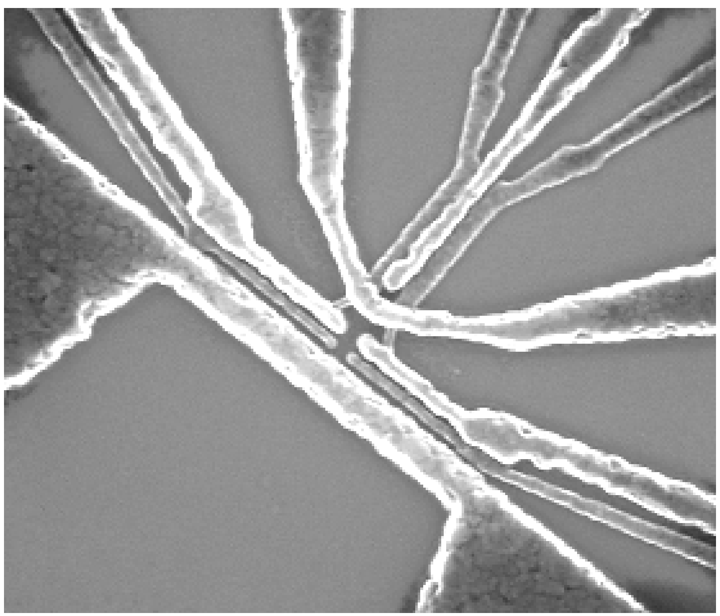
Electron spin relaxation effects of a single phosphorus donor in silicon at low temperatures: tunnel effects summary



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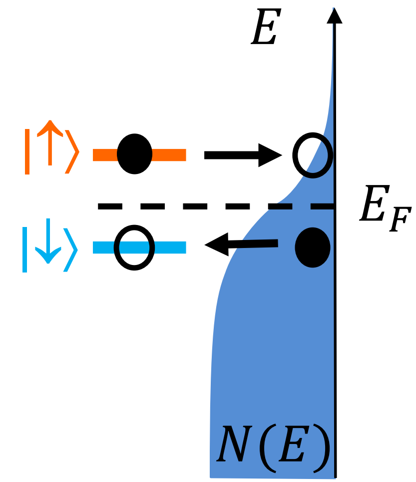
Tunnelling processes between donor and SET

- First order tunnelling (direct tunnelling):

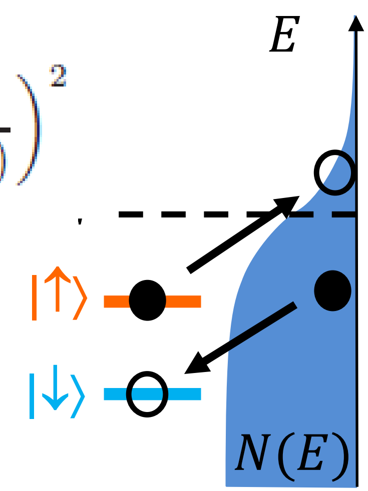
$$\Gamma = \Gamma_0 e^{-\beta V_p}\left[1 - \left(1 + e^{\frac{-e\alpha V_p}{k_B T}}\right)^{-1}\right]$$

$\Rightarrow$ exponentially suppressed with the donor distance to the Fermi level



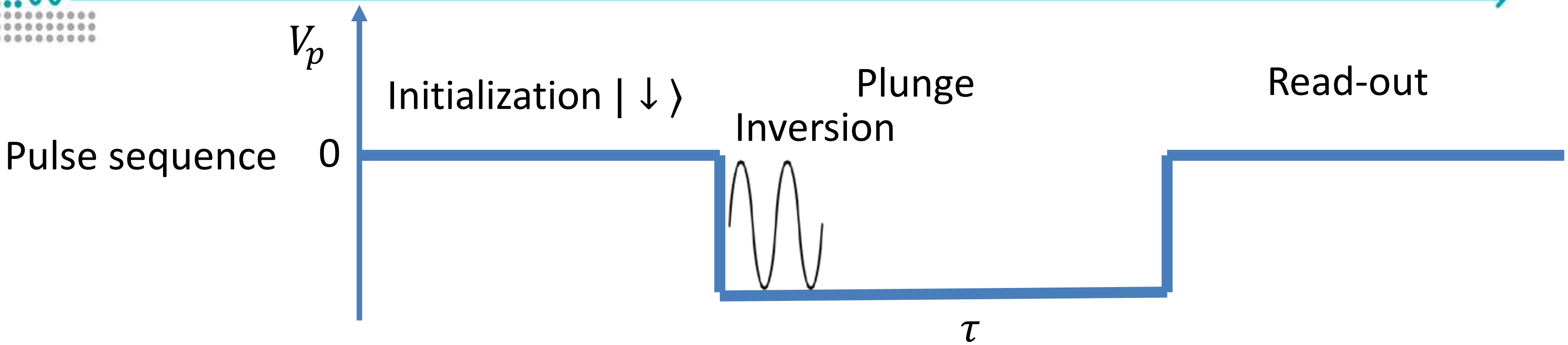
- Second order tunnelling (co-tunnelling):

