Optical orientation of single spins in individual semiconductor quantum dots

Quantum Optoelectronics Group

Laboratory for Physics and Chemistry of Nano-Objects LPCNO

Collaborations

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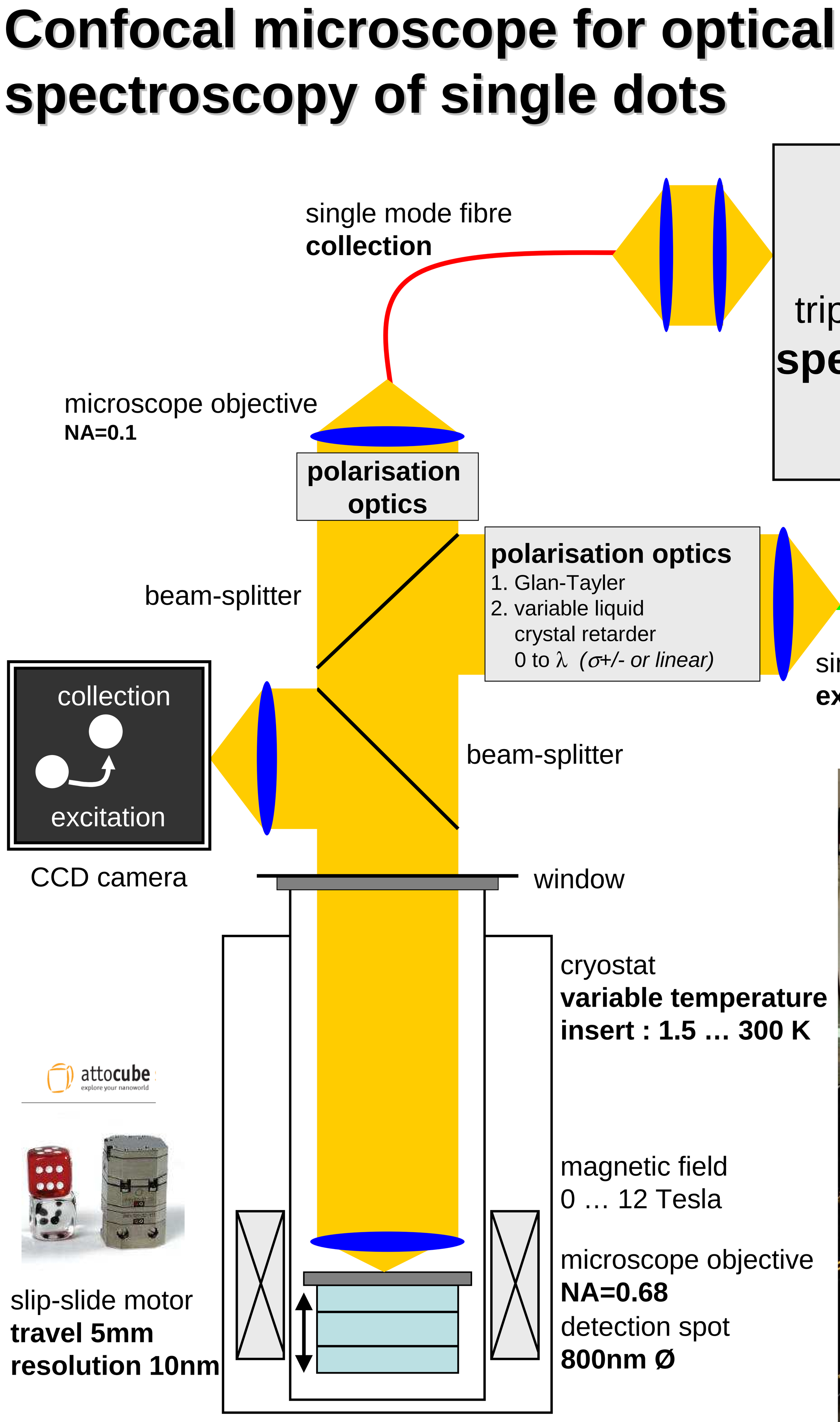
Confocal microscope for optical spectroscopy of single dots

