16th International Spin Physics Symposium, spin2004,
October 10-16, 2004 in Trieste, Italy

High-accuracy measurement of the spin-dependent neutron scattering length of the deuteron

P. Hautle
Paul Scherrer Institute
CH-5232 Villigen,Switzerland

B. van den Brandt, P. Hautle, J. Kohlbrecher, J.A. Konter, A. Michels (PSI)
H. Glättli (CEA-Saclay)
H. Griesshammer, F. Piegsa, O. Zimmer (TU München)

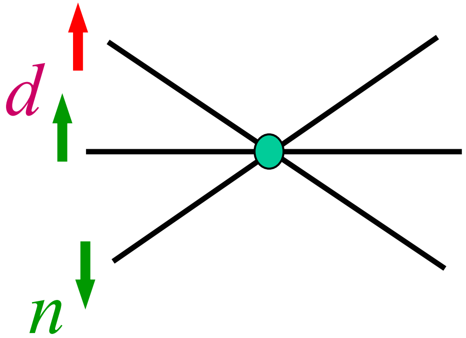
nd-doublet scattering length – why ?

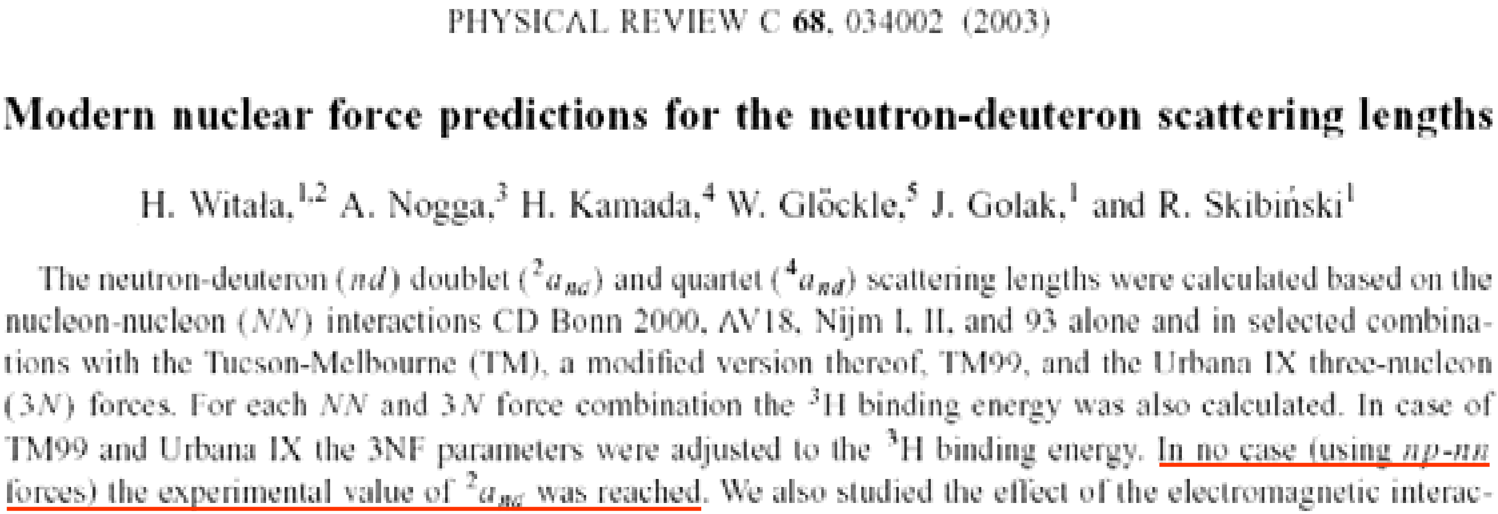
- 3 nucleon system

  Low energy nuclear three-body forces

- modern (NN) potentials fail to describe 3N observables !!

  even with ***ad hoc*** admixture of 3N forces





PHYSICAL REVIEW C **68**, 034002 (2003)

Modern nuclear force predictions for the neutron-deuteron scattering lengths

H. Witala,[1,2] A. Nogga,[3] H. Kamada,[4] W. Glöckle,[5] J. Golak,[1] and R. Skibiński[1]

The neutron-deuteron (nd) doublet (${}^2a_{nd}$) and quartet (${}^4a_{nd}$) scattering lengths were calculated based on the nucleon-nucleon (NN) interactions CD Bonn 2000, AV18, Nijm I, II, and 93 alone and in selected combinations with the Tucson-Melbourne (TM), a modified version thereof, TM99, and the Urbana IX three-nucleon ($3N$) forces. For each NN and $3N$ force combination the ^{3}H binding energy was also calculated. In case of TM99 and Urbana IX the 3NF parameters were adjusted to the ^{3}H binding energy. In no case (using np-nn forces) the experimental value of ${}^2a_{nd}$ was reached. We also studied the effect of the electromagnetic interac-

Effective Field Theories, EFT($\not\pi$)

[Bedaque, van Kolck, Ann.Rev.Nucl.Part.Sci.**52** (2002) 339 / nucl-th/0203055]

Systematic, model-independent approach to describe nuclear forces at low energy

Chiral Perturbation theory χPT (Weinberg, 1991)

- systematic expansion of scattering amplitude
- EFT, pion degrees of freedom

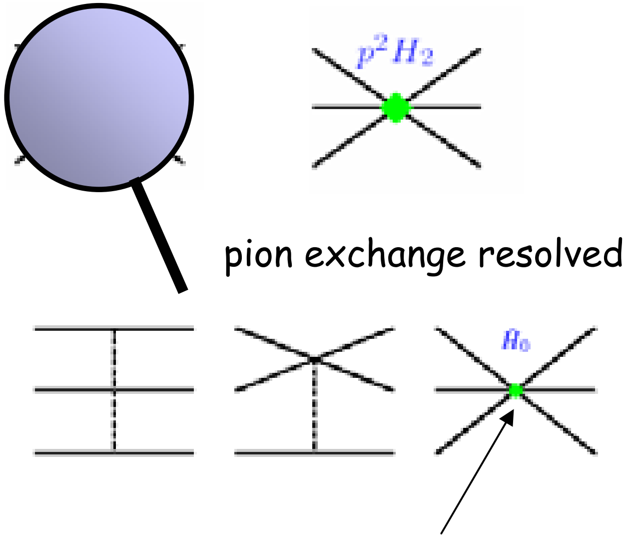
At very low energy, EFT($\not\pi$), pionless

- point like interactions between nucleons only
- two parameters characterise 3N forces

two independent three-body observables are needed to predict observables with 1% accuracy

→ triton binding energy (5 x 10^{-7})
nd doublet scattering length (6 % !!)

