Ramsey Experiments using Neutron Beams

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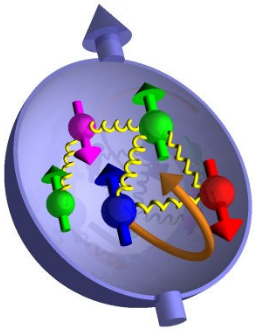
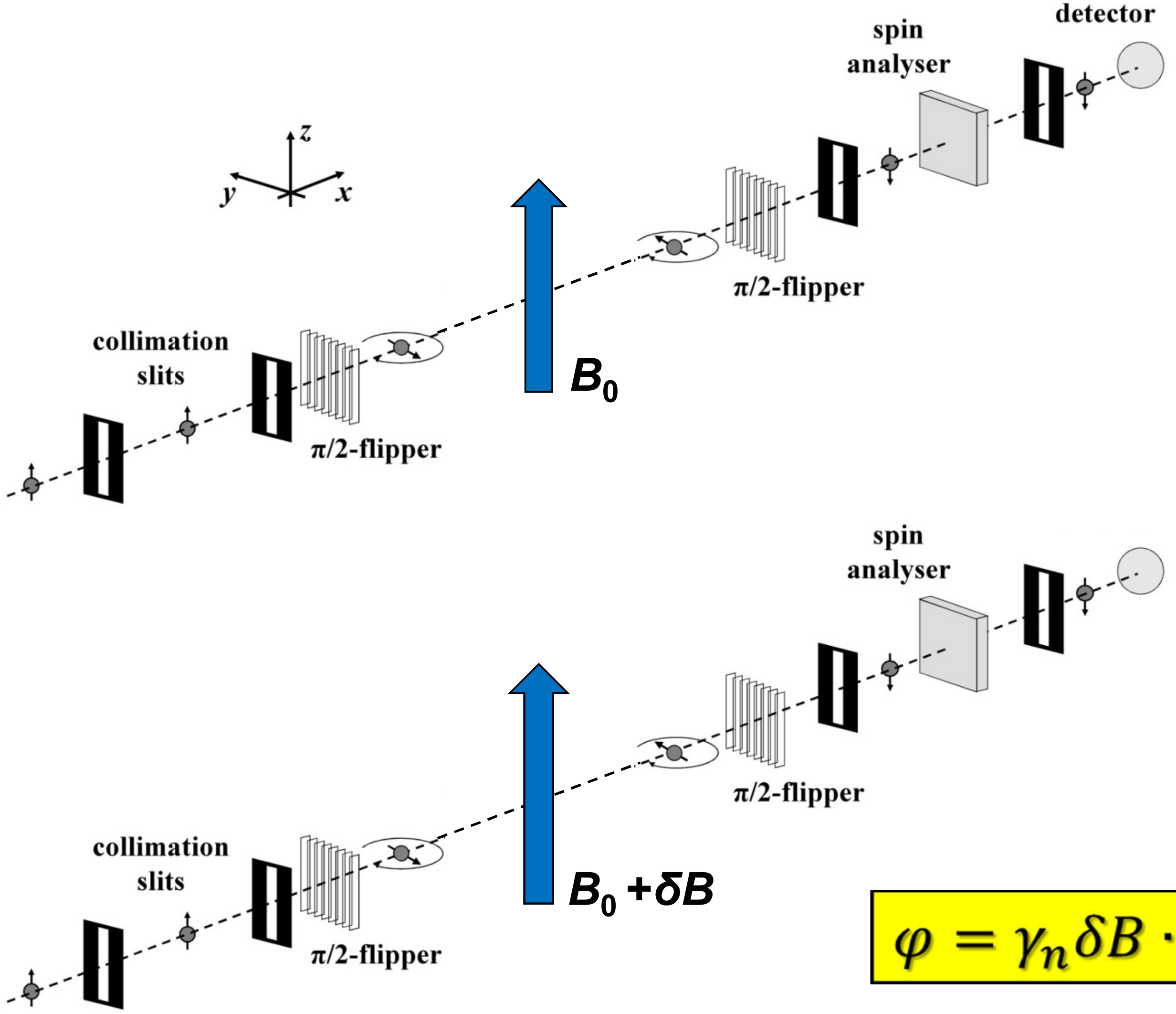
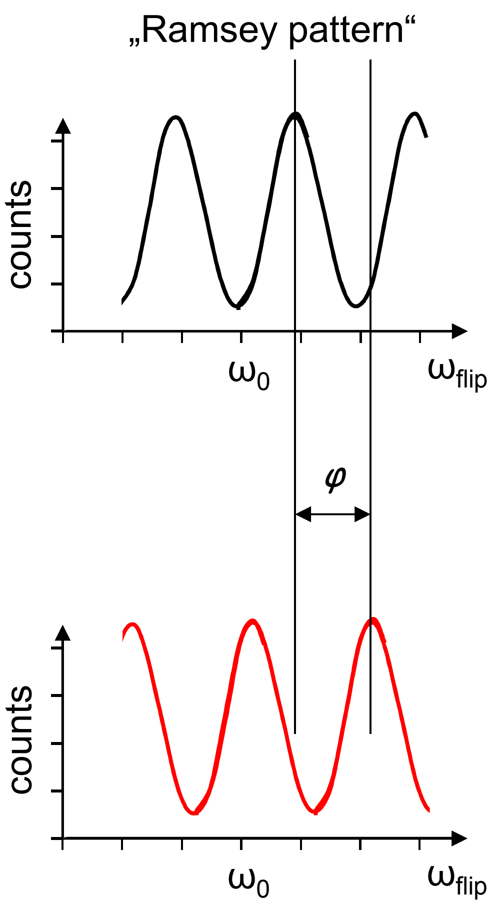
outline

- **Ramsey's method of separated oscillating fields**
- **Measurement of incoherent scattering lengths**
- **Neutron spin phase imaging**
- **Search for new light spin-1 bosons**
- **Conclusions for a pulsed spallation source**



