Tunneling Systems in Glasses at Ultra-low Temperatures

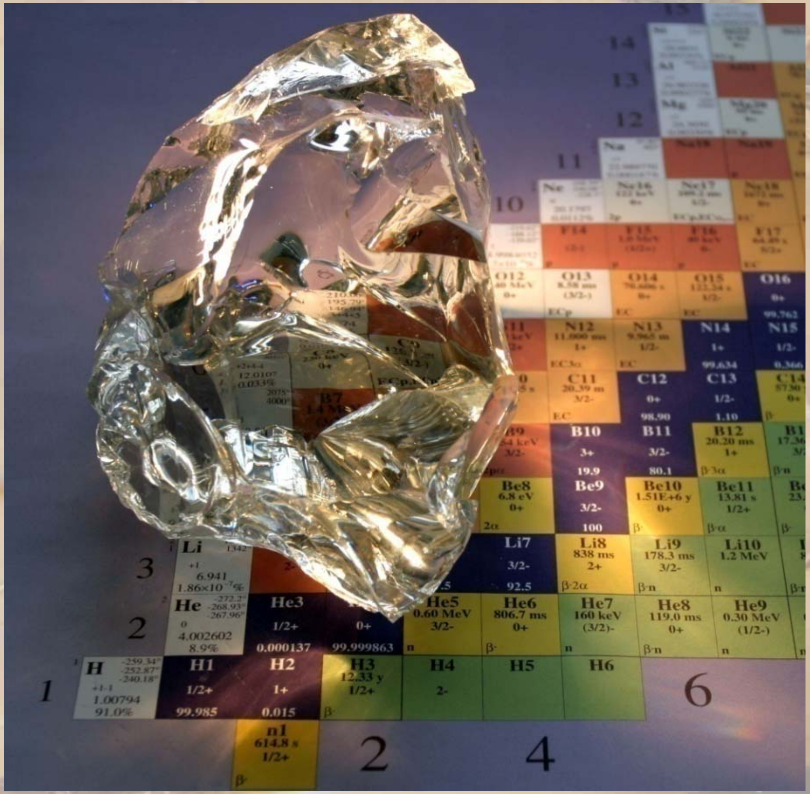
Indroduction

Polarisation Echo Experiments

Nuclear Quadrupol Model

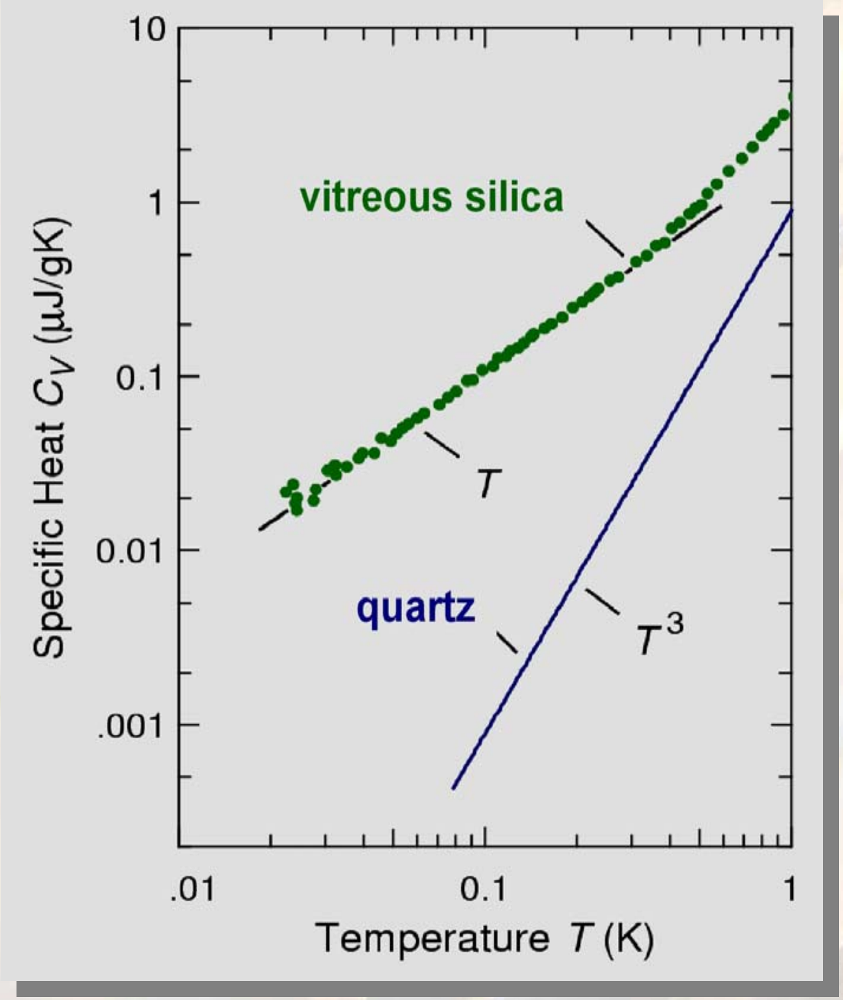
Dipole-Dipole-Effect

Spectral Diffusion



Christian Enss
Kirchhoff-Institut für Physik
Universität Heidelberg

Specific Heat

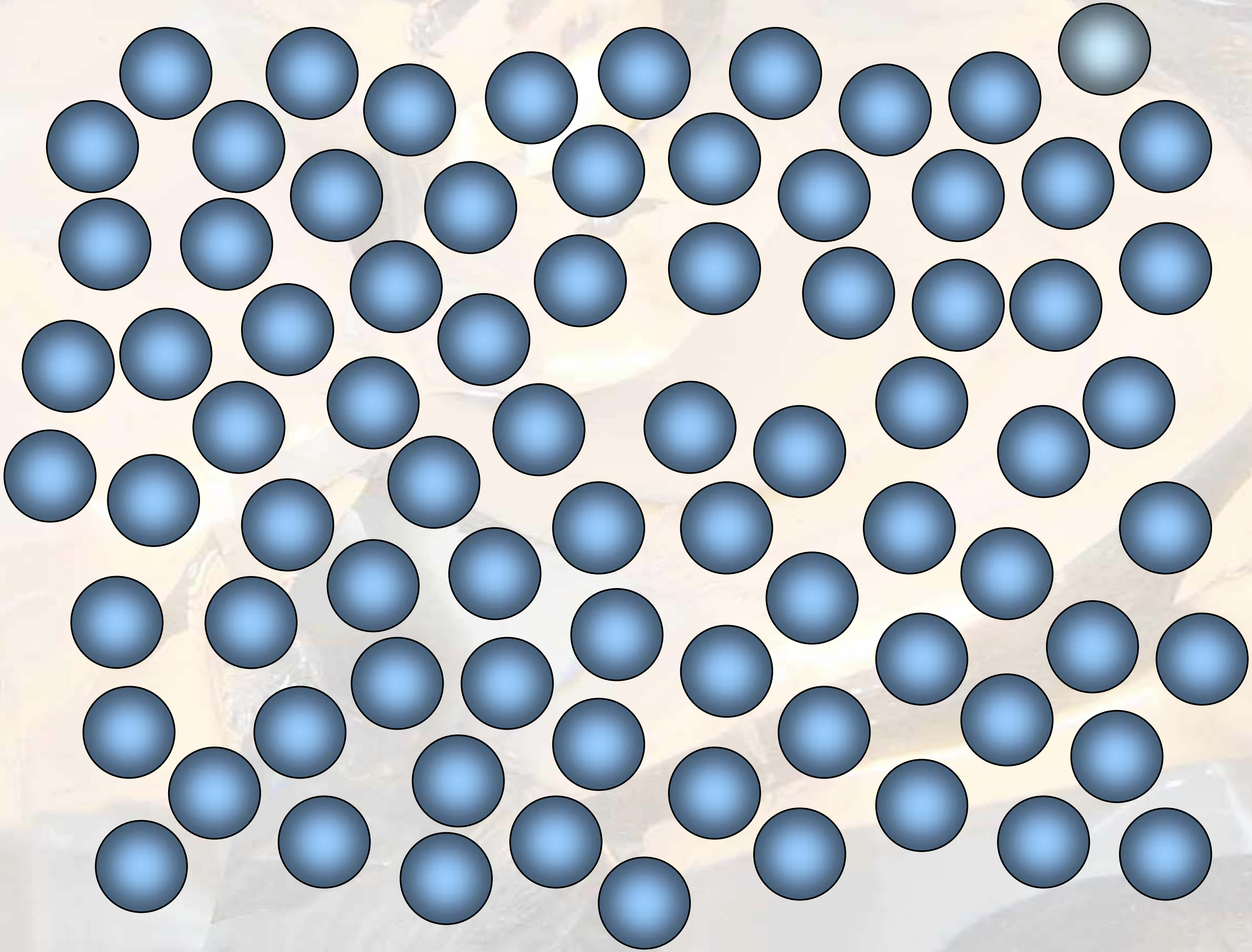


broad distribution of
low-energy excitations

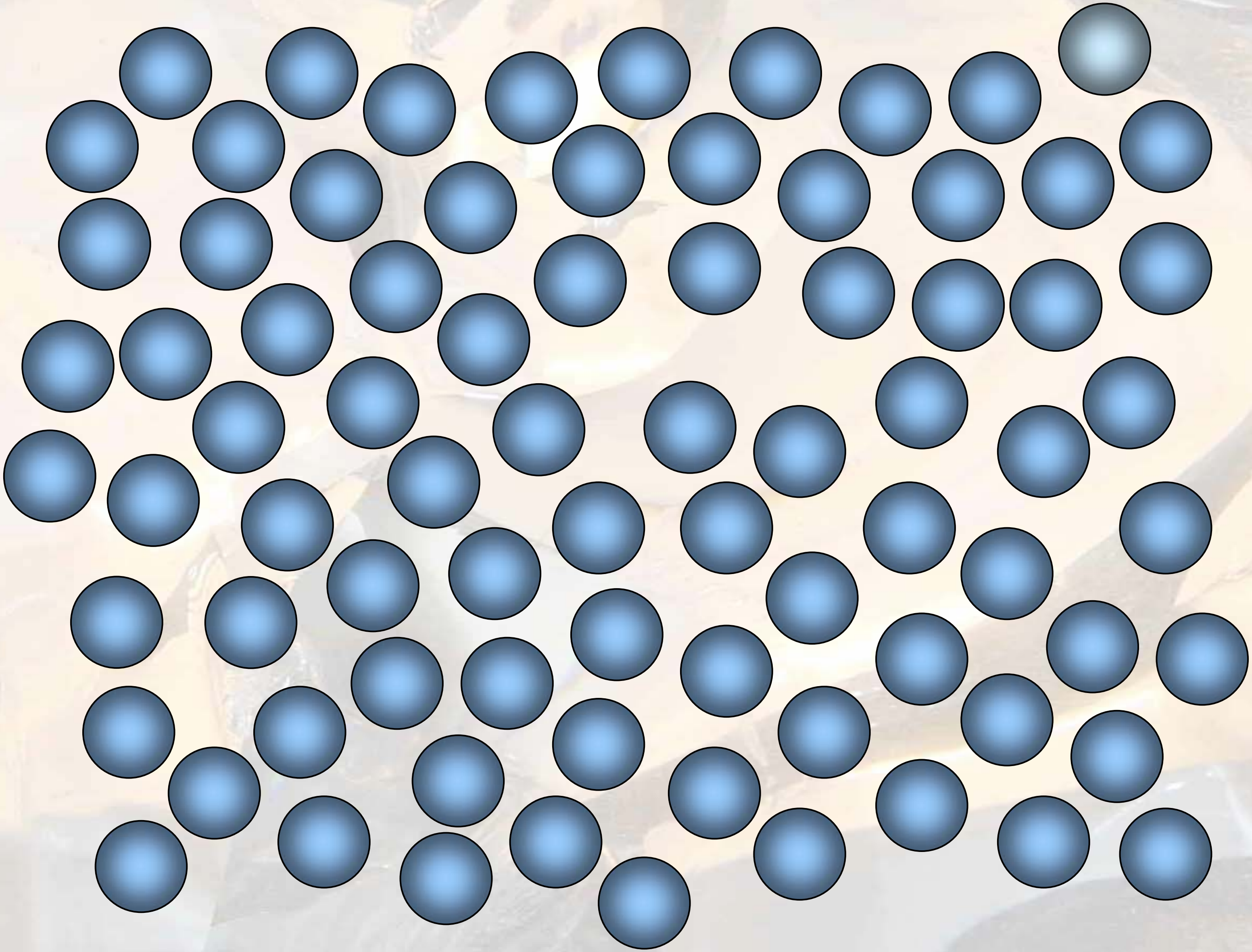
R.C. Zeller, R.O. Pohl,
Phys. Rev. **B 4**, 2029 (1971)

J.C. Lasjaunias et al.,
Sol. State Commun. **17**, 1045 (1975)