[Bedaque, Rupak, Griesshammer, Hammer, Nucl. Phys. A **714** (2003) 589]



pion exchange resolved

Core strength needs input of the 3N observables !!

[Eppelbaum et al, Phys. Rev. C **66** (2002) 064001]

→ $nd \rightarrow \gamma t$

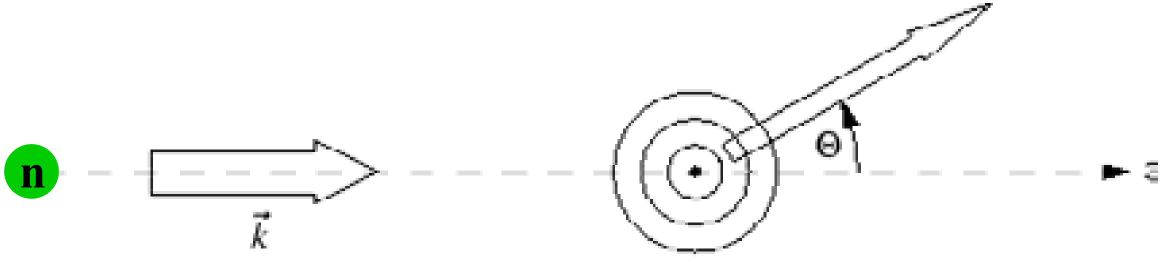
calibrate solar neutrino oscillation (SNO)

Big Bang Nuclear Synthesis

Neutron Scattering Length

Cold neutrons 4 Å (≈ 5 meV) ⟶ s-wave scattering

scattering amplitude *f* constant



$$\psi = e^{i\vec{k}\cdot r} - f(\theta)\frac{e^{ikr}}{r} \quad \rightarrow \quad e^{i\vec{k}\cdot r} - a\frac{e^{ikr}}{r}$$

free scattering length [fm]

bound scattering length:

$$b = \left(\frac{A+1}{A}\right)a$$

mass number of
the nucleus

Spin dependent n-Scattering Length

$$\vec{J} = \vec{s} + \vec{I}$$

$\vec{s}$ spin of the neutron

$\vec{I}$ spin of the nucleus

$$\boxed{a = a_c + \frac{2}{\sqrt{I(I+1)}} a_i \, \vec{s} \cdot \vec{I}}$$

coherent
(spin independent)

"incoherent"
(spin dependent)

case of the **Deuteron**
$I = 1$

$$a_2 = a_{c,d} - \sqrt{2}\, a_{i,d} \qquad (J = 1/2 \text{ , doublet})$$

$$a_4 = a_{c,d} + \frac{1}{\sqrt{2}} a_{i,d} \qquad (J = 3/2 \text{ , quartet})$$

Quartet Channel: both neutrons have spin parallel

➡ Pauli Priciple: only a_2 sensitive to 3N forces

Present knowledge: np & nd

np-system:

$$b_{c,p} = -3.7409 \pm 0.0011\, fm$$

$$b_{i,p} = 25.217 \pm 0.006\, fm$$

nd-system:

$$b_{c,d} = 6.6683 \pm 0.0030\, fm$$ [K. Schoen et al, Phys. Rev. **C 67** (2003) 044005]

$$a_2 = 0.65 \pm 0.04\, fm$$ [W. Dilg, L. Koester, W. Nistler, Phys. Lett. **36** (1971) 208]

➔ semi-empirical value: $a_2 = 0.654 \pm 0.003 \pm 0.007\, fm$

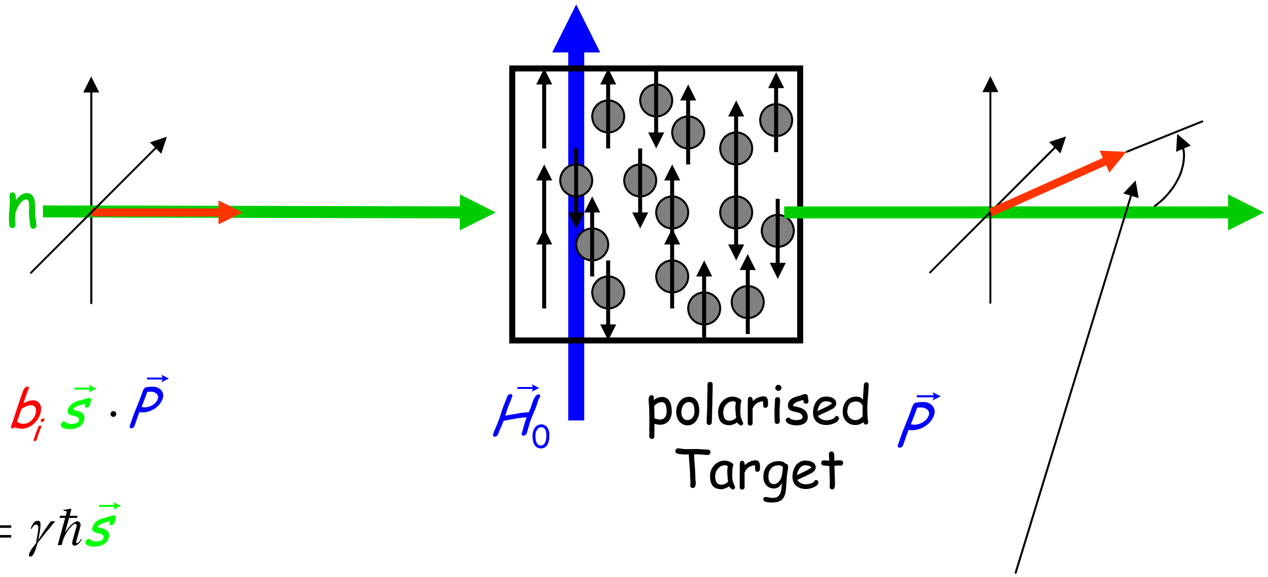
Goal of presented experiment:

- direct measurement of $a_{i,d}$
- minimum accuracy of 10^{-3}
- new value for $a_{i,d}$ with uncertainty of 0.004 fm

Method: Pseudomagnetic Precession

[V. Barychevsky, M. Podgoretsky, JETP **20** (1965) 704]