Ramsey’s technique

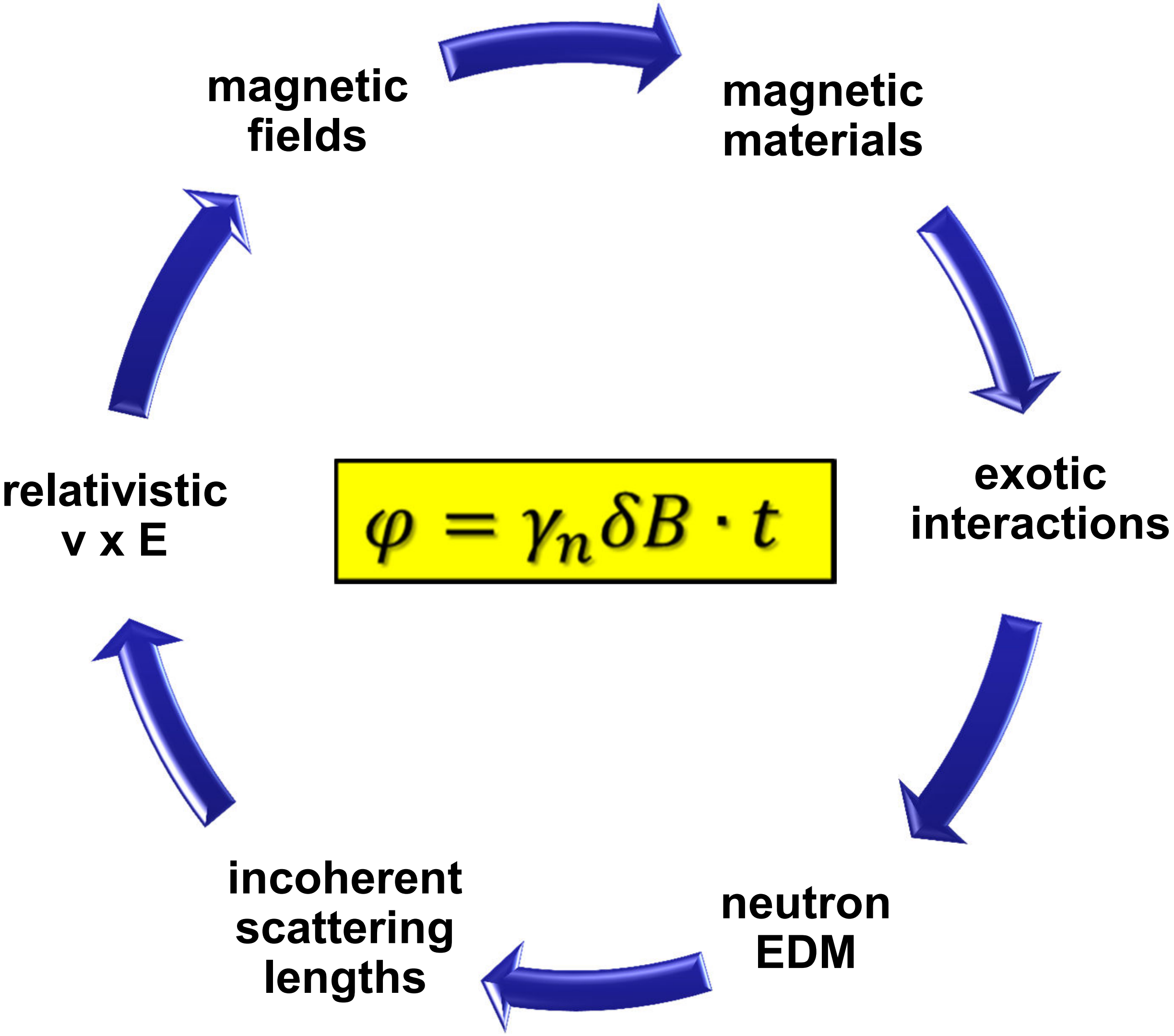




$$\boxed{\varphi = \gamma_n \delta B \cdot t}$$

Ramsey, PR **78** (1950) 695

magnetic and pseudomagnetic interaction



magnetic fields

magnetic materials

exotic interactions

neutron EDM

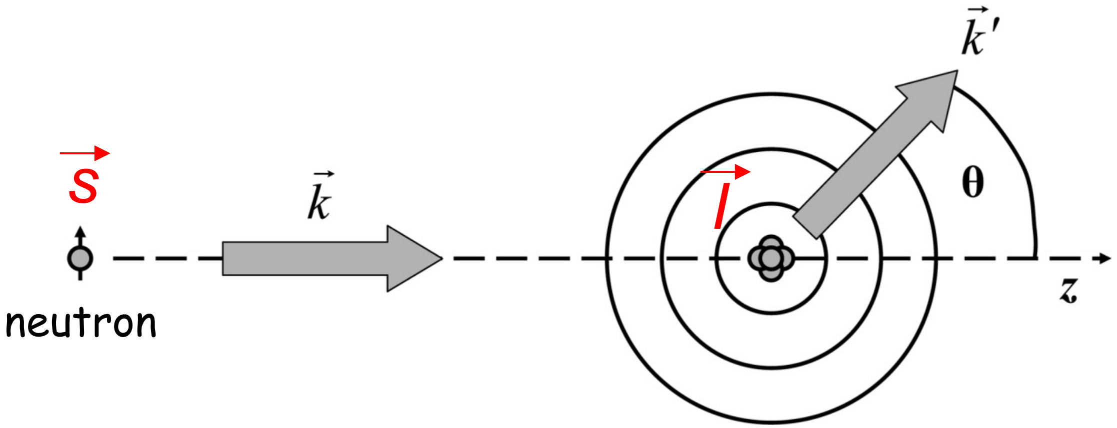
incoherent scattering lengths

relativistic v x E

$$\boxed{\varphi = \gamma_n \delta B \cdot t}$$

Incoherent Scattering Lengths

neutron scattering length



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

b_c **= spin-independent (coherent)**

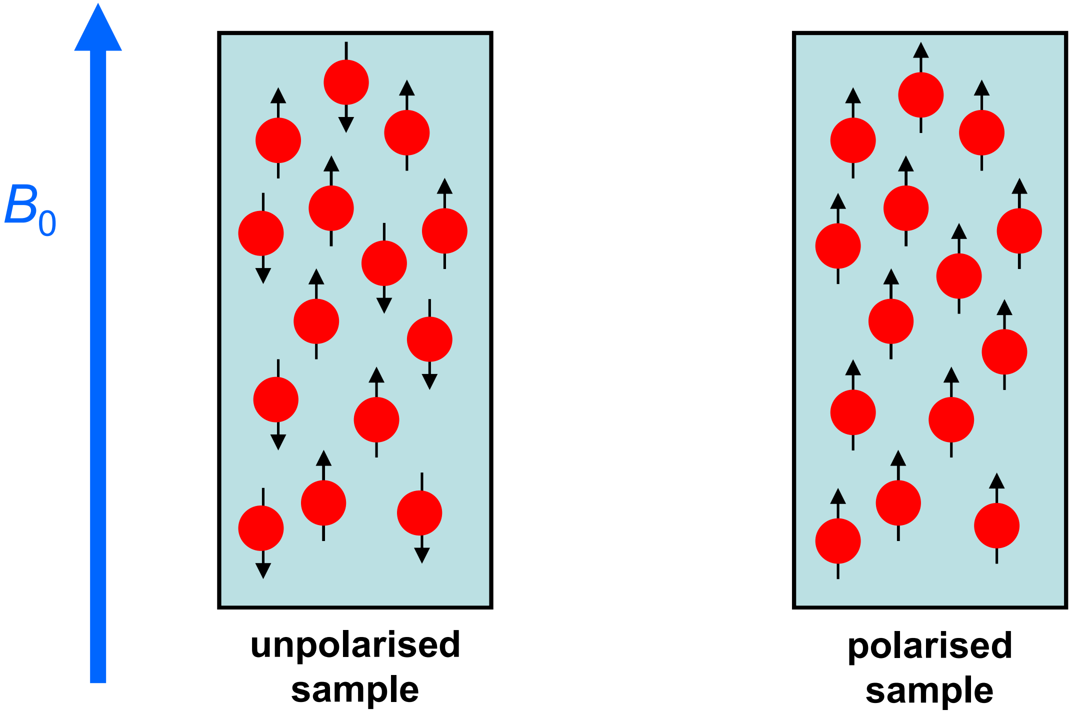
b_i **= spin-dependent (incoherent)**

Deuteron b_i interesting for Effective Field Theories/Cosmology:

- input parameter for 3 nucleons interaction
- absence of Coulomb forces and Pauli blocking in the doublet channel
- big-bang nucleosynthesis, e.g. $d(d,n)^3He$, $d(p,\gamma)^3He$, $d(d,p)^3H$.

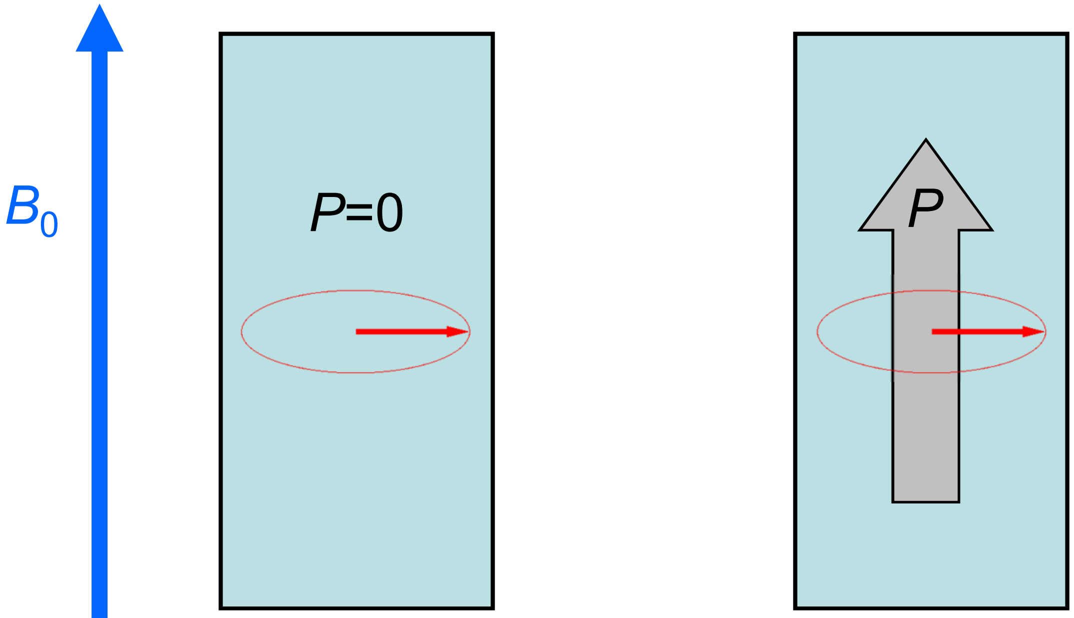
Other interesting nuclei: ^{3}He, Xe, Hg, …

effect of pseudomagnetic precession



Barychevsky et al., *JETP* 20 (1965) 704
Abragam et al., *PRL* 31 (1973) 776

effect of pseudomagnetic precession



unpolarised sample

polarised sample

neutron spins sense a spin-dependent strong interaction

$$\boxed{\omega_0 = -\gamma_\mathrm{n} B_0}$$

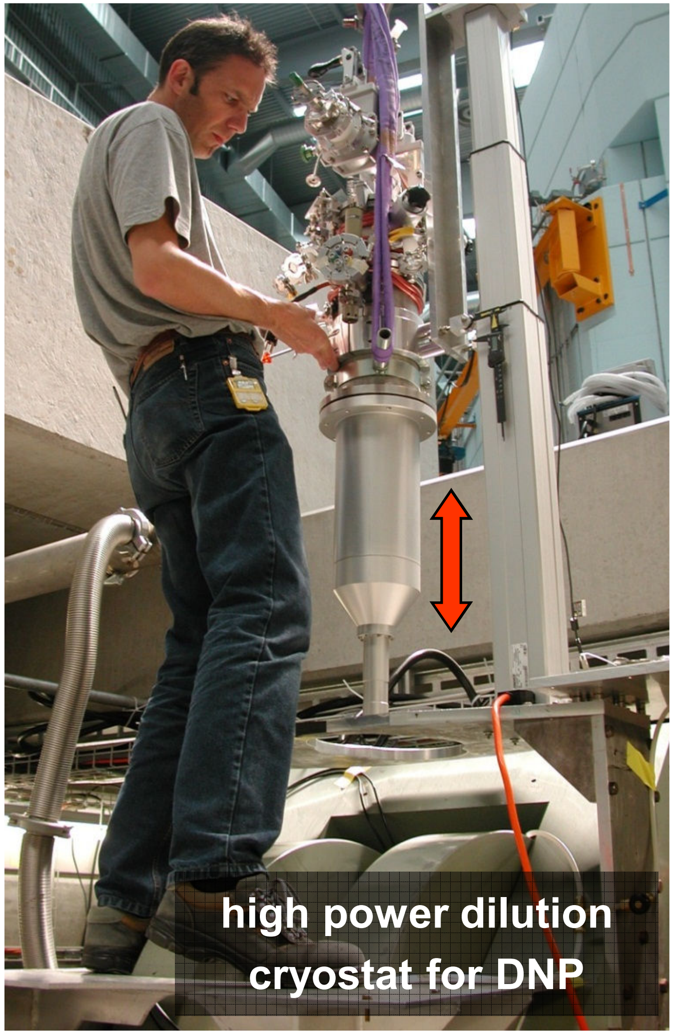
$$\boxed{\omega' = \omega_0 + \omega^*}$$

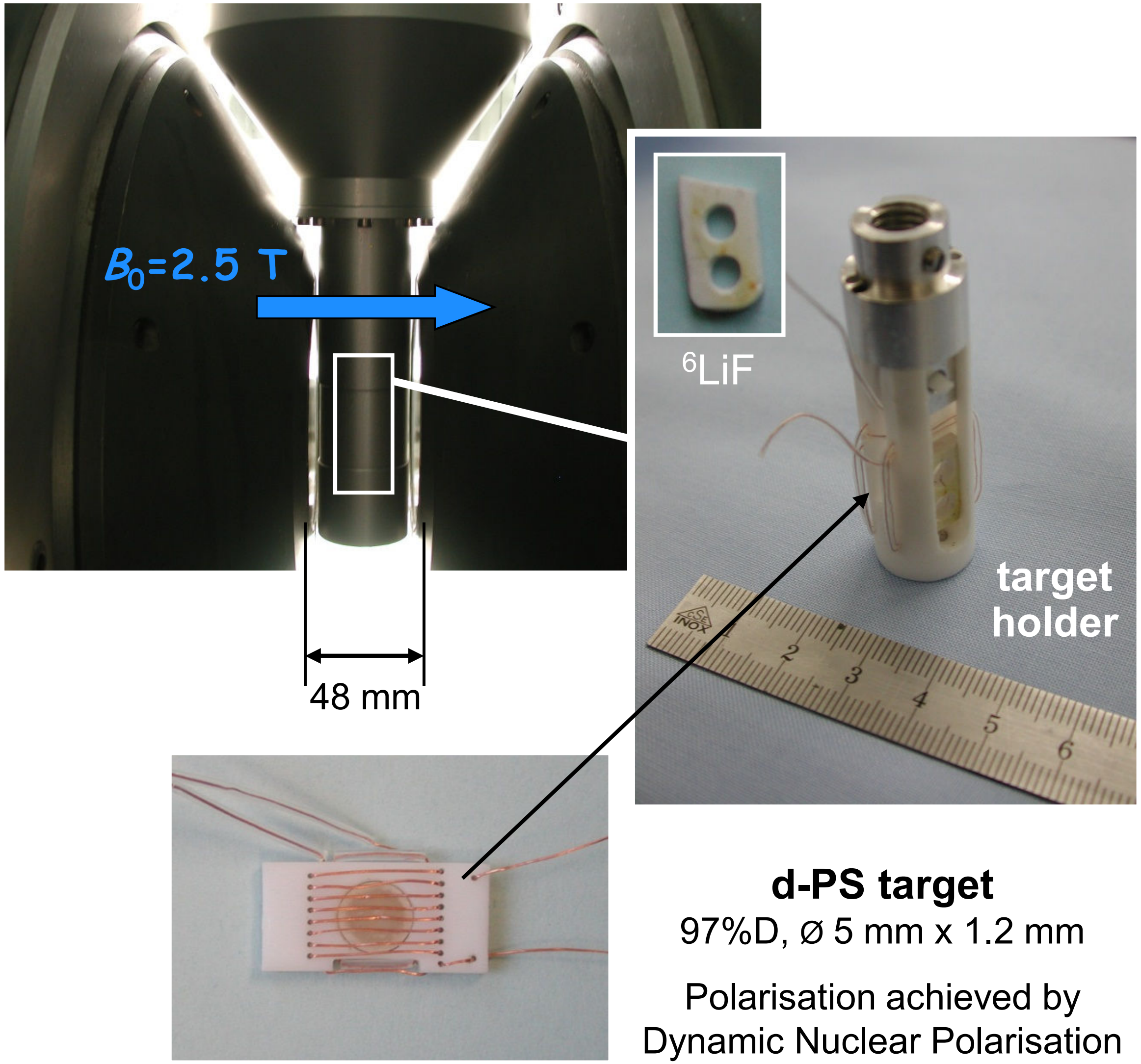
additional precession angle due to pseudomagnetic interaction:

$$\boxed{\varphi^* = \omega^* t \,\propto\, b_\mathrm{i} \cdot \rho \cdot P \cdot t}$$

Barychevsky et al., *JETP* 20 (1965) 704
Abragam et al., *PRL* 31 (1973) 776

nd-experiment $b_{i,d}$ – cryostat & target



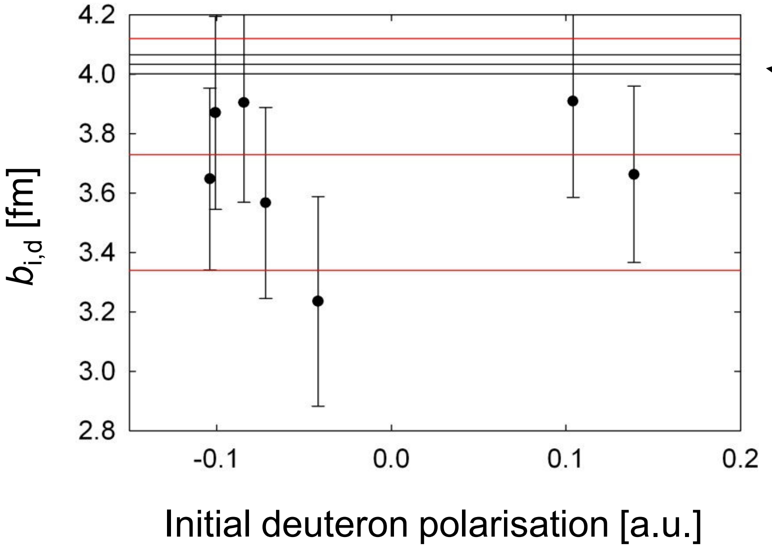


d-PS target
97%D, ø 5 mm x 1.2 mm

Polarisation achieved by Dynamic Nuclear Polarisation and measured using cw-NMR

Piegsa et al., NIM A **589** (2008) 318
v.d. Brandt et al., J. Phys. Conf. Ser. **150** (2009) 012024

nd-experiment $b_{i,d}$ – results & limitation



$b_{i,d}$ = (4.033 ± 0.032) fm

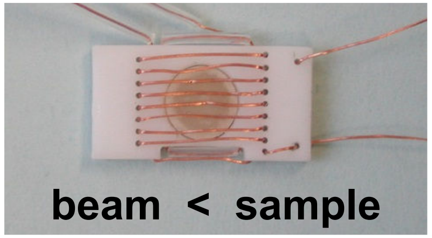
Dilg et al., *PLB* 36 (1971) 208

$$\boxed{\sigma_s = 4\pi\left(|b_c|^2 + |b_i|^2\right)}$$

$b_{i,d}$ = (3.73 ± 0.05 ± 0.34 ± ?) fm

stat. uncertainty of **NMR** and
the **pseudomagn. phase shift**
measurement

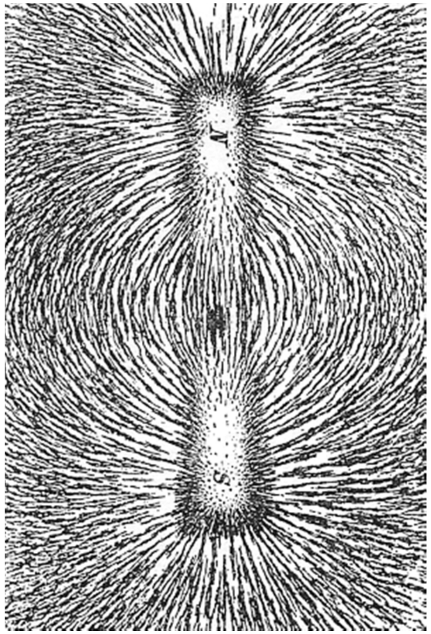
NMR cross-calibration
(upper limit)



v.d. Brandt et al., NIM A **611** (2009) 231

Neutron Spin Phase Imaging

imaging of magnetic fields …



… with iron powder and …

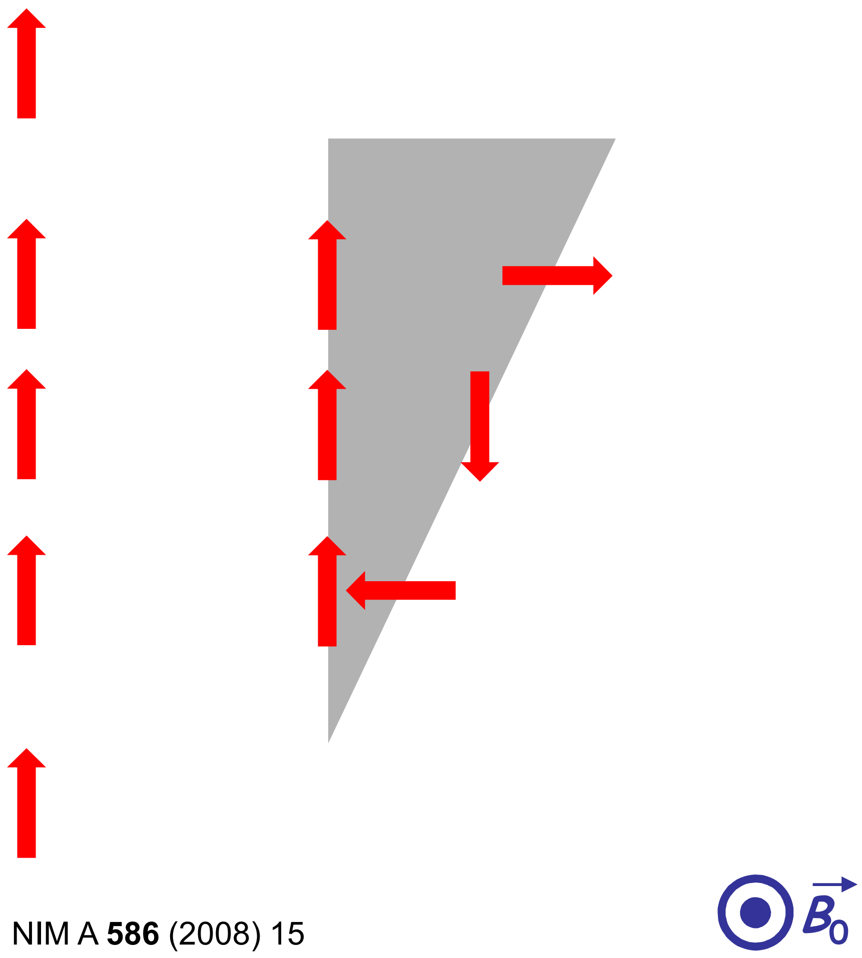
… with neutrons.*

Piegsa et al., PRL **102** (2009) 145501

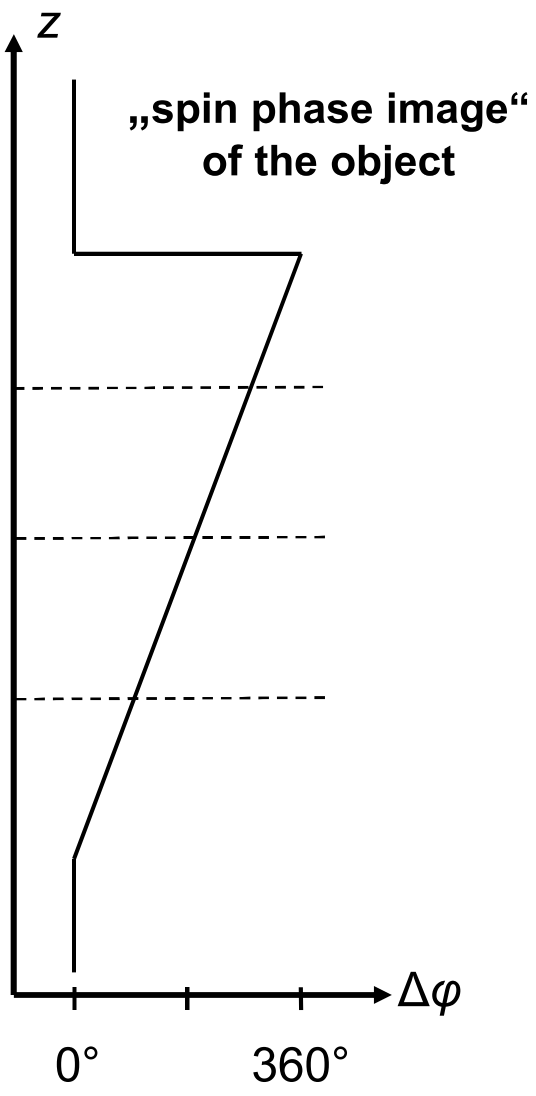
* image of a 9 mm long cylindrical ferromagnetic steel rod placed in an external magn. field.

