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AndQC

Report on the parity lifetime, T_{parity} of the ALQ and its mitigation techniques

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1. Introduction

While experiments in semiconducting nanowire Josephson junctions are rapidly progressing [1-4], the available data on the coherent dynamics of Andreev levels in such devices is still limited. In contrast, for superconducting atomic contacts, the CEA team has obtained a fair amount of data within this project AndQC. In the one atom limit, a single well-transmitted channel dominates the physics. In this case, there is just one Andreev level, which can be populated with zero, one or two quasiparticles, leading respectively to three many body states |g>, |o> and |e>. The odd state |o> is two-fold degenerate due to spin [5]. The other two states are the even ground state |g> and even excited state |e>. First insight into parity switching stemmed from previous results by the CEA team [6] and theory by the UAM team [7]. We present here new results from the CEA team, where a circuit QED setup similar to that of Ref. [5] has been used but including a quantum limited amplifier based on a Josephson Parametric Converter (JPC) [8,9], which allows for an improved resolution. These new data and the theoretical analysis reported by the Madrid team in deliverable 5.1 provide a deeper insight into the parity lifetime of the ALQ and ASQ.

2. Transition rates at the single photon limit

The CEA team has performed continuous measurements of the quasiparticle occupation of the Andreev states in atomic point contacts using the setup illustrated in Fig. 1. Atomic contacts were obtained by elongating a suspended aluminum bridge on a flexible substrate. The bridge is part of a 100 μm x 20 μm aluminum loop, placed at the shorted end of a quarter-wavelength coplanar wave-guide resonator with bare frequency f_R=8.77 GHz. A magnetic flux threading the loop controls the superconducting phase difference ϕ across the contact. The actual resonance frequency of the resonator encodes the state of the ALQ in the contact. A weak microwave tone at frequency f_R is sent into the resonator and the reflected signal is amplified first by a JPC [9] placed at the mixing chamber, then by a HEMT at 1.2K. After homodyne mixing, one obtains the in-phase (I) and out-of phase (Q) quadratures of the reflected signal. The microwave resonator was characterized while the bridge was open, leading to a total photon decay rate $\kappa/2\pi$= 9.5μs^{-1}. When a contact is formed, time-domain measurements are used to perform the spectroscopy of the Andreev levels in the contact, i.e. to determine the transition frequency $f_A(\phi)$ between the even states.

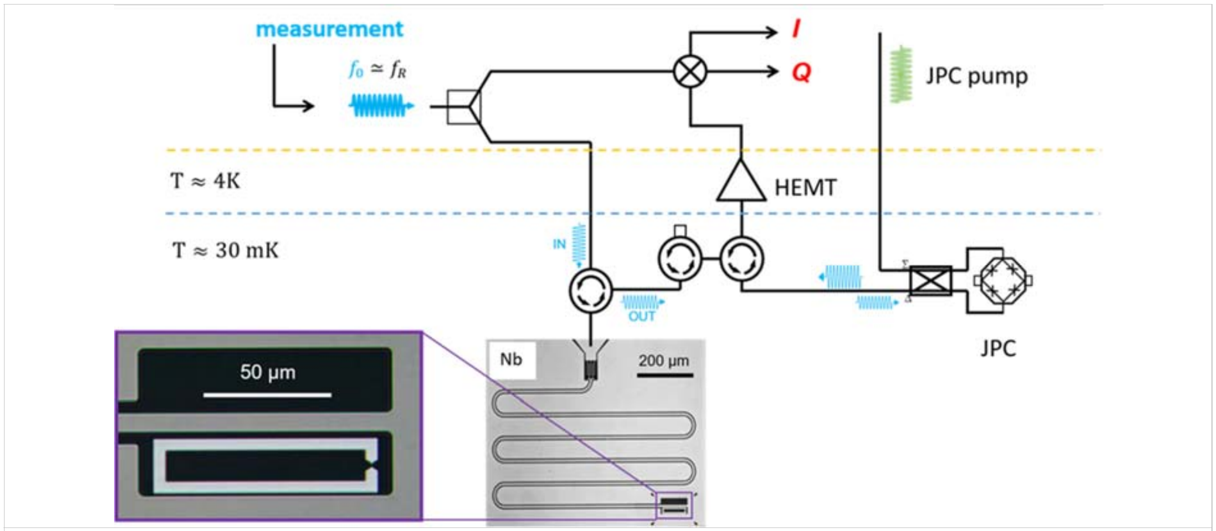

Fig.1. Schematics of the setup used for the continuous monitoring of the Andreev states population in an atomic contact. The inset shows the SQUID loop with the atomic contact inductively coupled to the center line of the shortened end of a $\lambda/4$ transmission line resonator. The system is probed by reflectometry, where the reflected signal is amplified first by a Josephson Parametric Converter (JPC) and then by the HEMT.

