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SAND2020-6211C

Hyperfine effects in hole GaAs/AlGaAs structures probed by EDSR measurements in a double quantum dot device

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This work was performed at the Center for Integrated Nanotechnologies, a U.S. DOE, Office of Basic Energy Sciences user facility, and Sandia National Laboratories, a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

National Research Council Canada

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Outline

1. Short historical excursion to EDSR DNP in 2DEG
2. Motivation: negative attempts to see DNP in 2DHG
3. Hole EDSR using strong spin-orbit interaction
4. DNP in p-EDSR experiments
5. Discussion
6. Double pulse EDSR revealing ^{75}As contribution
7. Conclusions

DNP in 2DEG: historical excursion

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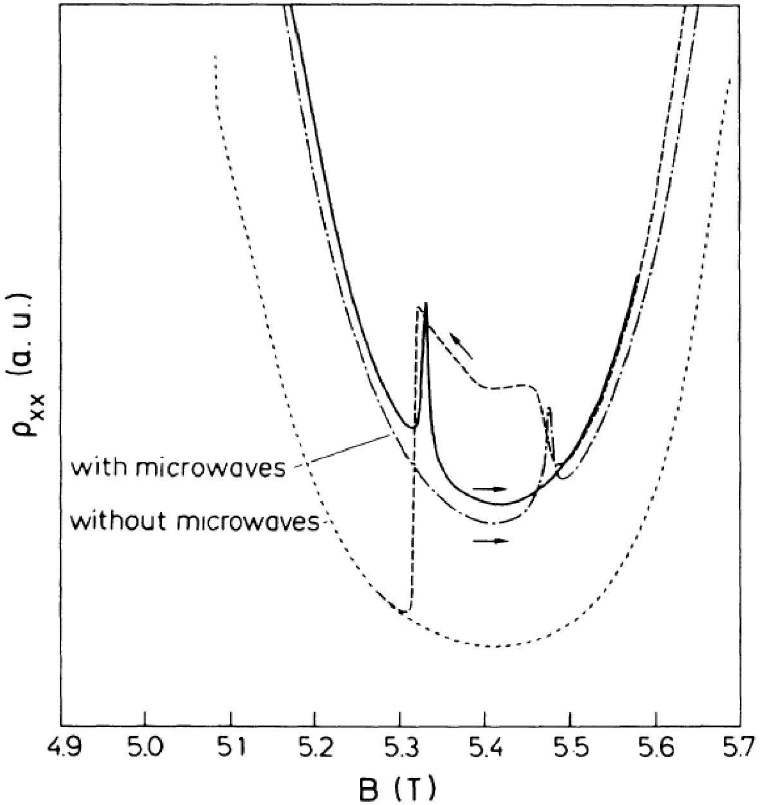
Dobers, K. v. Klitzing, J. Schneider, G. Weimann, and K. Ploog., PRL (1988)



ESR in QHE, ν=3

Unidirectional dragging of ESR for sweep down direction due to DNP

Nuclear Overhauser field $B_N > 0$, $T_N \sim 20$ min

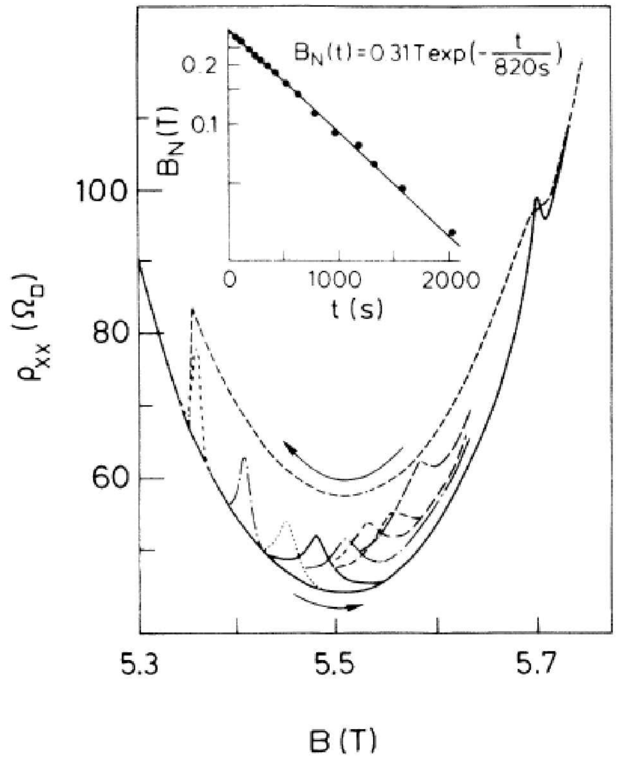
Maximum shift for 100% polarization can reach ~5T for electrons in GaAs

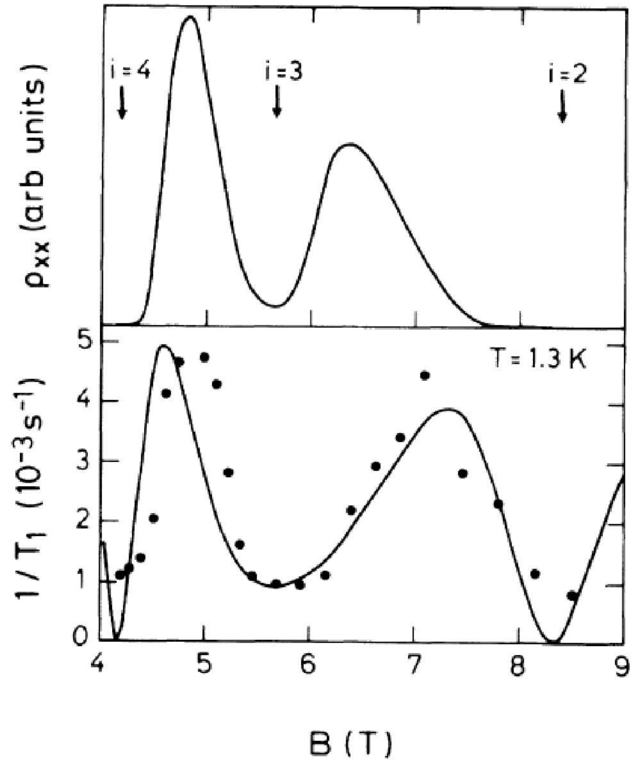
DNP in 2DEG: historical excursion

NRC·CNRC

A. Berg, M. Dobers, R. R. Gerhardts, and K. v. Klitzing, PRL 1990

VOLUME 64, NUMBER 21 PHYSICAL REVIEW LETTERS 21 MAY 1990





Is it possible to observe similar nuclei physics in 2DHG structures?

Motivation

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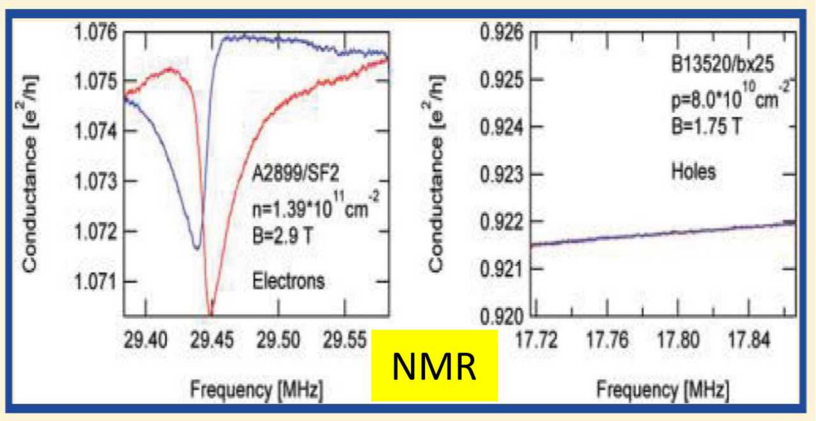
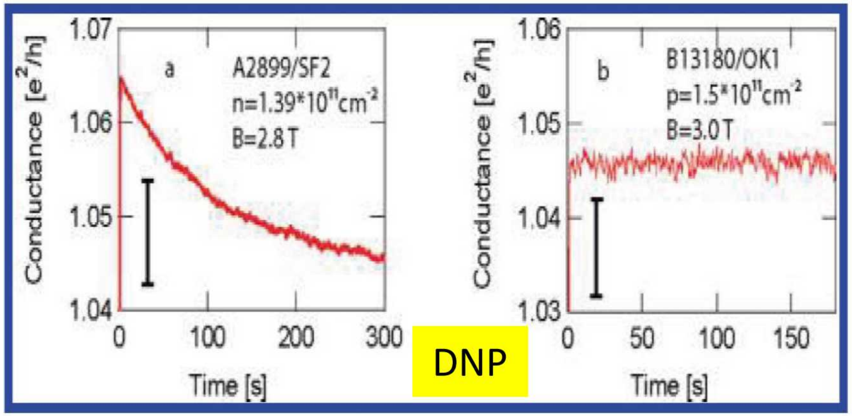
- Reduced hyperfine interaction of holes with nuclei
  J.Fischer, W. A. Coish, D. V. Bulaev, and D. Loss, PRB **78** 155329 (2008)
  R.Fallahi, S. T. Yılmaz, and A. Imamoğlu, PRL **105**, 257402 (2010)

- Earlier attempt to measure hyperfine (HF) effects in GaAs electron- and hole-QPC structures
  Keane et al. Nano. Lett. 11, 3147 (2011)

