Incoherent Scattering of ^{199}Hg

Another Physics Measurement

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FOR FUNDAMENTAL PHYSICS

- Neutrons interact with polarized ^{199}Hg atoms via strong interaction
- Interaction large enough to be measured – potential system. effect
- Sign of the pseudomagnetic effect/interaction is unknown
- Can be considered as a ”calibration measurement” – non-zero

LINK: https://nedmpsi.atlassian.net/wiki/display/nedmcoll/2016/10/28/Spin-Dependent+Interaction+of+UCN%27s+with+Polarized+199Hg?focusedCommentId=100368386#comment-100368386

Neutron-Hg Scattering Length

Neutron scattering lengths and cross sections							
Isotope	**conc**	**Coh b**	**Inc b**	**Coh xs**	**Inc xs**	**Scatt xs**	**Abs xs**
Hg	---	12.692	---	20.24	6.6	26.8	372.3(4.0)
196Hg	0.2	30.3(1.0)	0	115.(8.)	0	115.(8.)	3080.(180.)
198Hg	10.1	---	0	---	0	---	2
199Hg	17	16.9	(+/-)15.5	36.(2.)	30.(3.)	66.(2.)	2150.(48.)
200Hg	23.1	---	0	---	0	---	<60.
201Hg	13.2	---	---	---	---	---	7.8(2.0)
202Hg	29.6	---	0	---	0	9.828	4.89
204Hg	6.8	---	0	---	0	---	0.43

Source: NIST

- **The ^{199}Hg incoherent scattering length value of ±15.5(8) fm is rather large (^{1}H: 25.3 fm), meaning this could lead to a potentially strong effect**
- **And the sign of the scattering length is unknown** $\sigma_s = 4\pi(|b_c|^2 + |b_i|^2)$

$$B^* = -\frac{4\pi\hbar}{m_n\gamma_n}\,\rho b_i P\sqrt{\frac{I}{I+1}}$$

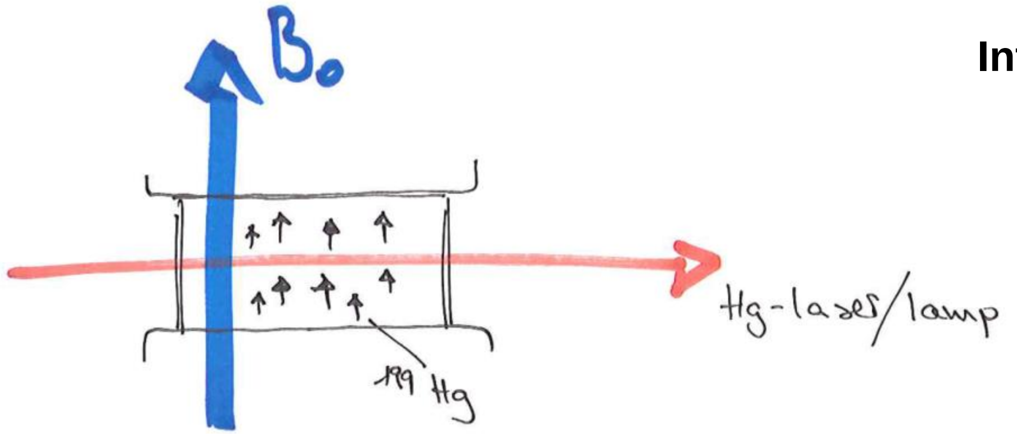
$b_{i,Hg} \approx \pm 15.5$ fm, $I = 1/2$

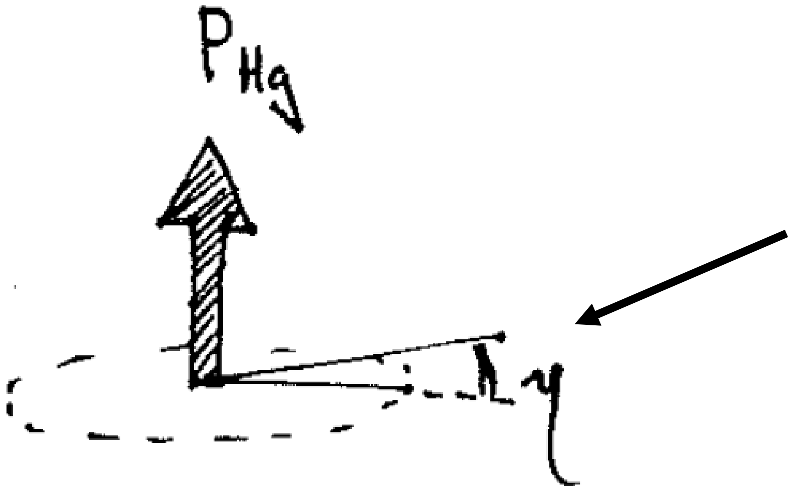
$\rho_{Hg} \approx 10^{16}$ m^{-3} (about 4×10^{-7} mbar)

$P_{Hg} \approx 30\%$

$B^* \approx \pm 120\ \mathrm{fT} \gg B_M$

nuclear magn. Interaction (~0.01 fT)





Imperfect π/2-flip pulse causes a residual Hg-polarization along the main magnetic field axis.