[A. Abragam, G.L. Bachella, H. Glättli *et al.*, PRL **31** (1973) 776]



$$V_{eff}^{s.d.} = \frac{4\pi\hbar}{m}\sqrt{\frac{I}{I+1}}\, N\, b_i\, \vec{s}\cdot\vec{P}$$

with $\vec{\mu}_n = \gamma\hbar\vec{s}$

$$V_{eff}^{s.d.} = -\vec{\mu}_n\cdot\vec{H}^* = \vec{\mu}_n\cdot\underbrace{\left[\frac{4\pi\hbar}{\gamma m}\sqrt{\frac{I}{I+1}}\, N\, b_i\vec{P}\right]}_{-\vec{H}^*}$$

$$\boxed{\varphi^* = \gamma H^* t = 2\sqrt{\frac{I}{I+1}}\,\lambda\, d\, N\, P\, b_i}$$

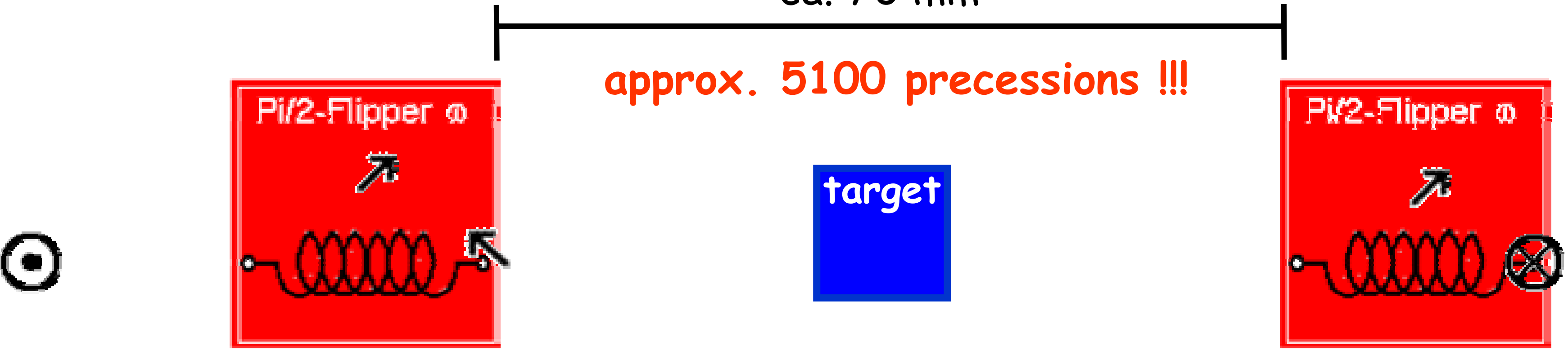
Pseudomagnetic Precession $\omega_L = -\gamma_n\left(H_0 + H^*\right)$

strong interaction

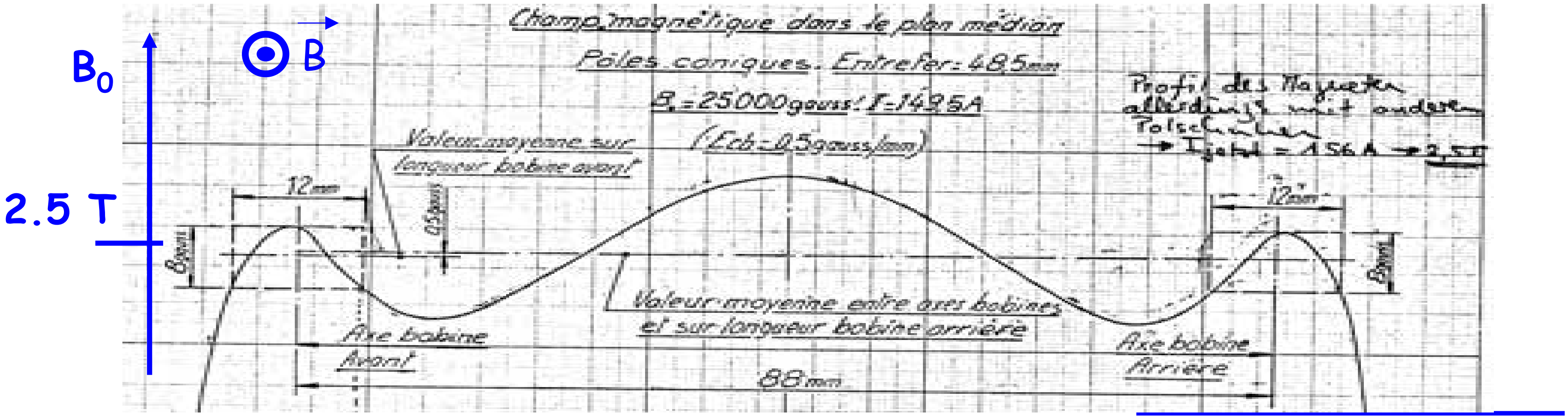
„Ramsey Technique“ The neutrons spin precession

[N. F. Ramsey, Phys. Rev. 78 (1950) 695]

Spinflipper regulated to have a fixed phase relation:
$\sigma_\varphi = \pm 0.06°$ at 73 MHz

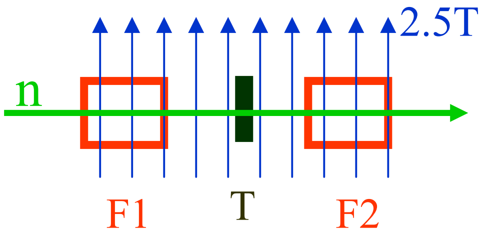


approx. 5100 precessions !!!