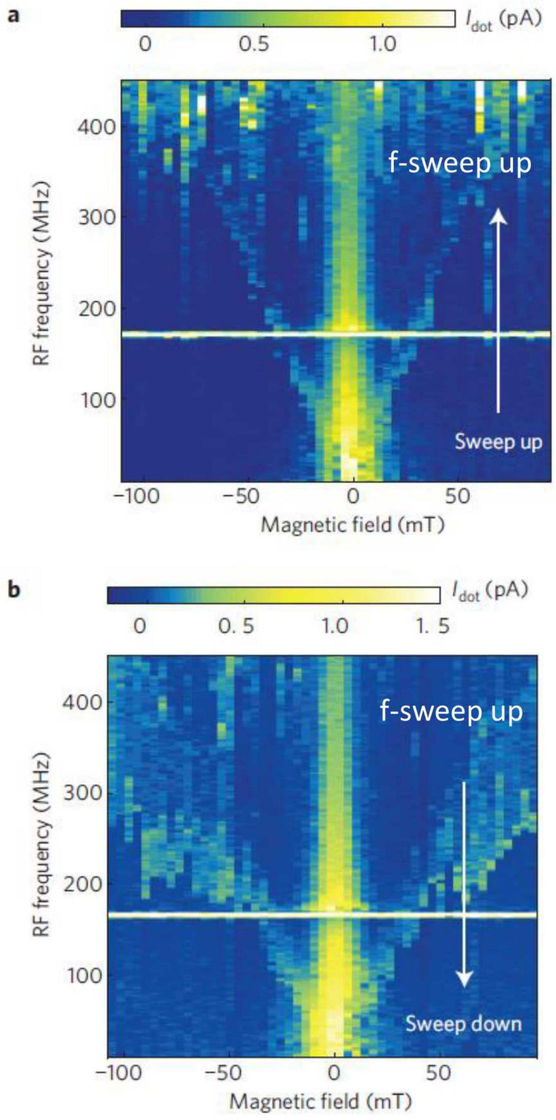




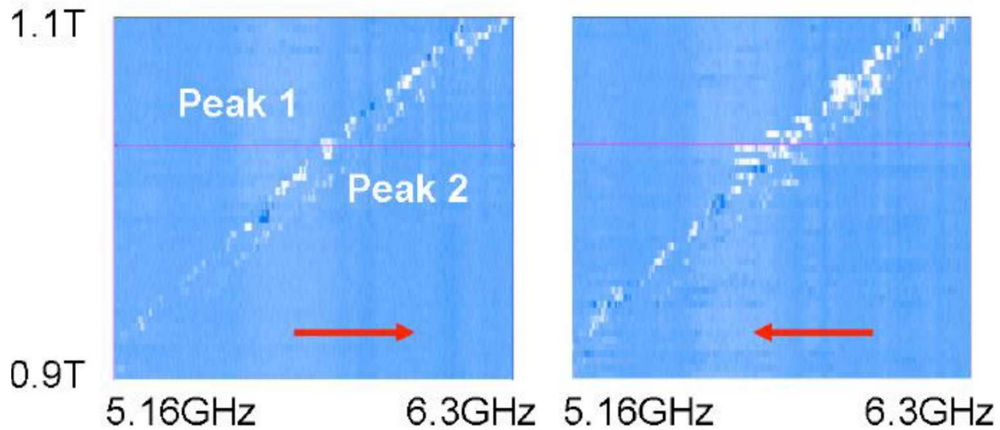
- In this talk: demonstrate direct influence of HF effects in EDSR dragging experiments via pumped Overhauser field

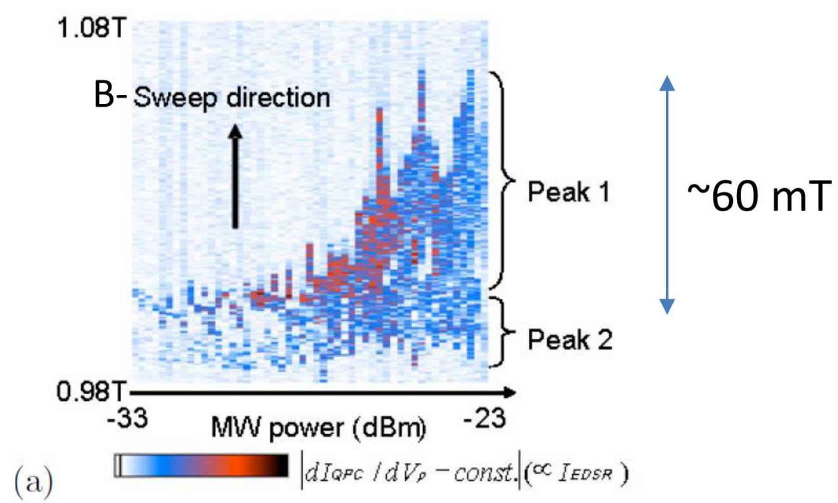
Examples EDSR-enabled DNP in DQDs with electrons

Vink, et al., Nat. Phys. *v. 5, p. 764 (2009)*



Obata, et al., *J. Phys. v.* ***193****, p. 012046 (2009)*



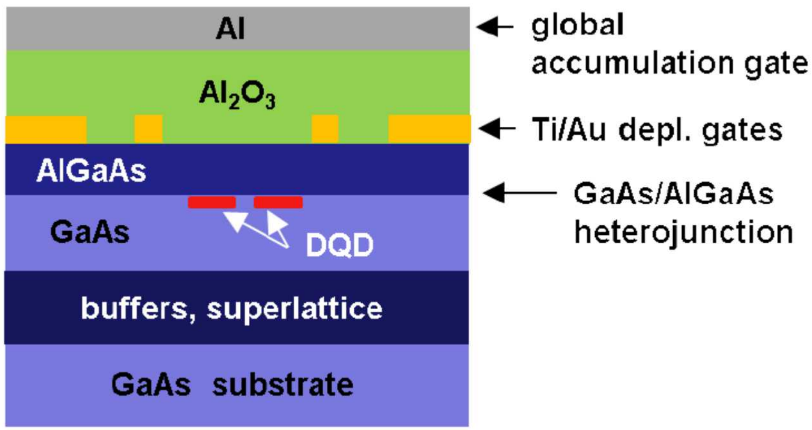


<u>Note:</u> Unidirectional DNP (strong pumping in one sweep direction)

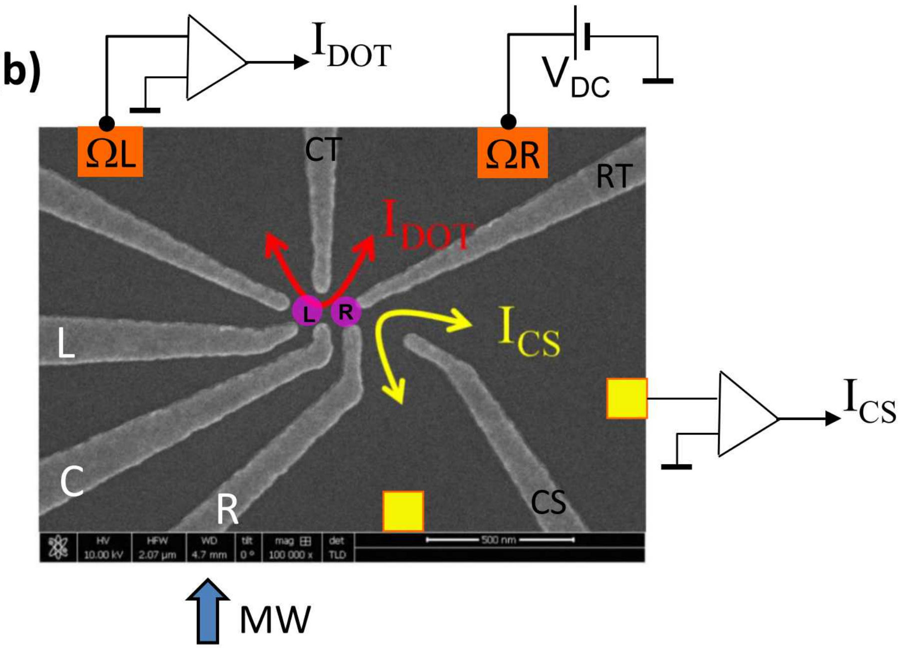
Details of the hole Double Quantum Dot (DQD)

L. A. Tracy, et al. *"Few-hole double quantum dot in an undoped GaAs/AlGaAs heterostructure," APL, v. 104, 123101 (2014).*

(a)



(b)



(a) Cross section, and (b) SEM image of the DQD device

Hole EDSR in large coupling regime: tunable g*

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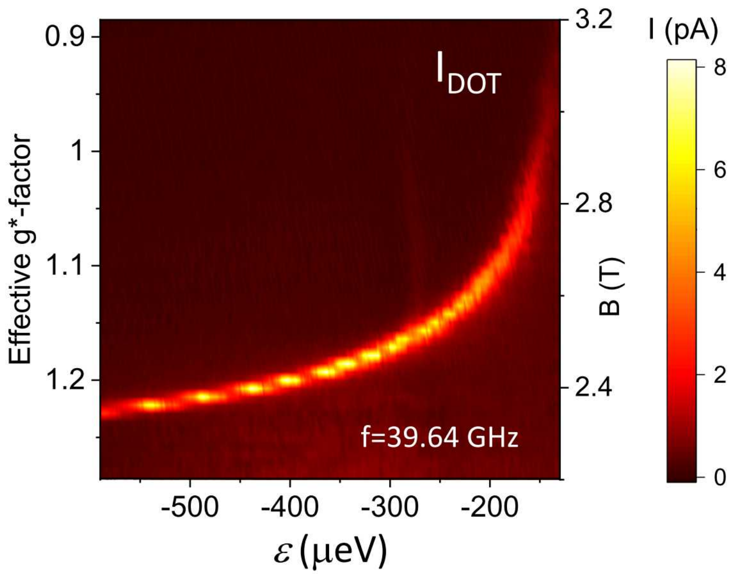
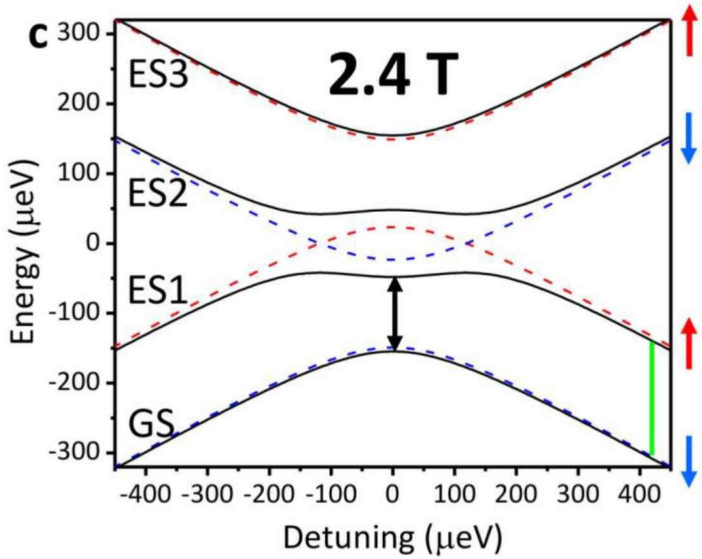
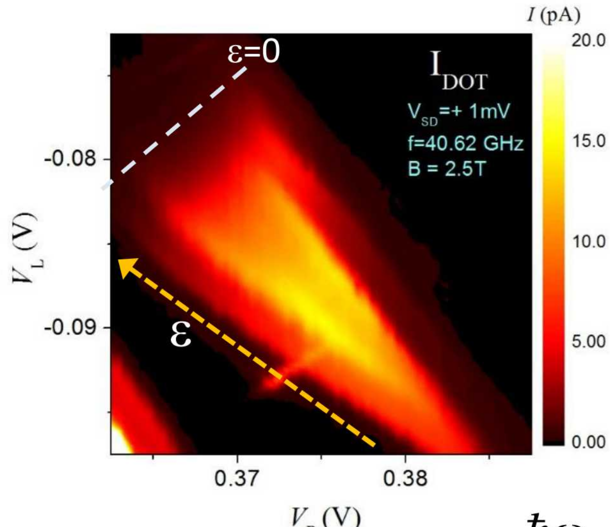
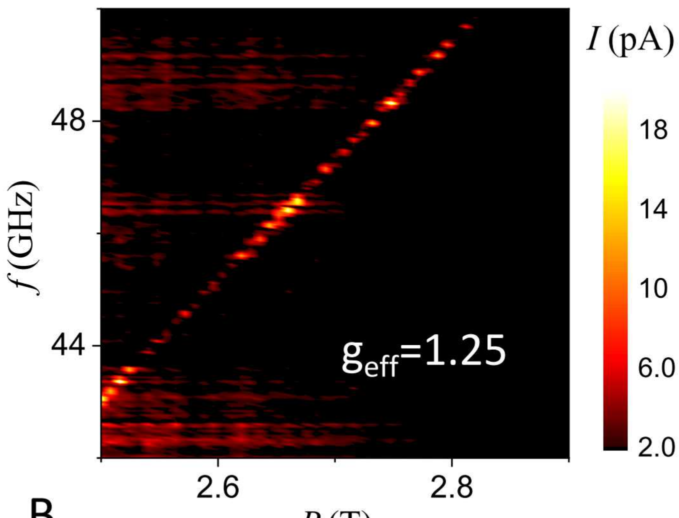
S.S. et al., Nat. Comms. Phys. (2019)

