta E_{tot} = \underbrace{\mu_B (\vec{S} \cdot \hat{g} \cdot \vec{B}) + (\vec{S} \cdot A \cdot \vec{I})}_{E_{inhom}} + \underbrace{E_D}_{E_{hom}}$$

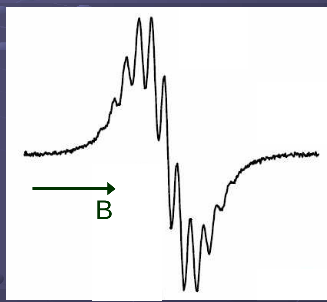
Abragam 1980)

en from 1995 in Bochum

F-Center:

- s-wave electron
- no g-anisotropy
- weak HF interaction





⇨ 7Li (large μ) Imurity has considerable influence on Pmax

- **1 Liter for COMPASS: Synthesized from highly enriched ^{6}LiD**

Experimental hint II:

Saturation measurements of the F-center system in ^{6}LiD

Measurement of the

Results: signal height (b+d)

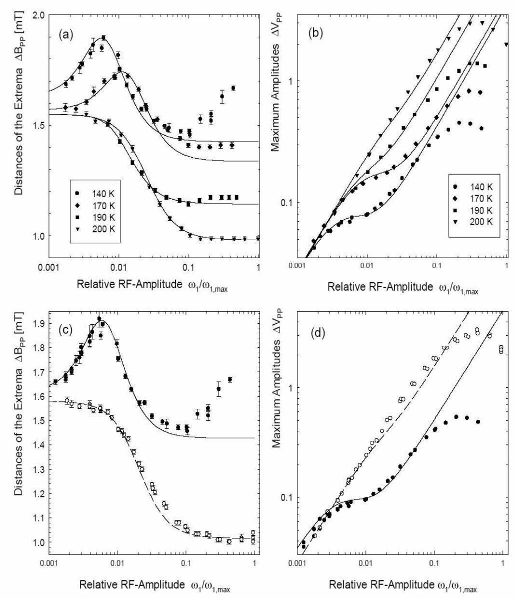
- signal width (a+c)

as a function of the μ-wave strength

- The F-center system behaves in complete agreement with the **Spin Temperature Theory**

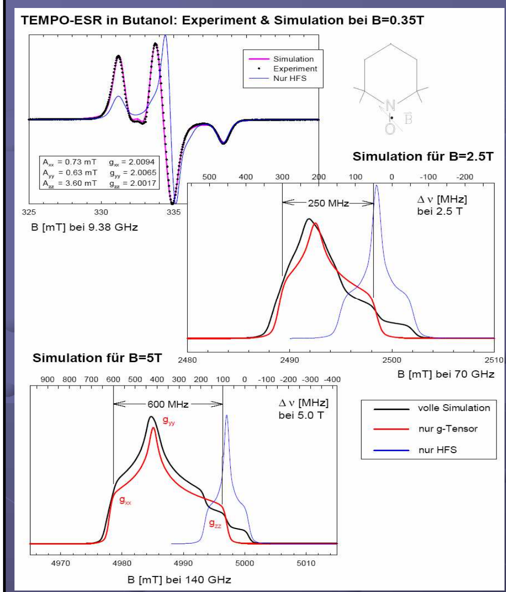
- Even its time constants T_Z, T_D may be extracted

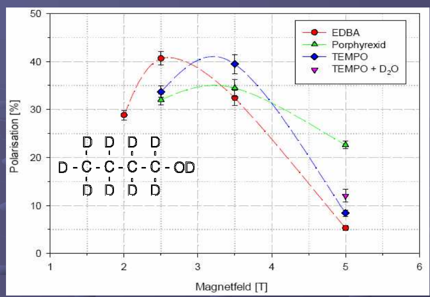
EPR-Saturation curves of F-centers irradiated ^{6}LiD at 9.4 GHz (0.34 T) and 77K