Time Evolution Operator

$$\hat{U}(t,t_0=0)=\exp\left(-\frac{i}{\hbar}\int_{t_0}^{t}\hat{H}(t')dt'\right) \quad with:\ \hat{H}(t)=-\gamma_n\frac{\hbar}{2}\vec{\sigma}\vec{B}$$



$$|\chi'\rangle=\hat{U}_{F2}\hat{U}_{free}\hat{U}_{target}\hat{U}_{F1}|\chi\rangle$$

$$measured: \quad \left|\langle\uparrow|\chi'\rangle\right|^2$$

parameters:

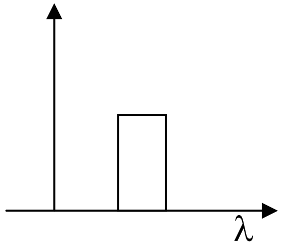
P_n = 90 %

λ_{TOF} = (4.5 ± 0.5) Å

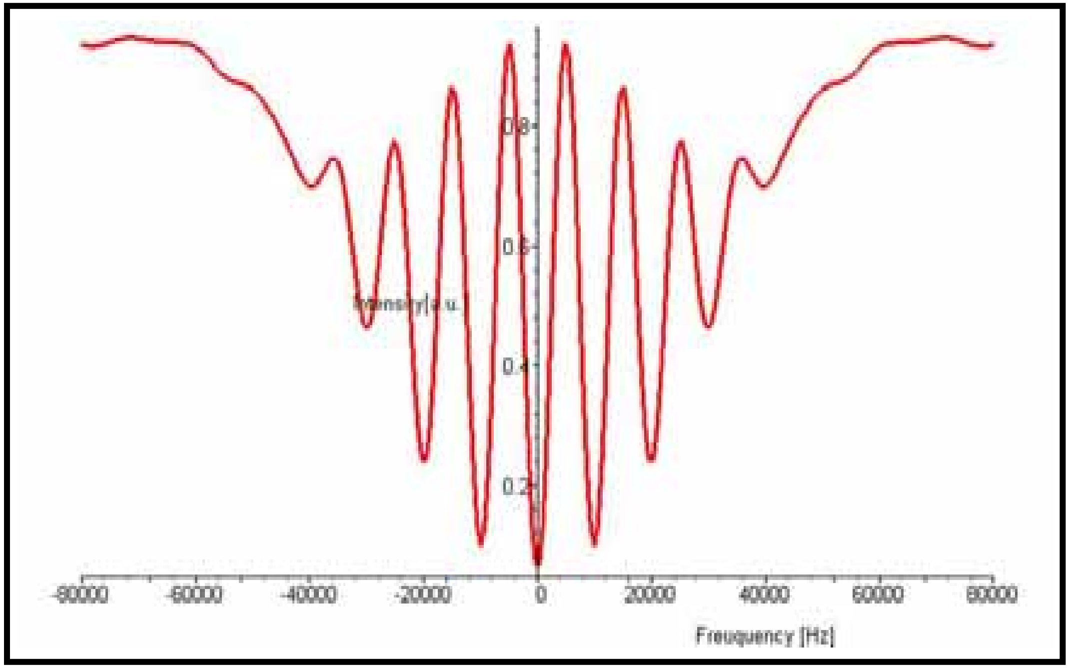
L = 7.1 cm

$l_{rf\text{-}coil}$ = 1.2 cm

B_1 fulfils $\pi/2$-condition



$$\Delta f = v_n / L = h/(L\lambda_0 m_n)$$

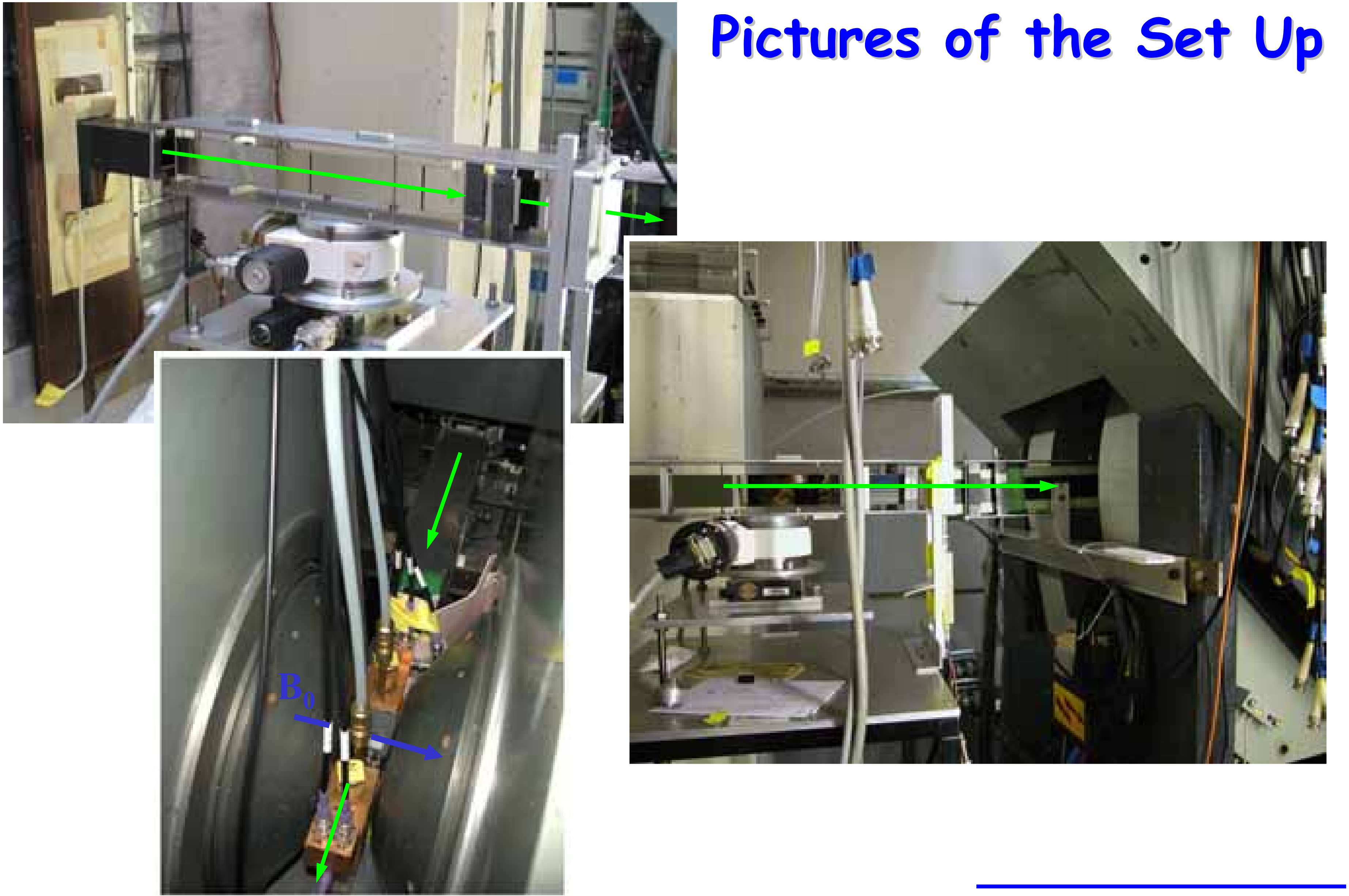


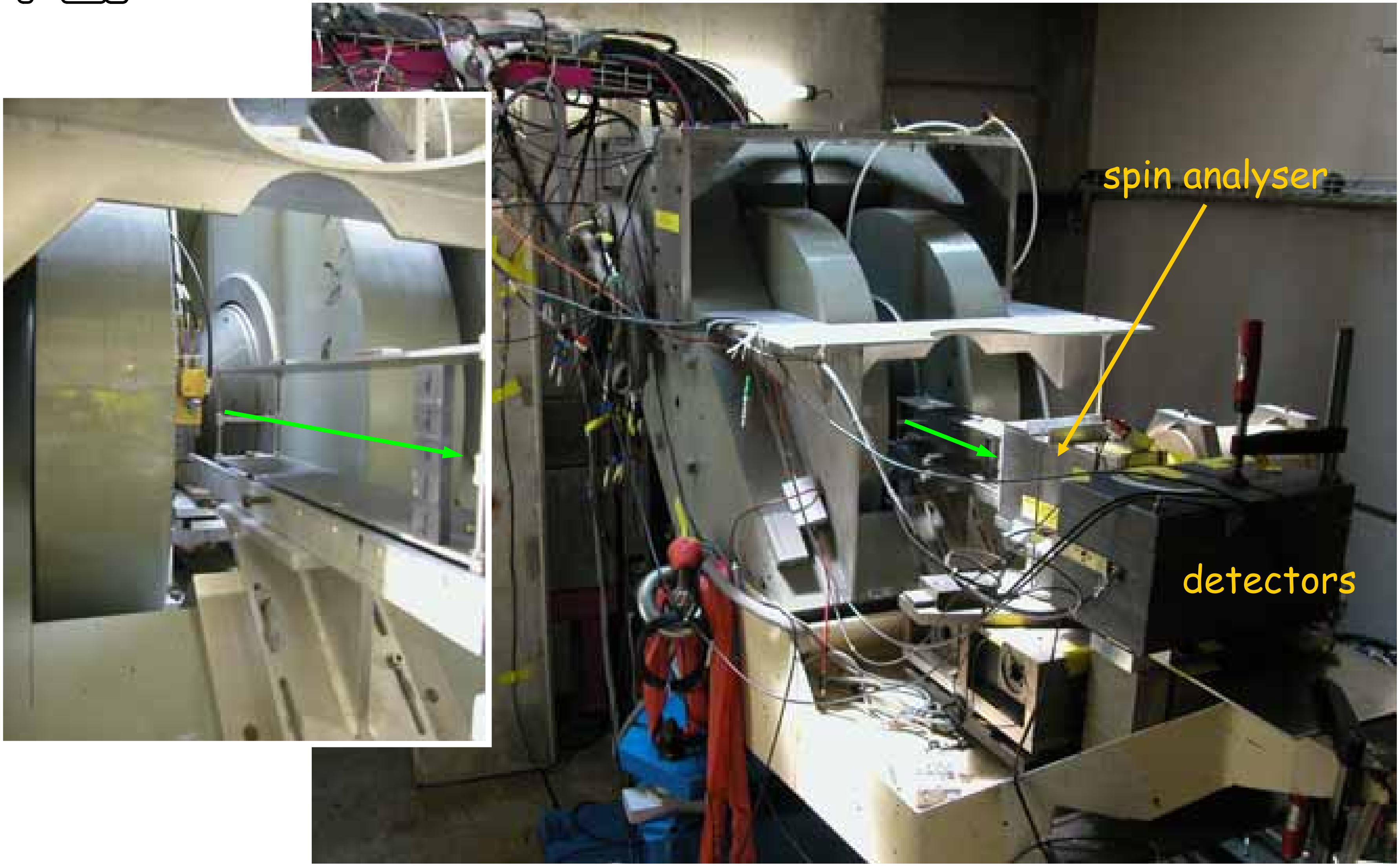
FUNSPIN at Paul Scherrer Institute

flux density of $\Phi = 2.46 \times 10^8$ [$n/cm^2 \cdot s \cdot mA$] **polarised** !!