Atomic Tunneling Systems in Glasses

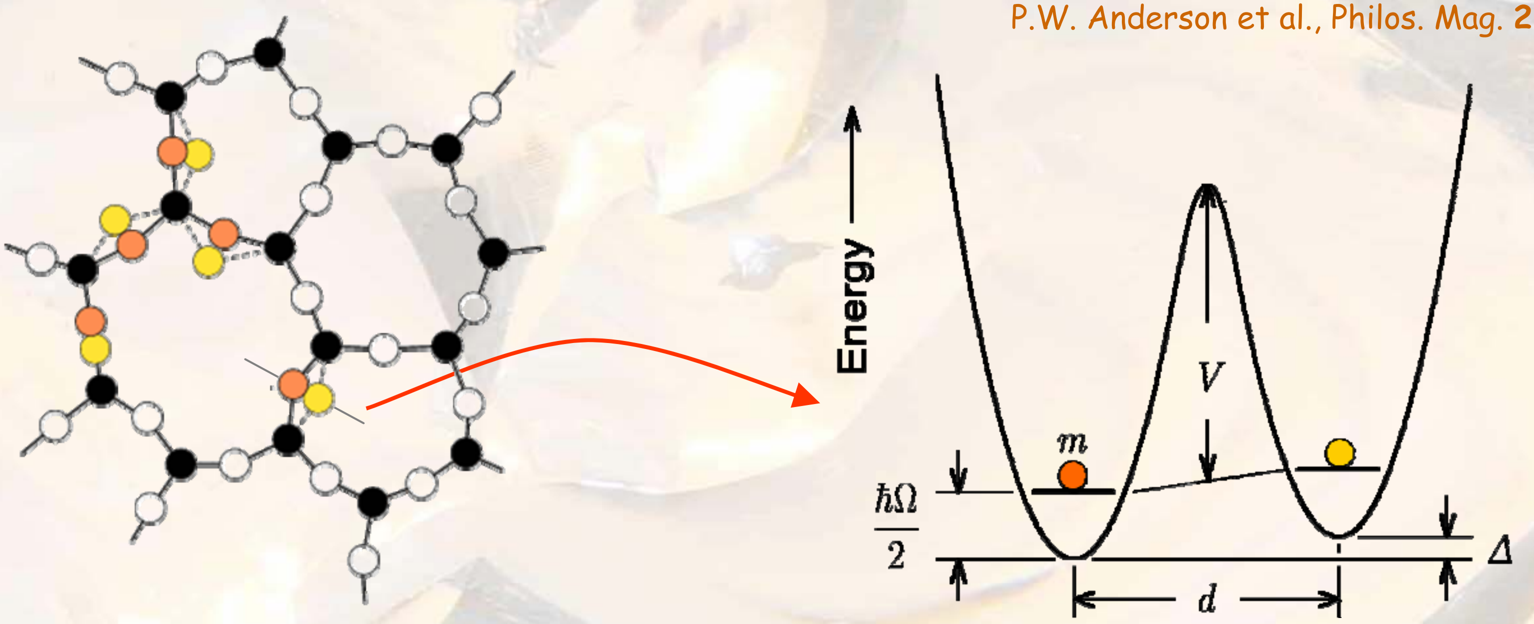


Atomic Tunneling Systems in Glasses



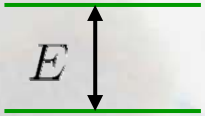
Atomic Tunneling Systems in Glasses

W.A. Phillips, J. Low. Temp. Phys. **7**, 351 (1972)
P.W. Anderson et al., Philos. Mag. **25**, 1 (1972)



energy splitting

$$E = \sqrt{\Delta_0^2 + \Delta^2}$$



tunnel splitting

$$\Delta_0 = \hbar\Omega\, e^{-\lambda}$$

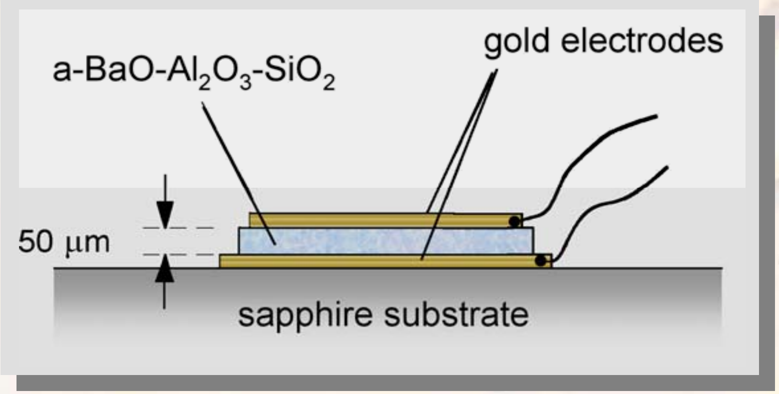
$$\lambda = \frac{d}{2\hbar}\sqrt{2mV}$$

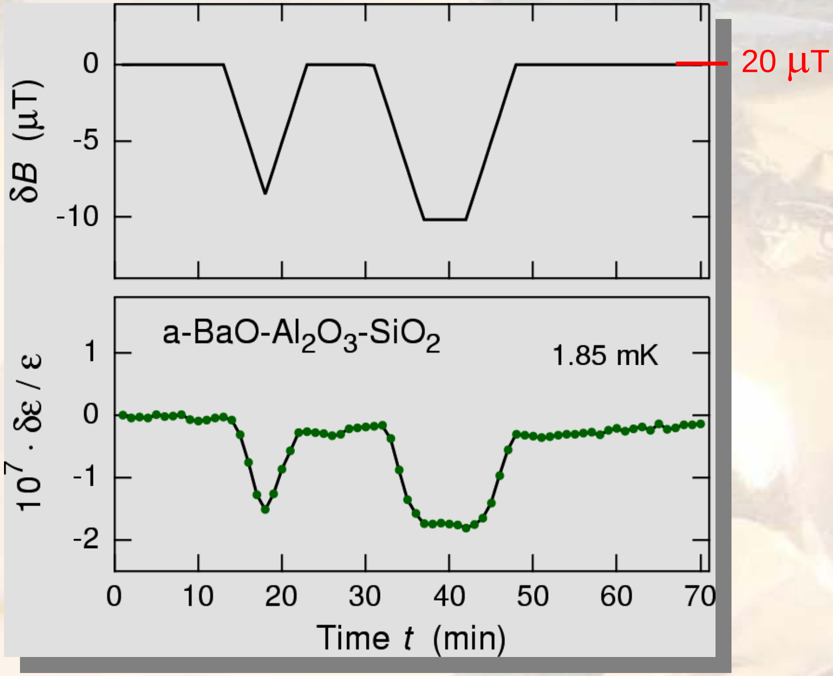
distribution function

$$P(\lambda, \Delta)\,d\lambda\,d\Delta = \overline{P}\,d\lambda\,d\Delta$$

⇒ elastic, dielectric und thermal properities

Dielectric Constant at Ultra-low Temperatures





- dielectric constant follows field variations
- extremely high sensitivity to magnetic fields

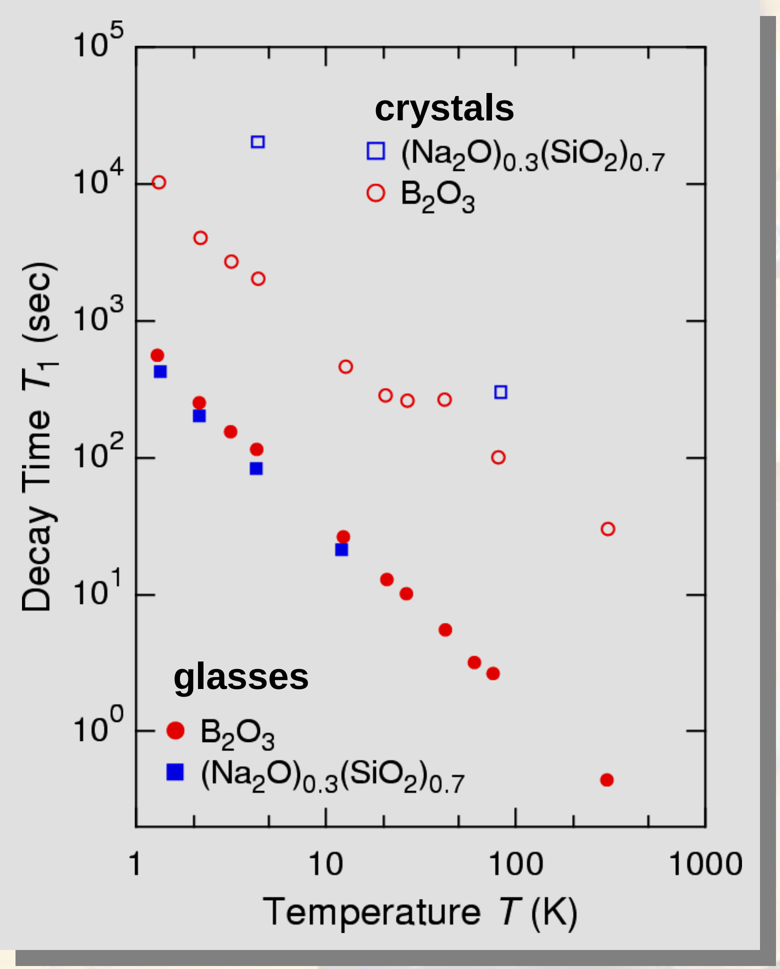
$B = 0.1\ \mathrm{T} \longrightarrow \delta\varepsilon/\varepsilon \approx 0.01$

P. Strehlow, C. Enss, S. Hunklinger,
Phys. Rev. Lett. **80**, 5361 (1998)

Origin of Magnetic Field Dependence

- nuclear spins
- magnetic impurites
- tunneling systems carry a magnetic moment

Nuclear Spins: NMR Experiments



J. Szeftel, A. Alloul, Phys. Rev. Lett. **34,** 657 (1975)

Relaxation time T_1 of nuclear spins

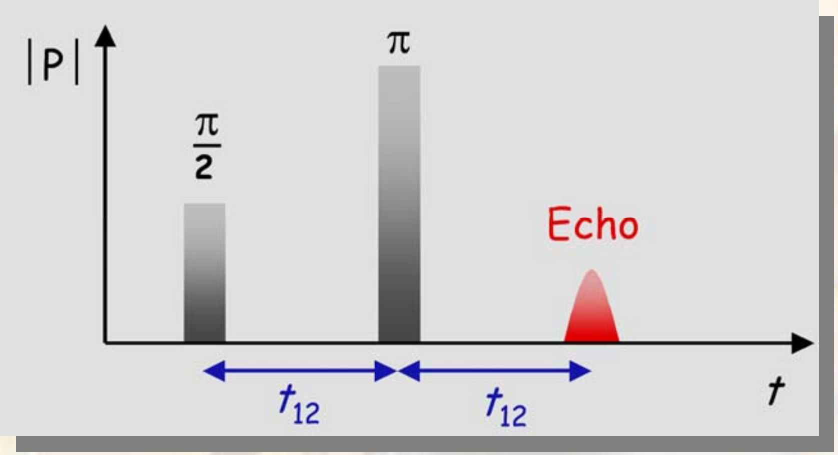
10 mK → 10^4 .... 10^5 s

too slow !!!