It could potentially be non-equal for E up/down.

$$\Delta\eta = \eta_+ - \eta_-$$

$$B_{false} \approx 400\ \text{fT} \cdot P_{Hg} \cdot \Delta\eta$$

- **To keep the false EDM below 10^{-27} ecm: $B_{false} < 0.3$ fT (assuming $E = 10$ kV/cm). And with $P_{Hg} = 30\%$, this yields a limit of:**

$$\Delta\eta < 2\ \text{mrad}$$

- **A corresponding limit for the Hg-pulse (equality) precision about 10^{-3}.**

► Measurements in 2016 (PSW):

- Test measurements were performed – total of 2-3 days
- Problems with laser (power stabilization) almost entire time
- Proposed SE method was not suitable to detect effect

► New Proposal:

Use standard Ramsey method with Hg-laser

Effect (typical): **2.5 μHz** (P = 30%, $\rho = 10^{-16}$ m^{-3}, π/4-pulse)
Stat. sensitivity per cycle: **< 10 μHz**

Two days are enough to measure effect on < 20% level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Maximum tilt angle of neutron spin due to Hg-Pulse:

$$\theta^* \approx 2\frac{\varphi}{\tau}\frac{R}{1+R}\frac{1}{\gamma_{Hg}B_0}$$

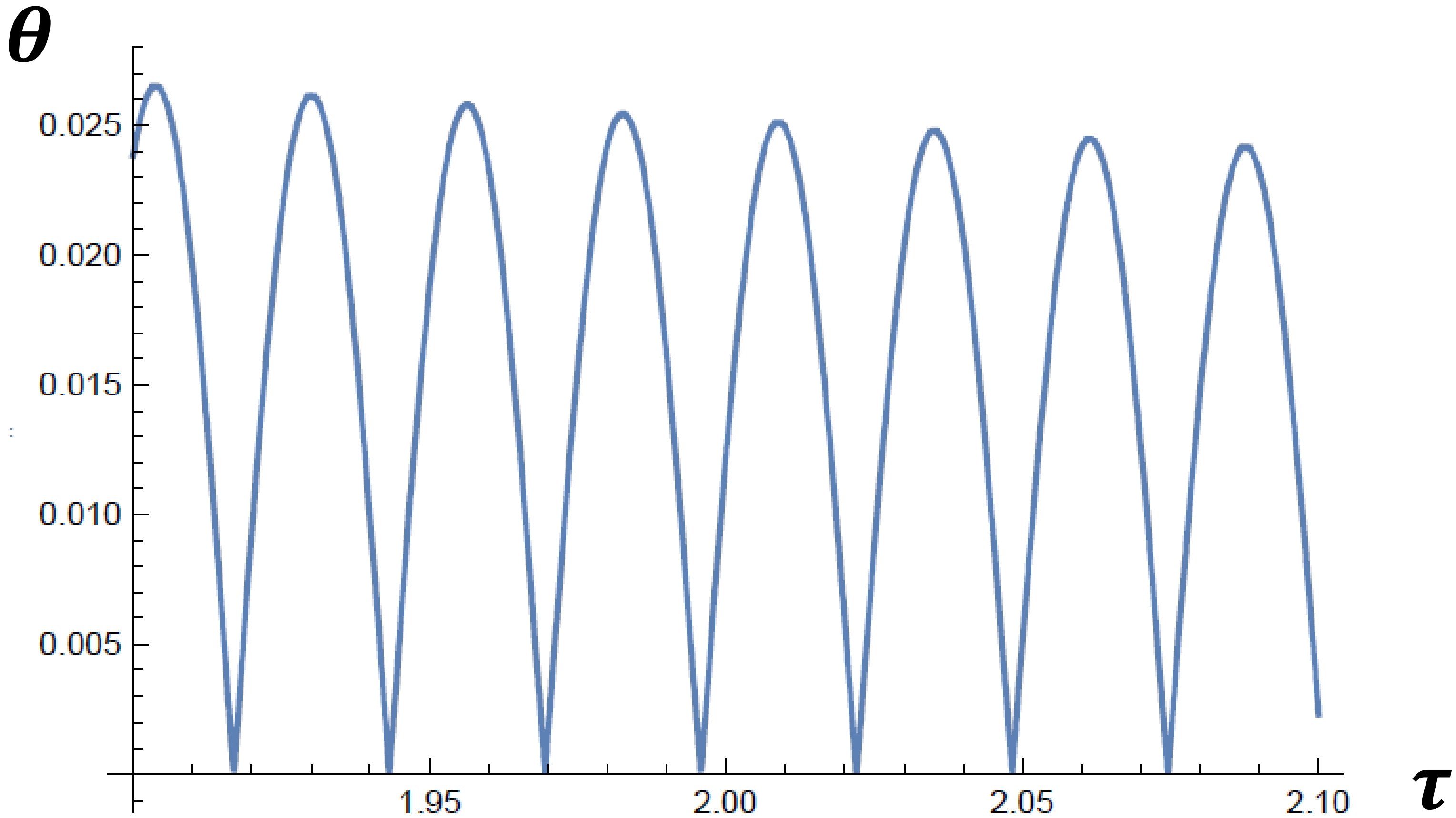
R = - 3.85

The tilt angle and the related (random) false effect is constant for constant $\omega_1 \propto \frac{\varphi}{\tau}$

Typical: $\theta^* = 25$ **mrad (**τ**=2 s,** φ**=Pi/2,** B_0**=1 μT)**

False eff.: 16 μHz (with *T*=180 s)

Can this effect be directly measured ???


θ
0.025
0.020