The results in Fig. 2 illustrate the continuous measurements of I and Q for a contact with f_A (π) = 6.33GHz. Three blobs are visible in a density plot of the values of (I, Q), corresponding to the states |g>, |o> and |e> of a contact having just a single low-energy Andreev level. The identification of the blobs is achieved from the time-domain measurements. By analyzing simultaneously, the traces I(t) and Q(t) with a hidden Markov model [10], the transition rates between the 3 states can be inferred. To account for the spin degeneracy of the odd state |o>, the rate from |g> (or |e>) to |o> is taken as twice the rate from |g> (or |e>) to |oσ>, where σ denotes either spin direction. The 10 resulting rates from i to j (labeling states within |g>, |o↑>, |o↓> or |e>) are denoted as Γ_{ij}. In most of the measurements, it is found that within experimental accuracy $\Gamma_{go\sigma} = \Gamma_{o\sigma e}$ and $\Gamma_{eo\sigma} = \Gamma_{o\sigma g}$. The corresponding processes are, respectively, the addition and the removal of one quasiparticle in the Andreev level. The approximate equality of the rates suggests that there are no charging effects. One can therefore define $\Gamma_{in} \equiv \Gamma_{go\sigma}$ and $\Gamma_{out} \equiv \Gamma_{o\sigma g}$ [6]. To make the notations more explicit, the excitation and relaxation rates in the even manifold are denoted $\Gamma_{exc} \equiv \Gamma_{ge}$ and $\Gamma_{rel} \equiv \Gamma_{eg}$.

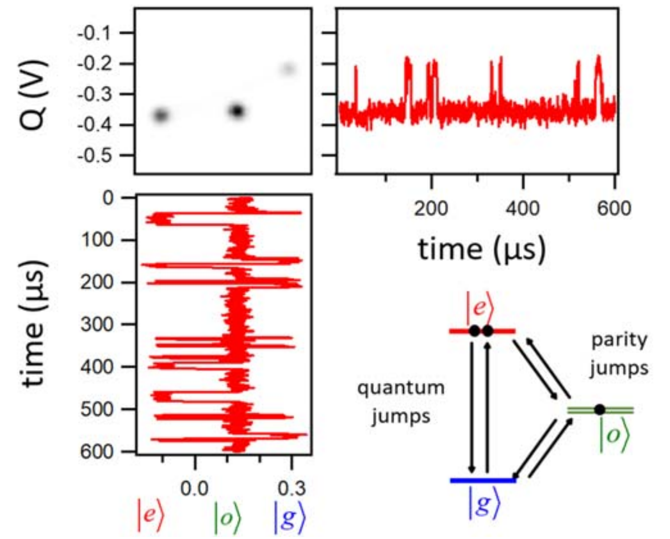

Fig.2. Quadratures I and Q of the reflected signal as a function of time measured on the atomic contact with Andreev frequency f_A (π)=6.33 GHz and a measurement power corresponding to $\langle n_{g,e} \rangle$=220 photons in the resonator. The phase difference ϕ is fixed at π. The upper-left panel shows a density plot of values of I and Q in a 0.8 ms time interval.

We find that, in general, the transition rates depend on the intensity of the probe tone at f_R. This intensity can be expressed in terms of the average number of photons in the cavity n, which characterizes the Poisson distribution in the driven cavity. It is important to notice that n depends also on the parity of the occupation of the Andreev levels, so that $n_{g,e}=n_0/(1+(2\chi/\kappa)^2)$, where χ is the cavity pull (or shift in the resonator frequency) when the system is in the |g> or |e> state. The number of photons is calibrated by measuring the Stark shift of the cavity and the cavity pull at a given power. Figure 3 illustrates the variation of the rates and the states populations with the mean number of photons 3 for the same contact as in Fig. 2.