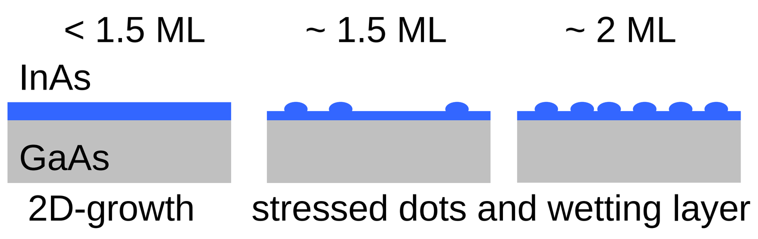


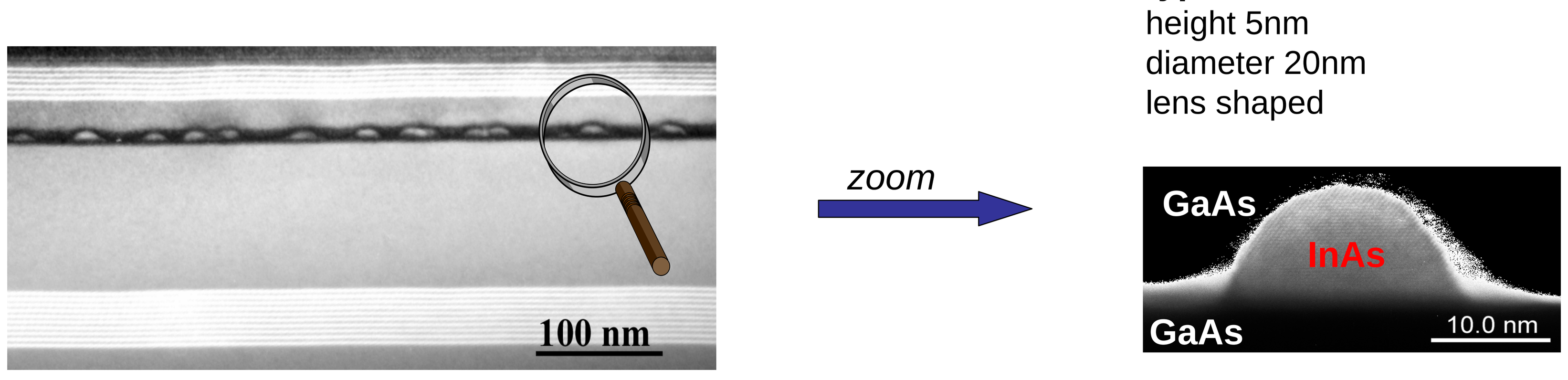
Semiconductor quantum dots

potential applications: - single photon emitter
- single spin memory
- bio-imaging

Self assembly of quantum dots :
Stranski-Krastanov mode for InAs on GaAs

band gap: E_G(GaAs) > E_G(InAs)
lattice constants: a_0(InAs) > a_0(GaAs)

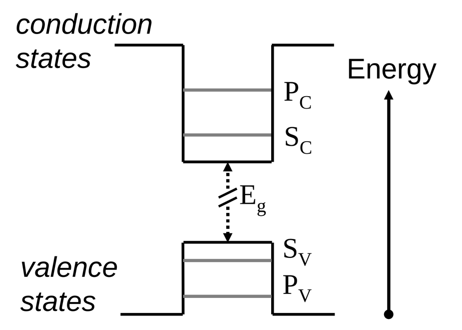




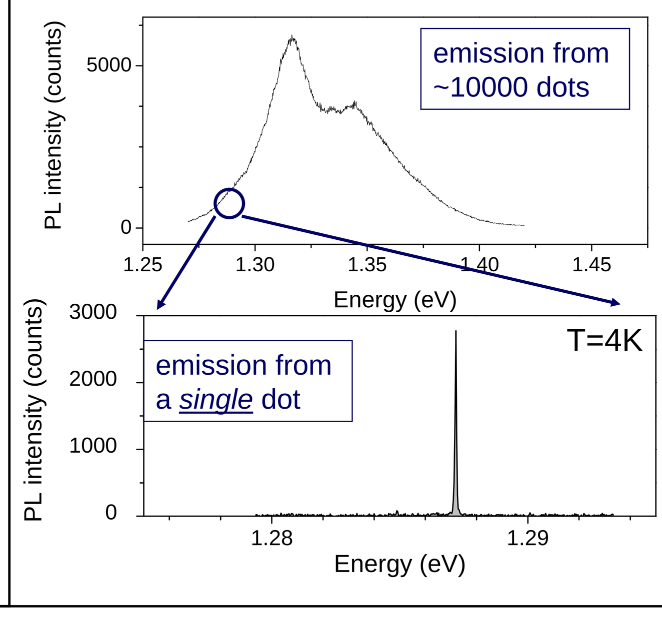
typical dimensions
height 5nm
diameter 20nm
lens shaped

TEM image:
J.P. Mc Caffey *et al.*, JAP 88, 2272(2000)