imaging principle

Object with a spin-dependent potential

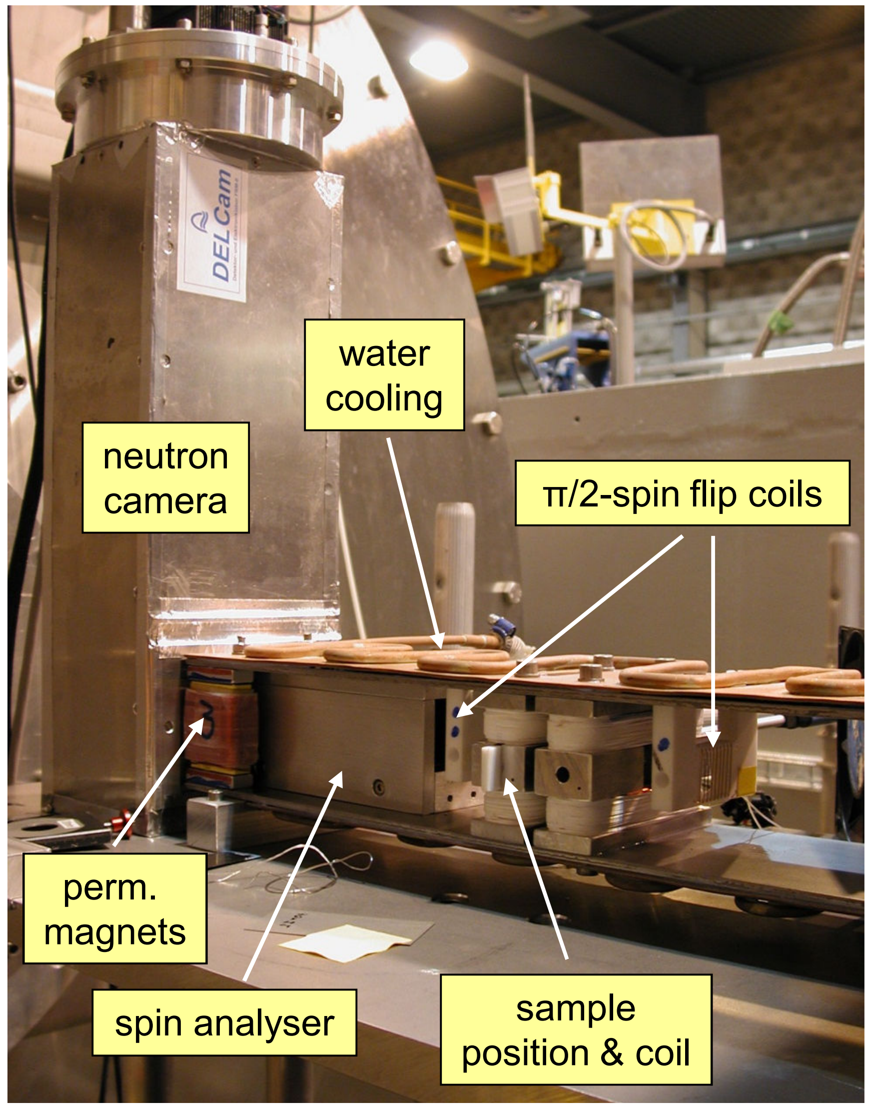


Piegsa et al., NIM A **586** (2008) 15

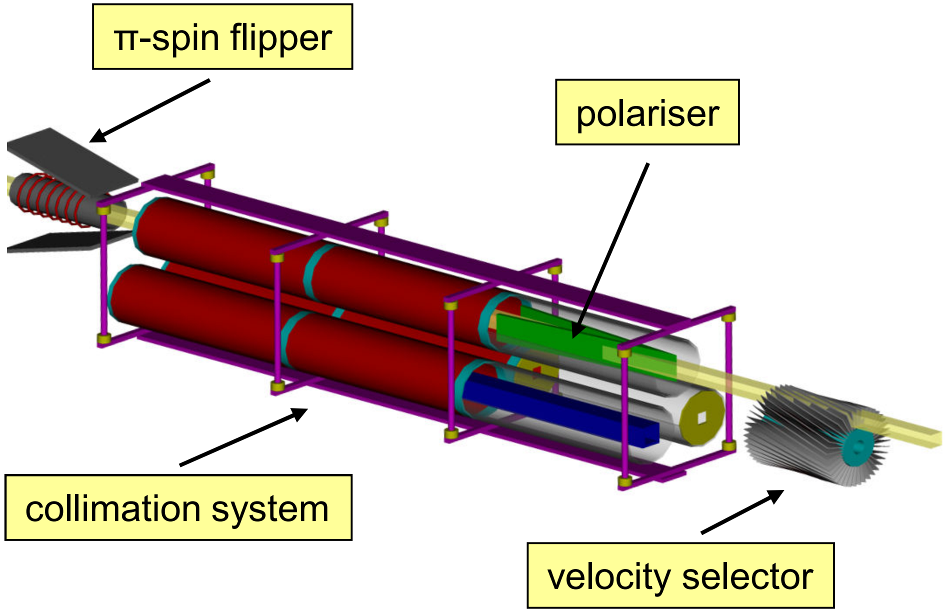


„spin phase image“ of the object

NSPI at SANS-I (PSI)



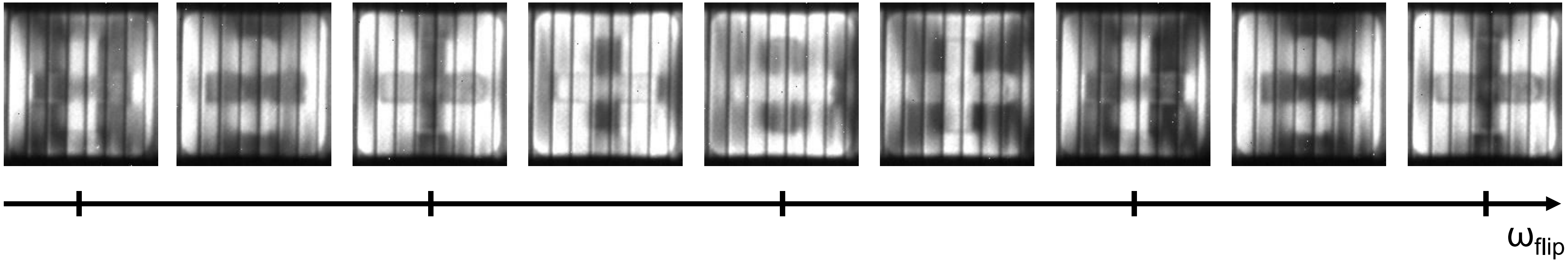
SANS-I:	beam divergence ≈ 0.2° Δλ/λ ≈ 10%
Resolution:	0.8 mm (FWHM-PSF)
Sensitivity:	±7.5 x 10^{-8} Tm
Expos. time:	1 min/image x 11
Sample field:	5 … 30 mT (adjustable !)



Piegsa et al., NIM A **605** (2009) 5
Piegsa & Schneider, NIM A **594** (2008) 74

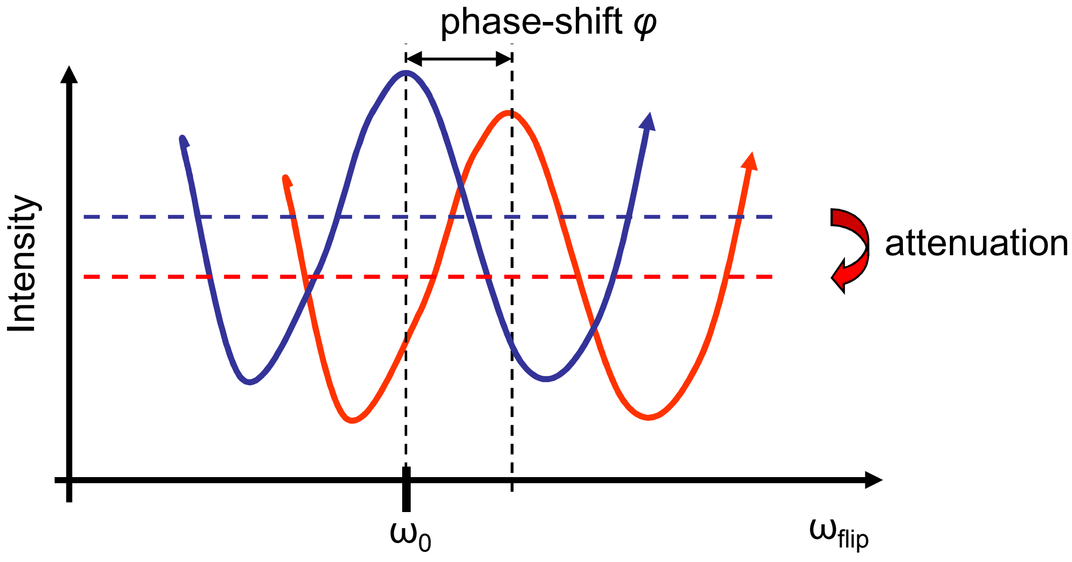
imaging principle

Measure a set of images at different frequencies:



Analysis for each pixel:

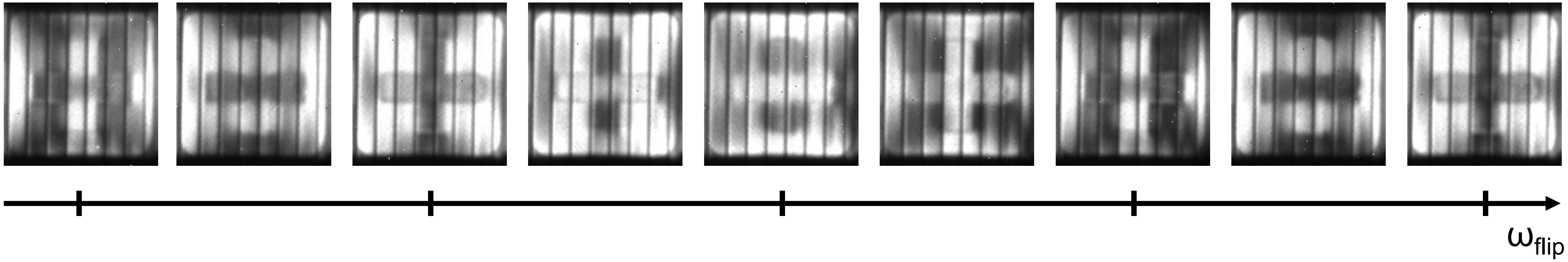
🟦 : without sample
🟥 : with sample

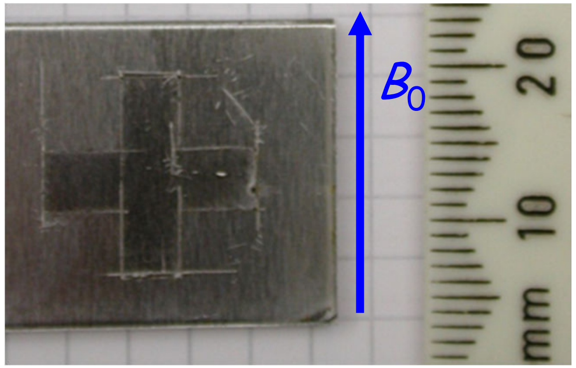


Simultaneous „Attenuation“ & „Spin phase“ imaging !