0.015
0.010
0.005
1.95
2.00
2.05
2.10
τ

MAGNETIC INTERACTION:

$$B_M = \mu_0 \frac{\hbar}{2} \gamma_{Hg} \rho_{Hg} P_{Hg}$$

$\gamma_{Hg} \approx 2\pi \times 7.6$ MHz/T

$\rho_{Hg} \approx 10^{16}$ m^{-3} (about 4×10^{-7} mbar)

$P_{Hg} \approx 30\%$

$$B_M \approx 0.01 \text{ fT}$$

STRONG INTERACTION:

$$b = b_c + \frac{2b_i}{\sqrt{I(I+1)}} \vec{s} \cdot \vec{I}$$

Bound Scattering Length

$\vec{s}$ = spin of the neutron

$\vec{I}$ = spin of the nucleus

b_c = coherent bound scattering length

b_i = incoherent bound scattering length

Spin-Dependent/Incoherent Part of the Fermi-Potential:

$$V_{F,i} = \frac{4\pi\hbar}{m_\mathrm{n}\gamma_\mathrm{n}} \rho b_i \sqrt{\frac{I}{I+1}} \vec{\mu}_\mathrm{n} \cdot \vec{P} = -\vec{\mu}_\mathrm{n} \cdot \vec{B^*}$$

Pseudomagnetic Field:

$$B^* = -\frac{4\pi\hbar}{m_\mathrm{n}\gamma_\mathrm{n}} \rho b_i P \sqrt{\frac{I}{I+1}} \propto \rho b_i P$$

For instance, the protons in solid polystyrene have a number density of about 0.08 mol/ml, which will create a pseudomagnetic field of **about 3 Tesla**, if the proton spin polarisation is 100%.

So what about the ^{199}Hg Spin-Dependent/Incoherent Scattering ?

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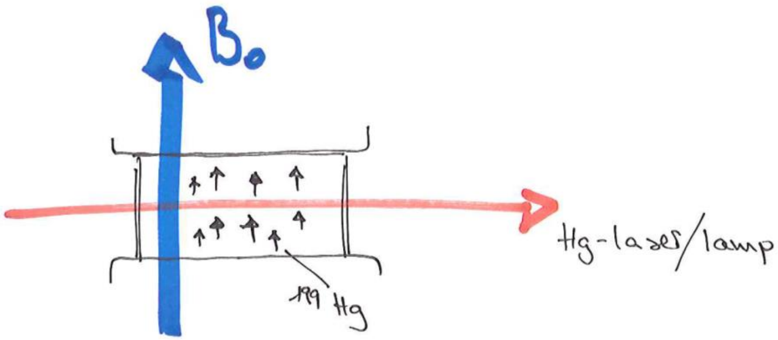
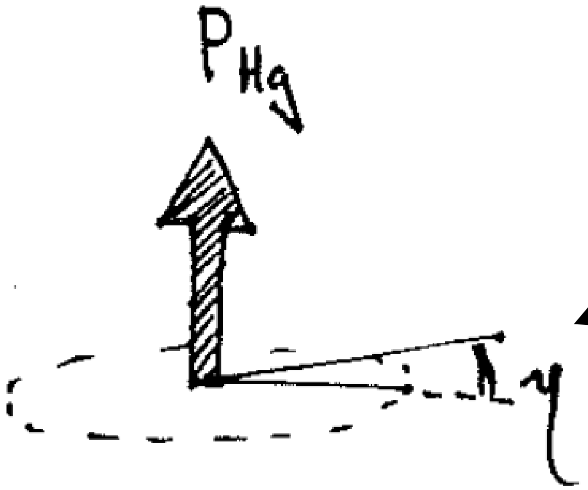
$$B^* = -\frac{4\pi\hbar}{m_n\gamma_n}\,\rho b_i P\sqrt{\frac{I}{I+1}}$$