Large interdot coupling $\mathbf{t_N} \approx$ **60 μeV**





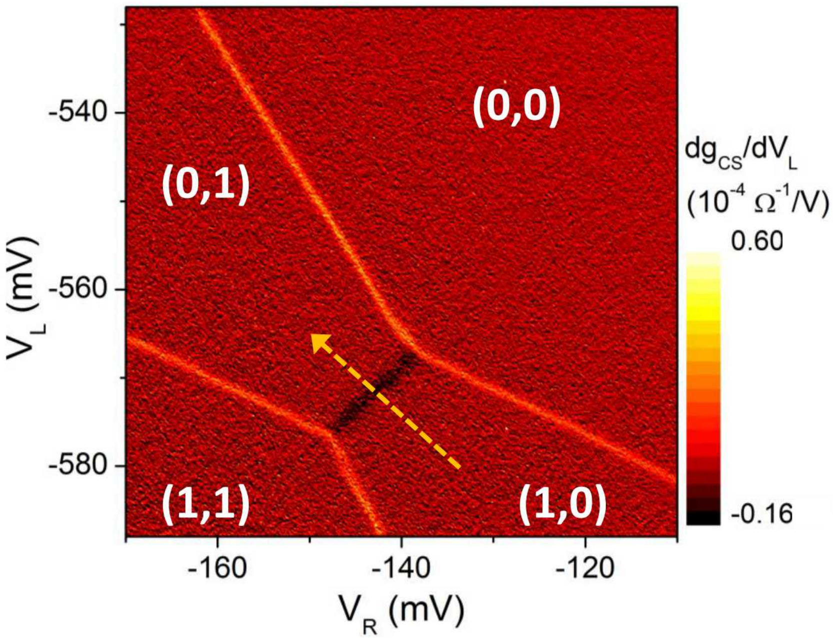


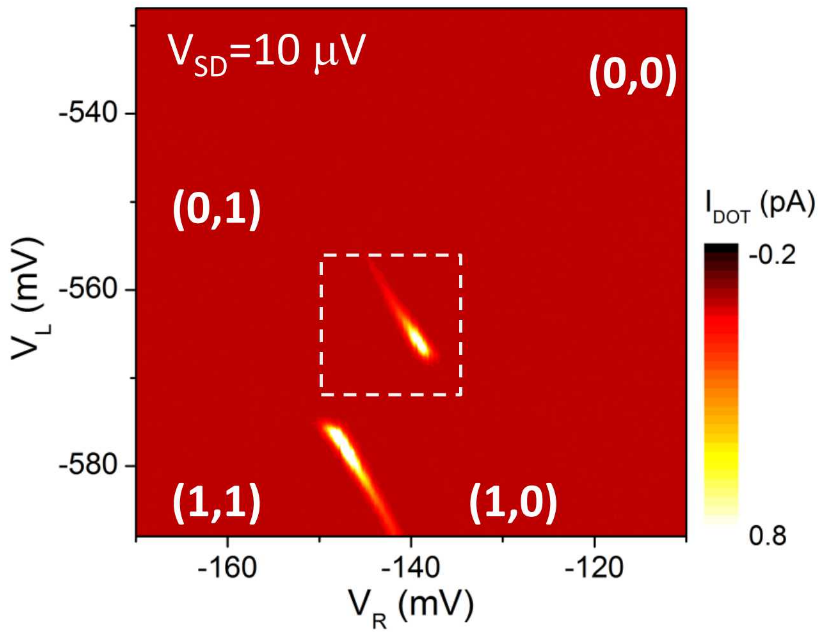


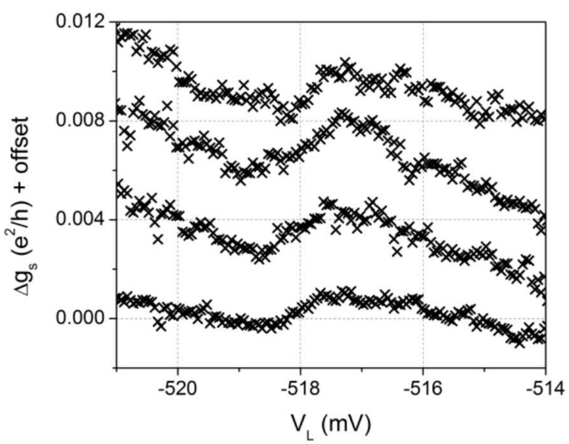
$$\hbar\omega_{MW}=g^*(\varepsilon)\ \mu_B\ B$$

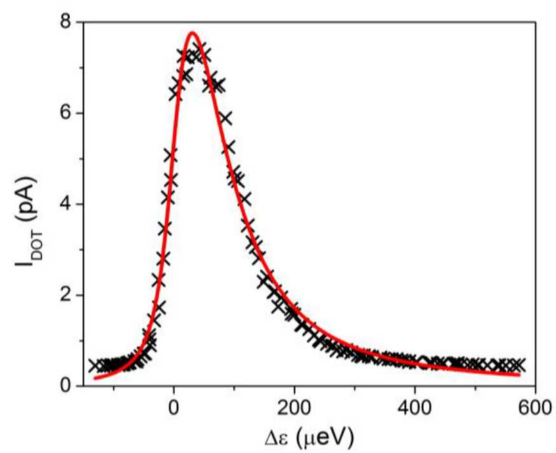
Small coupling, asymmetric regime: Charge stability and transport diagrams

Small interdot coupling $\mathbf{t_N} \approx \mathbf{7\ \mu eV}$







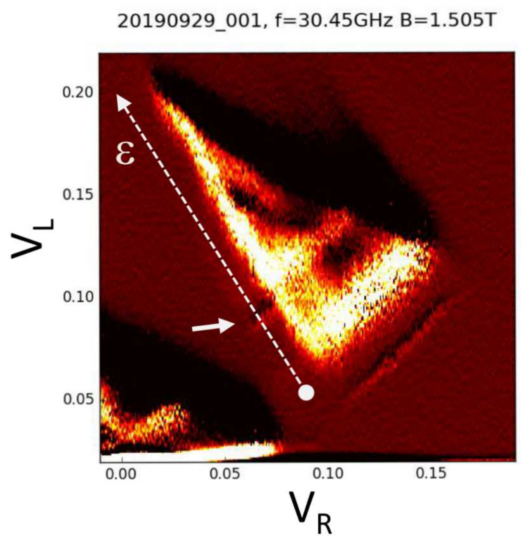


Lead couplings:

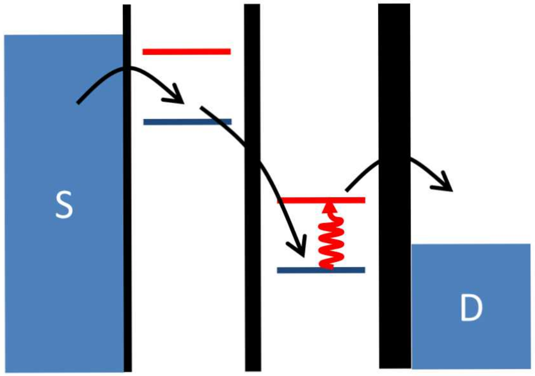
Γ_L = 6.9GHz

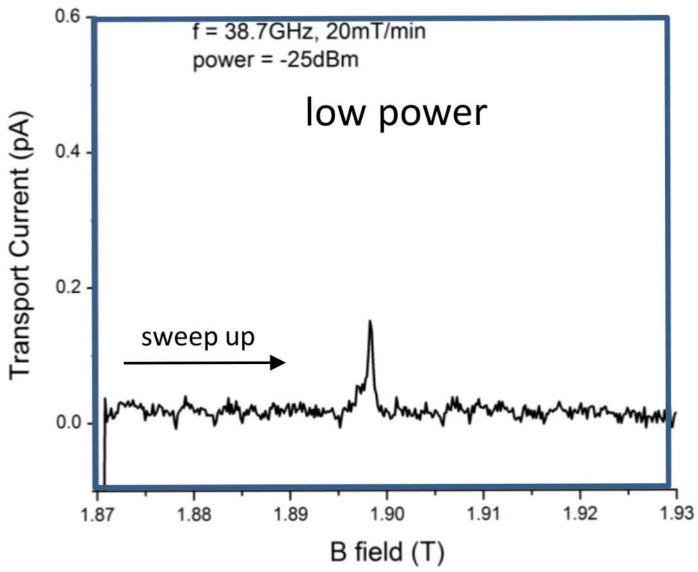
Γ_R = 122MHz

EDSR measurements: hyperfine interactions cannot be ignored

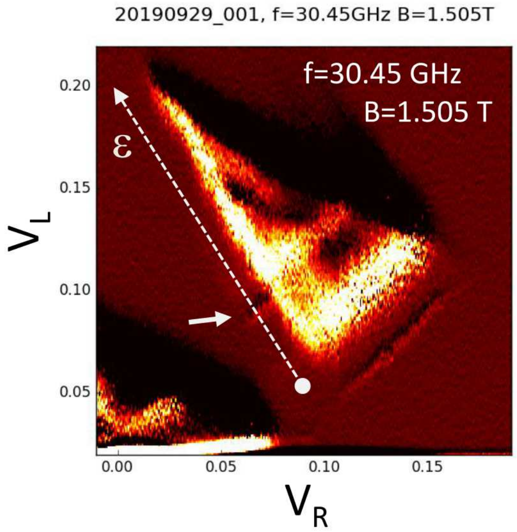


Weak interdot coupling $\mathbf{t_N = 6.8\ \mu eV}$

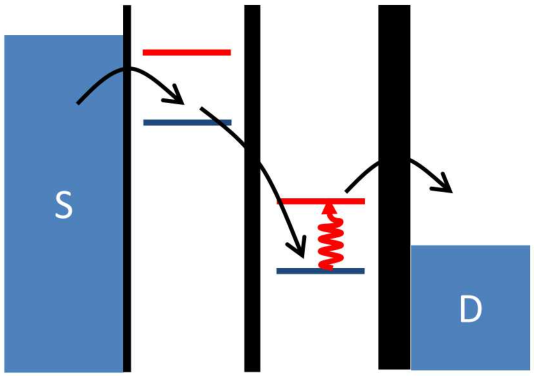


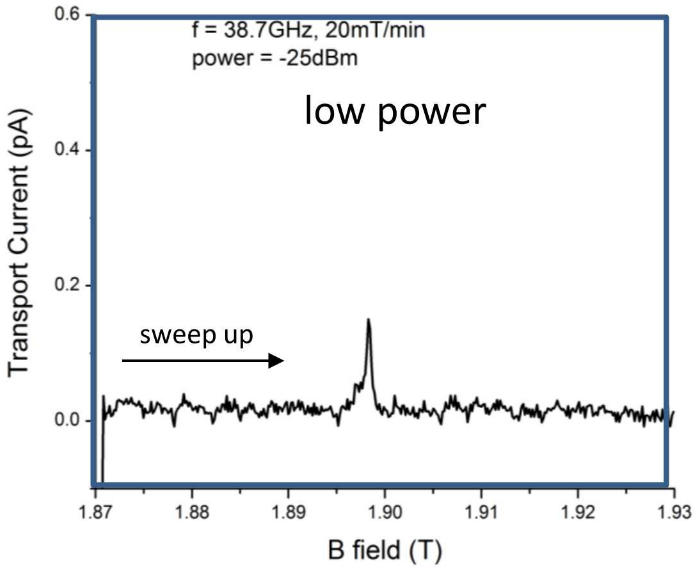


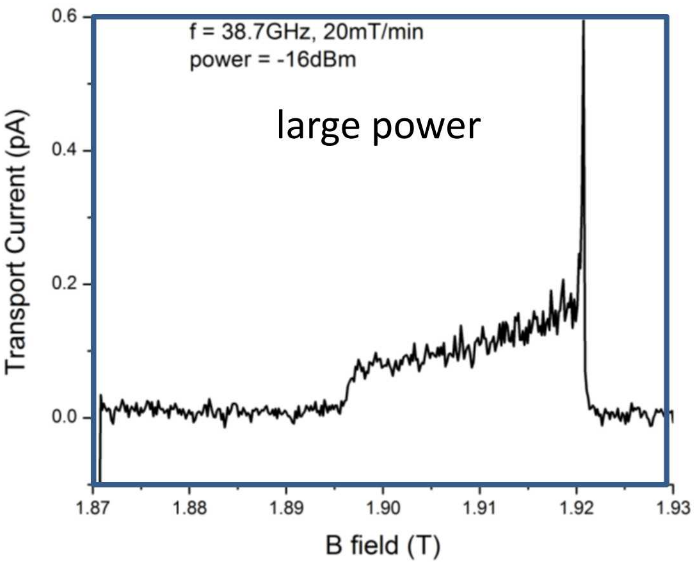
EDSR measurements: hyperfine interactions cannot be ignored



Weak interdot coupling $\mathbf{t_N = 6.8\ \mu eV}$







EDSR measurements: hyperfine interactions cannot be ignored

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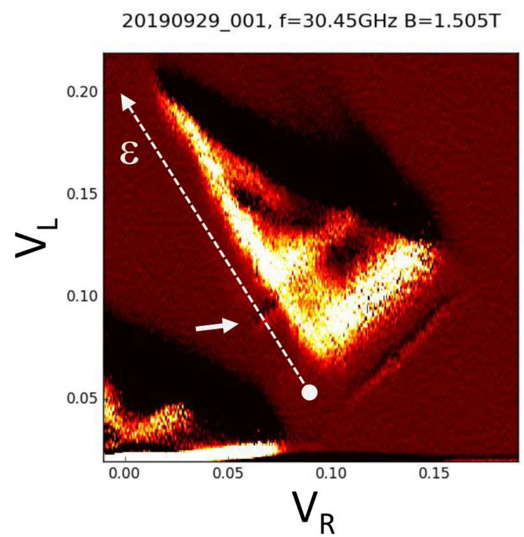
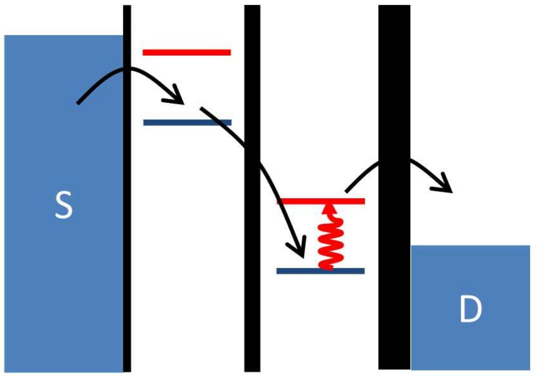
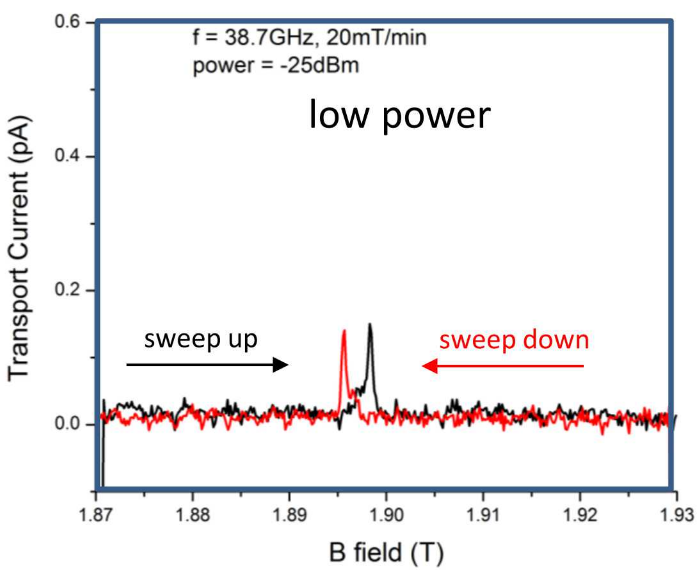
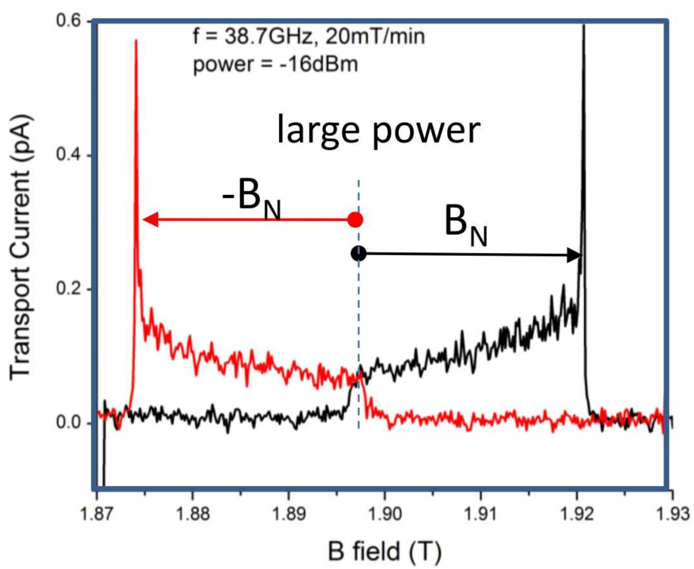


Weak interdot coupling $\mathbf{t_N}$ **= 6.8 μeV**







<u>Note:</u> DNP effect in p-DQD is **bidirectional**

Overhauser field locks dynamically when sweeping is stopped

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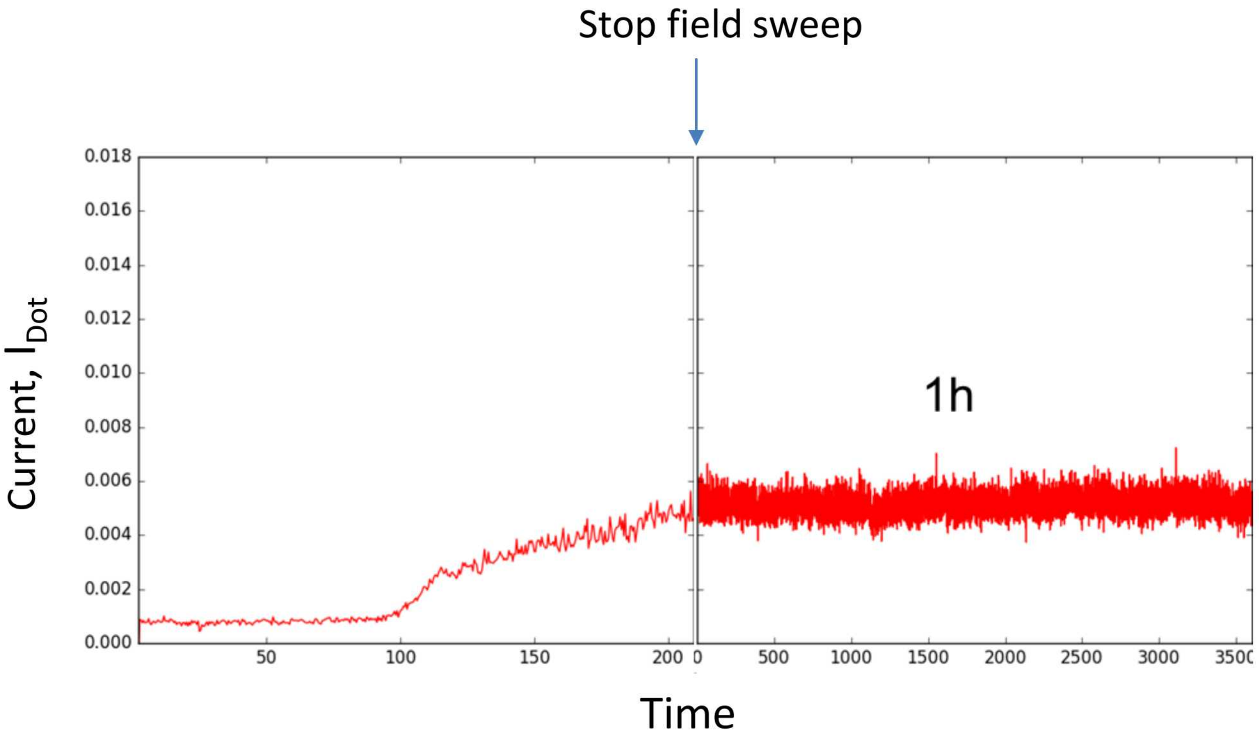