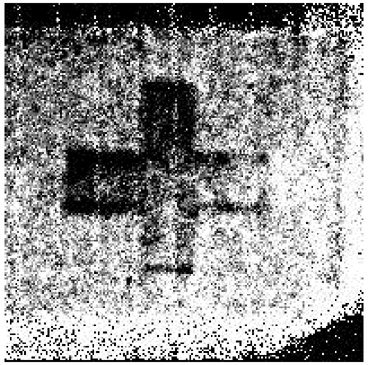
imaging principle

Measure a set of images at different frequencies:

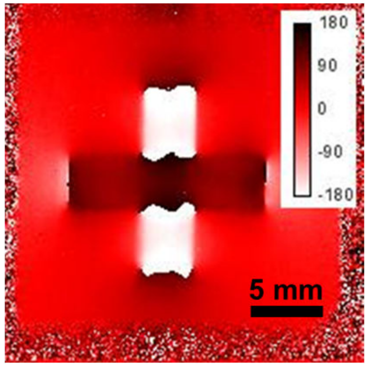




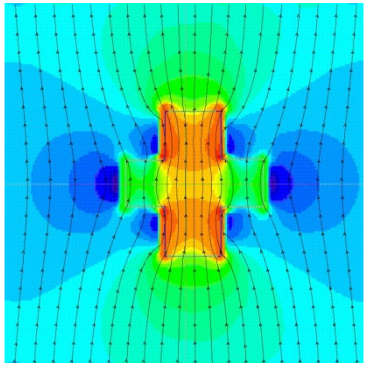
7.7 µm Fe sputtered on Aluminium



absorption image



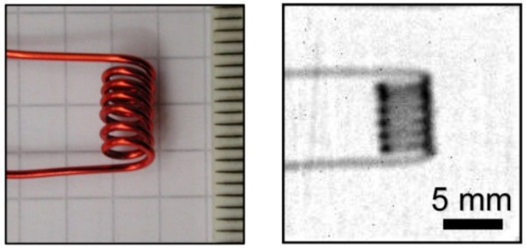
spin phase image

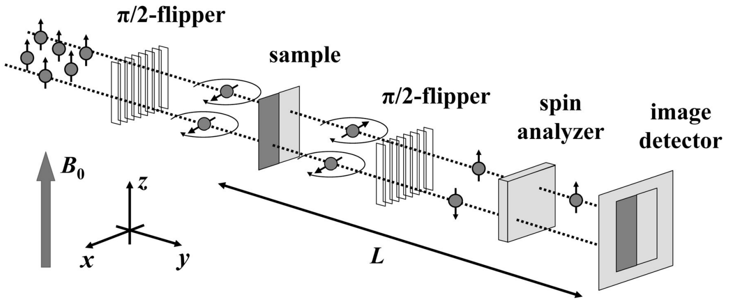


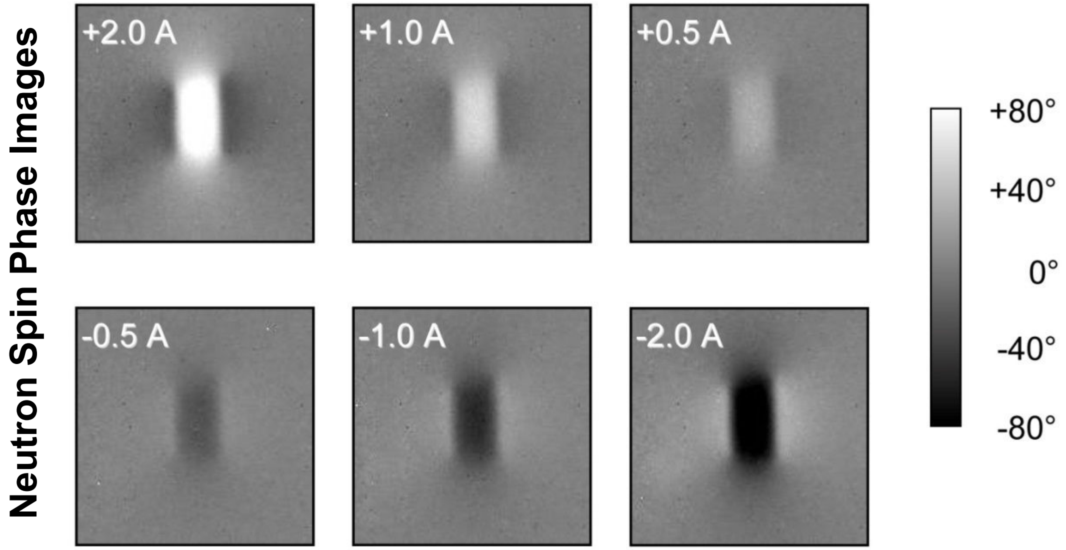
Qualitative simulation with “Vizimag”

Simultaneous „Attenuation“ & „Spin phase“ imaging !

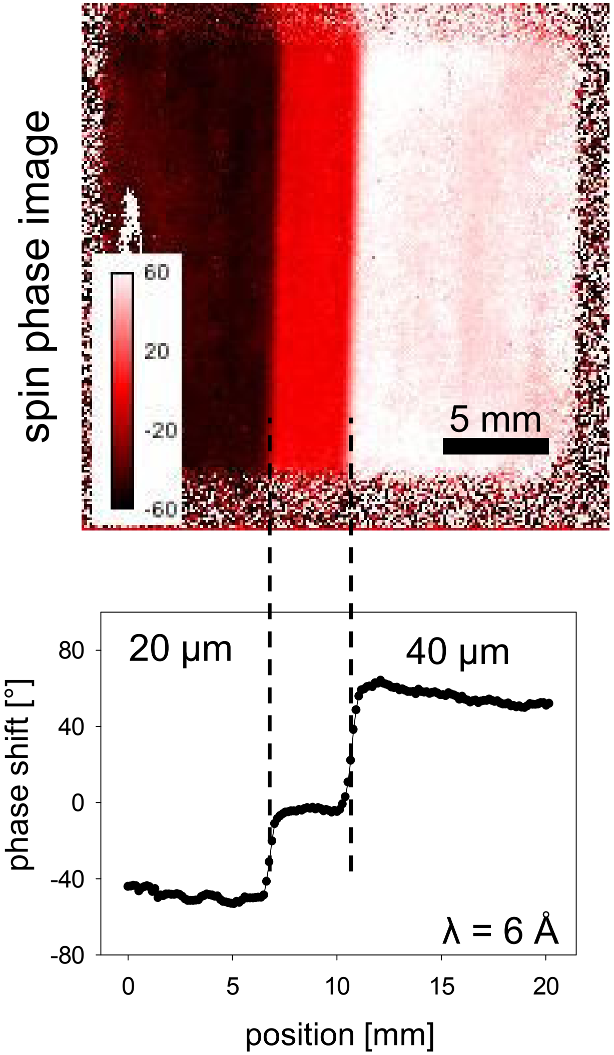
magnetic field of a coil

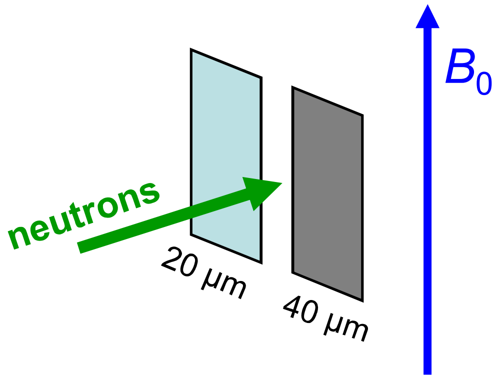




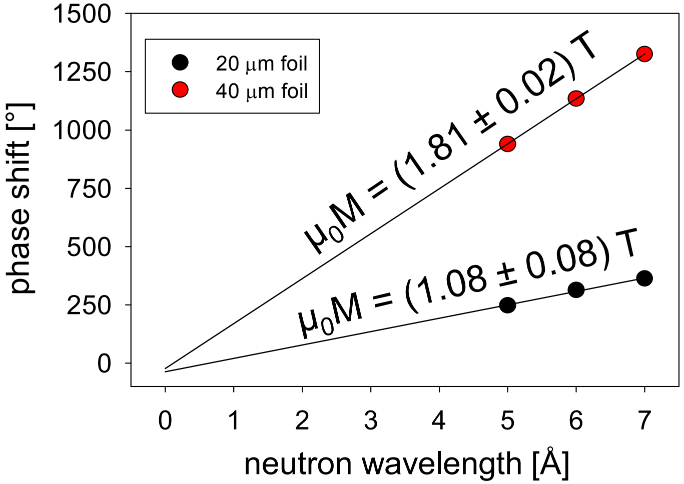


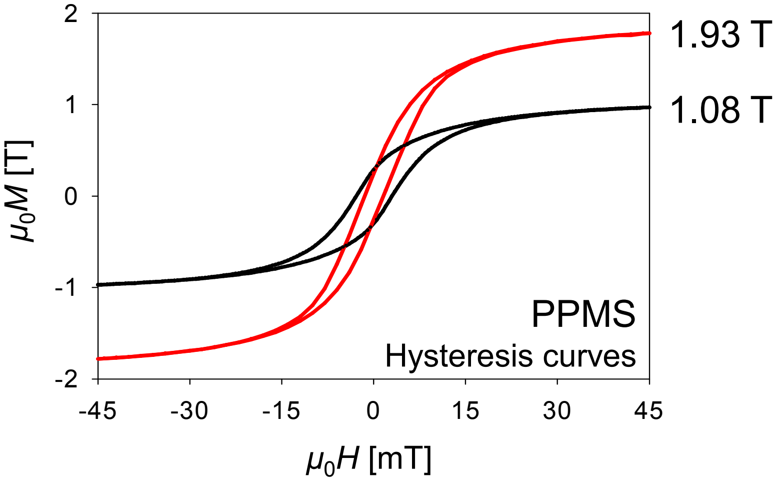
thin ferromagnetic steel foils





thin ferromagnetic steel foils



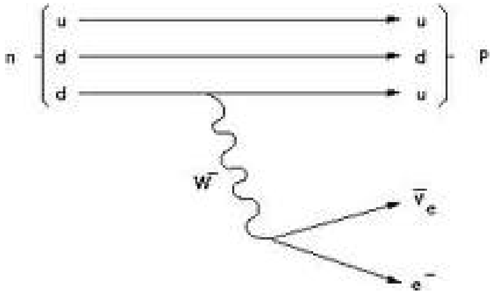


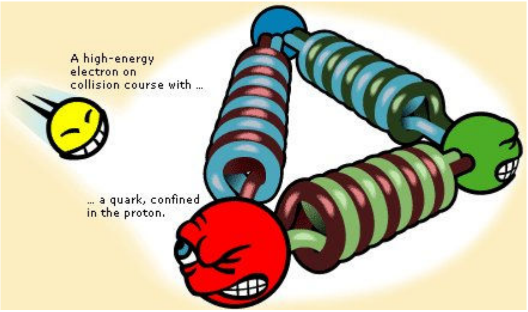
Neutron spin phase imaging is a quantitative radiography method to image magnetic fields & samples.