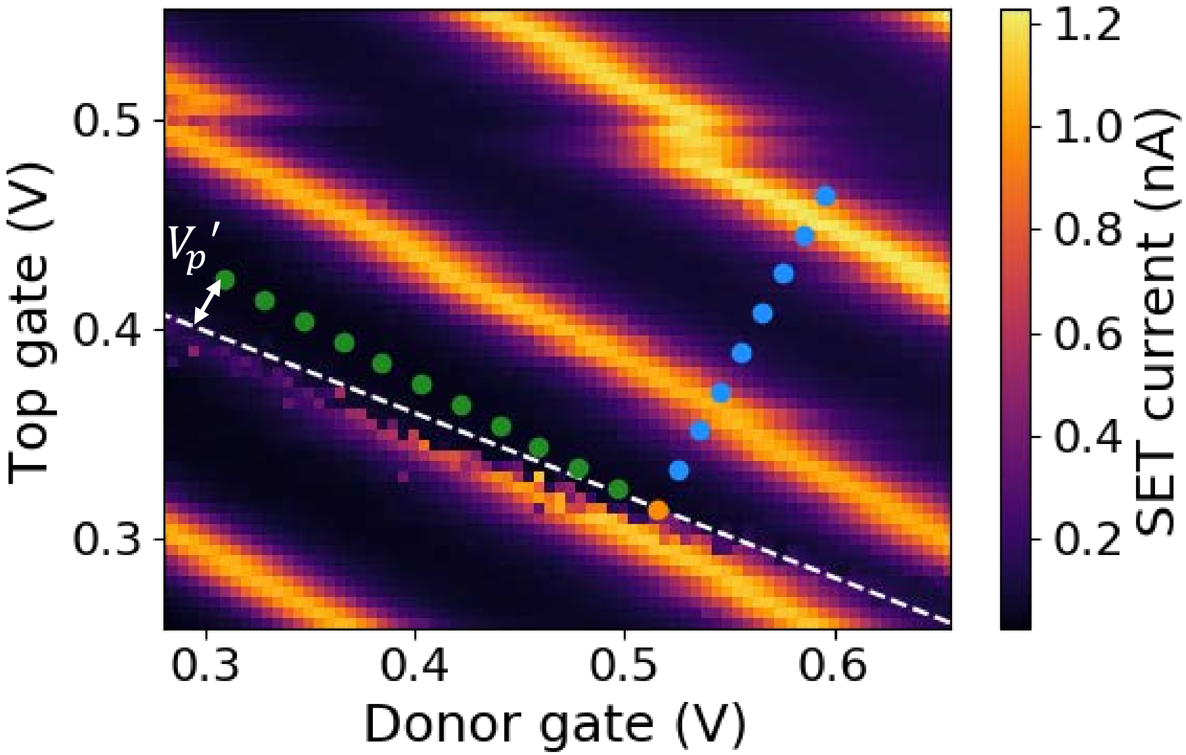
$$\Gamma_{\sigma\to\overline{\sigma}} = \frac{\hbar}{2\pi}\Gamma_\sigma\Gamma_{\overline{\sigma}}\frac{2\sigma E_z}{\exp\left(\frac{2\sigma E_z}{k_B T} - 1\right)}\left(\frac{1}{\mu(2)-\mu_F} + \frac{1}{\mu_F - \mu(1)}\right)^2$$