Observed Overhauser field B_N locked over 30 hours

Nuclear spin pumping effects with long duration,

e.g. Ono, Tarucha, PRL **92**, 256803(2004)
Hennel et al. PRL **116**, 136804 (2016)

DNP pump-probe measurement of nuclear relaxation time

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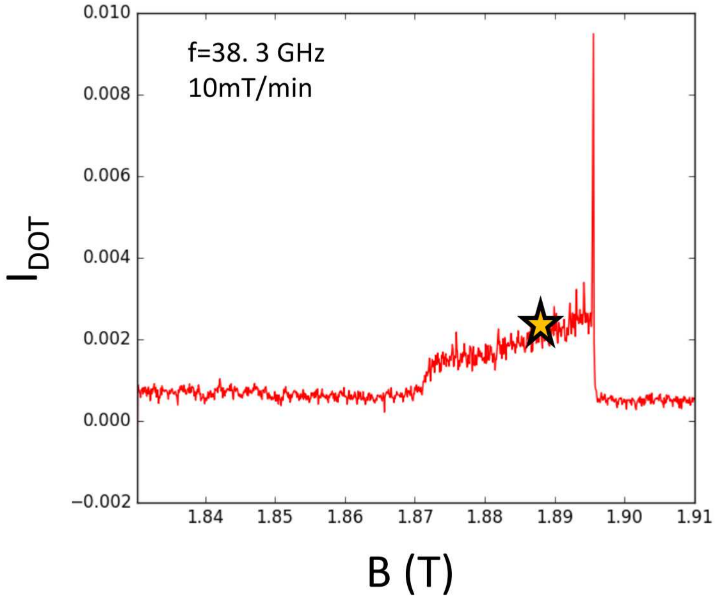
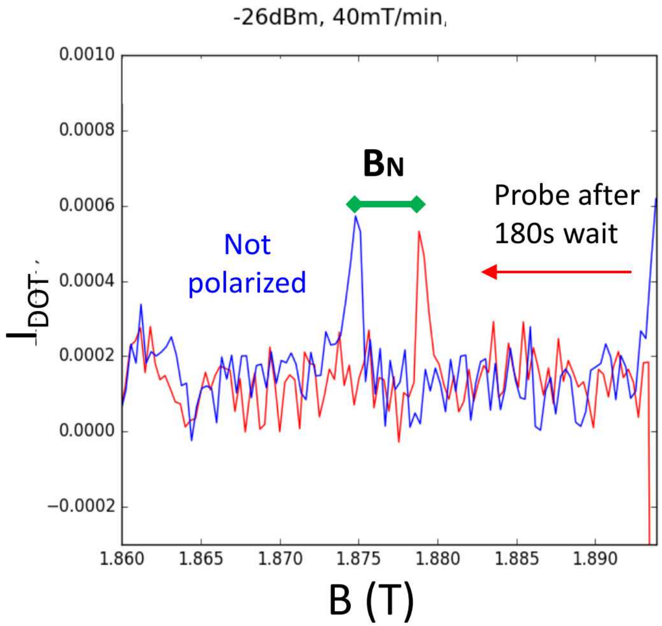