Search for new light Bosons

Gravity

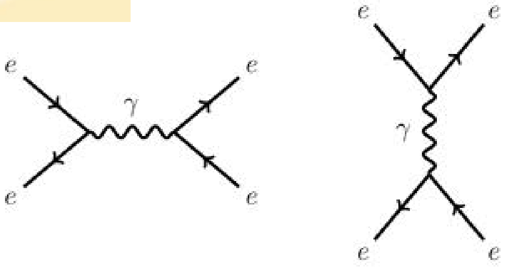
Weak





Strong

Electromagnetic



Are there additional forces ???

new interaction – new exchange boson

Scalar boson: $\mathcal{L} = \bar{\psi}\,(g_S + i g_P \gamma^5)\psi\phi$

Vector boson: $\mathcal{L} = \bar{\psi}\,(g_V \gamma^\mu + g_A \gamma^\mu \gamma^5)\psi\chi_\mu$

e.g. photon: $\mathcal{L} = e\bar{\psi}\gamma^\mu\psi A_\mu$

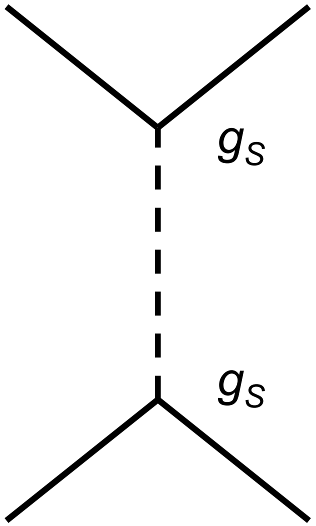
Compton wavelength: $\lambda_c = \frac{\hbar}{Mc}$ e.g. $M = 10^{-4}$ eV/c^2 ⟷ 2 mm

$m_\gamma = 0$, $m_{W,Z} = 80 \ldots 90$ GeV/c^2

⇩

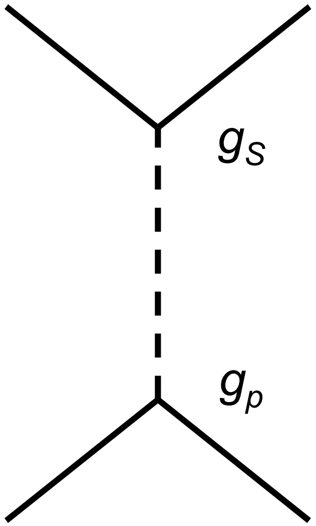
In general a new force is described by a set of dimensionless coupling constants and its interaction range λ_c.

new scalar boson (spin 0)



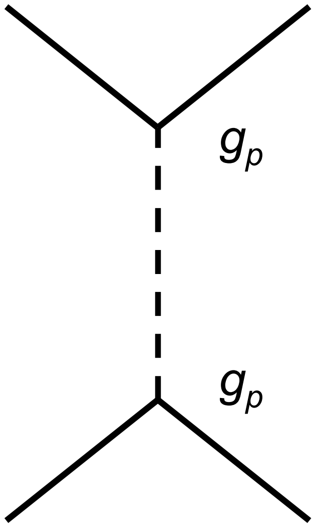
scalar-scalar coupling

‘5th force’



scalar-pseudoscalar coupling

‘Axion-like’

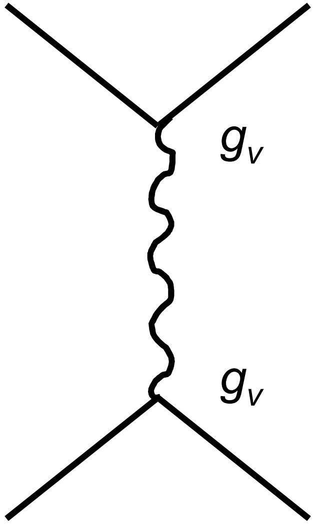


pseudoscalar-pseudoscalar coupling

Further reading:

Fischbach & Talmadge, Nature **356** (1992) 207.	(Review Article on 5th force)
Schlamminger et al., PRL **100** (2008) 041101.	(Torsion Balance - Seattle)
Petukov et al., PRL **105** (2010) 170401.	(polarised ^{3}He gas - ILL)
Serebrov et al., JETP Lett. **91** (2010) 6.	(polarised UCN - ILL)
Vasilakis et al., PRL **103** (2009) 261801	(^{3}He-K/^{3}He - Princeton)
Yan & Snow, PRL **110** (2013) 082003	($g_V g_A$ in L^{4}He - NIST)

new vector boson (spin 1)



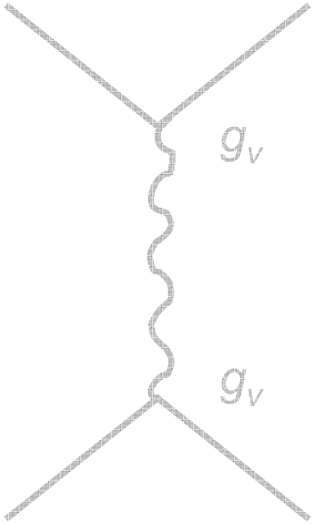
vector-vector coupling

'photon-like'

(in e.m. g_v^2 corresponds to $\alpha \approx 1/137$)

...

new vector boson (spin 1)



vector-vector coupling

’photon-like’

(in e.m. g_v^2 corresponds to α ≈ 1/137)

Additionally a vector boson would mediate also spin-velocity interactions (Yukawa-like):

$$V_{\mathrm{VA}}^{\mathrm{point}}(r) = \frac{g_{\mathrm{V}} g_{\mathrm{A}}}{2\pi} \hbar c \, \boldsymbol{\sigma} \cdot \frac{\boldsymbol{v}}{c} \frac{e^{-r/\lambda_c}}{r}$$

$$V_{\mathrm{AA}}^{\mathrm{point}}(r) = \frac{g_{\mathrm{A}}^2}{16\pi} \frac{(\hbar c)^2}{mc^2} \boldsymbol{\sigma} \cdot \left(\frac{\boldsymbol{v}}{c} \times \frac{\boldsymbol{r}}{r} \right) \left(\frac{1}{\lambda_c} + \frac{1}{r} \right) \frac{e^{-r/\lambda_c}}{r}$$

v = relative velocity between source and probe particle

r = distance between source and probe particle

m = mass of probe particle

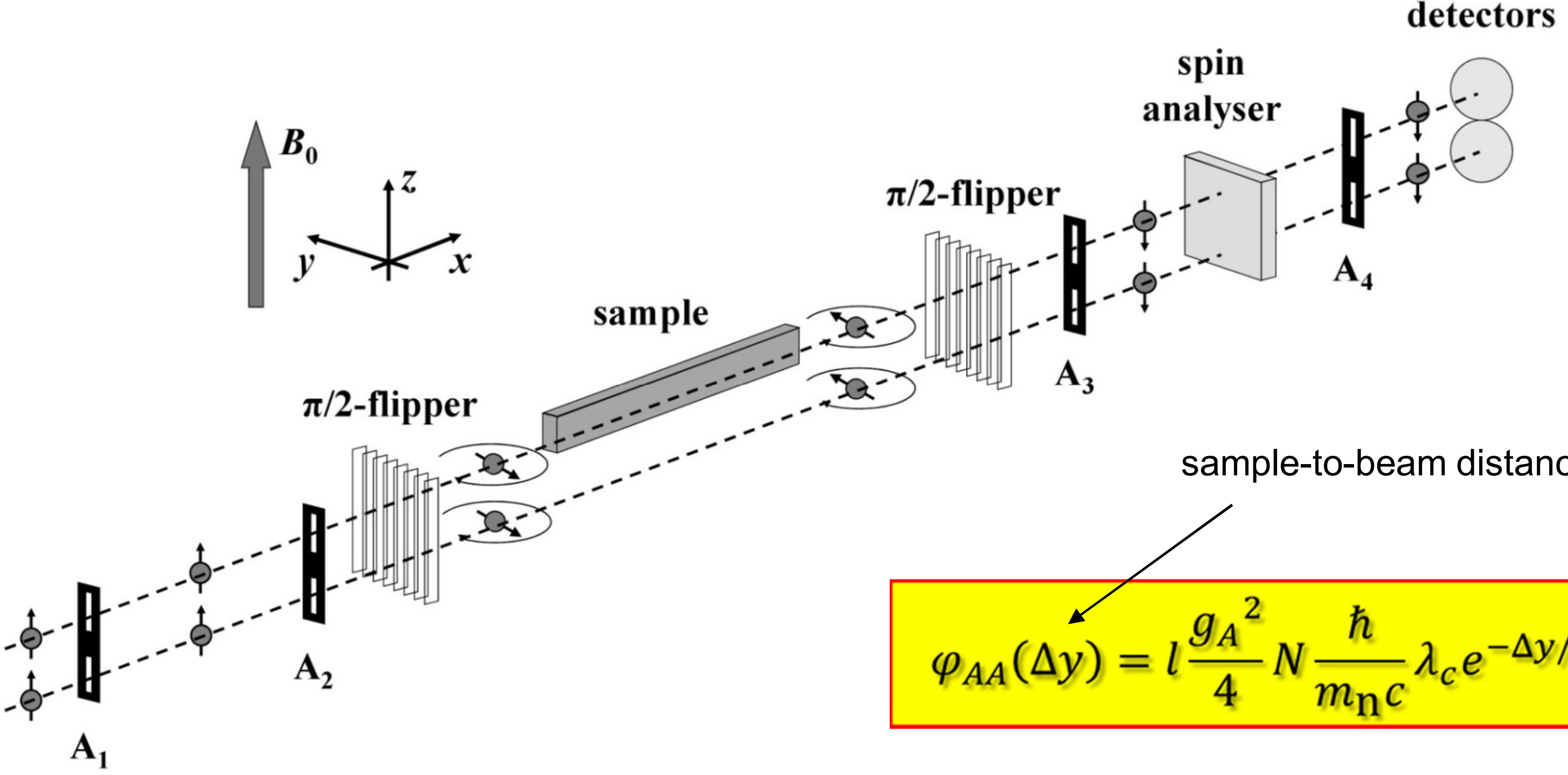
σ = spin of probe particle

Dubrescu & Mocioiu, JHEP **11** (2006) 005

probe the exotic $g_A g_A$-interaction (spin 1)

Search for axial-axial coupling:

- Use polarised neutrons as ‘probe’ and non-magnetic macroscopic bulk matter as ‘source’
- Two beam-method helps to compensate for drifts (field, spin flippers, temperature, etc.).
- However, still measure with and without sample.