Coherent Properties

$t \ll \tau_1, \tau_2 \to \infty$ → coherent regime

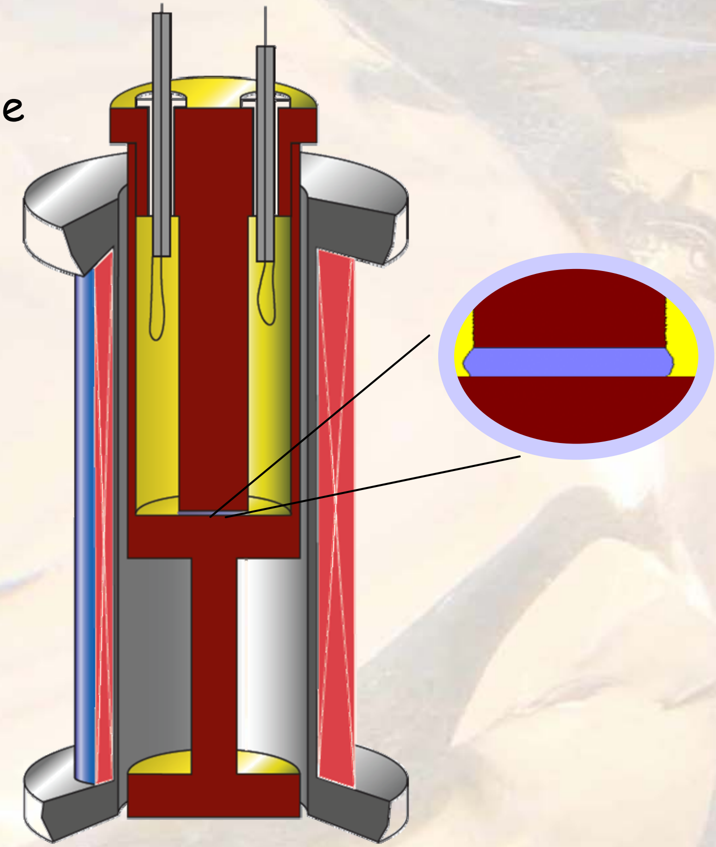
two-pulse polarization echoes:



$$\Theta_\mathrm{p} = \Omega_\mathrm{R} t_\mathrm{p}$$

Rabi frequency

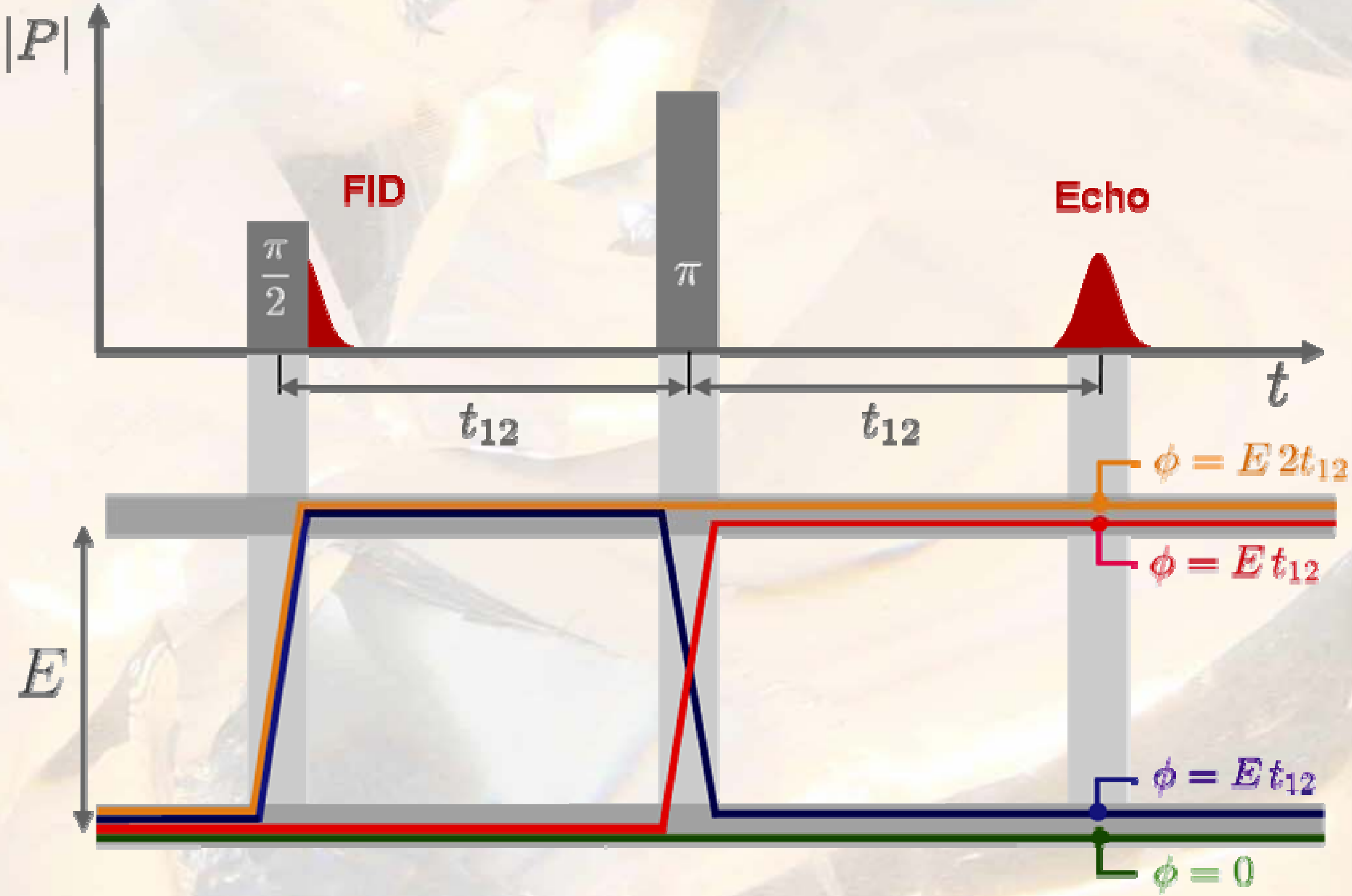
$$\Omega_\mathrm{R} = \frac{1}{\hbar}\frac{\Delta_0}{E}\,\boldsymbol{p}\cdot\boldsymbol{F}$$



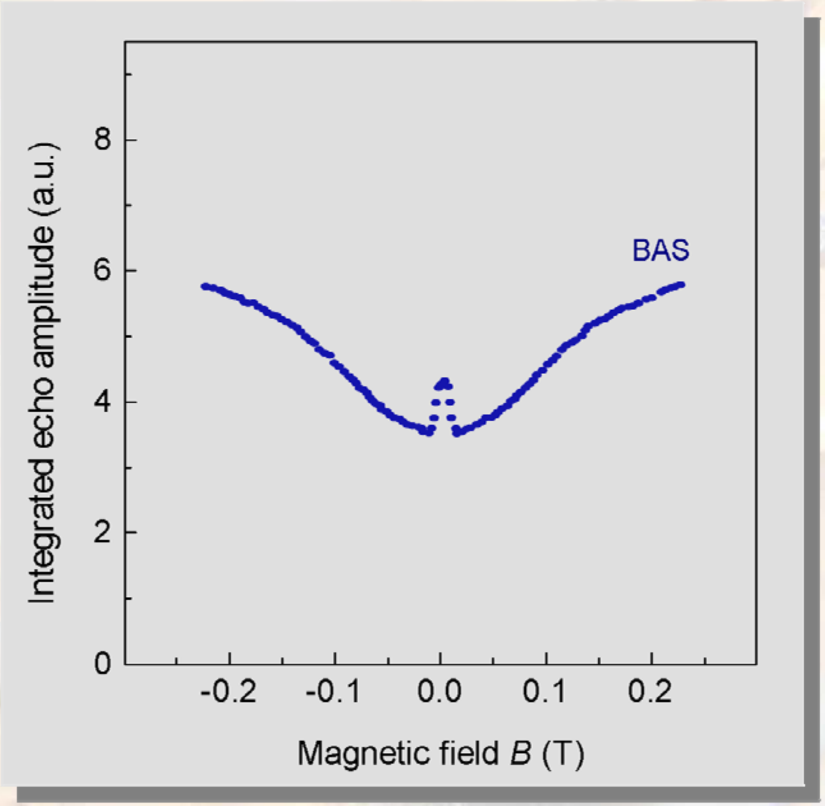
microwave cavity

1 GHz ⇒ 50 mK

Origin of Spontaneous Echoes



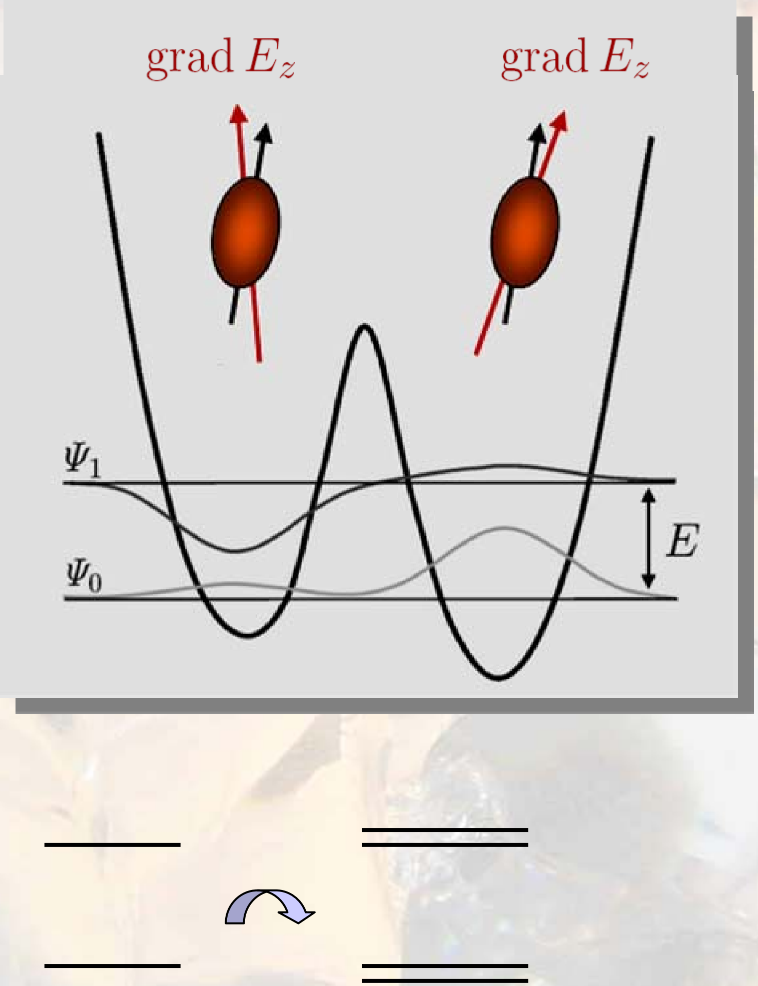
Echo Amplitude: Magnetic Field Dependence



- Tunneling systems couple to magnetic fields
- What is different in case of a-SiO_2?

S. Ludwig. C. Enss, S. Hunklinger, P. Strehlow,
Phys. Rev. Lett. **88**, 75501 (2002)

Nuclear Quadrupole Moment is Important



A. Würger, A. Fleischmann, C.Enss,
Phys. Rev. Lett. **89**, 237601 (2002)

- nuclear quadrupole moment of tunneling particle sees the electric field gradient in the two wells

→ splitting of tunneling levels

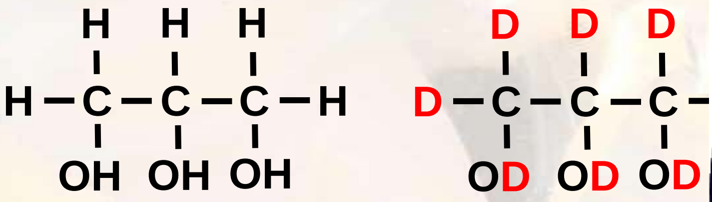
→ multi-level systems

- magnetic field causes an additional Zeeman splitting of nuclear levels

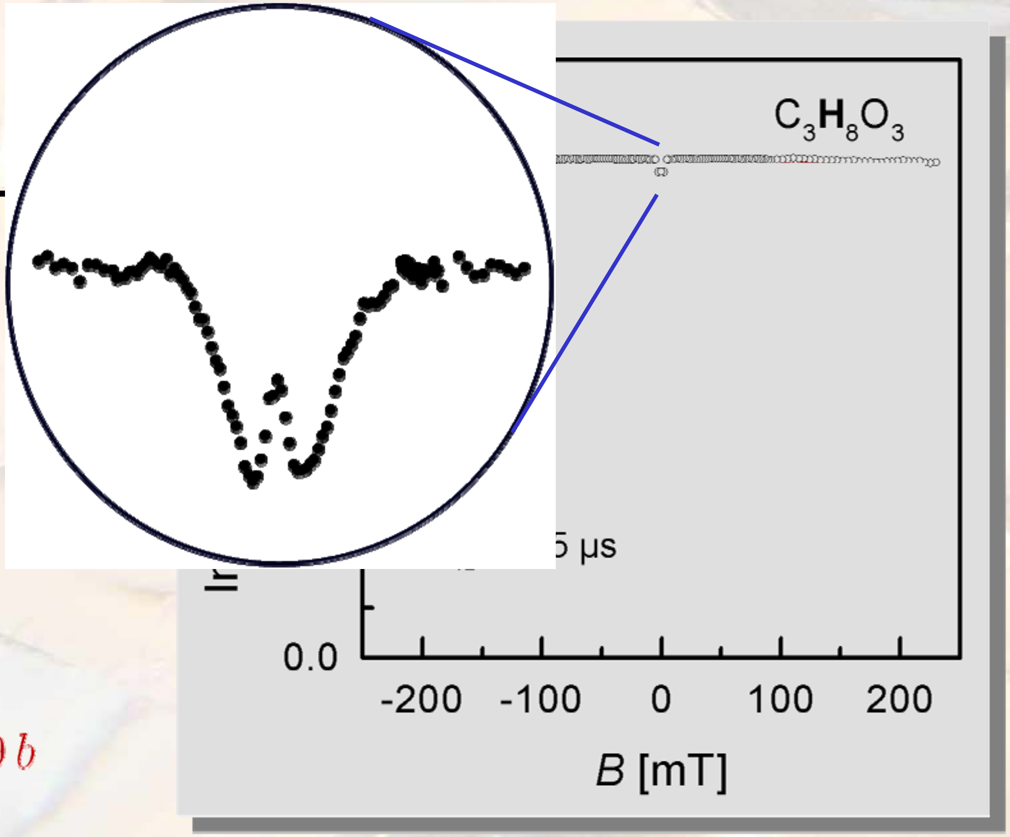
no effect for a-SiO_2 because no quadrupole moment