$$\left.\begin{array}{l} b_{i,Hg} \approx \pm 15.5\ \text{fm}, \quad I = 1/2 \\ \rho_{Hg} \approx 10^{16}\ \text{m}^{-3} \quad \text{(about } 4\times10^{-7}\ \text{mbar)} \\ P_{Hg} \approx 30\% \end{array}\right\} \; B^* \approx \pm 120\ \text{fT} \gg B_M$$

- **Neutrons sense a pseudomagnetic field due to the polarized Hg nuclei. This field is maximum if spins are aligned with B_0-field, e.g. before Hg-pulse.**
- **And it is large enough to be measured with the UCN Ramsey apparatus.**





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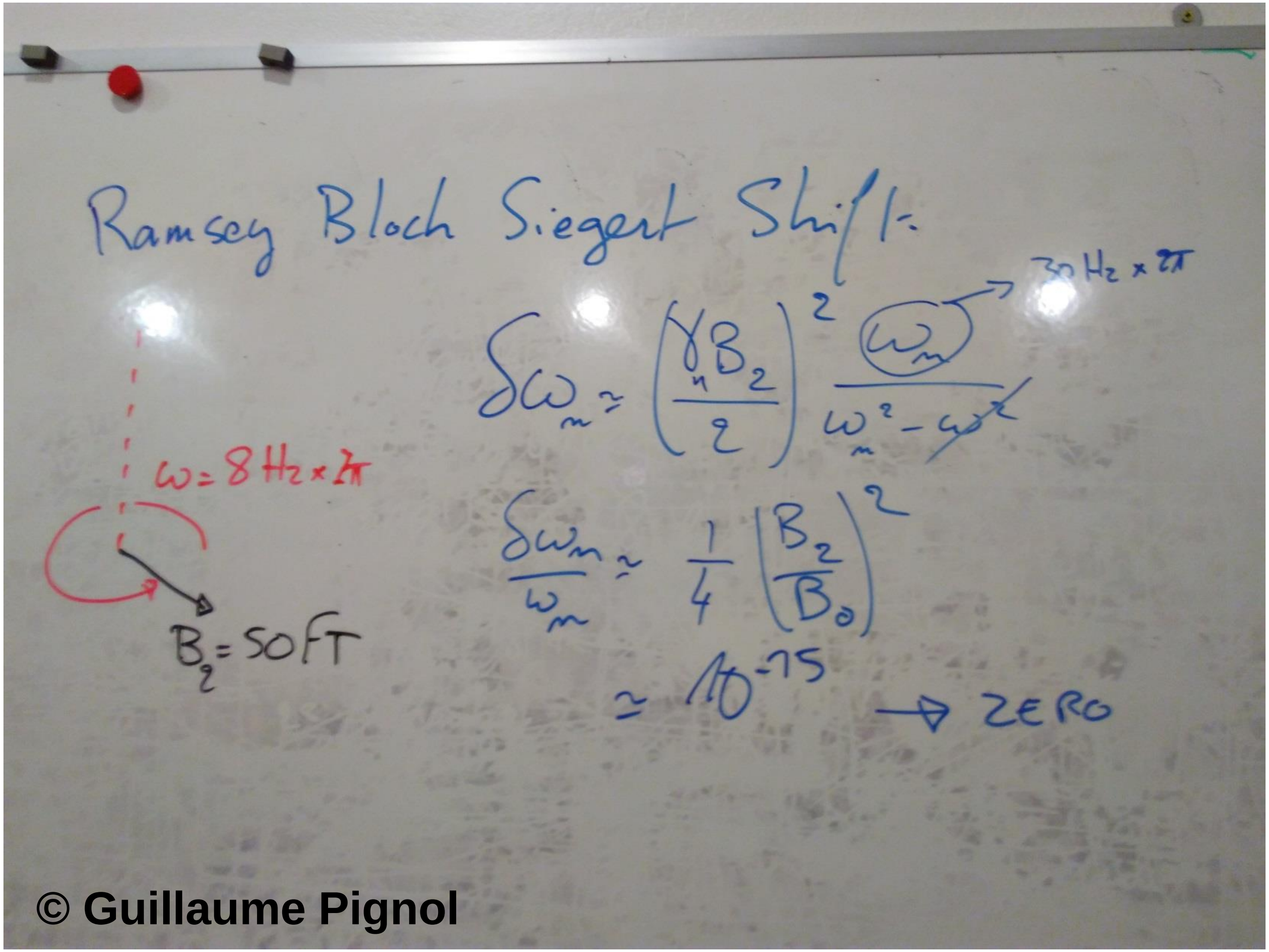
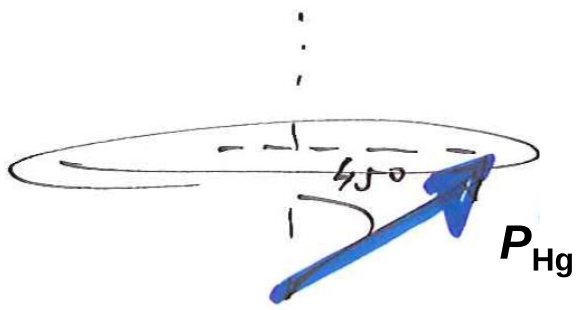