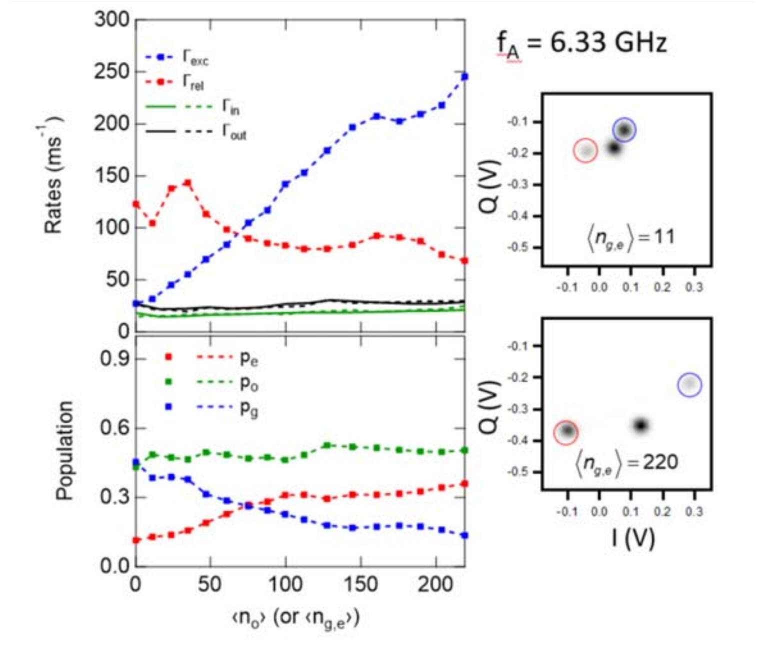

Fig.3. Rates and population dependence on the mean number of photons in the cavity. For very low photon number the ALQ is with almost equal probability in the odd or the even ground state. There is a population inversion in the even manifold at larger photon number. Parity switching rates essentially do not depend on the number of photons in the cavity The parity switching rate is in this example around 25 ms^{-1}. Since $\boldsymbol{\Gamma_{in}} \approx \boldsymbol{\Gamma_{out}}$ the live time for both the ALQ and the ASQ would be around 40μs.

As can be observed, while Γ_{in} and Γ_{out} remain roughly constant, Γ_{exc} and Γ_{rel} exhibit a strong variation with *n*. At large number of photons there is an inversion of population in the even manifold while the odd states population remains roughly constant.

In order to extract information on the intrinsic dynamics of the Andreev qubit, the rates in the limit *n* →0 were determined for several contacts at phase π. Figure 4 collects the results.

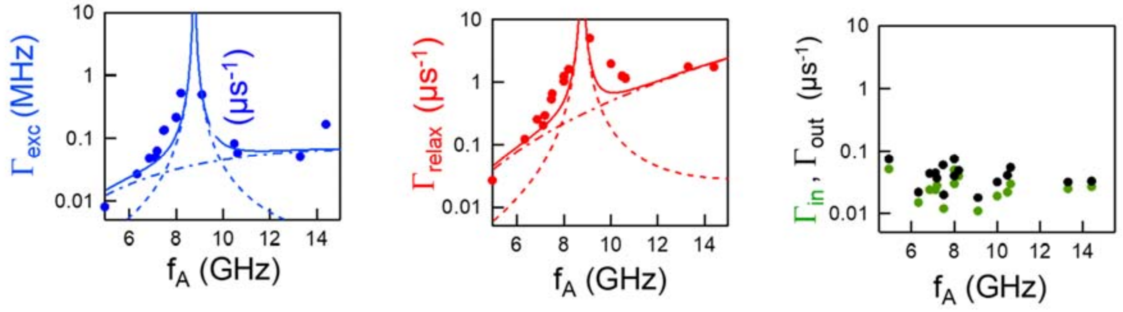

Fig.4. Frequency dependence of the rates obtained for several contacts with different f$_A$ *(at* $\phi=\pi$*). Dashed lines are rates calculated taking into account the field fluctuations in the resonator (Purcell effect). The dash-dotted lines are rates calculated by considering the emission and absorption of phonons in the leads. The full lines are the sum of both rates. The rightmost plot shows that transition rates for parity switching essentially do not depend on energy on the explored range. Details on the calculation and fits can be found in the deliverable D5.1.*