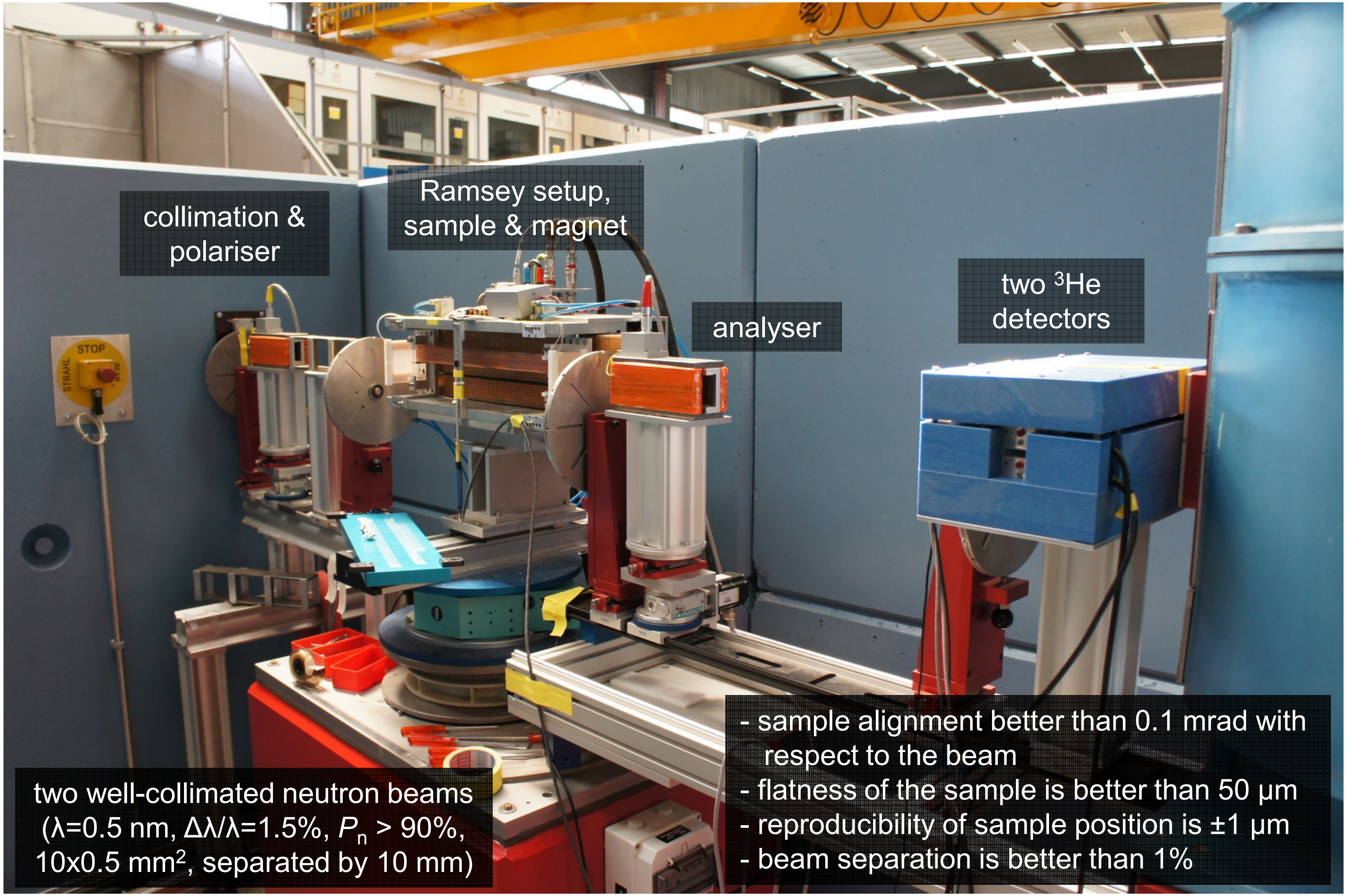


sample-to-beam distance

$$\varphi_{AA}(\Delta y) = l\frac{{g_A}^2}{4}N\frac{\hbar}{m_n c}\lambda_c e^{-\Delta y/\lambda_c}$$

Piegsa & Pignol, Jour. Phys. Conf. Ser. **340** (2012) 012043

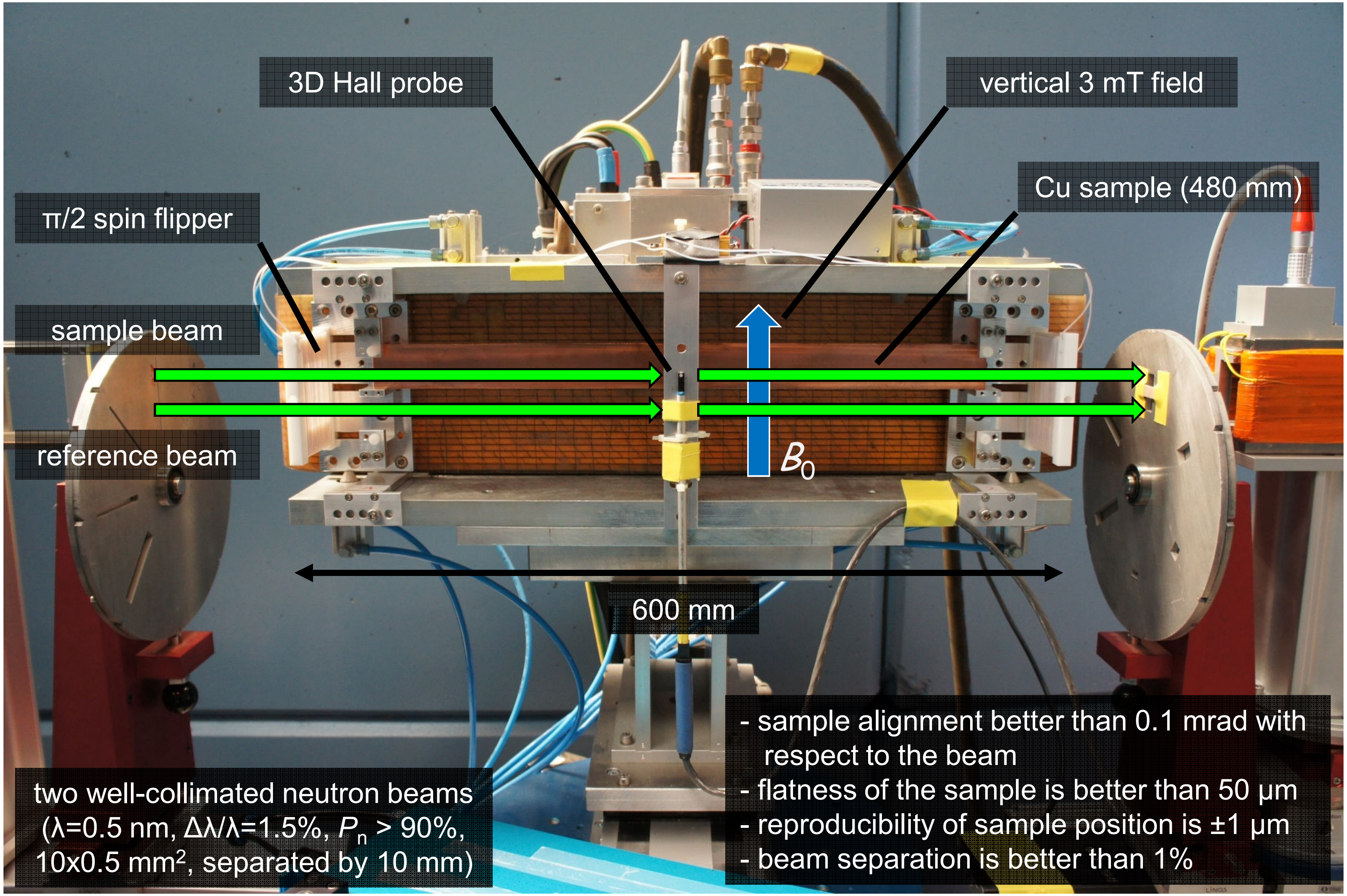
Ramsey setup at Narziss (PSI)



two well-collimated neutron beams (λ=0.5 nm, $\Delta\lambda/\lambda$=1.5%, P_n > 90%, 10x0.5 mm^2, separated by 10 mm)

- sample alignment better than 0.1 mrad with respect to the beam
- flatness of the sample is better than 50 μm
- reproducibility of sample position is ±1 μm
- beam separation is better than 1%

Ramsey setup at Narziss (PSI)



3D Hall probe

vertical 3 mT field

Cu sample (480 mm)

$\pi/2$ spin flipper

sample beam

reference beam

B_0

600 mm

two well-collimated neutron beams (λ=0.5 nm, $\Delta\lambda/\lambda$=1.5%, P_n > 90%, 10x0.5 mm^2, separated by 10 mm)

- sample alignment better than 0.1 mrad with respect to the beam
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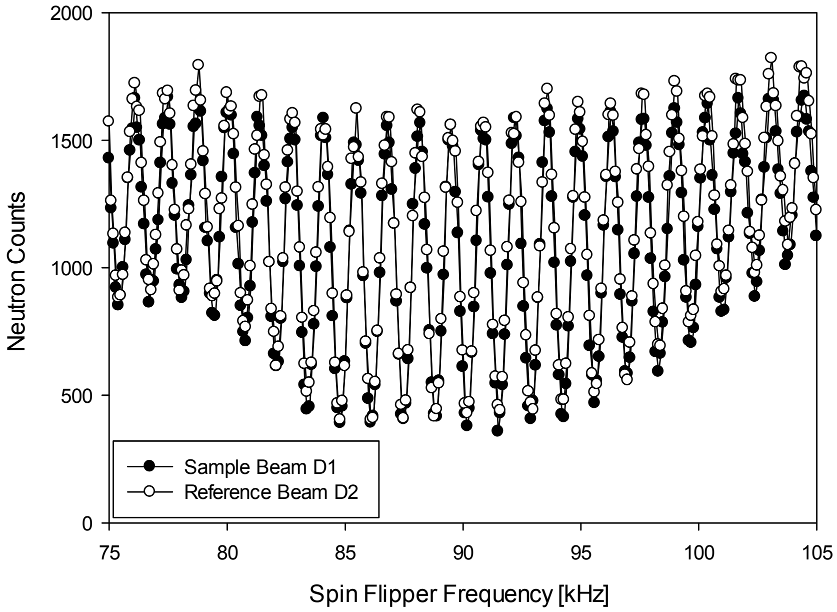
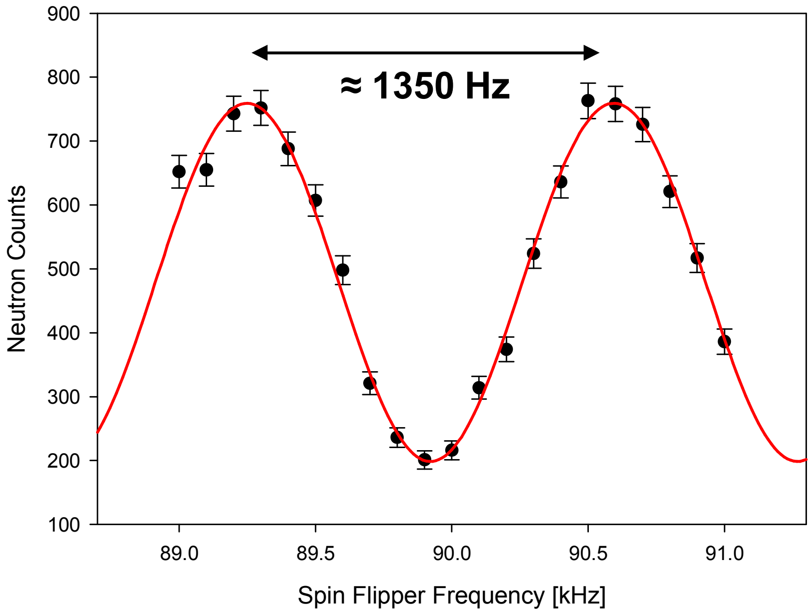
obtained Ramsey resonance patterns