Ramsey Bloch Siegert Shift:
30 Hz × 2π
ω = 8 Hz × 2π
B2 = 50 fT
→ ZERO
© Guillaume Pignol

How to Measure the Effect:

- ► **Standard nEDM Runs (without *E*-field), however …**
- ► **Modify Hg RF-pulse to a 0- or π-pulse (amplitude and/or pulse-length)**
  - Incoherent scattering effect is maximum
  - No Hg-comagnetometer signal
- ► **Or modify Hg RF-pulse to a π/4- or 3π/4-pulse**
  - Incoherent scattering effect reduced by a factor $\sqrt{2}$ (component along B_0) to around 80 fT
  - Hg-comagnetometry possible, however with reduced signal visibility
  - (in addition one can intentionally vary the Hg-density/Hg-polarisation)



What can we learn from this:

- **Physics Result: Sign of the Hg incoherent scattering length (signs !!)**
- **One measures a quantity proportional to** $\rho b_{i,Hg} P_{Hg}$

  So if one later is able to access the Hg density and polarisation (offline), e.g. with the lase, one can determine the value for $b_{i,Hg}$
- **Handle on a possible systematic effect**
  One can later (offline) investigate the Hg RF-pulse as a function of the electric field polarity
- **Other ?**

Open Questions/Comments (by Guillaume)

… after thinking about it I have three comments:

1) Do we actually know the initial direction of the Hg spins? It depends whether the optical pumping is done with σ_+ or σ_- helicity of the light.

2) What about precise knowledge of the mercury density in the chamber? […] Therefore I think a clean measurement should be done with the laser in spring 2017.

3) […] the neutron wavelength is much larger than the distance between the Hg atoms. Are you sure the pseudomagnetic description really applies here?

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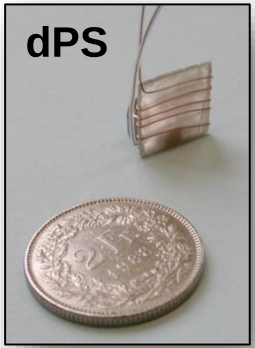

	Wavlength	Atom. distance	Factor
UCN	0.1 µm	1-5 µm	10-50
Cold Neutron	0.4 nm	1 nm	2.5

- Polarized Hg nuclei produce a pseudomagnetic field of order 100 fT via the spin-dependent strong interaction
- This can potentially cause a systematic effect
- The (sign of the) pseudomagnetic field can be measured within a few days – Physics result