Otsuka et. al. Scientific Reports 2017,
DOI:10.1038/s41598-017-12217-6

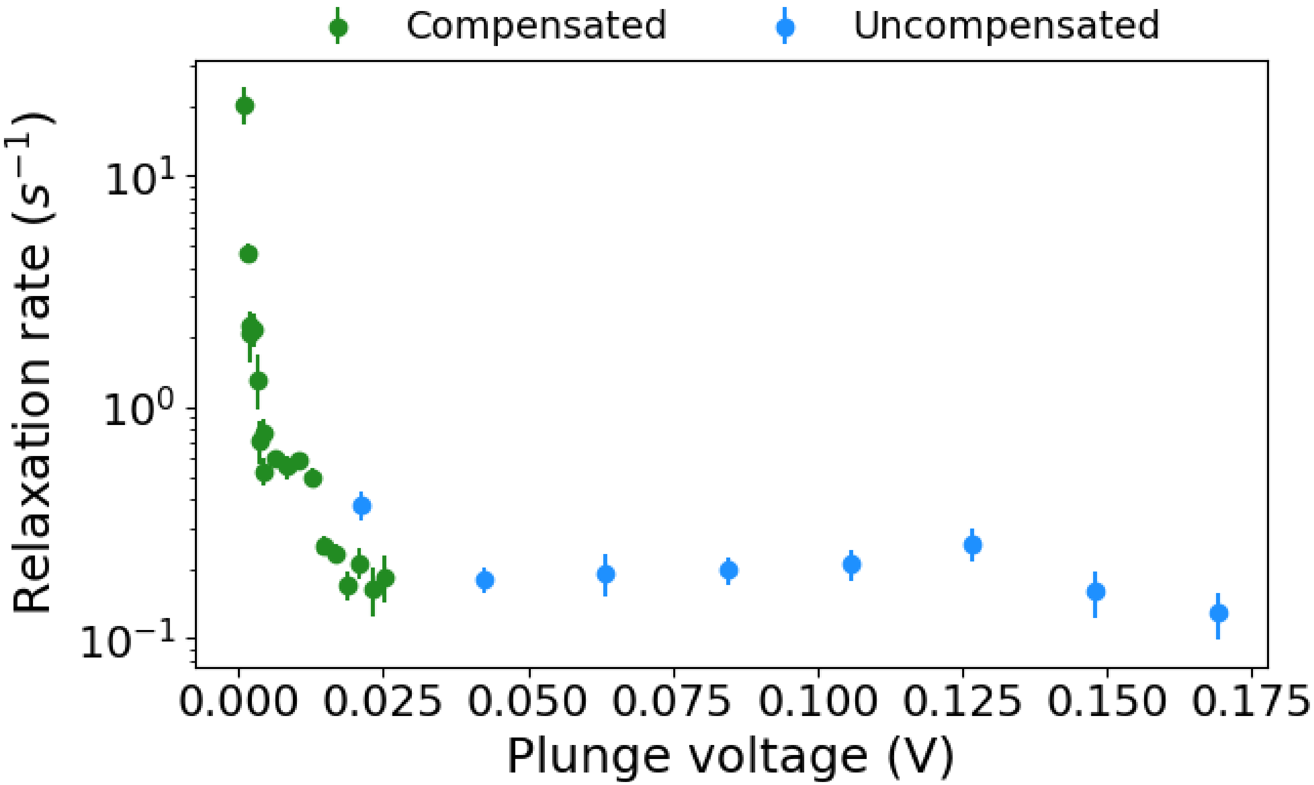
Sequence to measure relaxation times





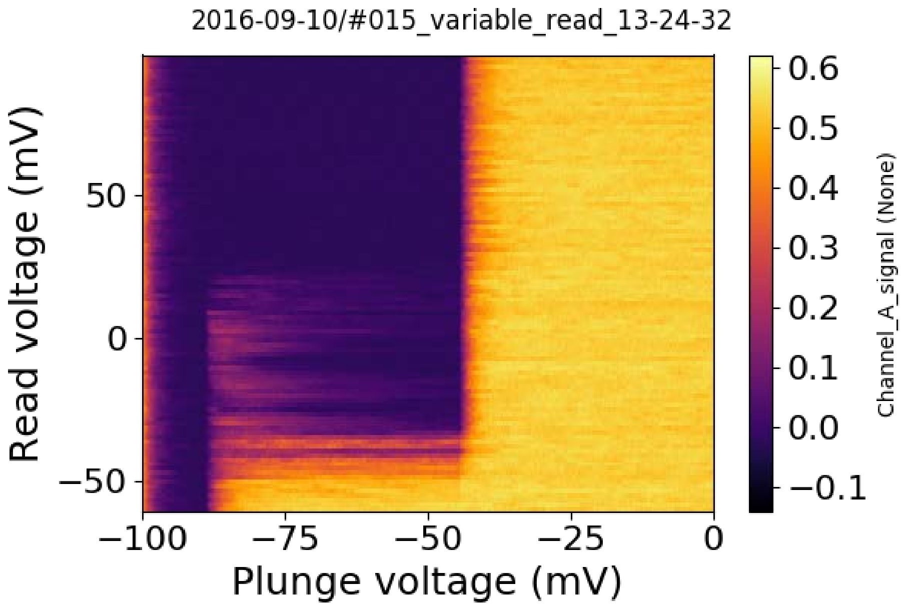
Plunge voltages, Fixed SET level (compensated) in green
Non compensated in blue