Isotope Effect H ↔ D

Glycerol



$$H-\overset{H}{\underset{OH}{C}}-\overset{H}{\underset{OH}{C}}-\overset{H}{\underset{OH}{C}}-H \qquad D-\overset{D}{\underset{OD}{C}}-\overset{D}{\underset{OD}{C}}-\overset{D}{\underset{OD}{C}}-$$



hydrogen

$$I = 1/2,\quad \mu = 2.79\,\mu_\mathrm{N},\quad Q = 0$$

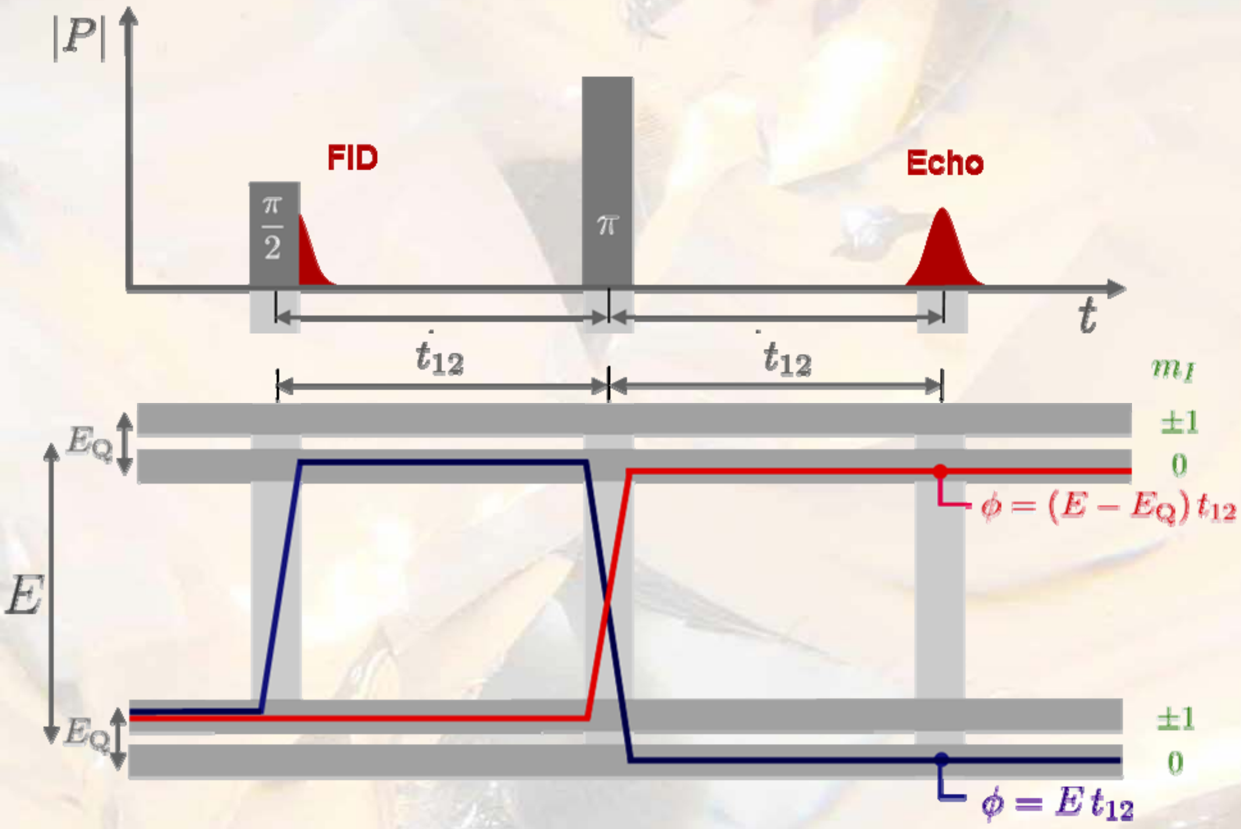
deuterium atom

$$I = 1,\quad \mu = 0.86\,\mu_\mathrm{N},\quad Q = 0.0029\,b$$

⇨ proof of the quadrupole model

P. Nagel, A. Fleischmann, S. Hunklinger, C. Enss,
Phys. Rev. Lett. **92**, 245511-1 (2004)

Zero Magnetic Field



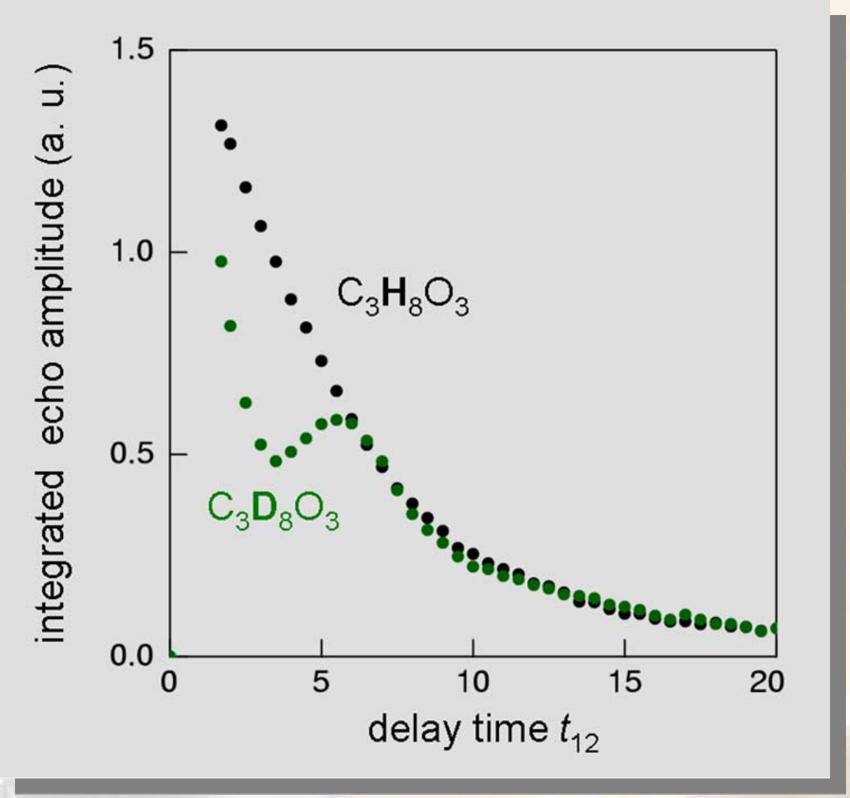
A. Würger, JLTP **137**, 143 (2004)

D.A. Parshin, JLTP **137**, 233 (2004)

$$A = A_0\left[a_1 + a_2\cos(\omega_Q t_{12}) + a_3\cos(2\omega_Q t_{12})\right]$$

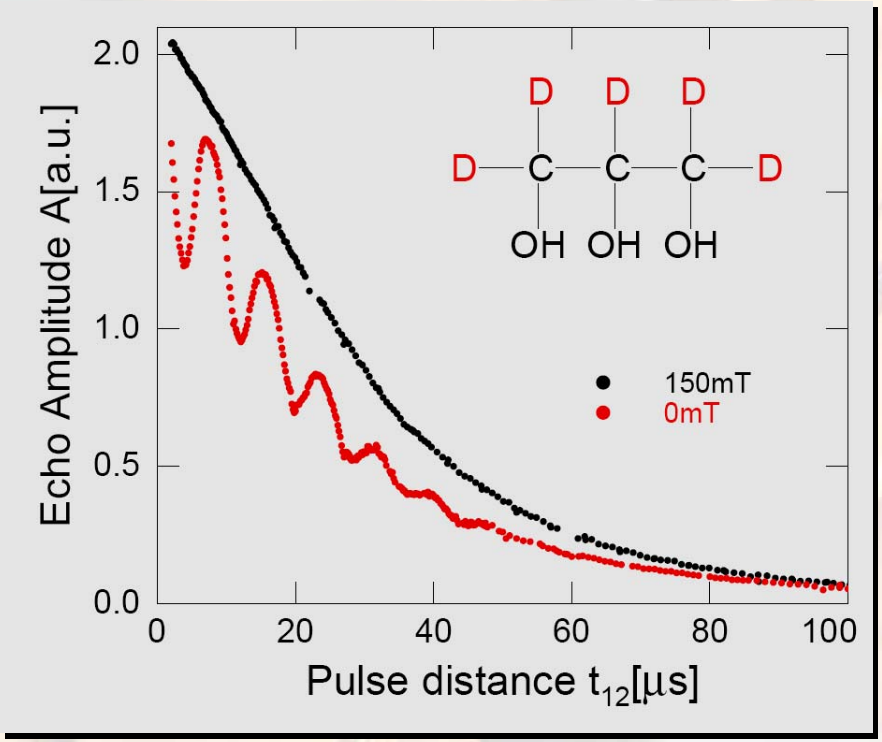
$$a_1 + a_2 + a_3 = 1$$

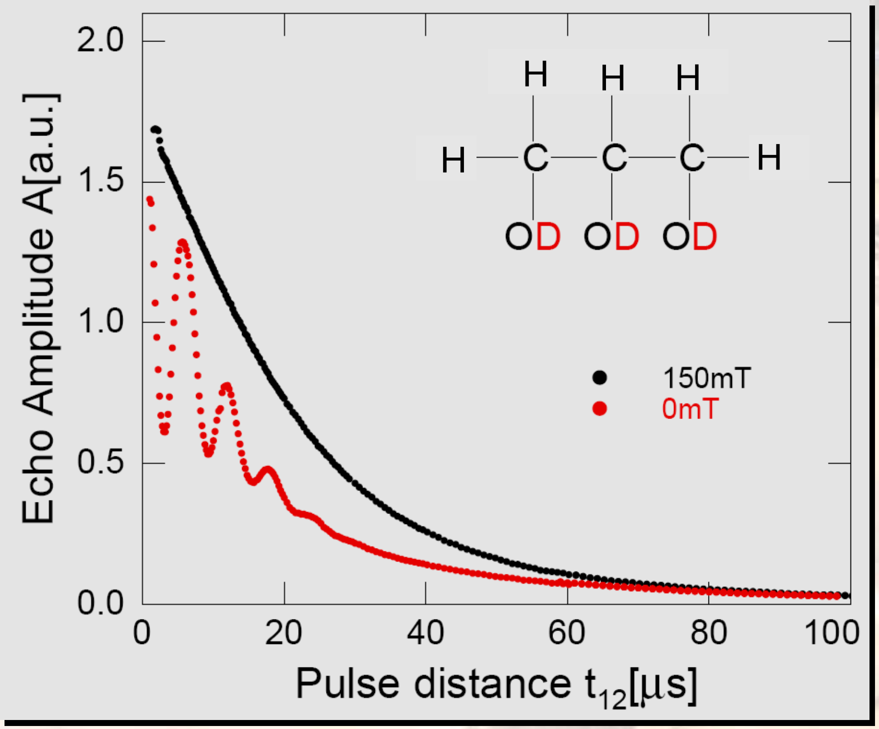
Quantum Beating



P. Nagel, A. Fleischmann, S. Hunklinger, C. Enss,
Phys. Rev. Lett. **92**, 245511-1 (2004)

Partially Deuterated Glycerol





$\nu_Q = 128\,\mathrm{kHz}$

$\nu_Q = 125\,\mathrm{kHz}$ (NMR)

$\nu_Q = 160\,\mathrm{kHz}$

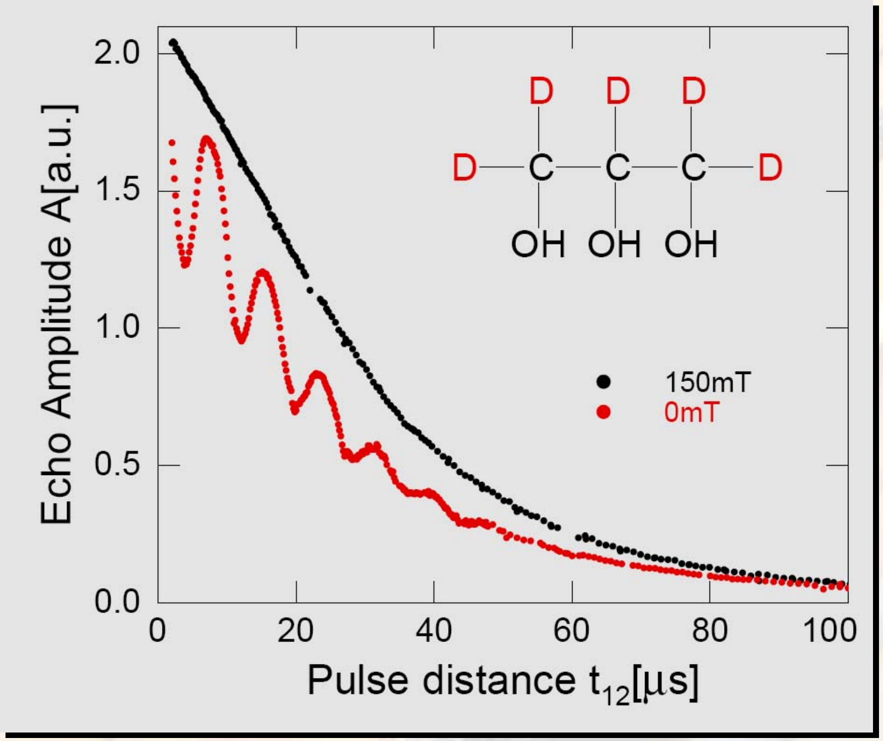
$\nu_Q = 158\,\mathrm{kHz}$ (NMR)