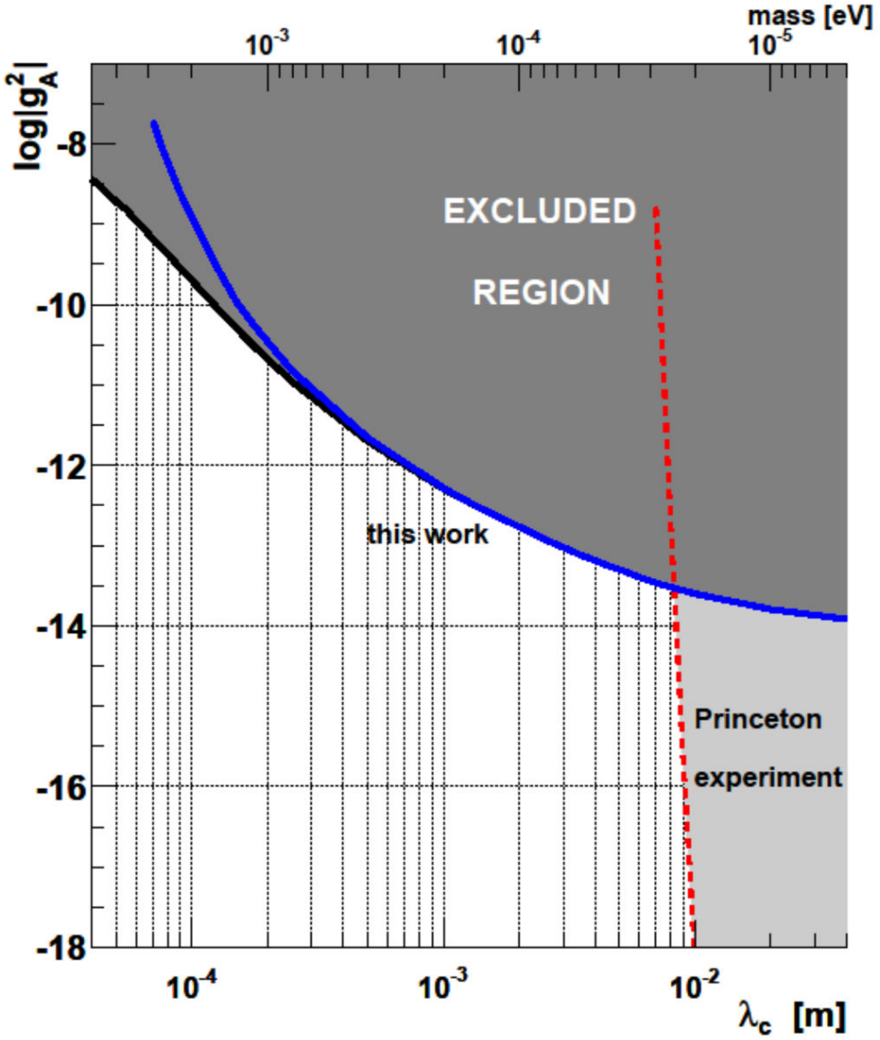


''full'' Ramsey signal
(about 2 hours / 90 kHz ≈ 3 mT)

measuring time about 5 min

sinusodial-fit: $\sigma_\varphi \approx 1.4°$

results



- ‘’standard fit’’
- fit taking beam width into account

$g_A^2 < 6 \times 10^{-13}$ @ $\lambda_c = 1$ mm (95 C.L.)

compare to

α_{strong}	≈	1
α	≈	1/137
α_{weak}	≈	10^{-12}
α_{grav}	≈	10^{-37}

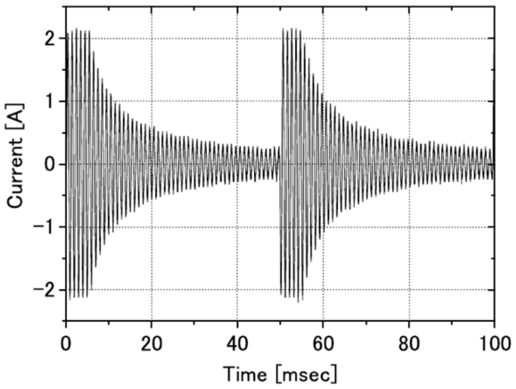
Piegsa & Pignol, PRL **108** (2012) 181801
Princeton: Vasilakis et al., PRL **103** (2009) 261801

Ramsey with a pulsed beam

conclusions

- All presented experiments **can be performed at a pulsed beam/source**.

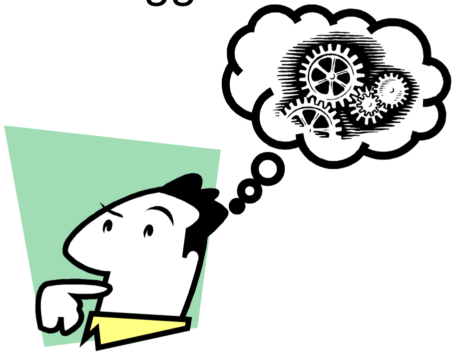
- In order to profit from the **velocity information/pulsed structure**, the RF fields of the π/2-spin flip coils have to be amplitude-modulated in time:



$$\boxed{B_1 = \frac{\pi}{2\gamma_n}\frac{1}{\tau}}$$

- **Imaging would be not so straight forward** as one would need a triggered neutron camera – only one wavelength at a time.

- Pulsed spallation source allows for relatively easy **separation of velocity dependent and independent effects ... !!! ???**



neutron EDM experiment using a beam ???

- The main systematic problem in beam nEDM-experiments was the ***vxE* effect**.

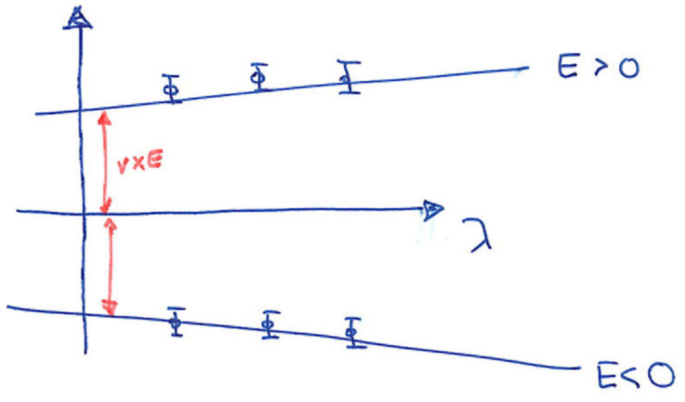
- The ***vxE*-effect can be be separated from the EDM-phase effect** using the pulsed structure of a spallation source like the ESS:

$$\boxed{\varphi_{tot} = \varphi_{EDM} + \varphi_{vxE} + \dots}$$

$$\varphi_{EDM} = \frac{2d_n E}{\hbar}\frac{L}{v} \propto \lambda$$

$$\varphi_{vxE} = \gamma_n \frac{L}{c^2} E \sin\theta_{EB}$$

angle between
E and B field



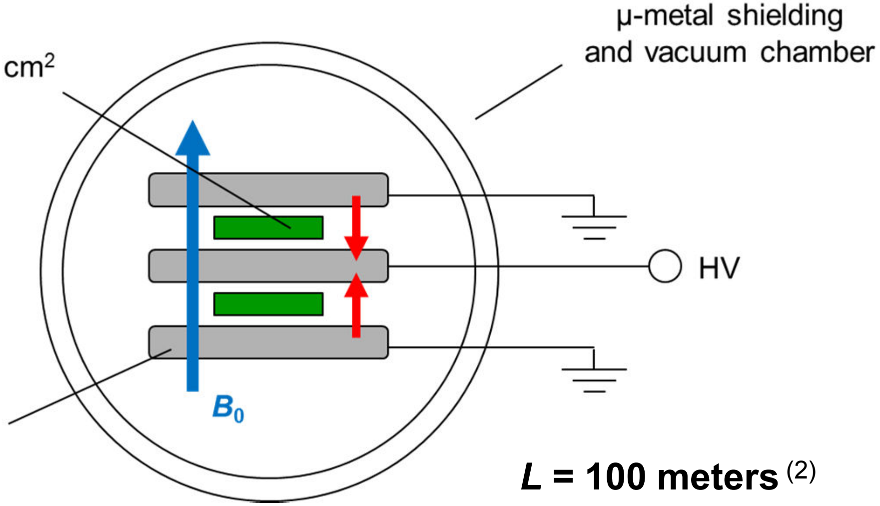
slope = nEDM

intersection = vxE

neutron EDM experiment using a beam ???

nEDM sensitivity

$$\boxed{\sigma_{EDM} \propto \frac{1}{T\,E\,\sqrt{N}}}$$



***L* = 100 meters** (2)

	UCN (1)	**Beam**	**Gain**
Observation time	130 sec	0.1 sec (2)	~ 0.001
Electric field	10 kV/cm	50 - 100 kV/cm (3,4)	~ 5
Intensity	14000 / 240 s ~ 60 / s	2.5×10^6 / s	$\sqrt{40000}$

⇨ **e.g. 10 cm² beam: 2.5×10^5 / cm²s**

(1) Baker et al., PRL **97** (2006) 131801 (UCN < 2.9×10^{-26}ecm)

(2) Baldo-Ceolin et al., Z. Phys. C **63** (1994) 409 (nnbar)

(3) Dress et al., PR D **15** (1977) 9 (beam < 3×10^{-24}ecm)

(4) Baumann et al., PR D **37** (1988) 3107 (n-charge)

Thank you for your attention.