Relaxation rate with plunge depth



Plunge voltage here is distance V_p' to the Fermi level

Relate voltages to energy



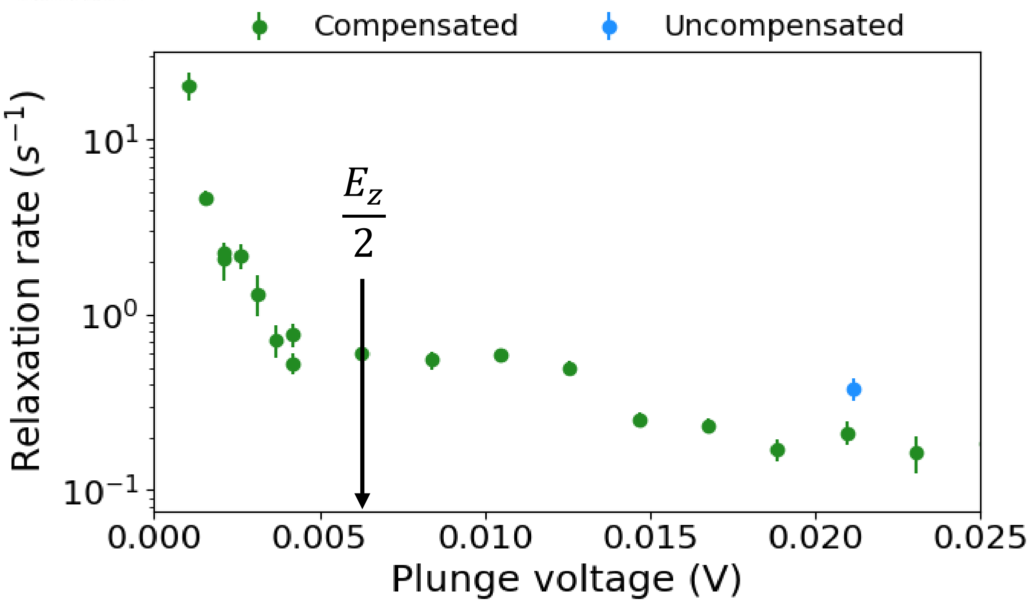
Spin tail measurement gives the lever arm and the Zeeman splitting in volts

$V_p = 70\text{mV}$ @5T

$\Rightarrow$ lever arm $\alpha = \frac{g\mu_B B}{eV_p} = 8.3 \cdot 10^{-3}$

Zeeman splitting @1T: 14mV

Zoomed in



Fitting:

Direct is $\Gamma = \Gamma_0 e^{-\beta V_p}[1 - \left(1 + e^{\frac{-e\alpha V_p}{k_B T}}\right)^{-1}]$

Results:

$\beta\ = 0$

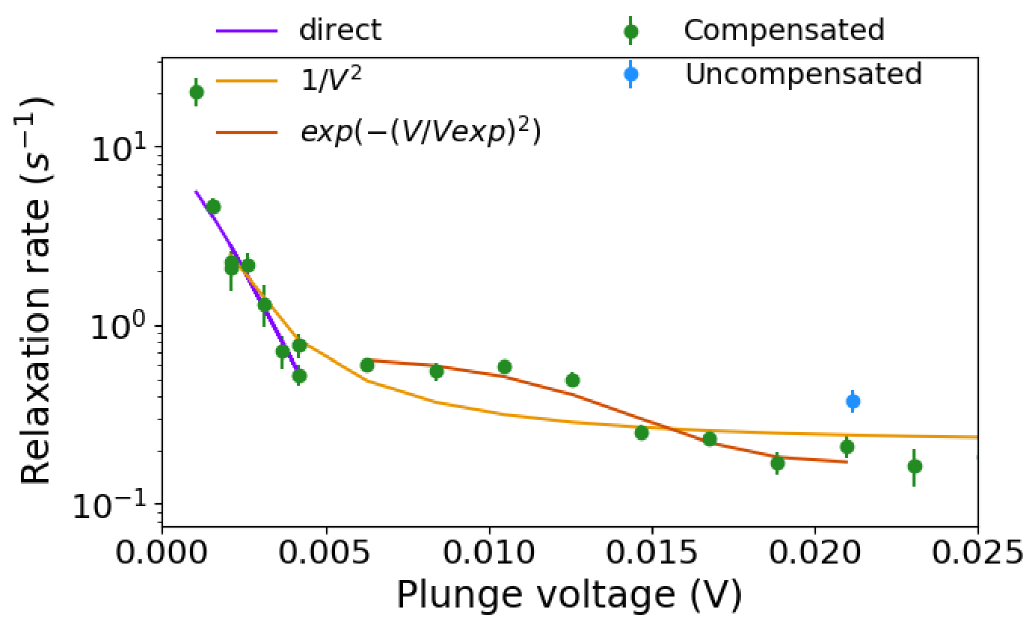
$\Gamma_0 = 25 \pm 3$ Hz

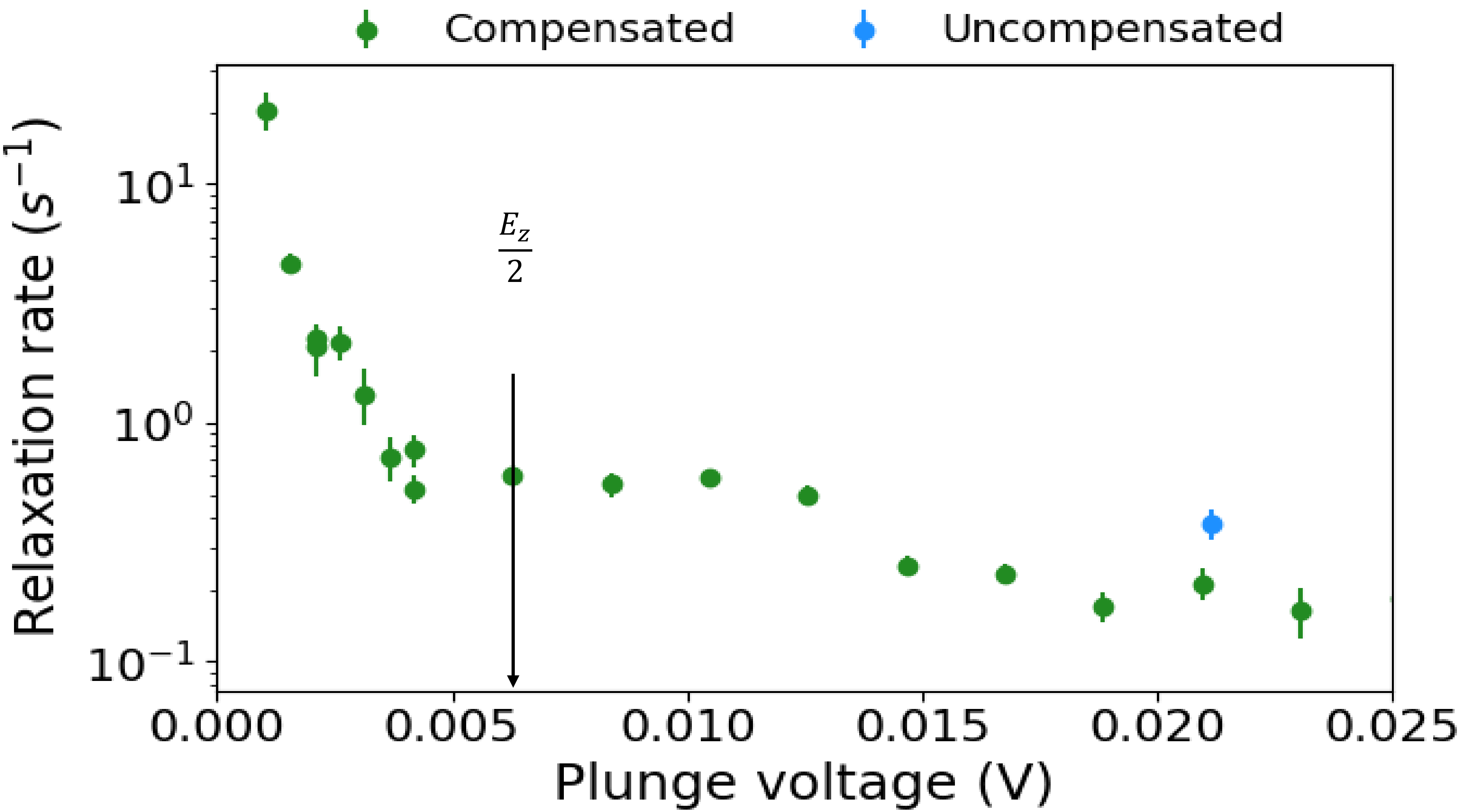