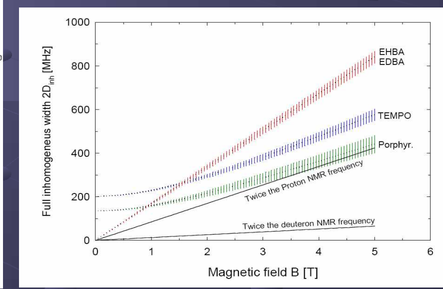


Experimental hint III:

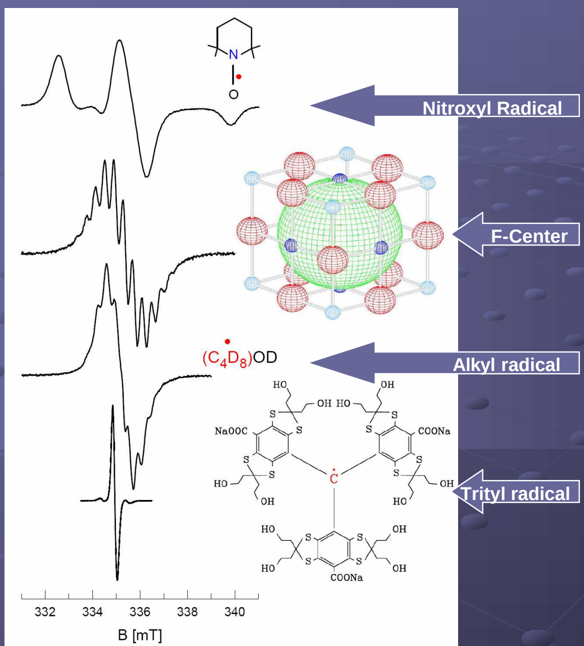
`Strange´ Polarization Behaviour of chemically doped d-butanol







EPR Lines and Polarization Results of deuterated substances



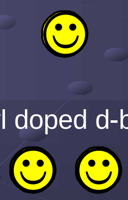
Cemically doped d-butanol

P_{max}^d ~ 30 %

Radiation doped ^{6}LiD

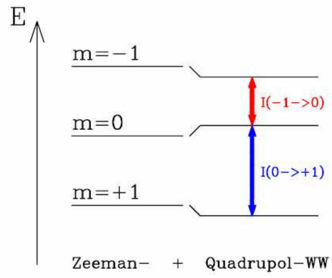
P_{max}^d ~ 55 %

Radiation doped d-butanol



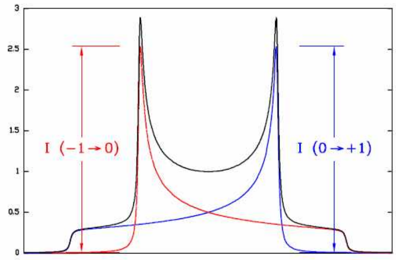
Trityl doped d-butanol

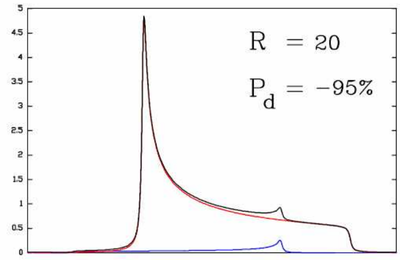
NMR Signals of spin-1 nuclei in presence of a crystal field