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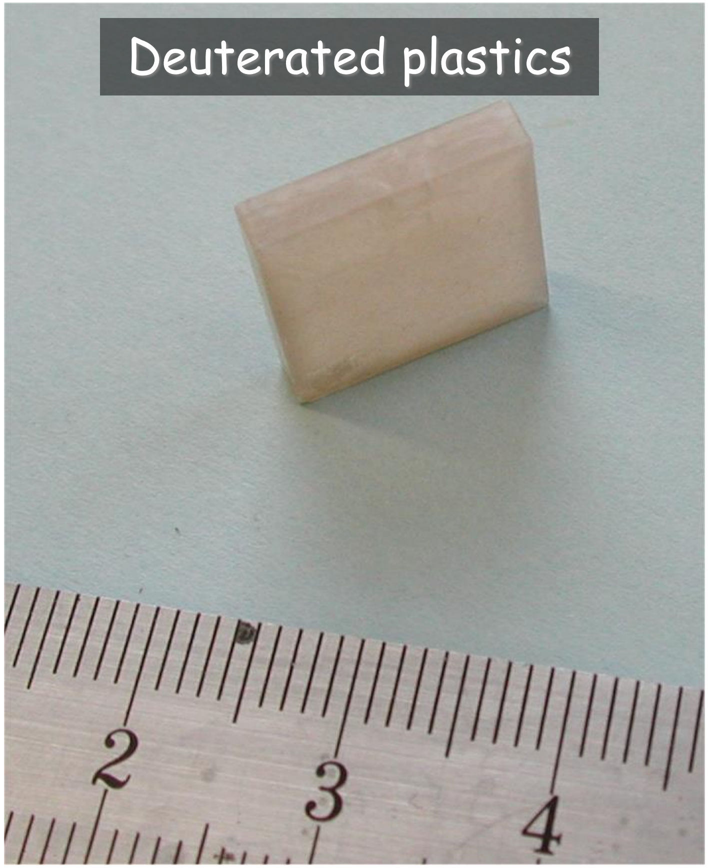
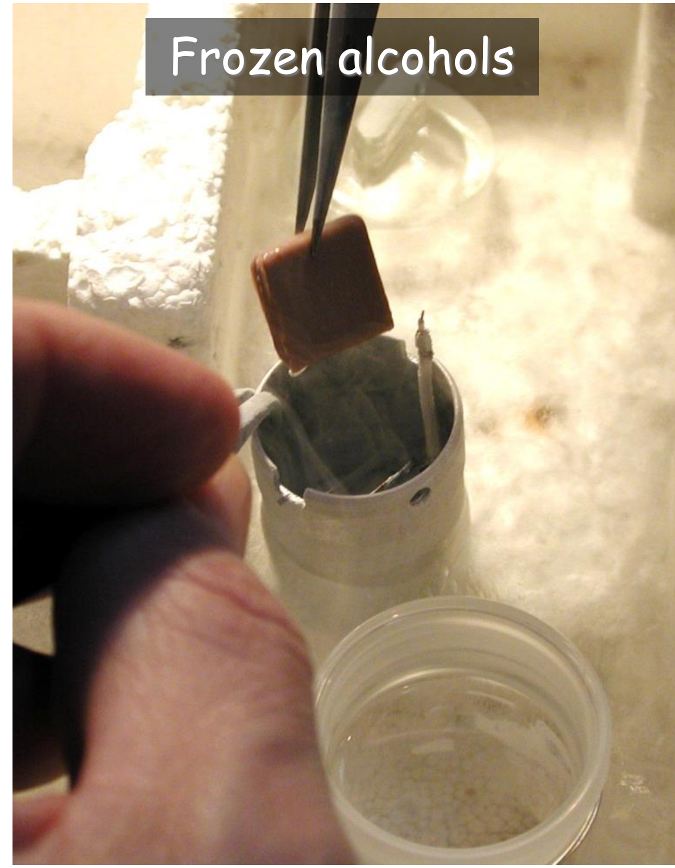
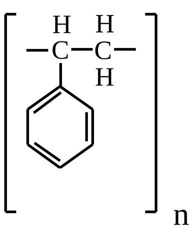
Elem. or Isot.	Natural Abundance (Atom %)	Atomic Mass or Weight	Half-Life/ Resonance Width (MeV)	Decay Mode/ Energy (/MeV)	Particle Energy/ Intensity (MeV/%)	Spin ($h/2\pi$)	Nuclear Magnetic Mom. (nm)	Elect. Quadr. Mom. (b)	γ-Energy/ Intensity (MeV/%)
^{196}Hg	0.155(12)	195.96583	> 2.5 × 10^{18} a	α		0+			
^{197m}Hg			23.8 h	I.T./(93)/0.2989		13/2+	−1.027684	+1.2	Hg k x-ray
									Au k x-ray
									0.13398
^{197}Hg		196.96721	2.69 d	EC/0.600		1/2-	+0.527374		Au k x-ray
									0.07735
^{198}Hg	10.038(16)	197.966769				0+			
^{199m}Hg			42.7 m	I.T./0.532		13/2+	−1.014703	+1.2	Hg k x-ray
									0.15841
^{199}Hg	16.938(39)	198.968281				1/2-	+0.505885		
^{200}Hg	23.138(65)	199.968327				0+			
^{201}Hg	13.170(66)	200.970303				3/2-	−0.560226	+0.37	
^{202}Hg	29.743(89)	201.970643				0+			
^{203}Hg		202.972873	46.61 d	β- /0.492	0.213/100	5/2-	+0.8489	+0.34	Tl k x-ray
									0.279188
^{204}Hg	6.818(35)	203.973494				0+			