Agrees with trace data

Co-tunnelling does not fit

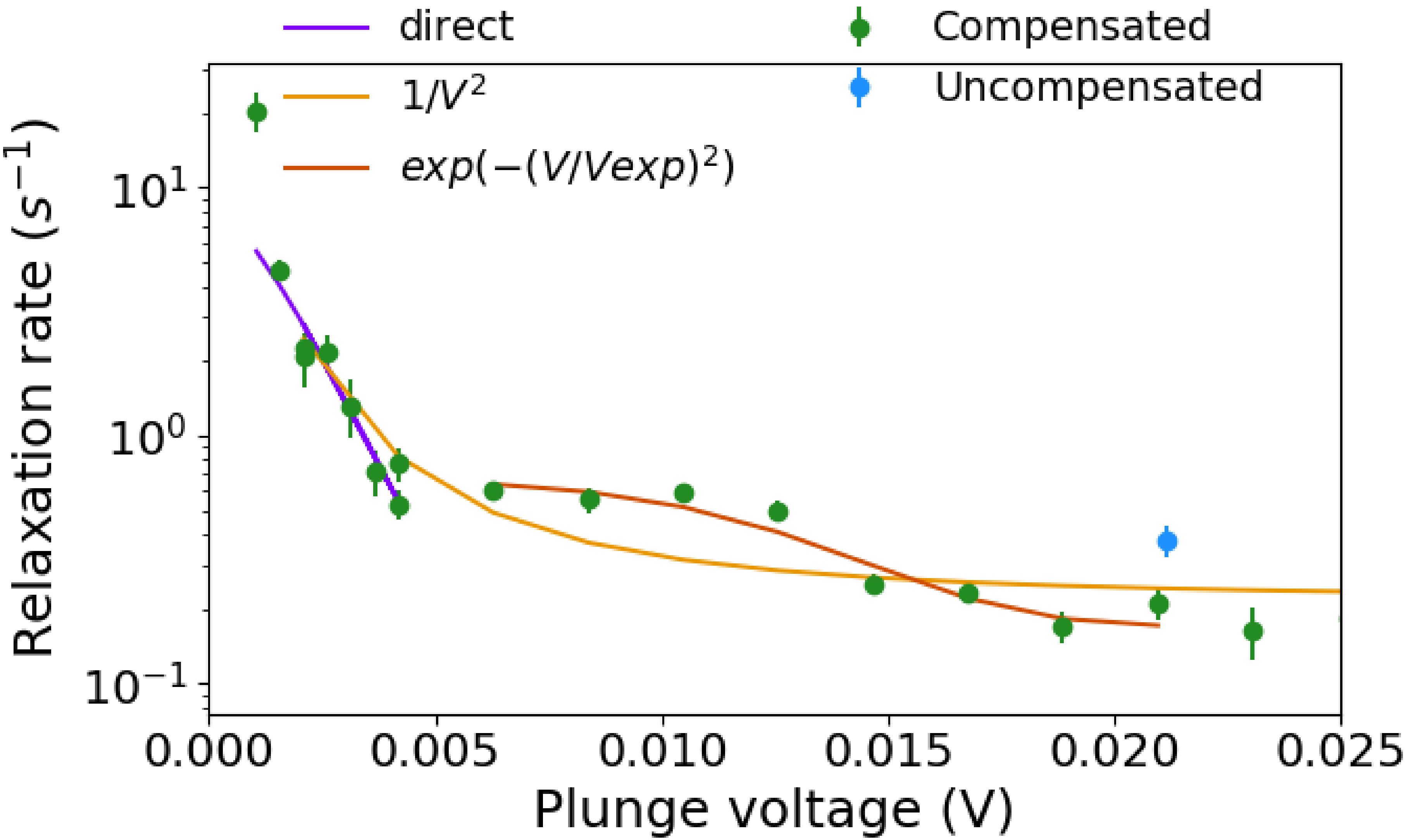
What is going on here?