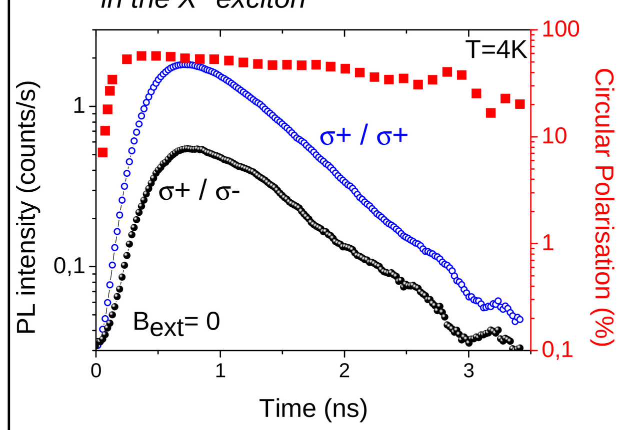
strong carrier confinement:
discrete, atom-like energy states inside the dot



Continuous wave and time resolved *single* dot photoluminescence

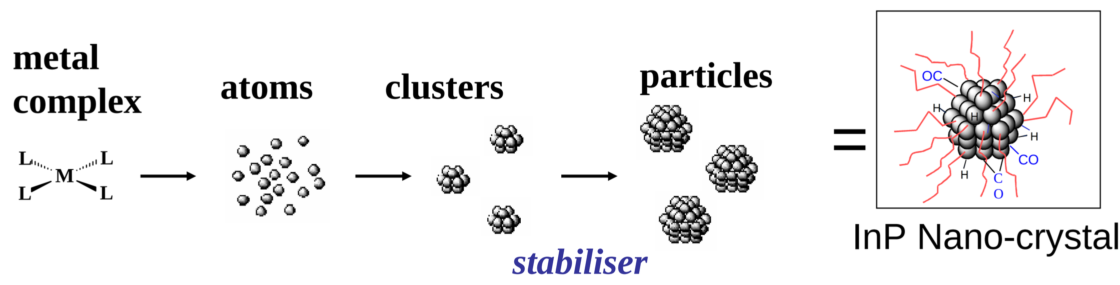


single electron spin coherence
in the X⁺ exciton

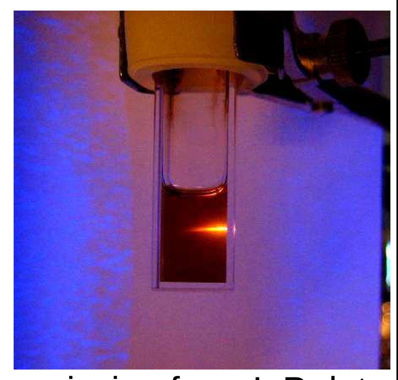


time resolution SPAD: 350ps

Semiconductor Nano-crystals: InP based core/shell dots
Elaboration by 'chimie douce': group of G. Viau (LPCNO)



InP Nano-crystal

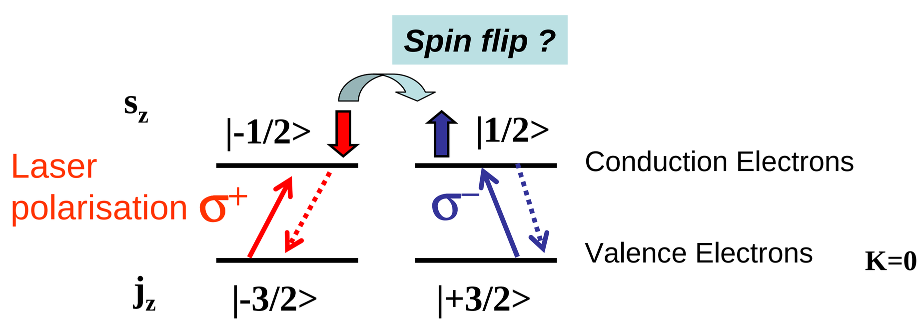


emission from InP dots in solution

PHYSICAL REVIEW B 74, 245306 (2006)
Bistability of the Nuclear Polarisation created through optical pumping in InGaAs Quantum Dots
PHYSICAL REVIEW B 76, 201301 (Rapid) (2007)
Efficient dynamical nuclear polarization in quantum dots: Temperature dependence

1. Optical Orientation:
Transfer photon polarisation ⬄ carrier spin polarisation

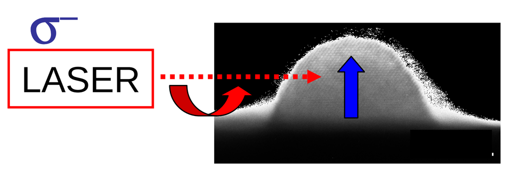
Optical selection rules for ***photon absorption*** in strained InAs dots
⬄ same selection rules for ***photon emission***