cold n from the spallation source (SINQ)
With an approx. 1.2mA proton beam

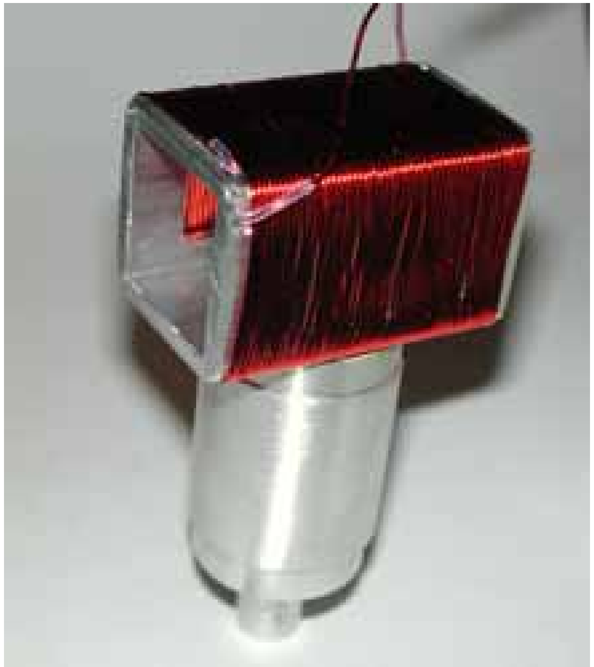
Pictures of the Set Up

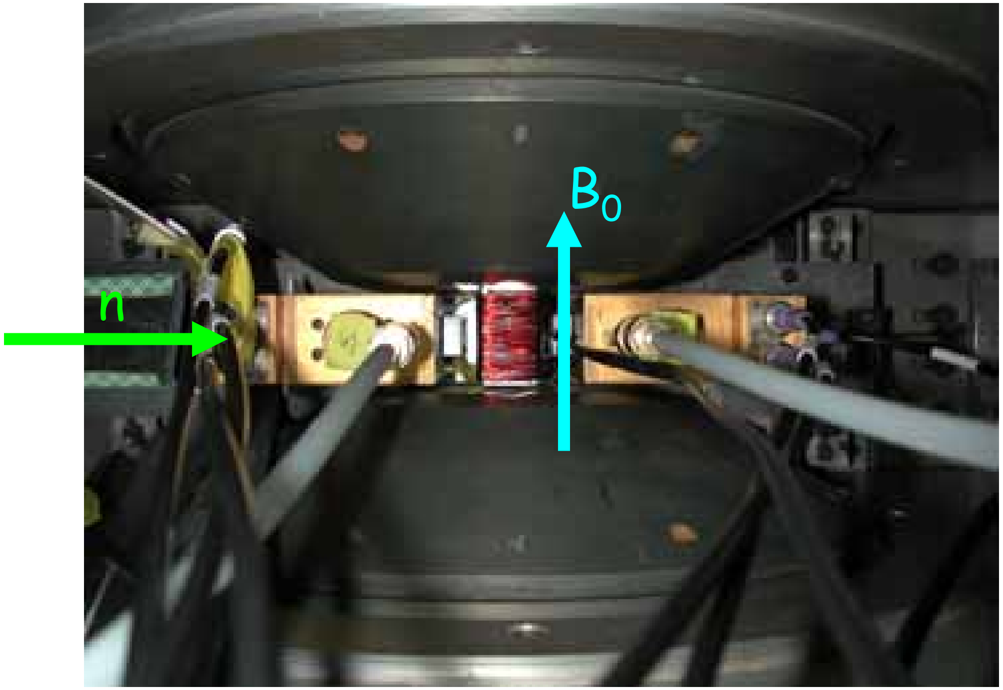




magnetic field stabilised to $\pm 6\,\mathrm{mG} / 2.5\,\mathrm{T} \rightarrow \pm 2.4 \times 10^{-7}$

Simulate Polarised Target

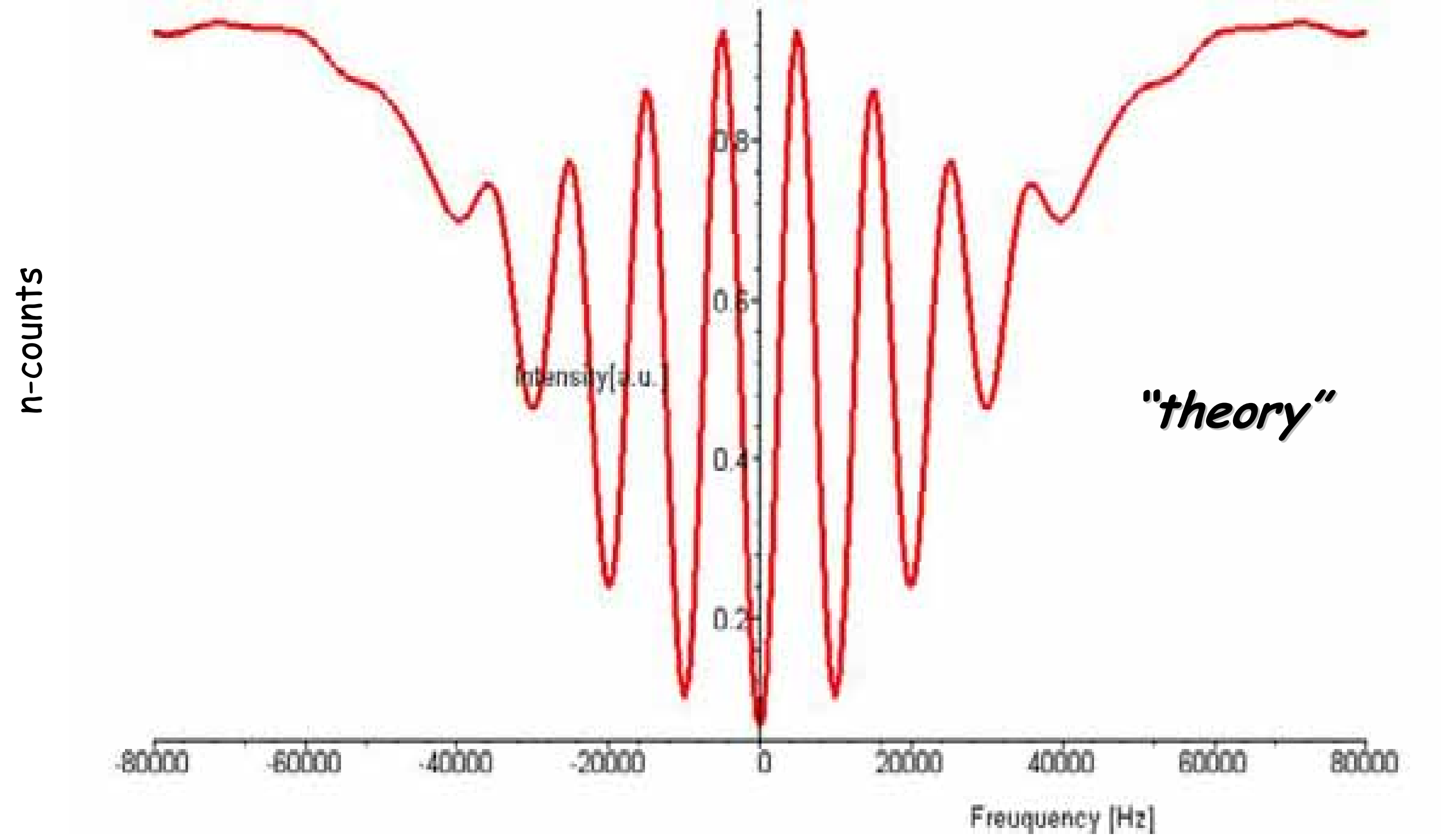




- the coil produces an
  additional magnetic field (anti-) parallel to the main field
- simulates the pseudomagnetic field of a polarised target
  acts as a substitute for the real target ➡ **„Pseudotarget“**