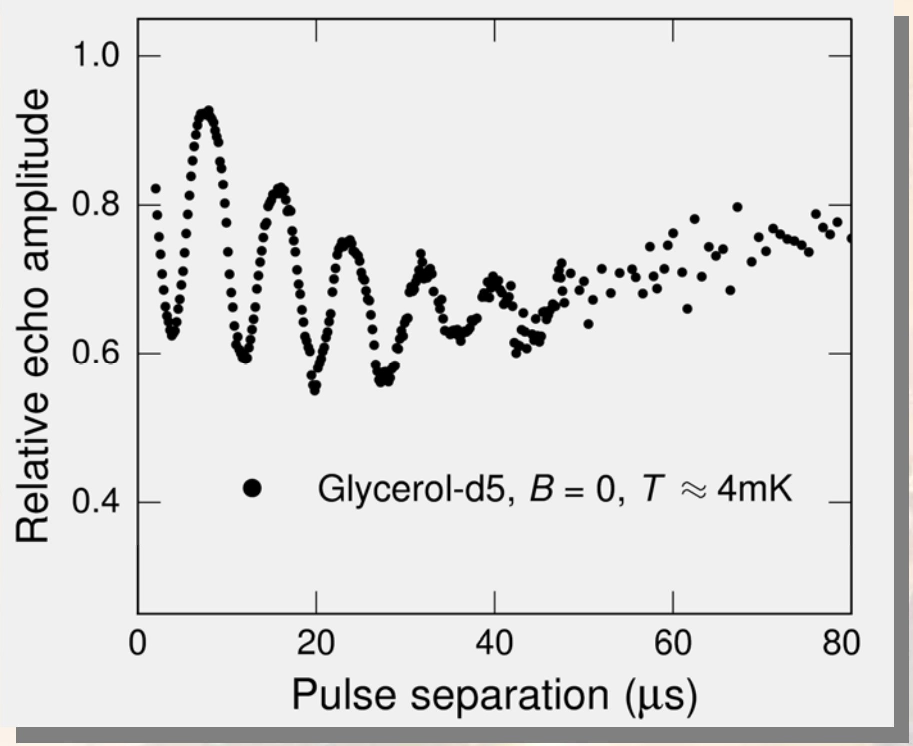
W. Schnauss, F. Fujara, H. Sillescu,
J. Chem. Phys. **97**, 1378 (1992).

Beating in case of d3 disappears *faster* → local enviroment ?

A. Bartkowiak, M. Brandt, C. Fischer, A. Fleischmann, C. Enss,
phys. stat. sol. **1**, 2875 (2006)
A. Fleischmann, C. Enss, Physik Journal **6**, 41 (2007)

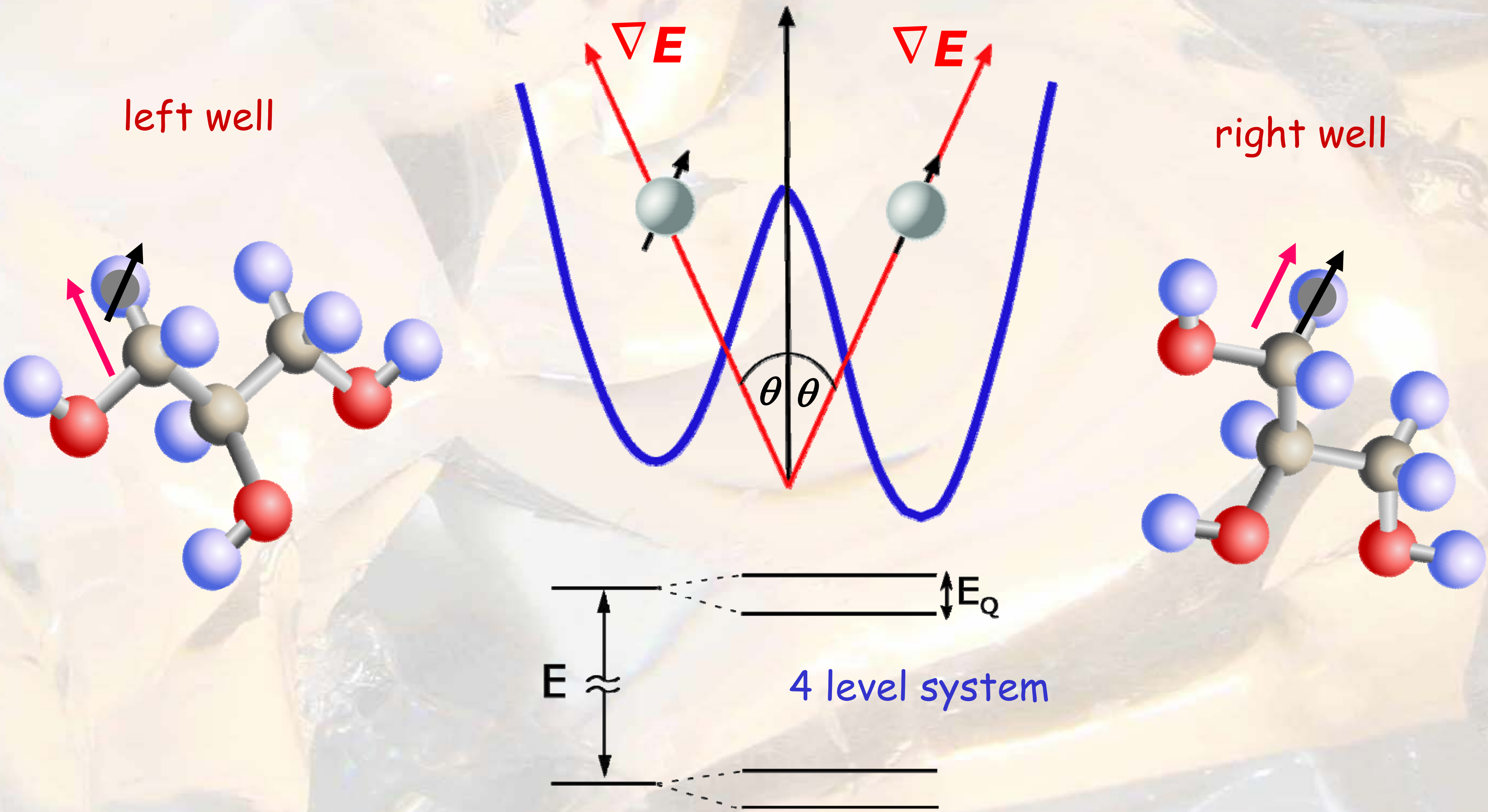
Glycerol D5





A. Bartkowiak, M. Brandt, C. Fischer, A. Fleischmann, C. Enss, phys. stat. sol. **1**, 2875 (2006)
A. Fleischmann, C. Enss, Physik Journal **6**, 41 (2007)