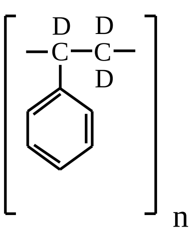




n-PS

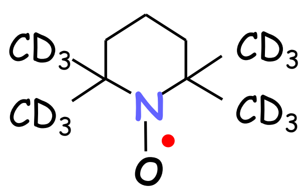


d-PS

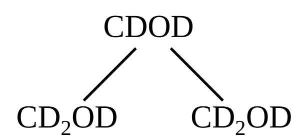


+

d-TEMPO



D_2O + d-Glycerol



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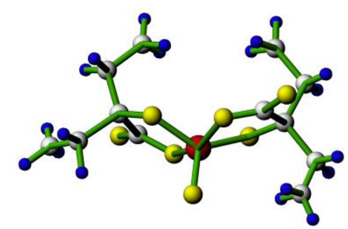
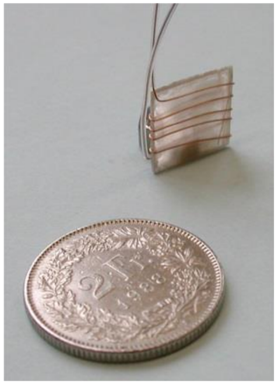
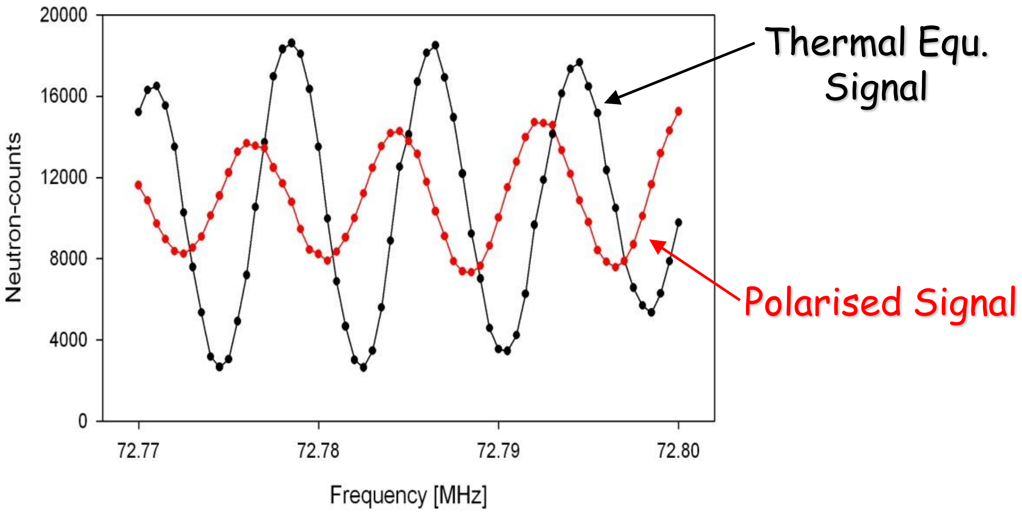
EHBA/EDBA-Cr(V)



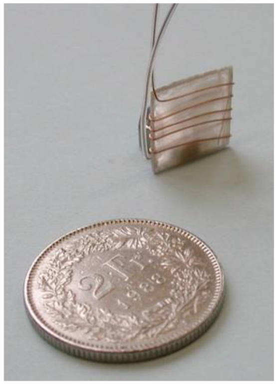


Sample: d-PS (ARMAR: 98%D) doped with: 2.7×10^{19} d-TEMPO/ml
thickness = 1.6 mm - 16.12.2005



Measuring time: 45 min each !