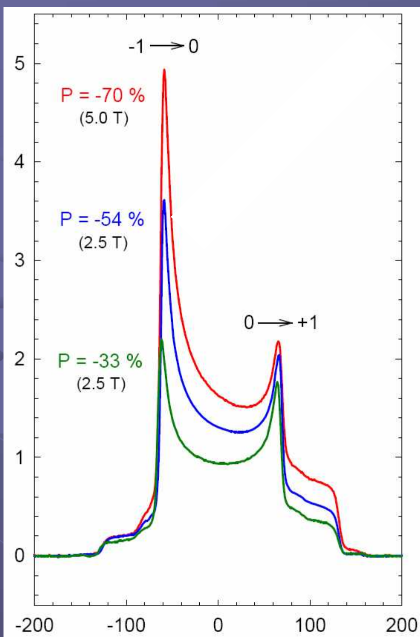
$$R = \frac{I(0->+1)}{I(-1->0)}$$

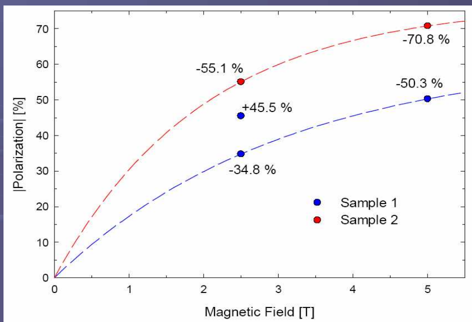
$$P_d = \frac{R^2-1}{R^2+R+1}$$

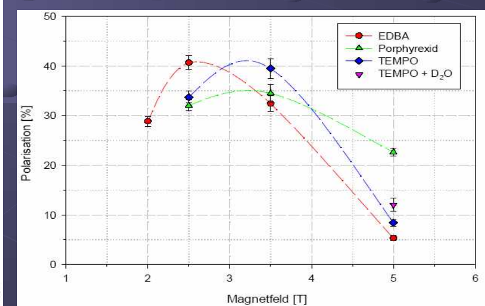




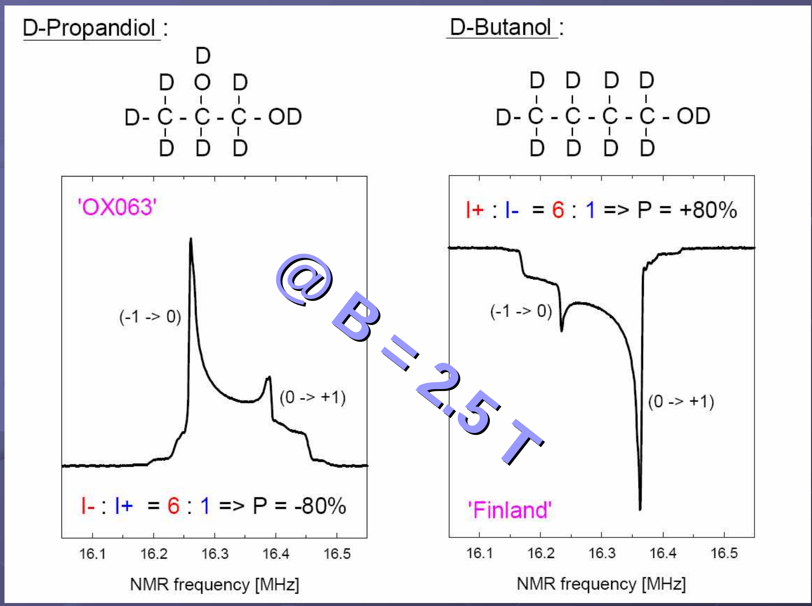
Results on Electron Irradiated deuterated n-Butanol







Results on Trityl doped deuterated alcohols and diols



Status of the Polarized Target from the Material Point of View

- **Proton target materials can be polarized almost completely**
- **Until 2003 not the case for the deuterated (neutron) materials**
- **New:** Radicals optimized for the cooling of nuclei with low μ
  - Theory: `Minimize the non-Zeeman interactions´
  - Recipe: Reduce the `inhomogeneus´ interactions $E_{inhom} \searrow \nu_D$

    Optimize the `homogeneus´ interactions E_{hom}
    (for a fast establishment of a common spin temperature)
  - In practice: Try radiation doping if HF interaction weak

    Use `narrow EPR radicals´ e.g. Trityl

Status of the Polarized Target from the Material Point of View

Latest Cornerstone of the Polarized Solid Target

- **Proton target materials can be polarized almost completely**

2003 Bochum:

- **Until 2003 not the case for the deuterated (neutron) materials**

Almost completely polarized neutron targets

- **New:** Radicals optimized for the cooling of nuclei with low µ

➡ **Neutron (deuteron) target materials of a new era**

Material	Doping	Polarization	Field
6LiD	Irradiation	**55 %**	2.5 T
Butanol	Irradiation	**55 %** **70 %**	2.5 T 5.0 T
Butanol Prop.diol	Chemically w. Trityl	**80 %**	**2.5 T**