Ramsey fringes

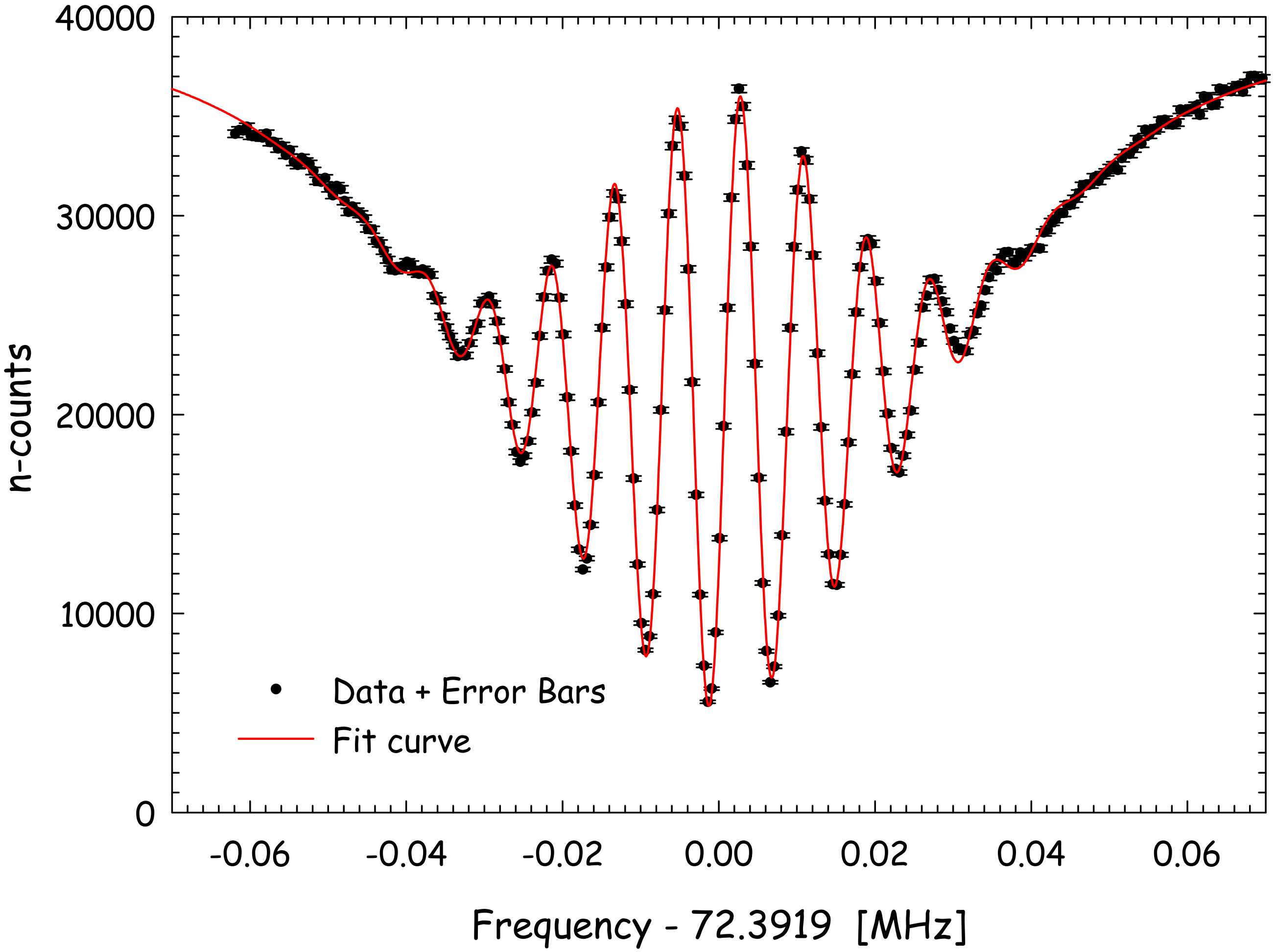
scans with different currents through the pseudotarget-coil



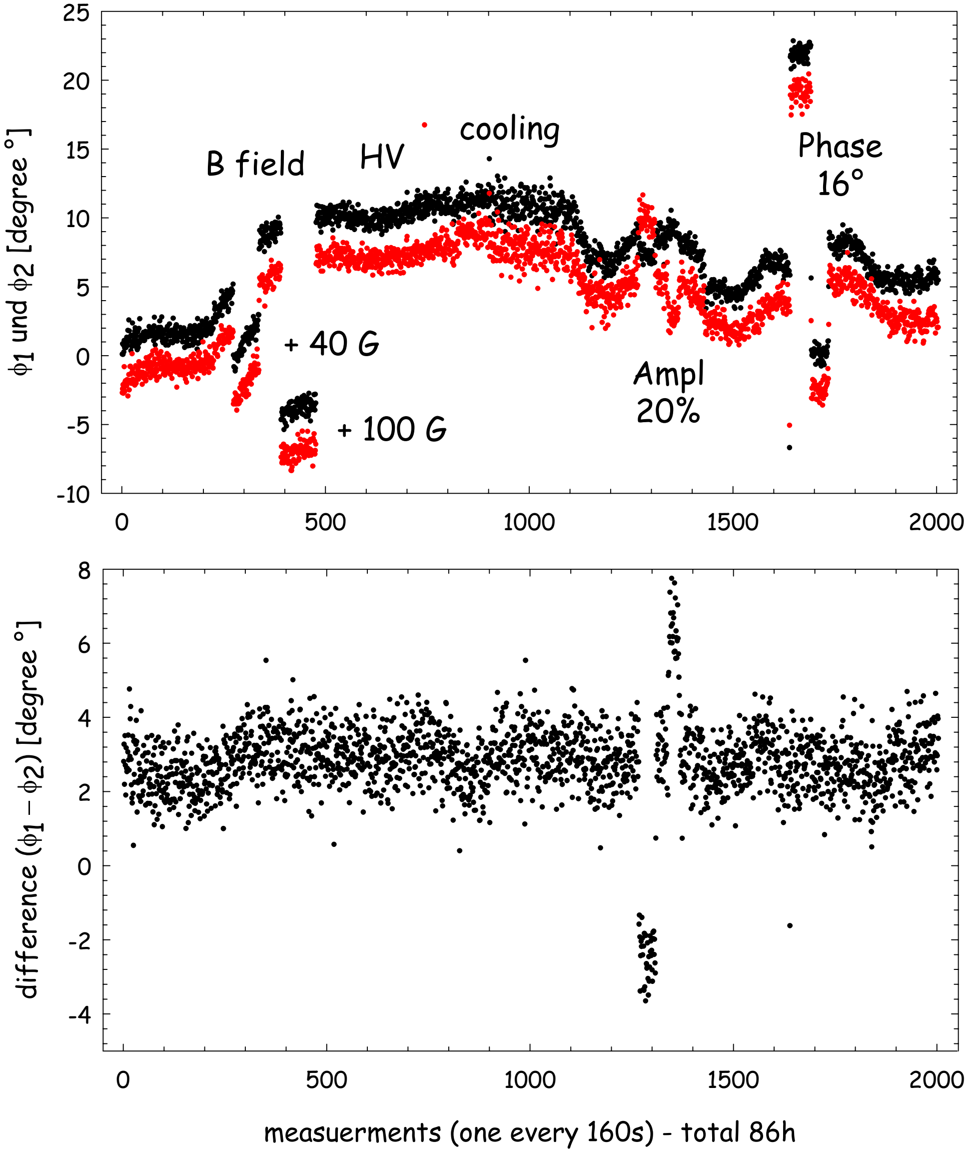
"theory"