How big is the phase-shift ???
approx. 270° + n x 360°



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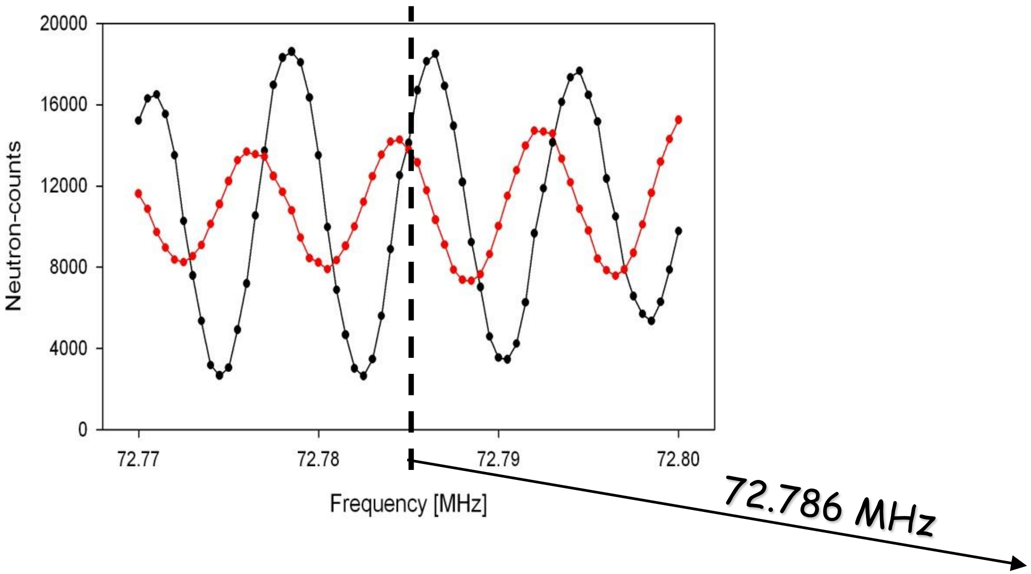
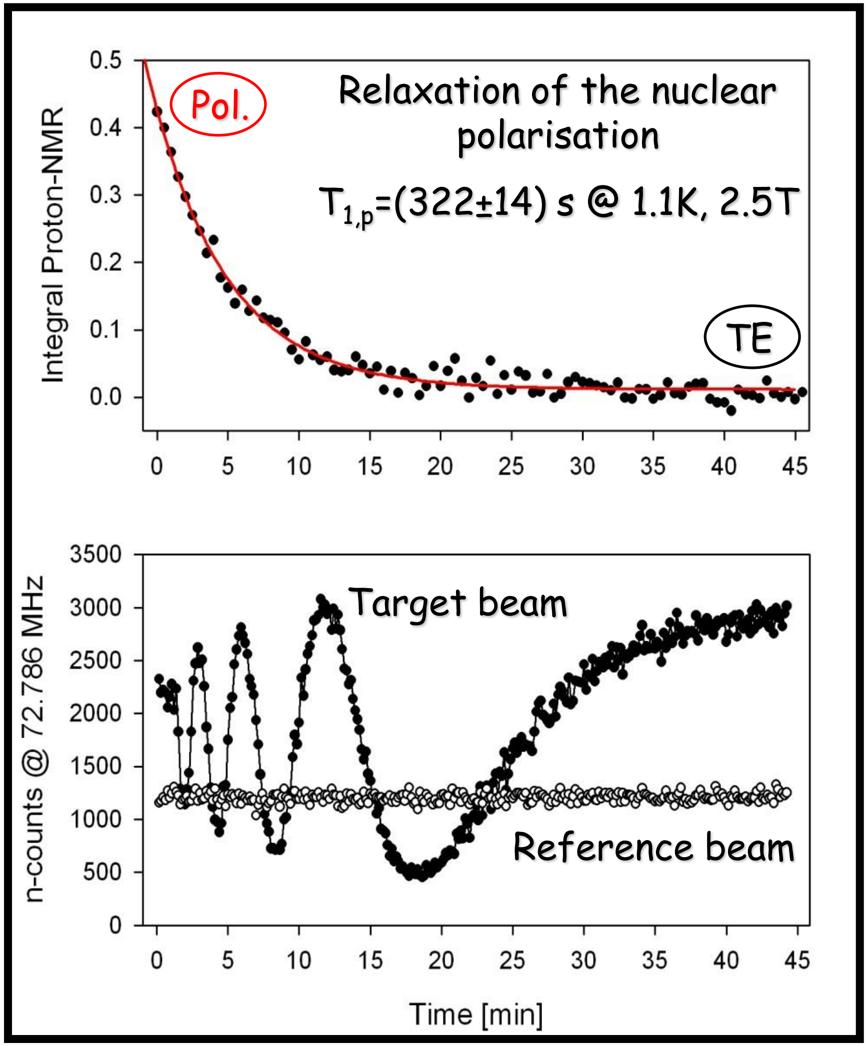
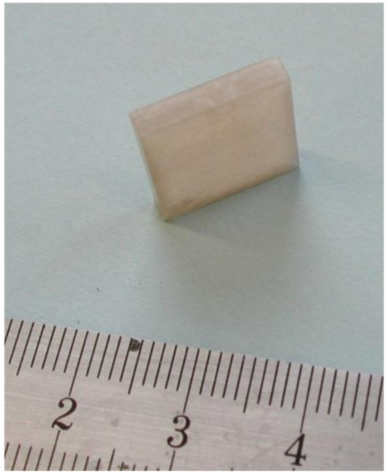




$P_p = 17\%$ $P_d = 12\%$ (from NMR)

$\varphi^*_{expect.} = (1503 \pm 132)°$

$\varphi^*_{meas.} = (1350.2 \pm 1.5)°$ → 10^{-3}



- 3 mm thick n-Polystyrene measured at 2.5 Tesla and various temperatures (25.11.05)
- Thermal equilibrium polarisation of proton spins cause pseudomagnetic precession