The exponential is a random fit we made up…

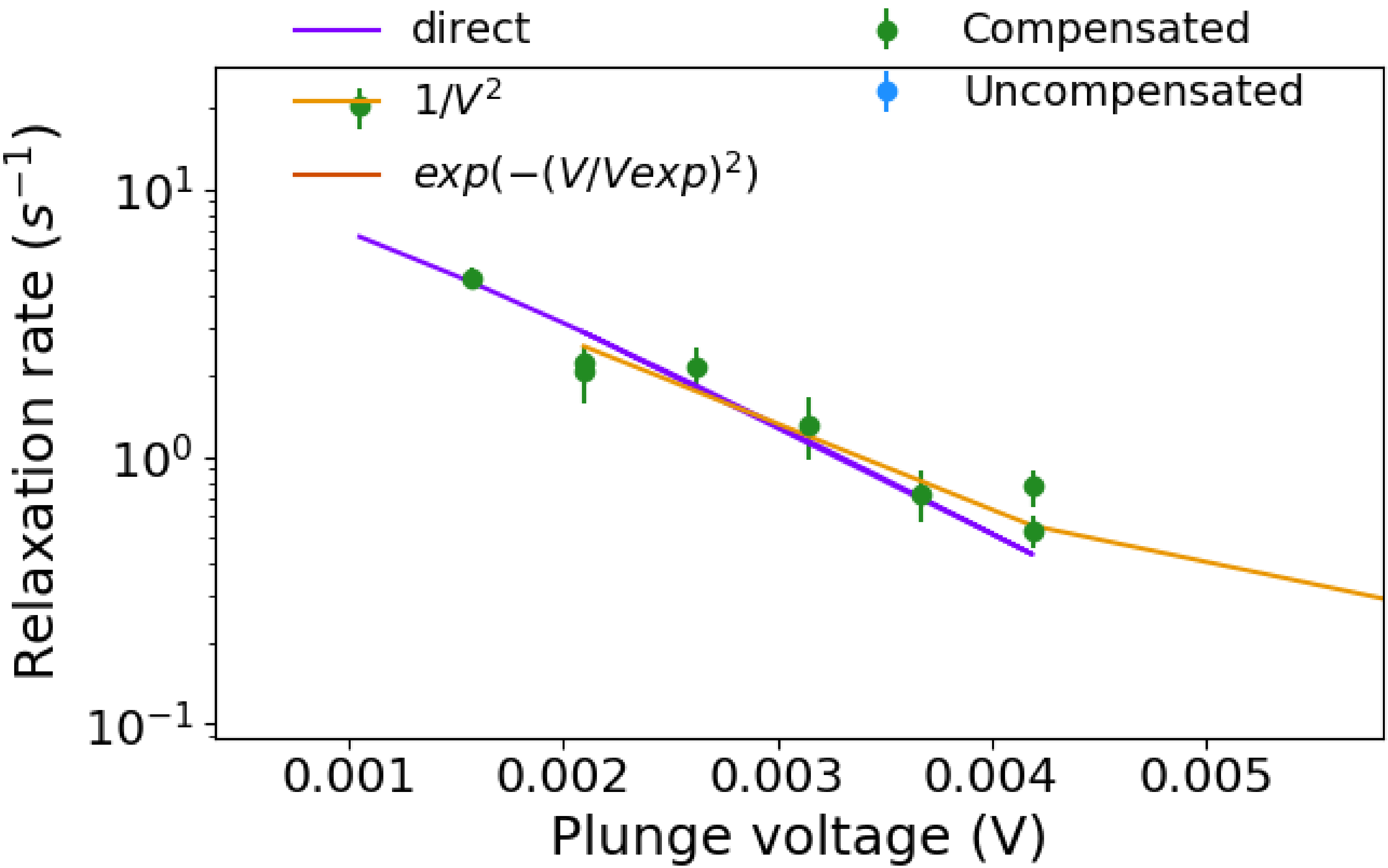




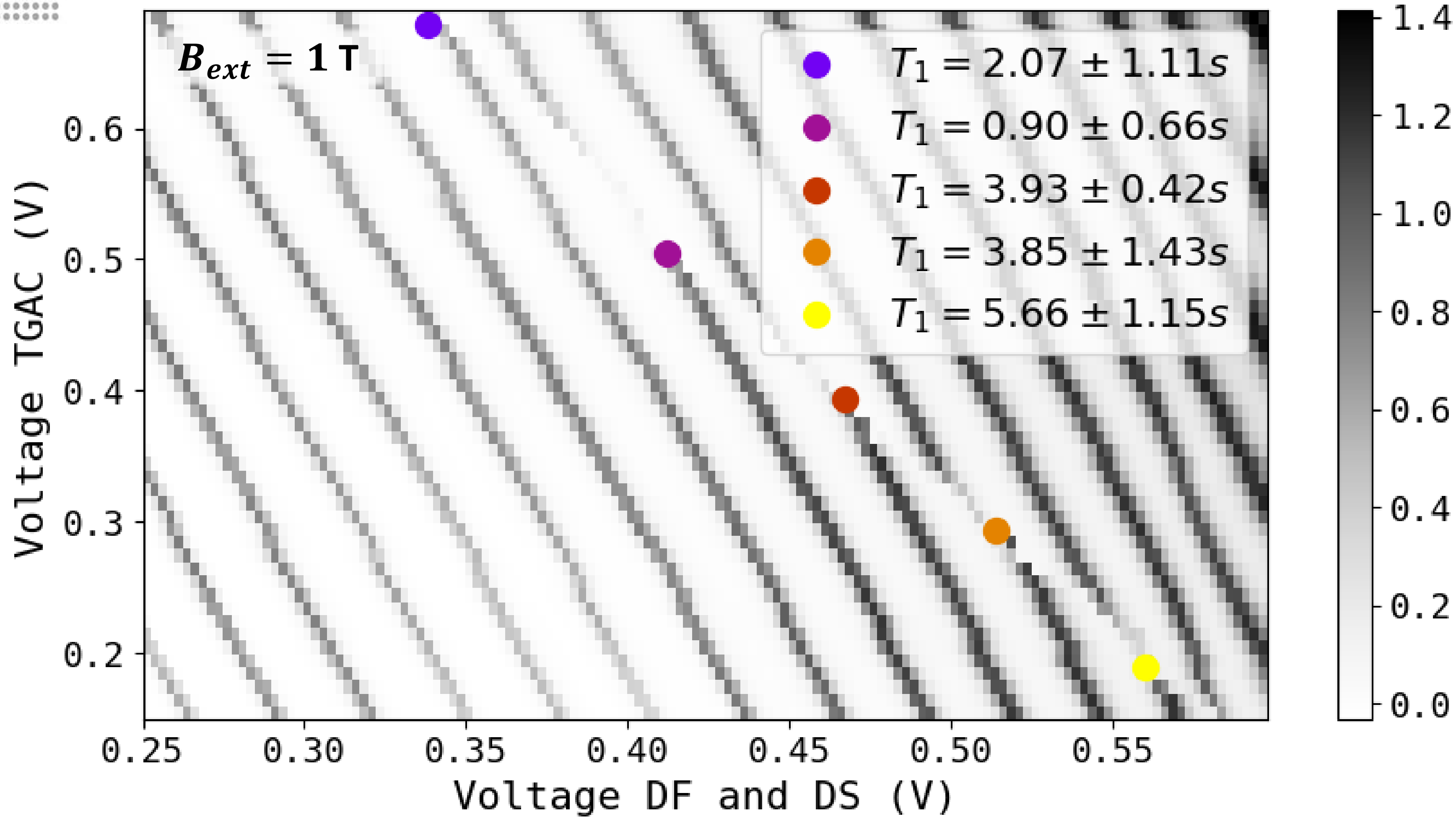
Compensated
Uncompensated
10^1
10^0
10^{-1}
Relaxation rate (s^{-1})
$\frac{E_z}{2}$
0.000
0.005
0.010
0.015
0.020
0.025
Plunge voltage (V)



direct
$1/V^2$
$exp(-(V/Vexp)^2)$
Compensated
Uncompensated
Relaxation rate (s^{-1})
10^1
10^0
10^{-1}
0.000
0.005
0.010
0.015
0.020
0.025
Plunge voltage (V)