Microscopic Interpretation

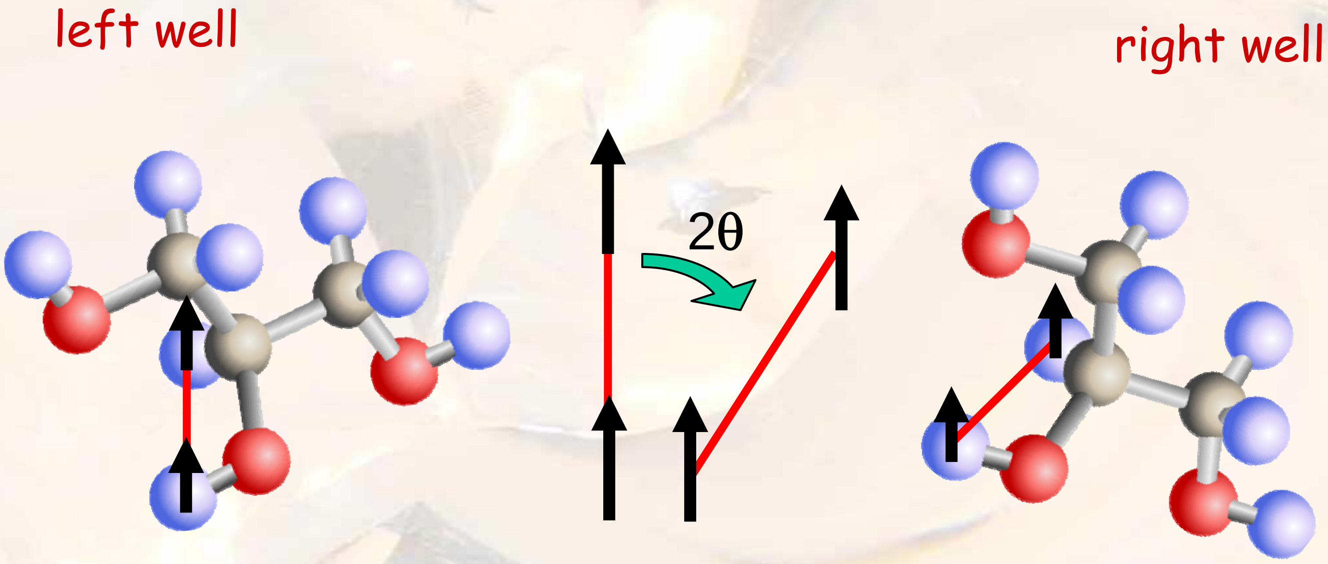


left well

right well

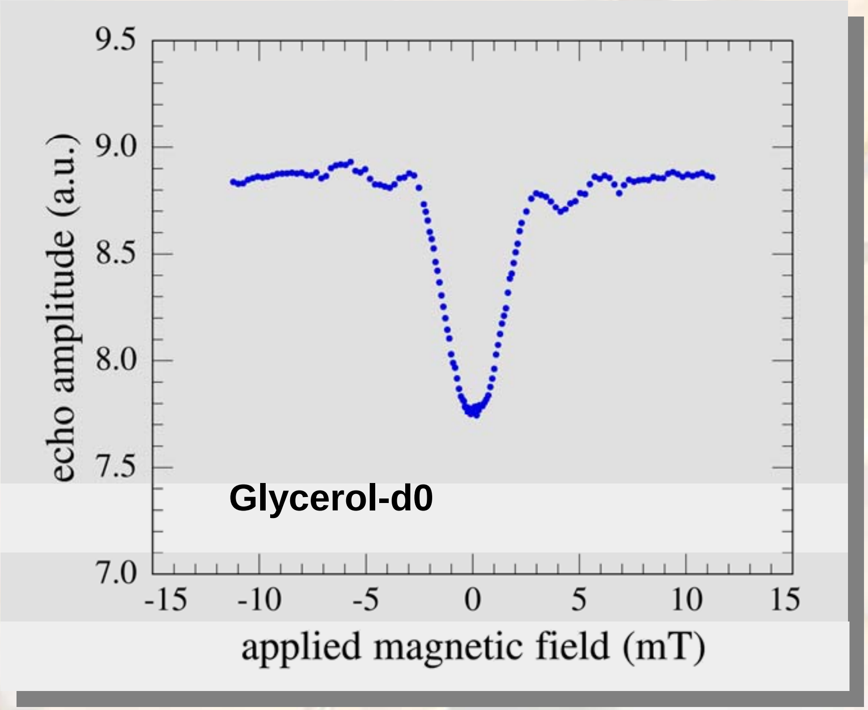
4 level system

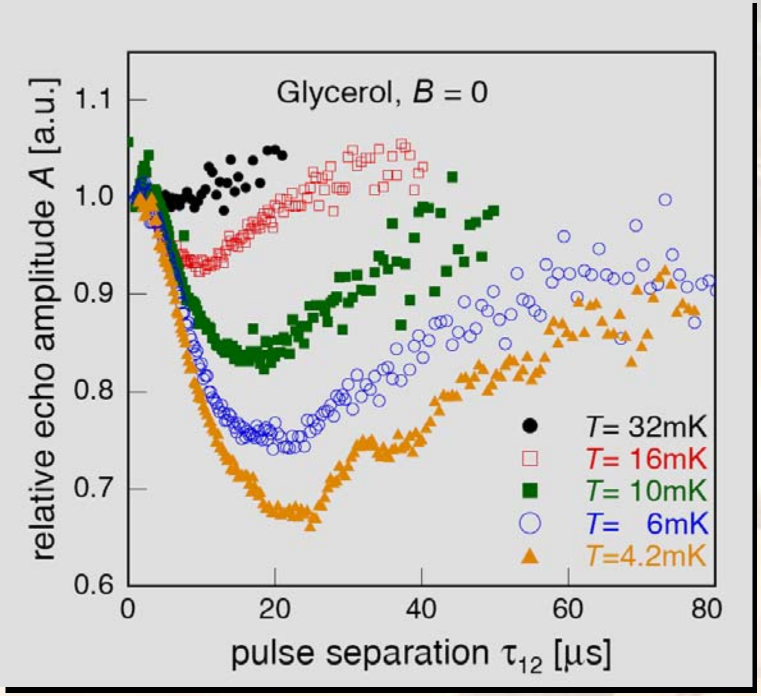
In Addition: Dipole-Dipole Effect



small saturation field: 5 mT

Dipole-Dipole-Effect: Gycerol-d0

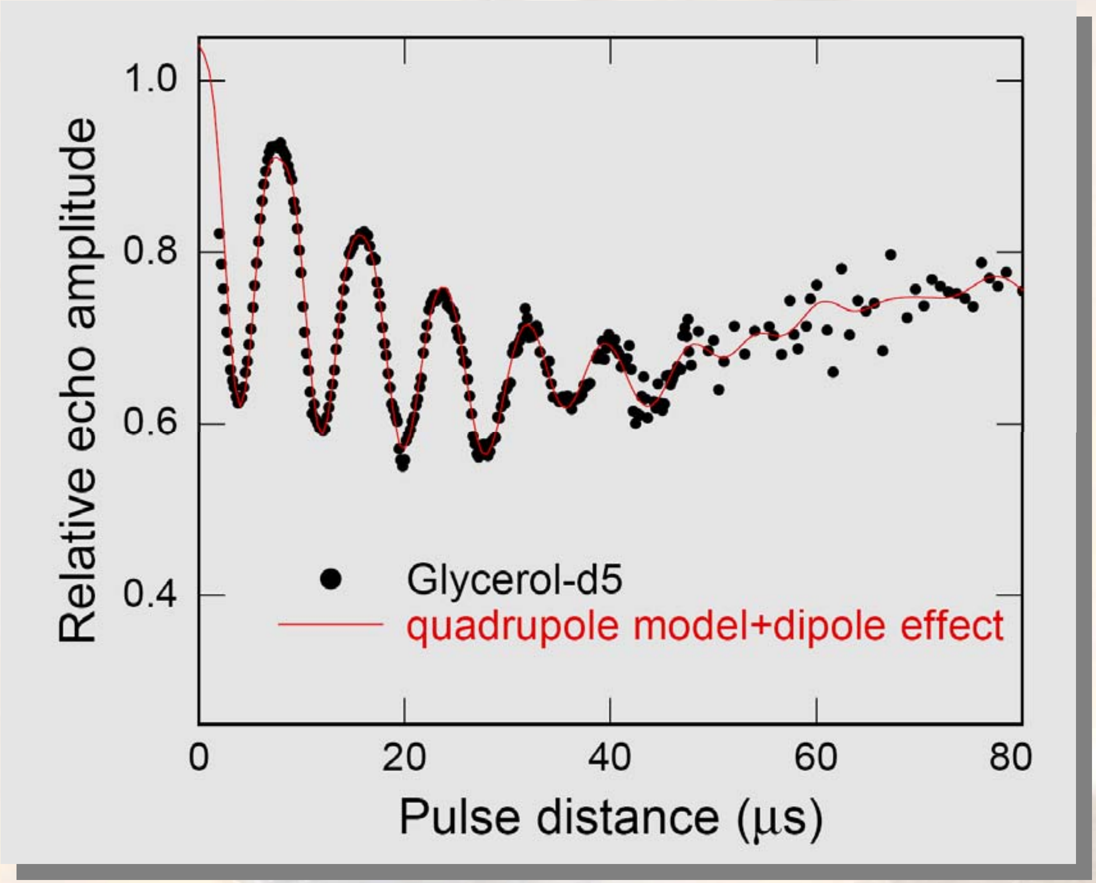




M. Bazrafshan, G. Fickenscher, M.v. Schickfus,
A. Fleischmann, C. Enss, J. Phys. **92**, 12135 (2007)

G. Fickenscher, M. Bazrafshan, K. Reinhold,
A. Fleischmann, C. Enss, J. Phys. **150**, 42032 (2009)

Modelling the Quantum-Beating of D5

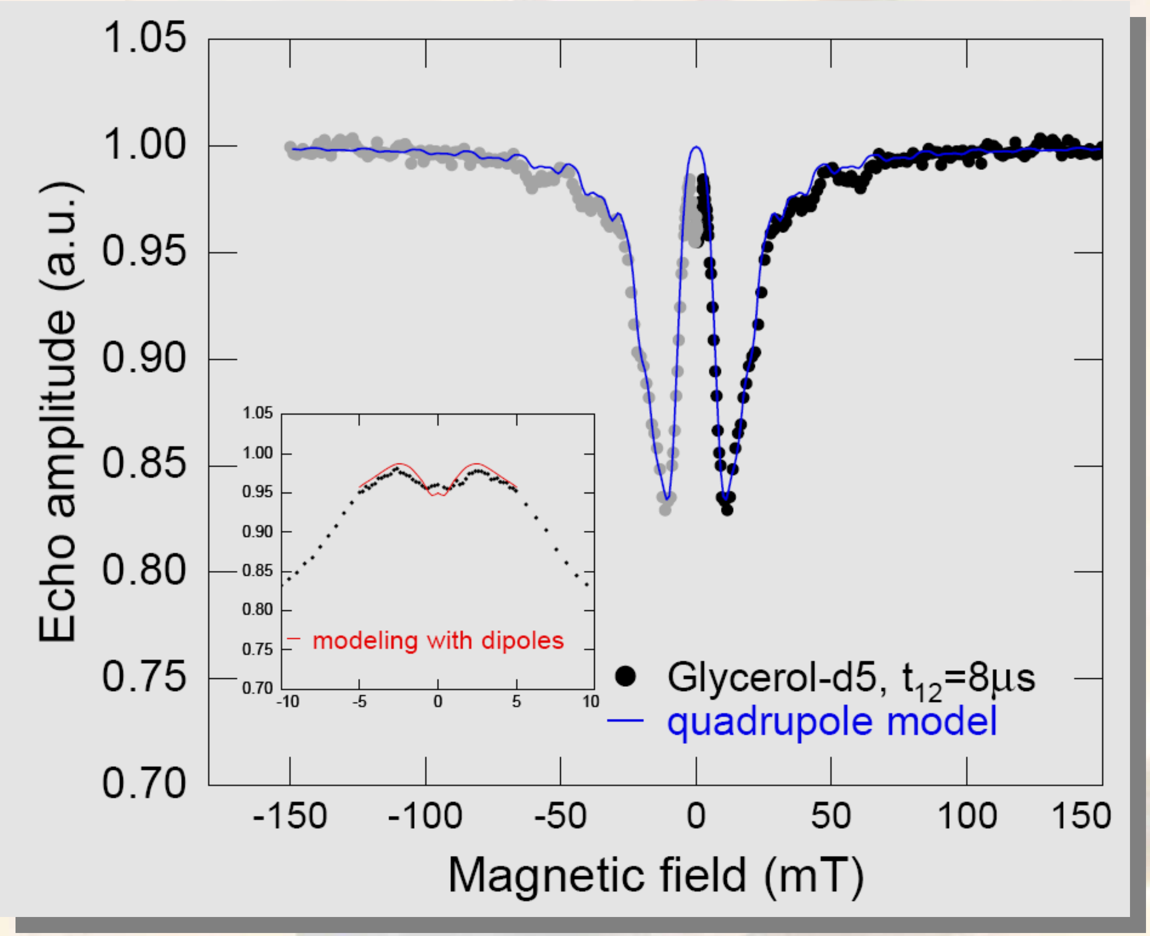


$\Delta_0/\Delta = 0.5$

$2\Theta = 16°$

M. Bazrafshan, PhD Thesis 2008

Modelling the B-Field Dependence of D5

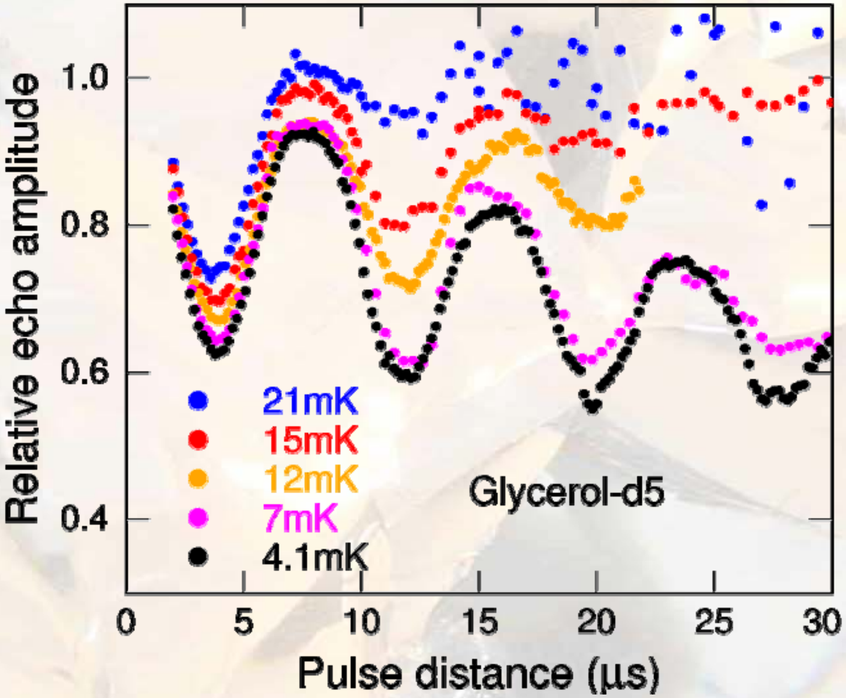


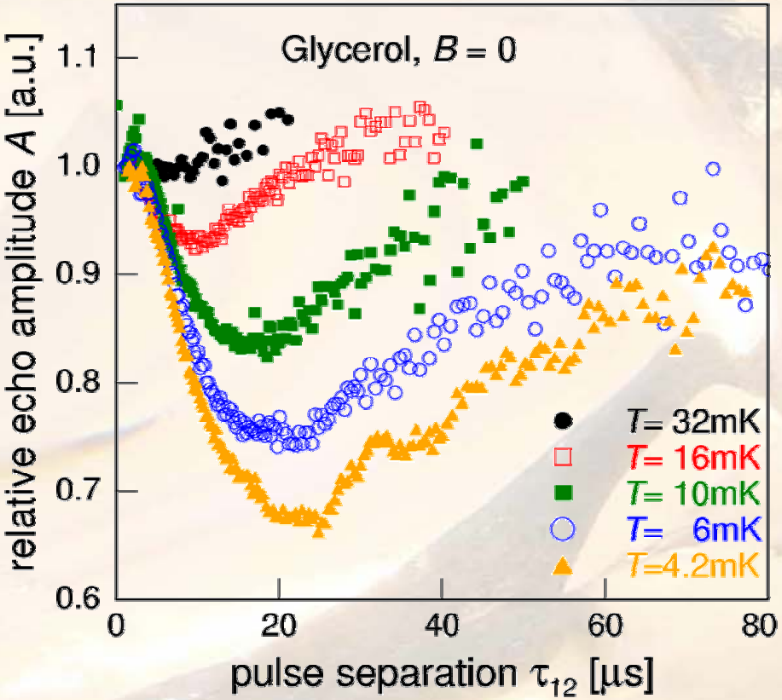
$$\Delta_0/\Delta = 0.5$$

$$2\Theta = 16°$$

M. Bazrafshan, PhD Thesis 2008

Temperature Dependence





G. Fickenscher, M. Bazrafshan, K. Reinhold,
A. Fleischmann, C. Enss, J. Phys. **150**, 42032 (2009)

Observations

- Modulation fades out in time
- Modulation disappears before echo amplitude vanishes
- Modulation fades out faster at higher temperatures

Origin of Temperature Dependence

Echo amplitude

$$A \propto \left(\frac{\Delta_0}{E}\right)^4$$

Beating amplitude

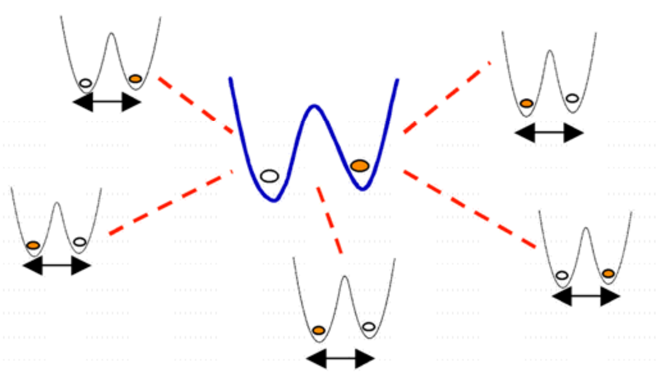
$$A_{\mathrm{mod}} \propto \left(\frac{\Delta}{E}\right)^2$$

Faster decoherence of more asymmetric tunneling systems?