Of particular interest are the rates for parity switching, seen in the rightmost graph. There is no obvious dependence of the parity switching rates on the Andreev frequency. However, there is a large scatter (note the logarithm scale). The fact that Γ_{out} is larger than Γ_{in} agrees with emission and absorption by phonons instead of photons. The parity-switching rate changes in an uncontrolled manner, suggesting that the density of quasiparticles changes in time. Previous work exploring a much broader range of Andreev energy showed that the parity-switching rate depends on the Andreev level energy [6,7]. The rate Γ_{in} was found to decrease with increasing Andreev energy, while the rate Γ_{out} showed the opposite dependence. To protect an ALQ or ASQ one should "park" the qubit at a higher energy by shifting the phase of the junction to an appropriate value. An alternative way would be to change the transmission probability from high to intermediate to protect the qubit. This is one possible mitigation approach. It has also been shown that one can reset the junction in the even ground state by sweeping the phase either through 0 or 2π, see supplementary in [6]. This happens because the Andreev level comes close to the quasiparticle continuum where a "trapped" quasiparticle can rapidly escape. Starting with an ALQ set to the even ground state, parity-switching requires the presence of quasiparticle. Hence, the best way to avoid it is to keep the number of quasiparticles low. In addition to low temperature and good filtering, this can be achieved with a quasiparticle trap. It is realized if the junction is in contact with a large enough normal metal electron reservoir or with contact lines that use a superconductor with a smaller bandgap. To keep dissipation low, the second method is the preferred one. For the ASQ, there is no reset (or better "set") protocol known that brings the junction into the odd state for certainty. However, this is required so that a set of ASQs can be operated in a deterministic way. Parity-switching rates have been demonstrated to be small enough, yielding qubit time scales in the 100μs range.

Conclusions

Coupling to microwave photons in the resonator and phonons in the leads forming the contact have been identified as the main mechanisms leading to relaxation and parity jumps in an ALQ defined on atomic point contacts. The relaxation and excitation rates were found to depend strongly on the number of photons in the resonator which can lead to an inversion of the steady state population in the even sector. In contrast, the rates associated to parity jumps remain almost constant with increasing number of photons, although exhibiting large fluctuations. Further details can be found in the theory part D5.1.

References

[1] D. J. van Woerkom, A. Proutski, B. van Heck, D. Bouman, J.I. Väyrynen, L. I. Glazman, P. Krogstrup, J. Nygård, L. P. Kouwenhoven and A. Geresdi, Microwave spectroscopy of spinful Andreev bound states in ballistic semiconductor Josephson junctions, Nature Phys 13, 876 (2017).

[2] M. Hays, G. de Lange, K. Serniak, D. J. van Woerkom, D. Bouman, P. Krogstrup, J. Nygård, A. Geresdi, and M. H. Devoret, Direct Microwave Measurement of Andreev-Bound-State Dynamics in a Semiconductor-Nanowire Josephson Junction, Phys. Rev. Lett. 121, 047001 (2018).

[3] L. Tosi, C. Metzger, M.F. Goffman, C. Urbina, H. Pothier, Sunghun Park, A. Levy Yeyati, J. Nygard, and P.Krogstrup, Spin-orbit splitting of Andreev states revealed by microwave spectroscopy, Phys. Rev. X 9, 011010 (2019).

[4] M. Hays, V. Fatemi, K. Serniak, D. Bouman, S. Dia-mond, G. de Lange, P. Krogstrup, J. Nygrd, A. Geresdi, M.H. Devoret, Continuous monitoring of a trapped,superconducting spin, arXiv:1908.02800.

[5] C. Janvier, L. Tosi, L. Bretheau, Ç.O. Girit, M. Stern, P. Bertet, P. Joyez, D. Vion, D. Esteve, M. F. Goffman, H. Pothier, and C. Urbina, Coherent manipulation of Andreev states in superconducting atomic contacts, Science **349**, 1199 (2015).[6] M. Zgirski et al., Evidence for Long-Lived Quasiparticles Trapped in Superconducting Point Contacts. Phys. Rev. Lett. **106**, 257003 (2011).

[7] D.G. Olivares, L. Bretheau, Ç.O. Girit, H. Pothier, C. Urbina, and A. Levy Yeyati, Dynamics of quasiparticle trapping in Andreev levels, Phys. Rev. B **89**, 104504 (2014).

[8] N. Bergeal, F. Schackert, M. Metcalfe, R. Vijay, V. E. Manucharyan, L. Frunzio, D. E. Prober, R. J. Schoelkopf, S. M. Girvin, and M. H. Devoret, Phase-preserving amplification near the quantum limit with a Josephson ring modulator, Nature **465**, 64 (2010).

[9] N. Roch, E. Flurin, F. Nguyen, P. Morin, P. Campagne-Ibarcq, M. H. Devoret and B. Huard, Phys. Rev. Lett. **108**, 147701 (2012).

[10] M. Greenfeld, D.S. Pavlichin, H. Mabuchi, and D. Herschlag, Single Molecule Analysis Research Tool (SMART): An Integrated Approach for Analyzing Single Molecule Data. PLoS ONE **7**, e30024 (2012).