Did the electron spin flip before the photon emission ?
Compare polarization of excitation light and emitted photons in photoluminescence experiments !
George Lampel, Phys. Rev. Lett. 20, 491 (1968)

2. The Hyperfine Interaction:
Transfer electron spin polarisation ⬄ nuclear spin polarisation

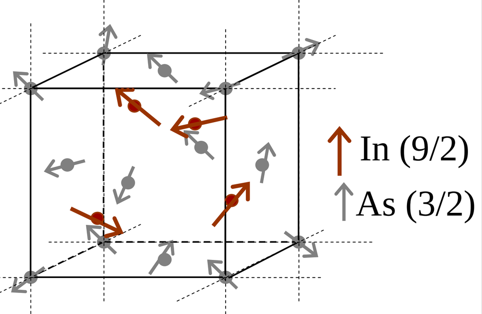
For potential applications – need stable spin states !
Does the electron optically or electrically injected into a dot keep its initial spin orientation ?



*Yes, up to milliseconds at 4K, **if** we control the hyperfine interaction with nuclear spins !*

Origin of nuclear spin:
Collection of protons and neutrons results in a total nuclear spin $\hat{\mathbf{I}}^j$

InAs: zincblende structure with sublattice of N_L nuclei with spin $\hat{\mathbf{I}}^j$



Why is it important in quantum dots?

Main challenge for coherent manipulation of carrier spins (*future qu-bits ?*):
Understanding and controlling the interaction with nuclear spins
(i) polarize nuclei in optical pumping experiments
➔ ***our recent results***
(i) 'put' nuclear spins in a know quantum state
➔ ***our future research***

the Fermi contact Hamiltonian

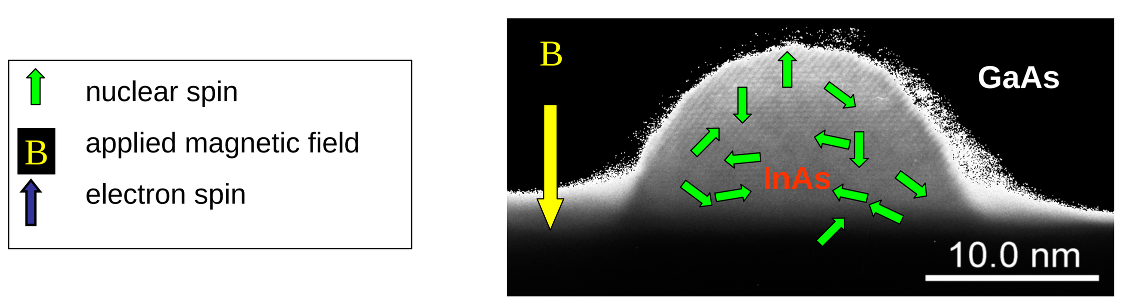
$$\hat{H}_{hf} = \frac{\nu_0}{2}\sum_j A^j |\psi(\mathbf{r}_j)|^2 (2\hat{I}_z^j \hat{S}_z^e + [\hat{I}_+^j \hat{S}_-^e + \hat{I}_-^j \hat{S}_+^e])$$

effective for localised carriers
▪ Donor bound electrons (1970s/1980s)
Optical Orientation, edited by Meier and Zakharchenya (1984)
▪ carriers in Quantum Dots: D. Gammon *et al* Phys. Rev.Lett. 2001

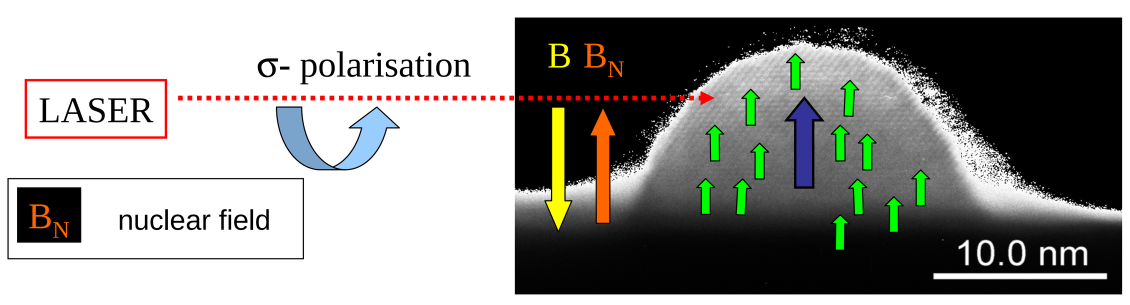
stronger for *electrons* than for *holes*
▪ factor 10…10⁴ depending on exact sample structure