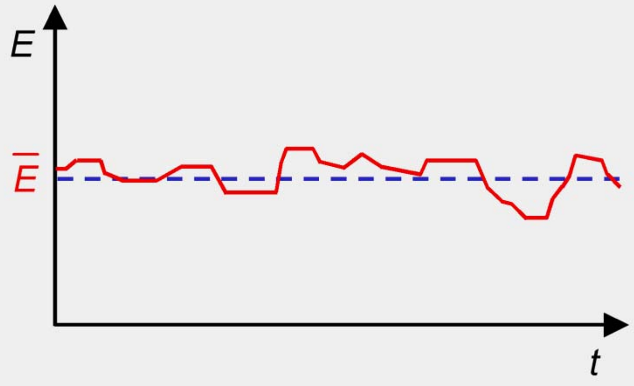
Spectral diffusion:

$$\delta\omega(\Delta) \propto \frac{\Delta}{E}$$

Spectral Diffusion



interaction between resonant TS
and thermally fluctuating TS



energy splitting of single TS
fluctuating with time

J.L. Black, B.I. Halperin, PRB **16**, 2879 (1976)

- short time limit (no flip limit): $t_{12} \ll \tau_{\min}$

$$\longrightarrow \quad A(2t_{12}) = A(0)\,\mathrm{e}^{-(2t_{12}/\tau_2)^2}$$

Gaussian decay

- long time limit (multiple flip limit): $t_{12} \gg \tau_{\min}$

$$\longrightarrow \quad A(2t_{12}) = A(0)\,\mathrm{e}^{-2t_{12}/\tau_2}$$

exponential decay

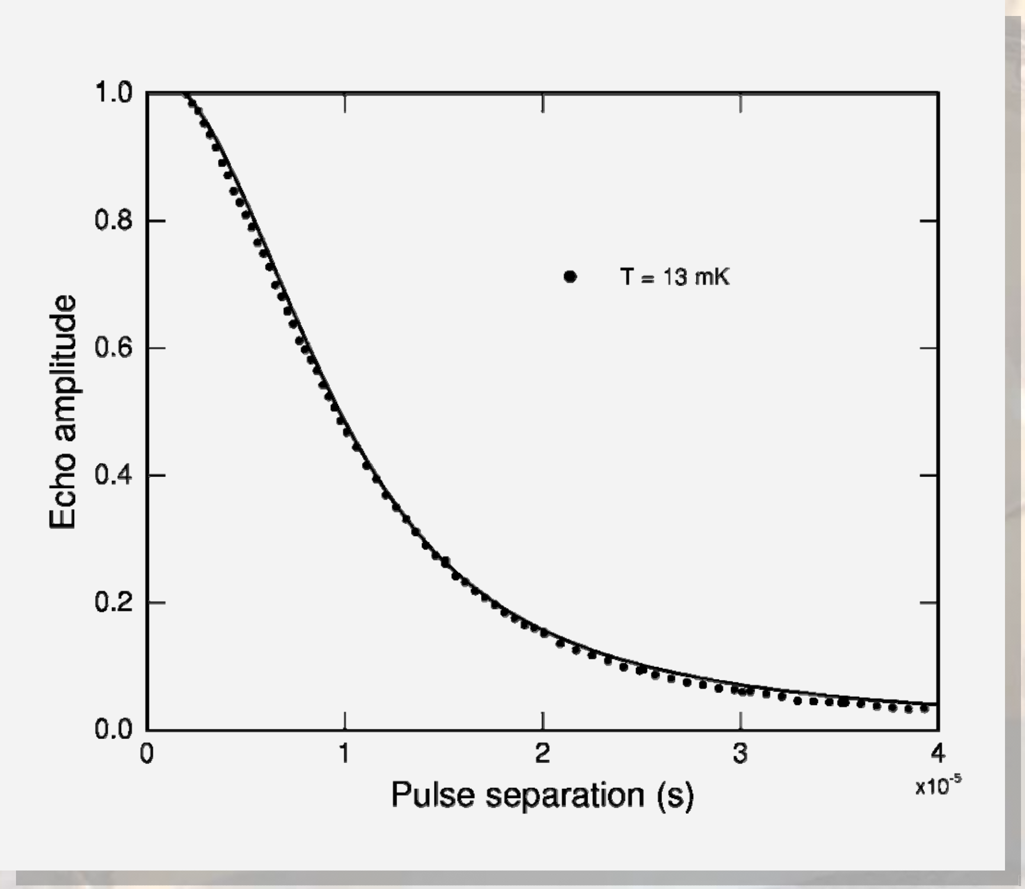
Spectral Diffusion - Short Time Regime

Echo decay:

$$\int_0^1 (1-q^2)^2 e^{-m_0 q T^4 t_{12}^2} \mathrm{d}q$$

$$q = \frac{\Delta}{E}$$

Gycerol



M. Basrafshan, A. Fleischmann, C.Enss to be published

Spectral Diffusion - Short Time Regime

Echo decay:

$$\int_0^1 (1-q^2)^2 e^{-m_0 q T^4 t_{12}^2} \mathrm{d}q$$

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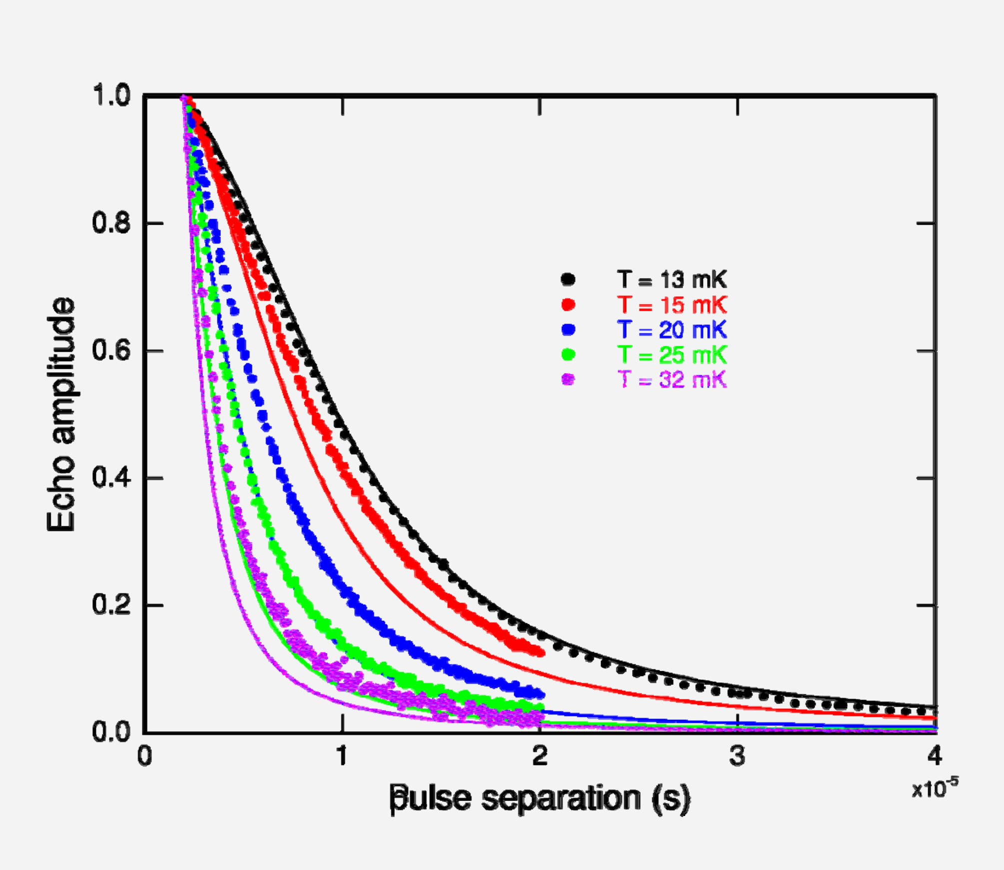
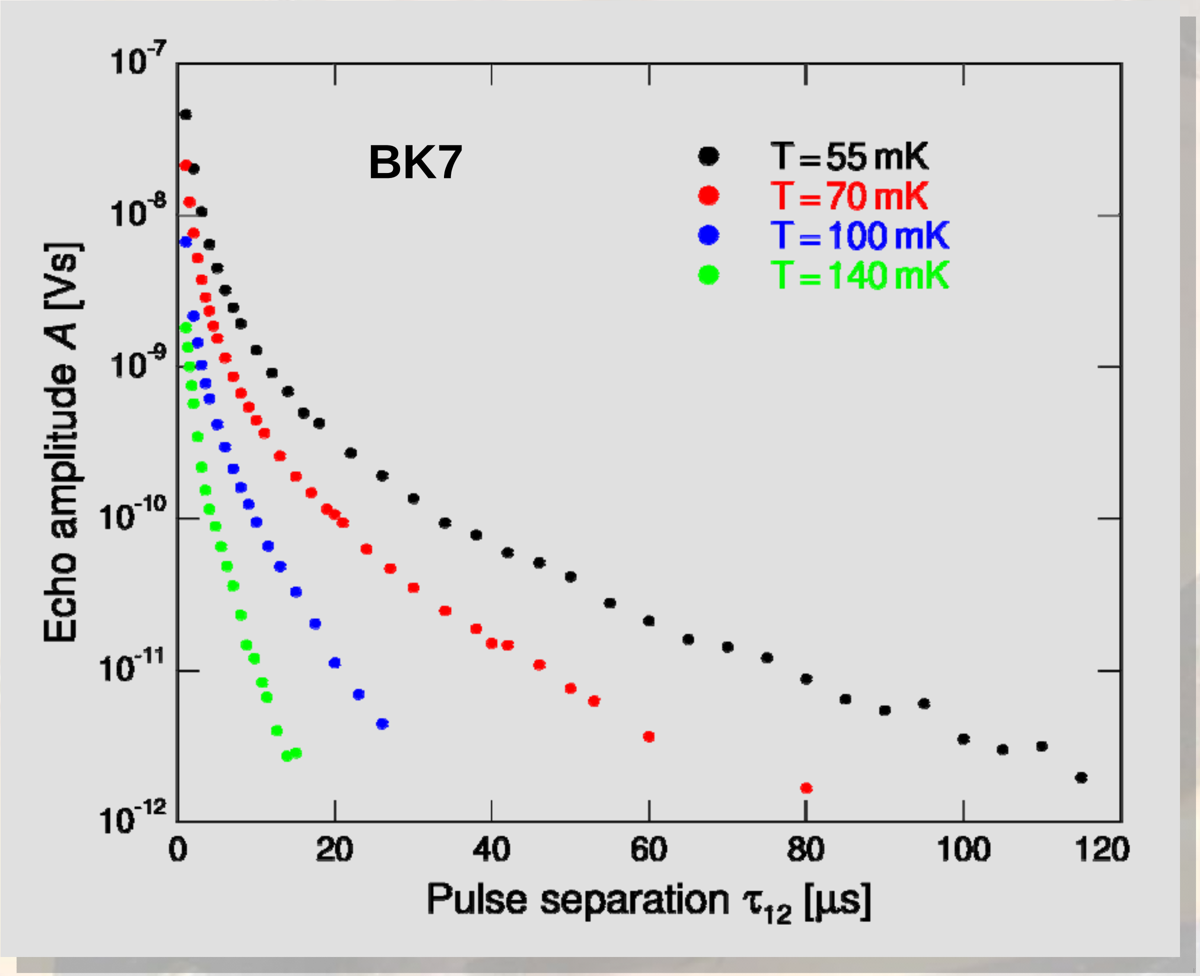
Gycerol