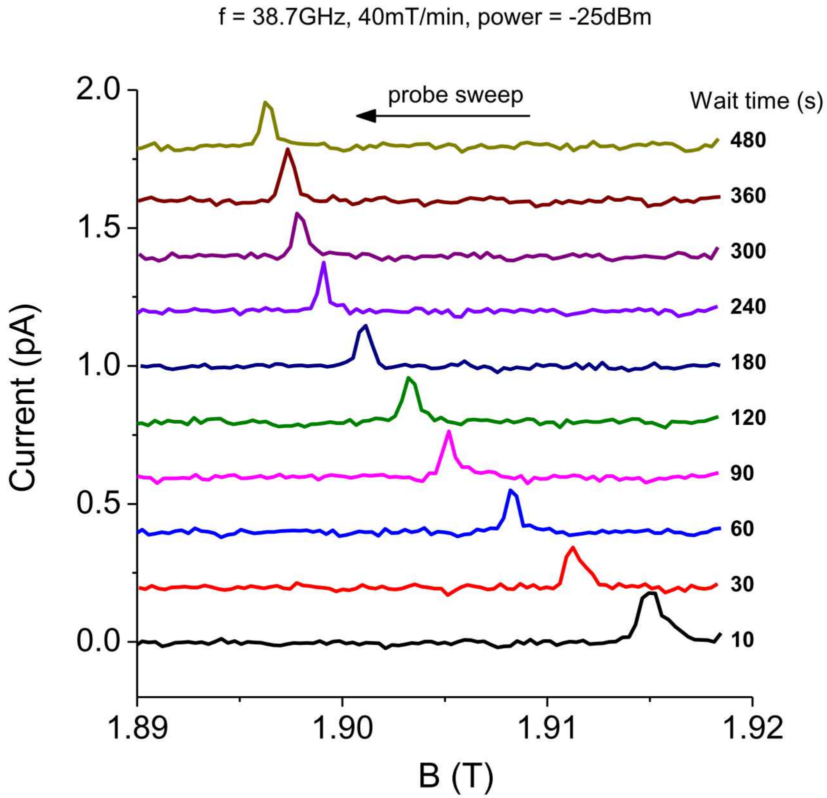
Extract B_N for many wait times

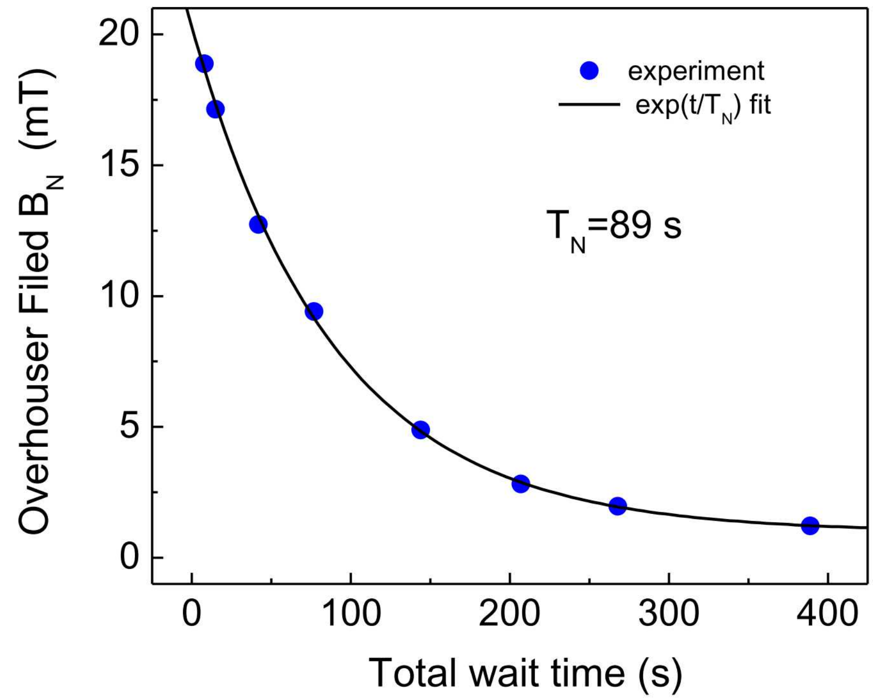
‘pump’ → Slow sweep up

wait Δt with no microwaves

‘probe’ ← Fast sweep down, small power

DNP pump-probe measurement of nuclear relaxation time





$$B_N(t) = B_0 e^{-t/T_N}$$

Overhauser field dependencies on power and sweep rate

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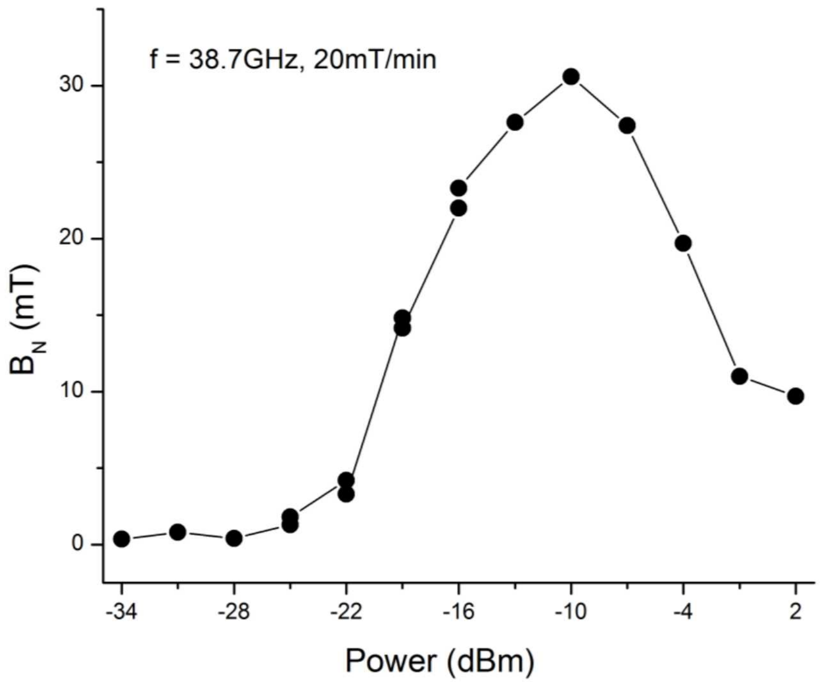
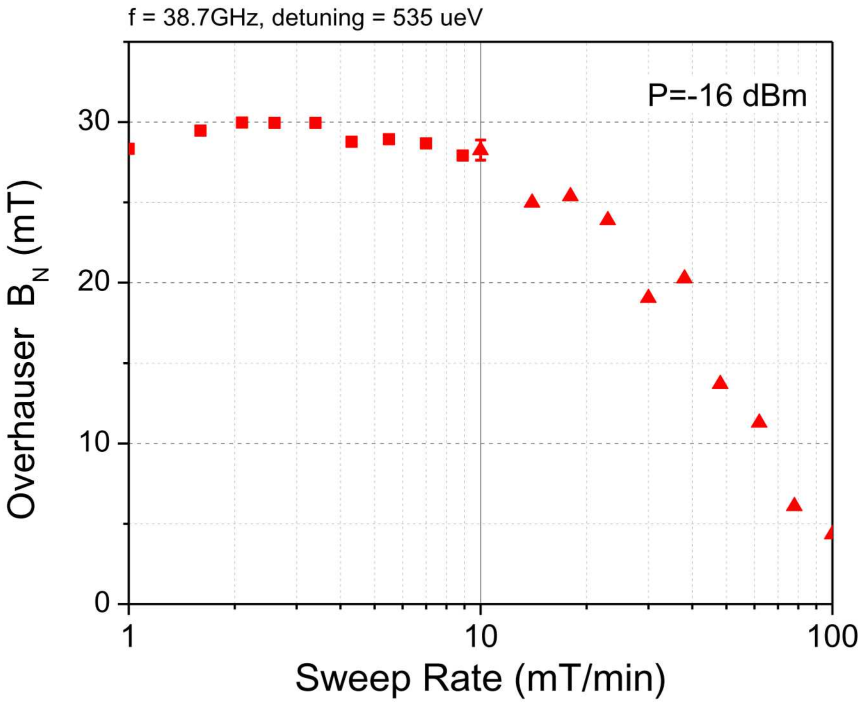
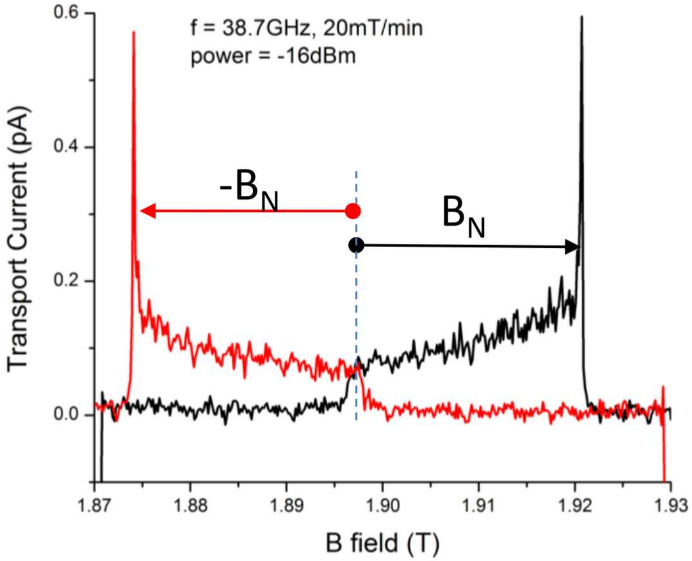
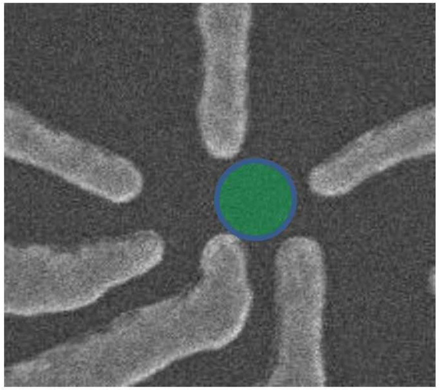
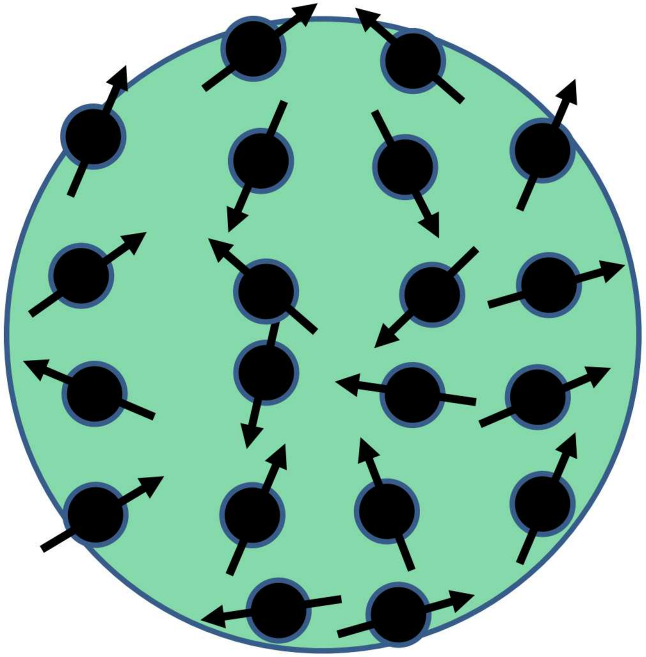




Theoretical model (under construction by M. Korkusinski)







$$H_{hf} = A_{||}S_Z I_Z + \frac{A_\perp}{2}(S_+I_+ + S_-I_-)$$

isotope (i)	(electrons) A^i (μeV)	(holes) $A^i_{\parallel}$ (μeV)	$A^i_{\perp}$ (μeV)
^{69}Ga in GaAs	74	1.4	0.35
^{71}Ga in GaAs	94	1.7	0.45
^{75}As in GaAs	78	11	0.02

Philippopoulos, et al. Phys. Rev. B 101, 115302 (2020)

Dragging of hole-EDSR resonance: what's going on?

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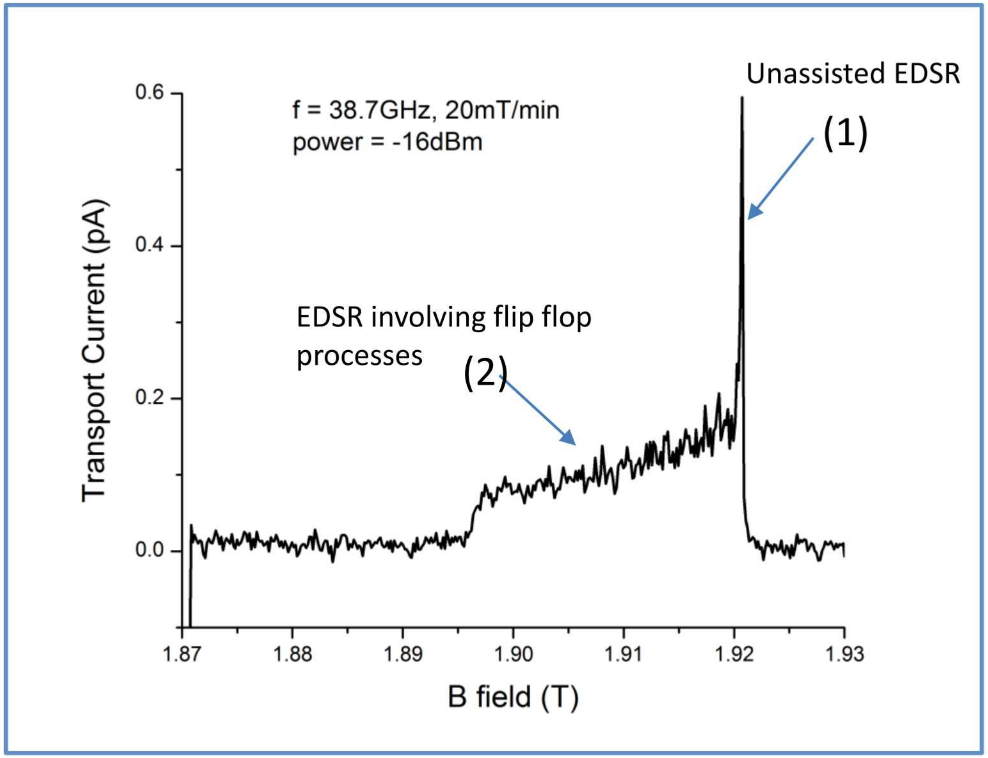
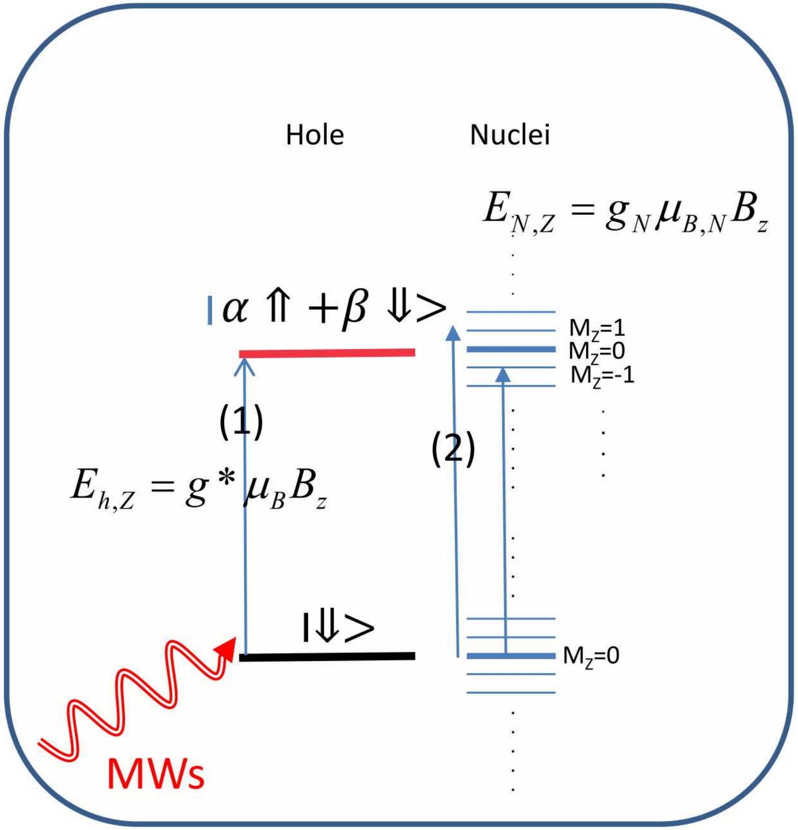
Theoretical model (under construction by M. Korkusinski)





$H_{hf} = A_{II}S_ZI_Z + A_{\perp}(S_+I_+ + S_-I_-)$

$B_{tot}=B_{ext}+B_N$

$M_{Z=0}$ = ….↑↓↑↓. . .