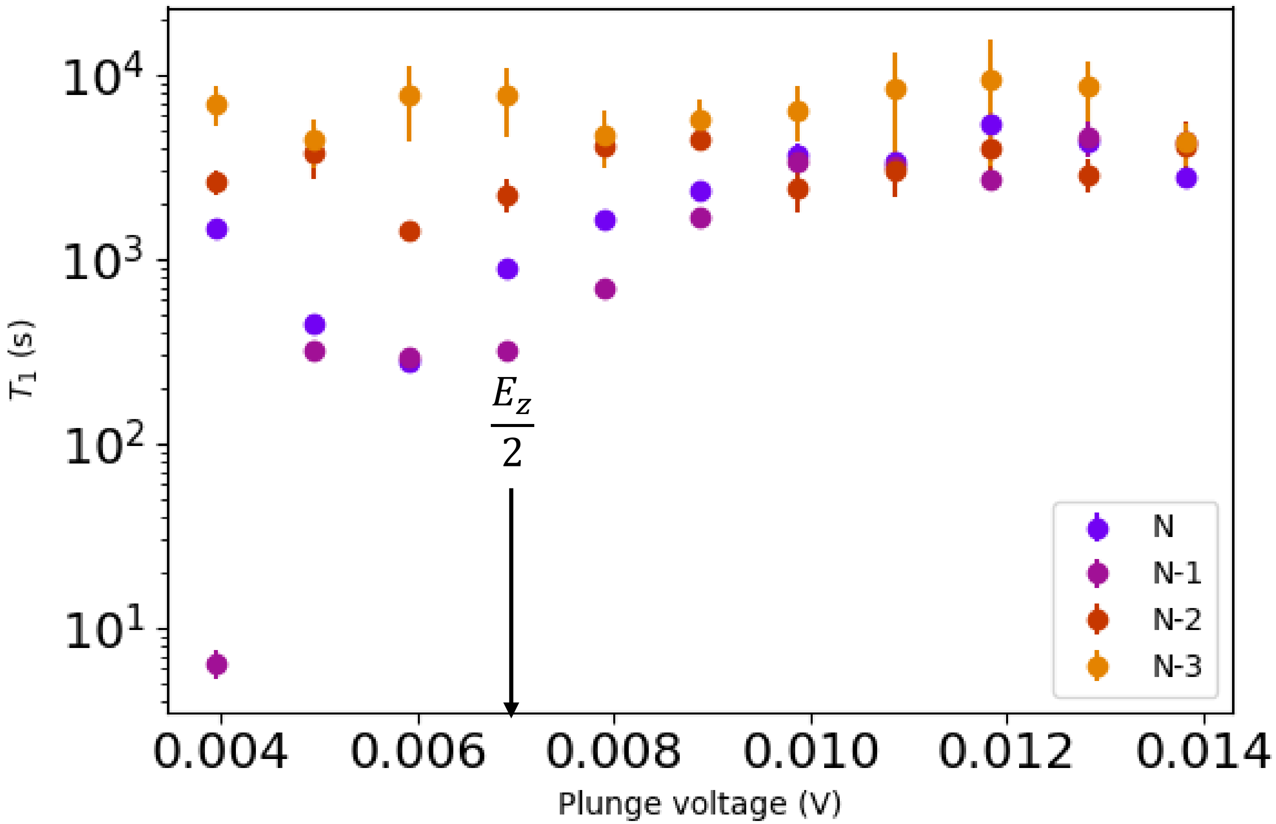

direct
1/V^2
exp(−(V/Vexp)^2)
Compensated
Uncompensated
Relaxation rate (s^−1)
10^1
10^0
10^−1
0.001
0.002
0.003
0.004
0.005
Plunge voltage (V)

Dependence of T_1 on SET electron number



- Tunnelling effects depend on the Fermi distribution in the SET
- The SET is with n≈100 in the intermediate regime between few and many electrons ⇒ the Fermi distribution has some variation with electron number

Dependence of T_1 on SET electron number



These measurements show less of an exponential like for direct tunnelling expected
→ Uneven Fermi distribution?

For large plunge voltages all tunnelling processes are suppressed
⇒ relaxation is independent of electron number

Questions for Bill

Do you have any idea what is going on for plunge voltages deeper than half the Zeeman energy?

It seems that we observe direct tunnelling until the spin up moves below the Fermi level – as expected. Below that there is still a drop of up at a factor of 5 until the relaxation rate reaches the phonon relaxation plateau. What is going on here?

Additional information:

Unfortunately this specific sample died so we cannot take any more measurements. Also, as we were changing over our measurement software at that time, we do not have the traces for this specific measurement set. Although we should have general traces somewhere to dig up, which I'm in the process of doing.