➡ **confirms the expectations from analytical treatment**

Fit to the Data



Split beams: stability measurements



Idea

have a reference beam to correct for drifts

Check sensitivity on changes of apparatus parameters:

- magnetic field strength B_0
- amplitude/phase of spin flippers
- cooling of flippers
- detector count rate (HV)

→ **Phase fluctuations are statistics dominated**

Polarised Solid Target (DNP)

under construction & test

- **no relaxation, frozen spin mode**
  - dilution refrigerator T < 100 mK
- **no ^{3}He on beam**
  - separate ^{4}He cell / heat exchanger

- **polystyrene sample (d = 3 mm)**
  - 96% D / 4% P, d-TEMPO
- **precise / stable NMR Signals**
  - NMR circuit close to sample at LT

The actual measurement: General Idea

[H. Glättli, J. Coustham, J. Physique. **44** (1983) 957]

measure deuterons ***relative*** to protons in the same sample

$$\varphi_p^* = \frac{2\lambda d}{\sqrt{3}} P_p N_p b_{i,p} \quad , \qquad \varphi_d^* = \frac{2\lambda d}{\sqrt{2}} P_d N_d b_{i,d}$$

1st step: *both isotopes polarised* $\phi_1 = \varphi_p^* + \varphi_d^* + \varphi_0$

2nd step: *protons depolarised* $\phi_2 = \varphi_d^* + \varphi_0$

3rd step: *both isotopes depolarised* $\phi_3 = \varphi_0$

$$\Rightarrow \quad b_{i,d} = \sqrt{\frac{2}{3}} \cdot \frac{\phi_2 - \phi_3}{\phi_1 - \phi_2} \cdot \boxed{\frac{P_d N_d}{P_p N_p}} \cdot b_{i,p}$$

NMR Signals: Proton vs Deuteron

NMR Signals

$$I_p = C_p \, P_p \, N_p$$

$$I_d = C_d \, P_d \, N_d$$

measure at the same frequency

$$C_p = C_d$$

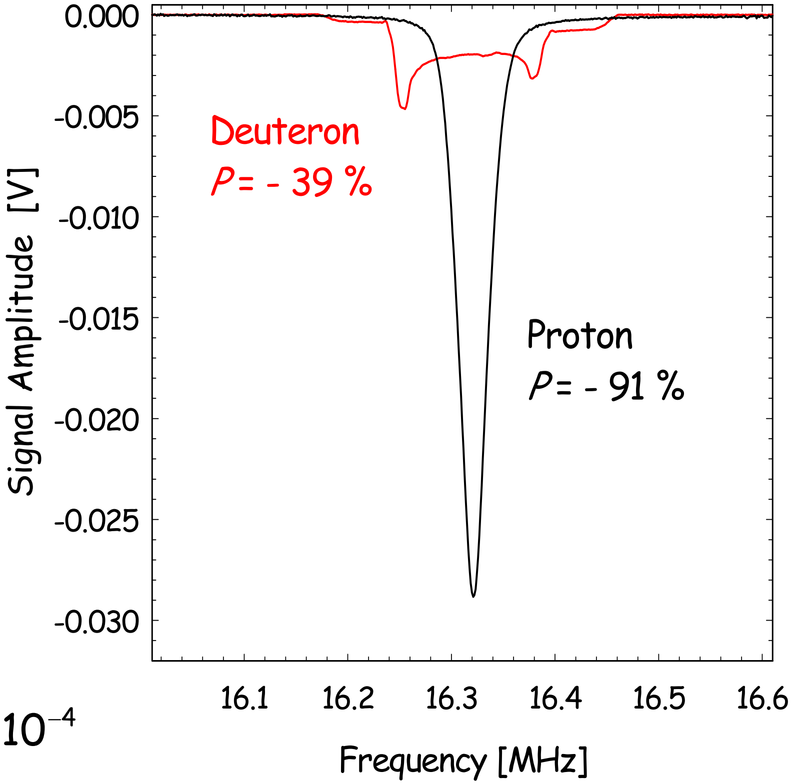
$$\boxed{b_{i,d} = \sqrt{\frac{2}{3}} \cdot \frac{\phi_2 - \phi_3}{\phi_1 - \phi_2} \cdot \frac{I_d}{I_p} \cdot b_{i,p}}$$

Accuracy: < 2.5×10^{-4}

Aim: $\delta \frac{I_d}{I_p} < 10^{-3}$

[P. Hautle, NIM A 526 (2004) 76]

Protons measured at B = 0.3 T with Deuteron Q-meter



Target composition
practical remarks & typical values

Sample containing 4% protons / 96% deuterons:

$N_{pd} = 6.7\times10^{22}\ \mathrm{cm}^{-3}$, $\lambda = 0.4$ nm , $d = 3$ mm

➡ $\varphi_p{}^{*} = 5200°\ P_p$ $\varphi_d{}^{*} = 25200°\ \mathrm{rad}\ P_d$

Proposed accuracy: $\delta\varphi \leq 5\times10^{-4} \cong 1° / 2000°$ ($\approx 11\pi$ precession)

➡ $P_p = 38$ % $P_d = 8$ %

Summary & outlook

- Set up a "Ramsey resonance apparatus":
  - measured ramsey patterns
  - "simulated" pseudomagnetic precession of target with a small coil
  - excellent agreement between theory and experiment
  - implemented the split beam method and investigated sensitivity on apparatus drifts:

→ we can achieve the necessary precision, about 1° phase angle

- Improvements: Spin flippers / wave-length selector
- PT cryostat is almost ready: NMR / DNP tests this winter
- Beam times scheduled:
  - Spring 2005: ramsey apparatus + polarised target
  - Fall 2005: production run

→ $a_{i,d}$ with 10^{-3} accuracy