…. ↑↑↓↓…

$B_N \sim M$

Maximum Overhauser field for heavy holes in GaAs

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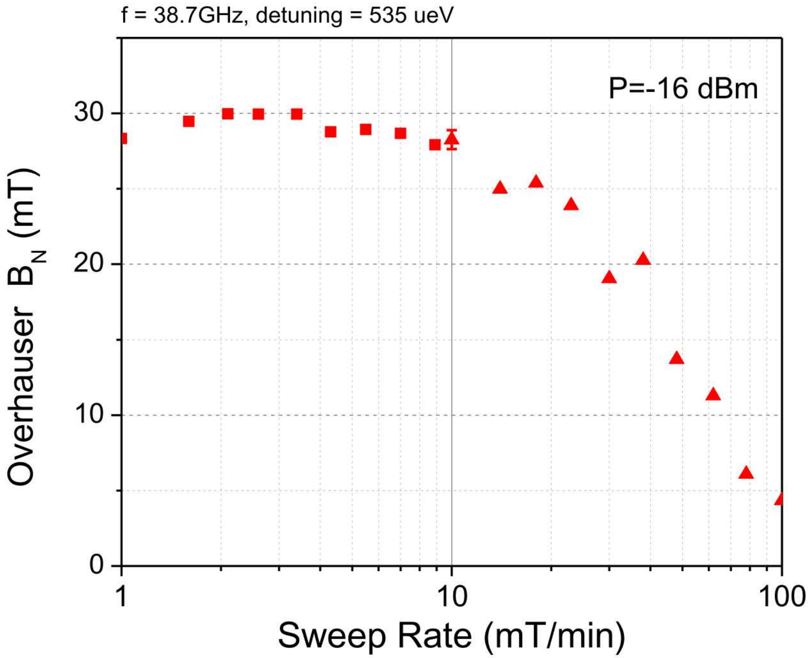


$$\langle H_{hf}\rangle_I = \vec{S}\sum_k A_k \langle \vec{I_k}\rangle_I$$

$$B_N(i) = \frac{\nu_i A_{\parallel}^i \langle I(i)\rangle}{g^* \mu_B}$$ Overhauser field

ν_i – abundance of i^{th} isotope
g^* - carrier effective g-factor
A - hyperfine coupling strength
$\langle I(i)\rangle$ - expectation value of nuclei state

ν, Abundance	isotope (i)	(electrons) A^i (μeV)	(holes) $A^i_{\parallel}$ (μeV)	$A^i_{\perp}$ (μeV)
0.3	^{69}Ga in GaAs	74	1.4	0.35
0.2	^{71}Ga in GaAs	94	1.7	0.45
0.5	^{75}As in GaAs	78	11	0.02

Maximum B_N for $\langle I\rangle = 1$
^{69}Ga B_{Max}~7.8 mT
^{71}Ga B_{Max}~6.3mT
^{75}As B_{Max}~ 102 mT
Total B_{Max}~ 116 mT

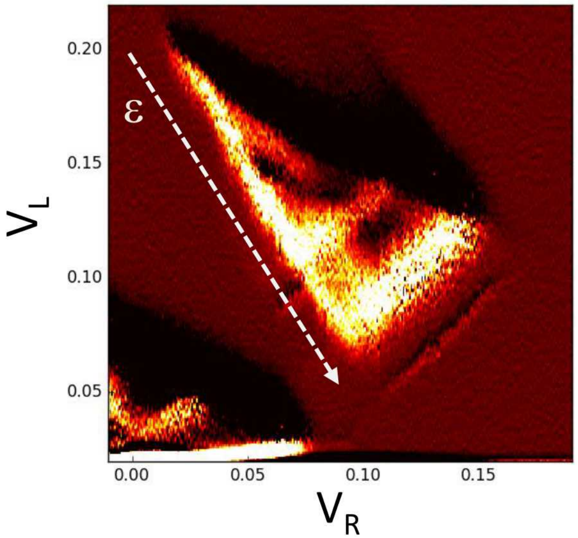
B_N=30 mT corresponds to ~25% polarization

Philippopoulos, et al. Phys. Rev. B 101, 115302 (2020)

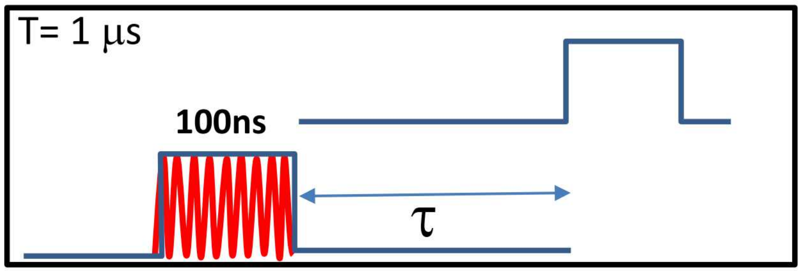
Note: for electrons B_{Max}=5.2 T

Double-pulse measurements demonstrating ^{75}As nuclei contribution

Similar to: Nichol, et al., Nat. Comm. (2015)

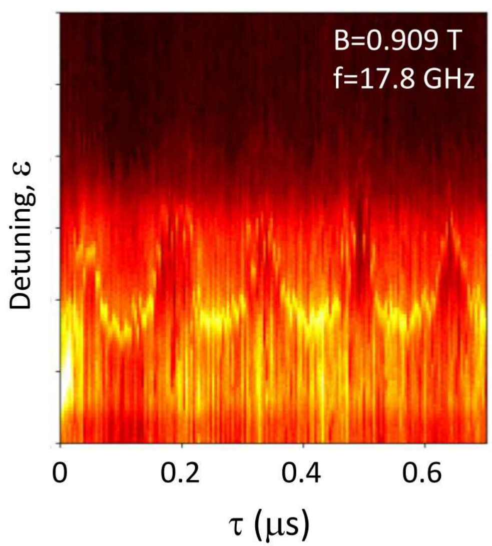


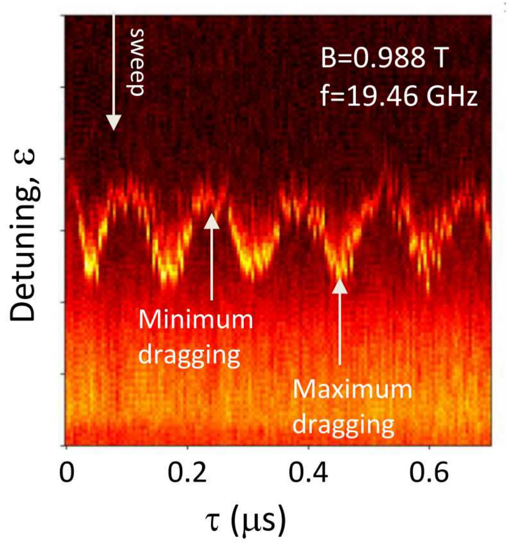
Initialize - Manipulate - Wait - Read

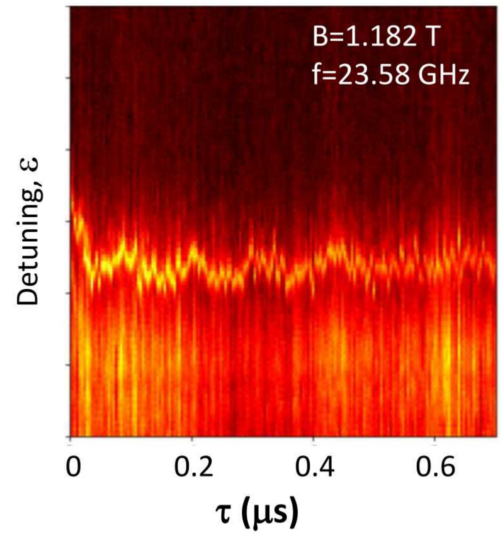


$\hbar\omega_{MW}=g^*(\varepsilon)\ \mu_B\ B$

S.S., et al., Comms. Phys. (2019)