M. Basrafshan, A. Fleischmann, C.Enss to be published

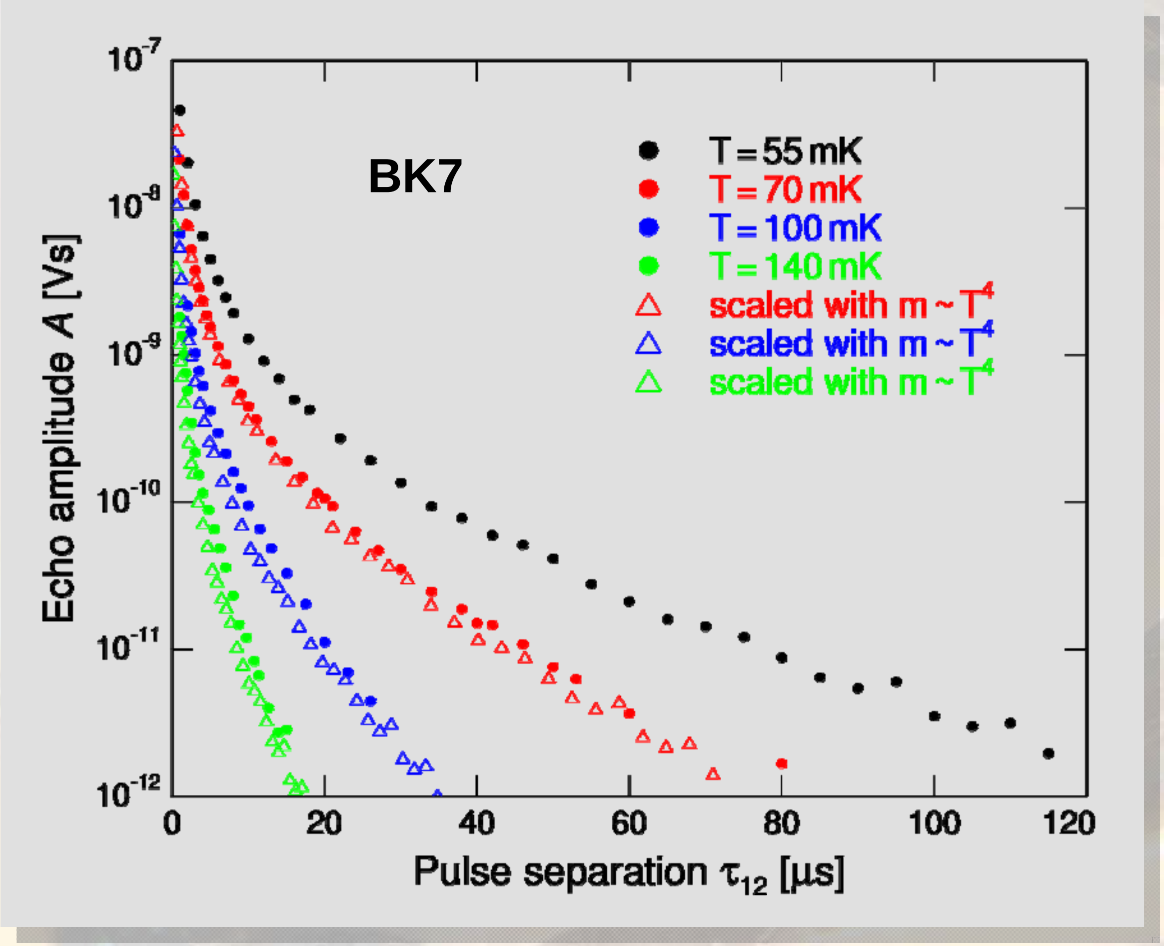
T_2 Measurments on BK7



M. Schwarze, M. Basrafshan, A. Fleischmann, C.Enss

to be published

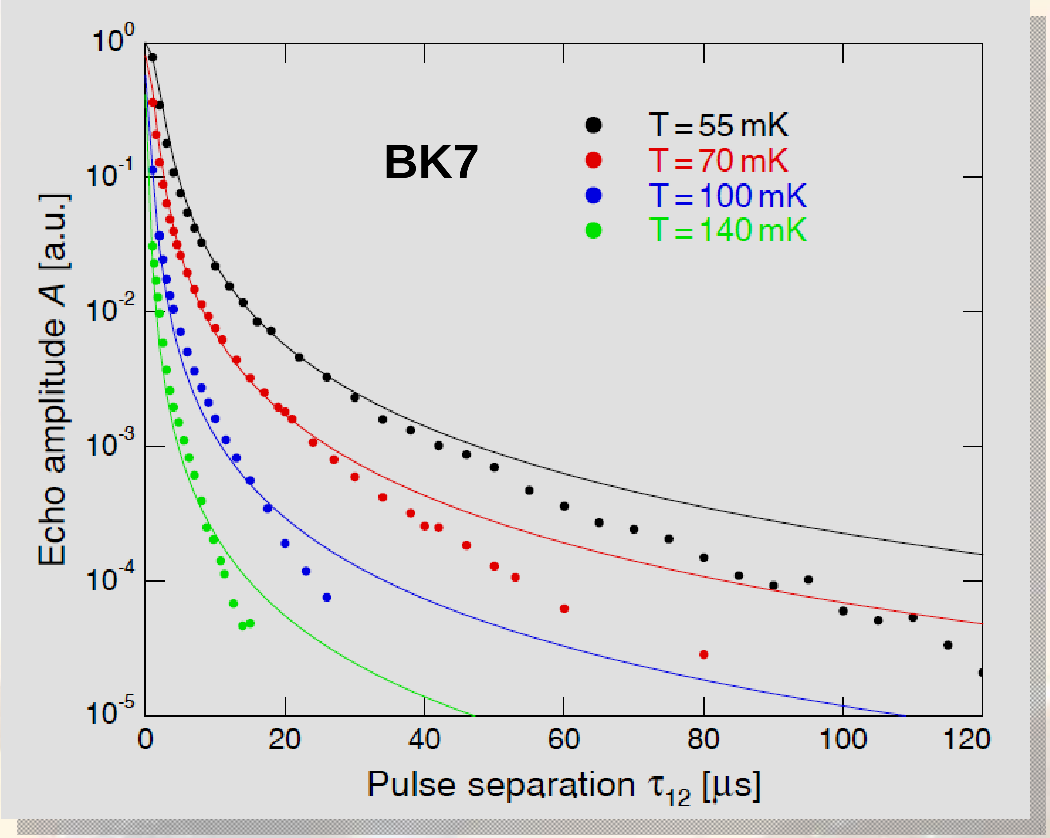
Temperature Dependence of T_2



M. Schwarze, M. Basrafshan, A. Fleischmann, C.Enss

to be published

Transition to Long Term Regime



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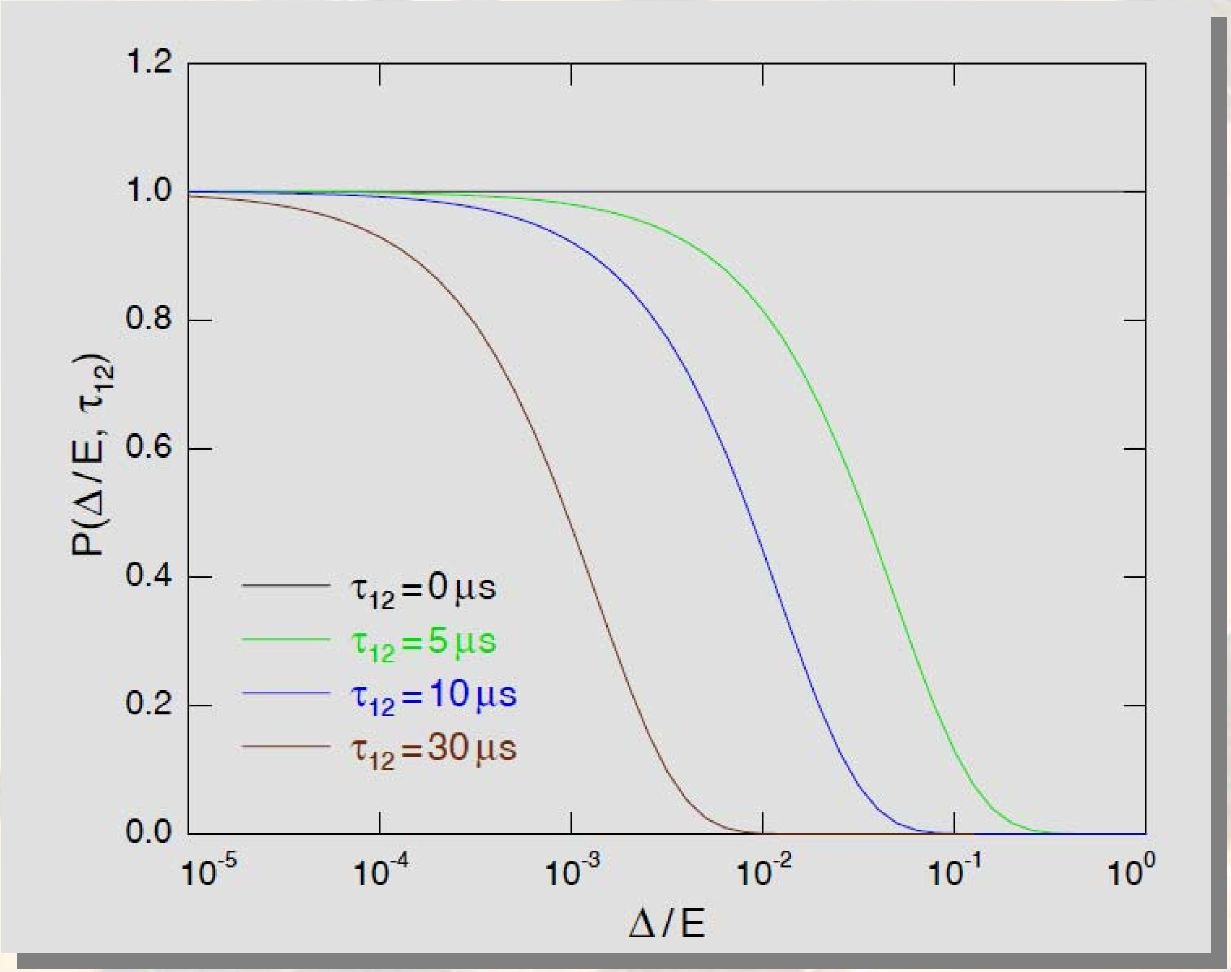
to be published

Lines are fits assuming spectral defusion in short time limit and tunneling model distribution

Width of Distribution of Asymmetry Energies



M. Schwarze, M. Basrafshan, A. Fleischmann, C.Enss

to be published

Summary and Outlook

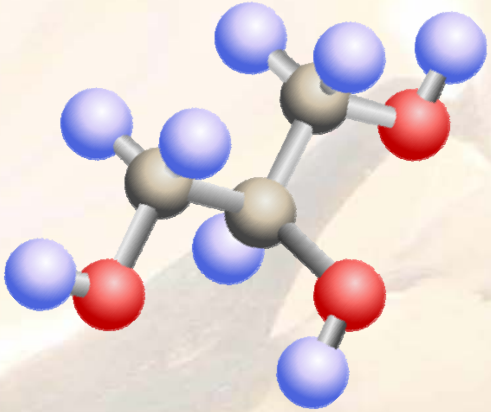
Summary:

low temperature properties of glasses are governed by atomic tunneling systems

nuclear moments play a crucial role

microscopic nature can be studied nuclear spins as local probes

dephasing is due to spectral diffusion



Outlook:

measurements at temperatures below 1 mK

microscopic nature of TS in oxid glasses

investigation of crystalline model system -> dressing effect

metallic glasses -> interactions with electrons

decoherence of TS due to nuclear spins


Andreas Fleischmann


Marek Bartkoviak


Peter Nagel

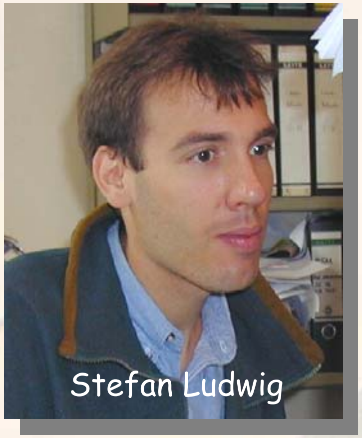

Catherine Fischer

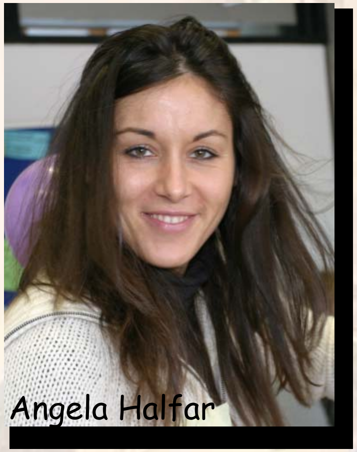

Florian Klotz


Celine Rüdiger

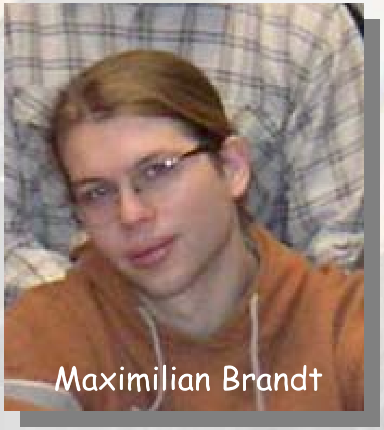

Gudrun Fickenscher


Mazomeeh Bazrafshan


Stefan Ludwig


Angela Halfar


Kathrin Reinhold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European Microkelvin Collaboration