3. Optical initialisation and manipulation of nuclear spins in a single quantum dot: *example of the X⁺ exciton*

before laser irradiation: arbitrary alignment of the 10⁵ nuclear spins



after laser irradiation: nuclear spins aligned parallel to electron spin



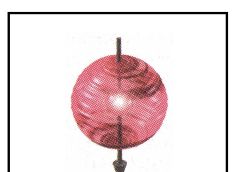
For how long do the ***nuclear spins*** keep this orientation ⬆
once the laser is switched off ?
Up to several hours ! ➔ potential application as ***spin memory***

How does the nuclear polarization depend on the electron polarization ?

Electron

$\langle S_z^e \rangle$ ⇔ $\langle I_z \rangle$

Can measure both simultaneously in single dot photoluminescence !



Nuclei

Contribution to Zeeman splitting ΔZ due to the effective nuclear field B_N: Overhaurshift δ_n

$$\delta_n = \Delta Z_{LIN} - \Delta Z_{\sigma-} = g_e \mu_B B_N = 2\tilde{A}\langle I_z \rangle$$

from σ⁺ and σ⁻ polarized photoluminescence intensity of the X⁺ exciton (2 holes, 1 electron)

$$\langle S_z^e \rangle = \frac{-P_c}{2} = \frac{1}{2}\frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow}$$

$n\uparrow(\downarrow)$ - population of spin UP (DOWN) electrons

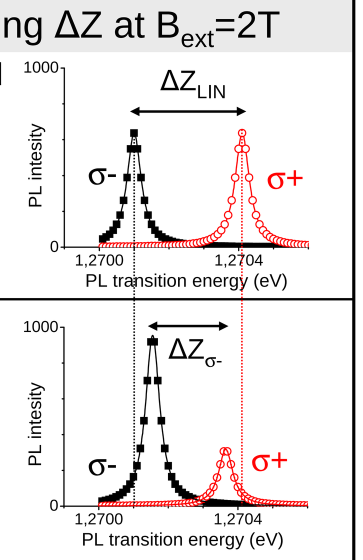
Zeeman splitting ΔZ at B_{ext}=2T

linearly polarized Laser excitation

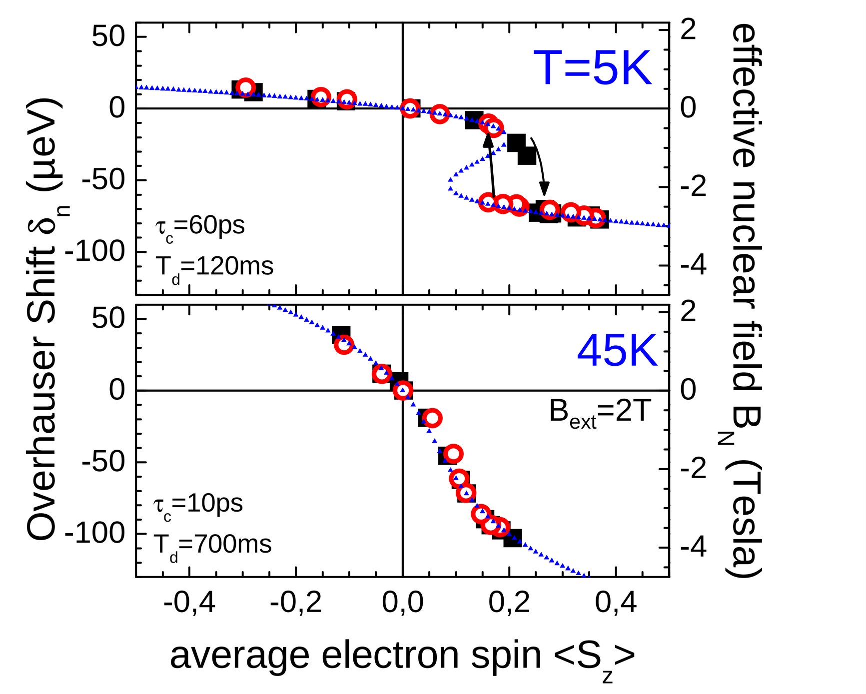
no nuclear polarization

σ- polarized Laser excitation

strong nuclear polarization up to 50%



• strength of nuclear field B_N created: *up to 4 Tesla !*
• **bistability of the nuclear polarization**
➔*turn nuclear field* ***ON*** *and* ***OFF*** *through small variation of*
- the laser power
- the applied magnetic field
- **the laser polarization** (time averaged electron spin)**:**



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