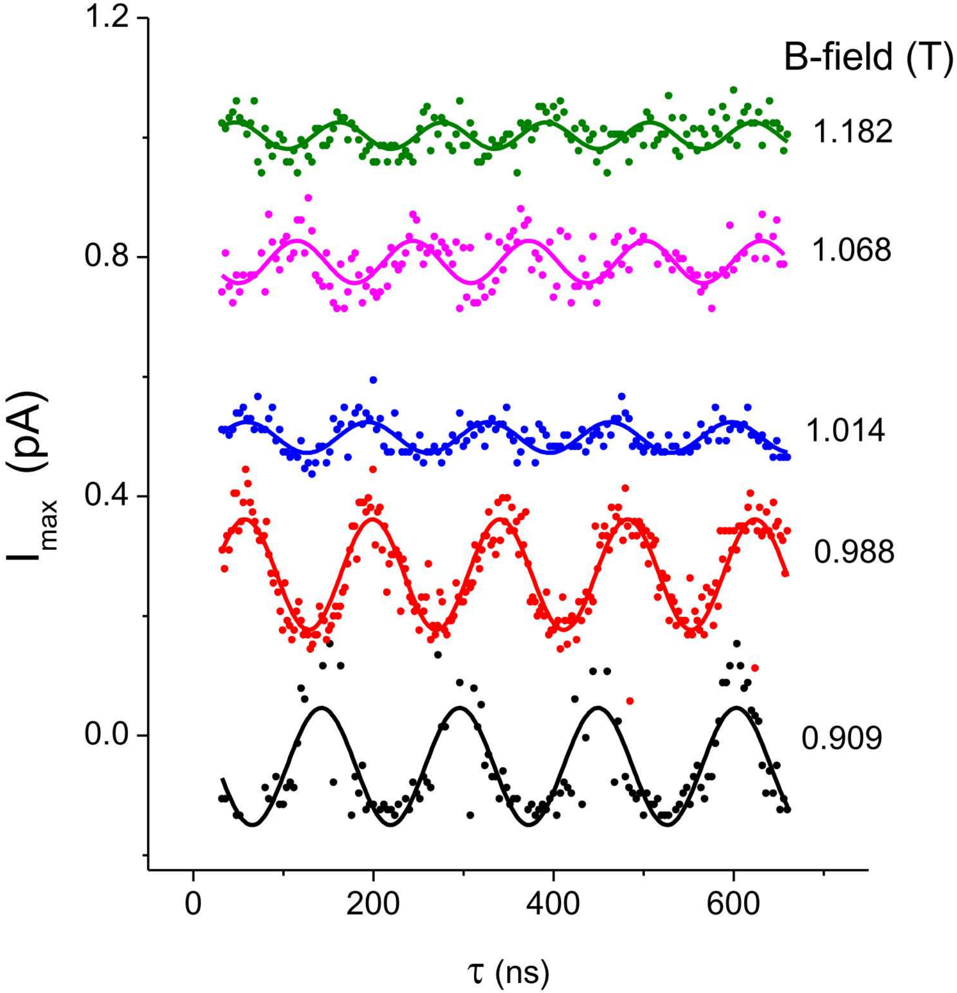


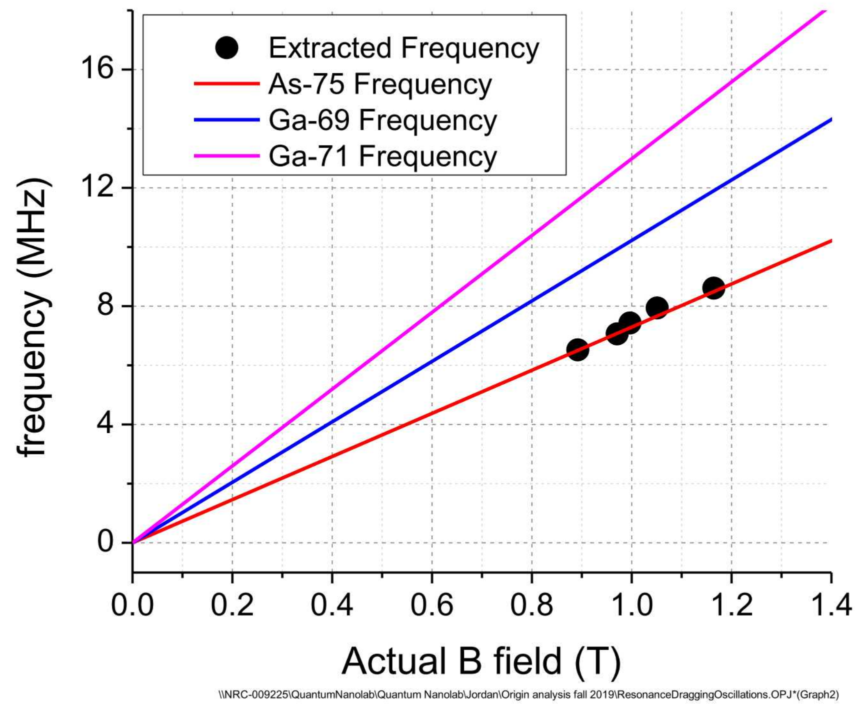




Period of oscillations ~100ns, *and is B-field dependent*

Analysis of the EDSR dragging effect oscillations





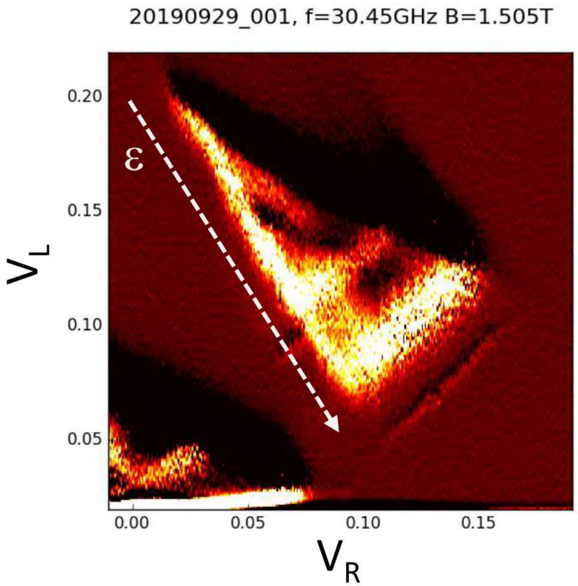
^{75}As NMR Larmor frequency
f=7.290 MHz/T (red line)

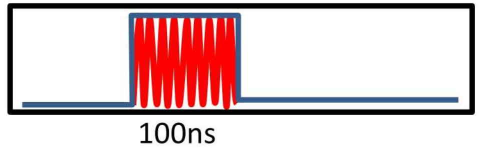
Summary

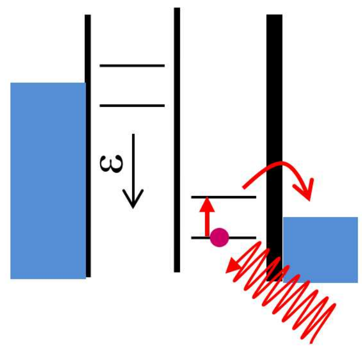
- ***Hyperfine heavy-hole effects demonstrated directly using Overhauser effect in EDSR-dragging experiments***
- ***The heavy hole Overhauser effect is bi-directional and very symmetric for both +/- directions***
- ***Relaxation time ~90s of the Overhauser field measured in gated hole quantum dot using common pump-probe technique***
- ***Up to 25% nuclear polarization achieved***
- ***A double-pulse experiment reveals temporal oscillations in the position of the EDSR peak with frequency corresponding to Larmor precession of ^{75}As nuclei***

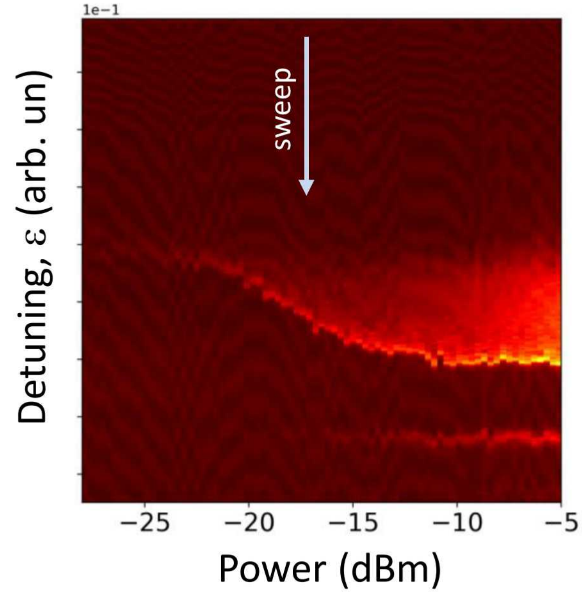
Thank you

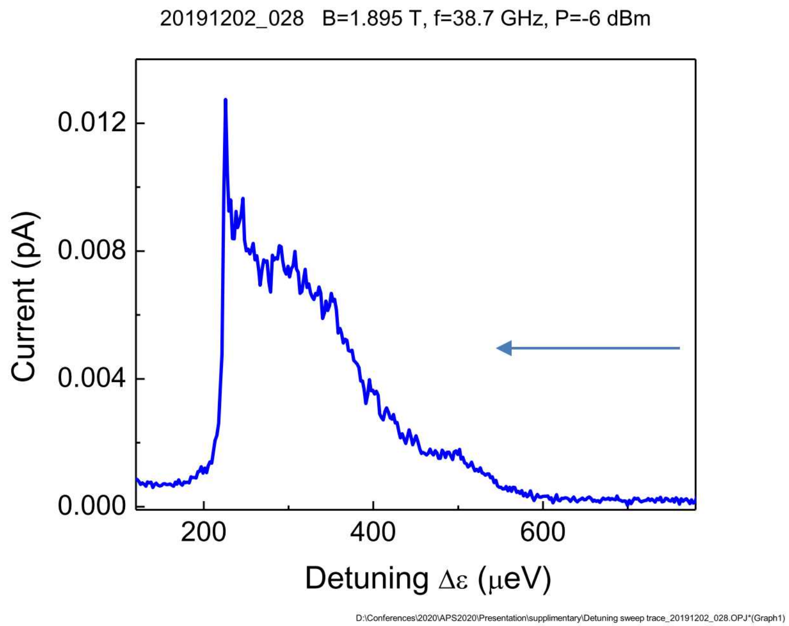
The Dragging Effect Using Detuning Gates







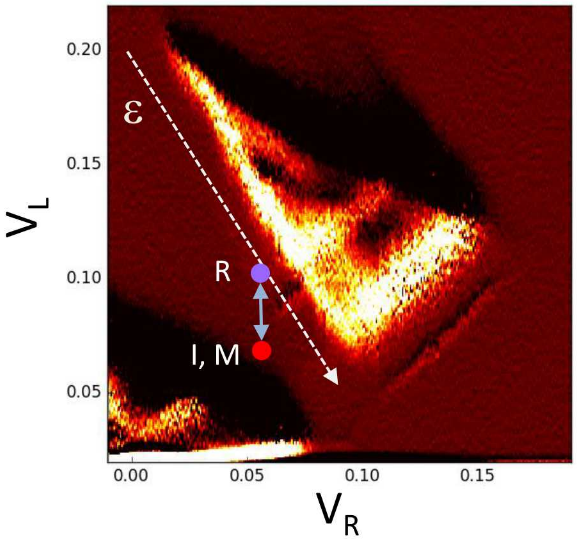




$$\hbar\omega_{MW}=g^*(\varepsilon)\ \mu_B\ B$$

S.S. Comms. Phys. (2019)

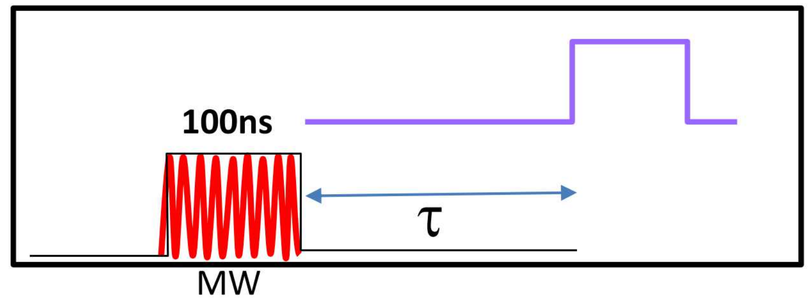
Double pulse technique to demonstrate ^{75}As nuclei contribution



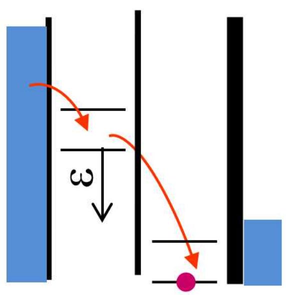
$\hbar\omega_{MW}=g^*(\varepsilon)\ \mu_B\ B$

S.S. Comms. Phys. (2019)

Initialize - Manipulate - Wait - Read

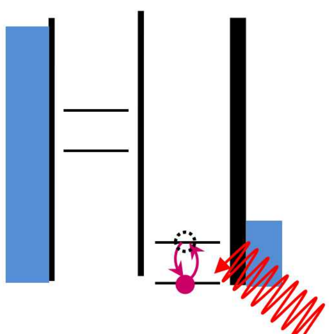


T= 1 μs

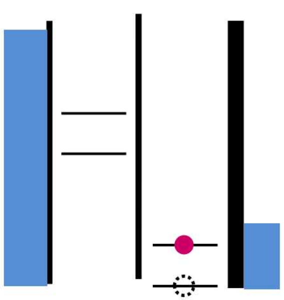


Initialize

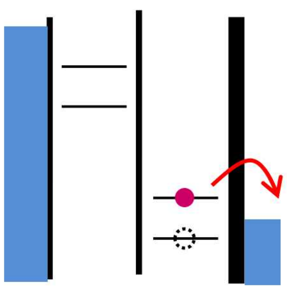
T_1(B=1T) ~ 1 μs



MW burst -
Create mixed
Single hole - N state



Wait τ
evolve



HH Spin read out,
Stop Nuclei evolution

Bogan et al. Comms. Phys. (2019)