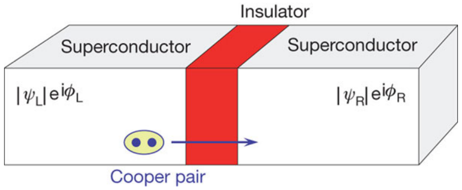
Possible resonance effect of dark matter axions in SNS Josephson junctions



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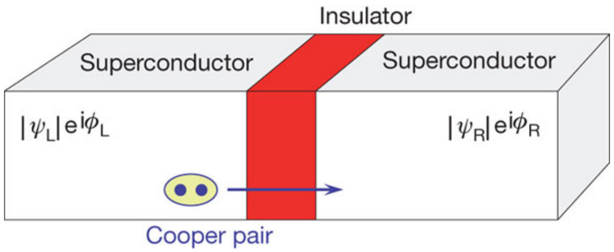
Contents

C. Beck, PRL 111, 221801 (2013)

C. Beck, Phys. Dark Univ. 7-8, 6 (2015)

C. Beck, Sci. Rep. 6, 28275 (2016)

1 All you need to know about Josephson junctions for this talk



- Josephson junction (JJ) consists of two superconductors separated by a weak-link region (red)
- weak link-region is an insulator for tunnel junctions and a normal metal for S/N/S junctions
- distance between superconducting plates: $d \sim 1nm$ for tunnel junctions, $d \sim 1\mu m$ for S/N/S junctions
- If a DC voltage V is applied then JJ emits Josephson radiation of frequency $\hbar\omega_J = 2eV$

  In this case the phase differences grows linearly in time $\delta := \Phi_L - \Phi_R \sim \omega_J t$.

2 Field equations of axions in a Josephson environment

$$\ddot{\theta} + \Gamma\dot{\theta} - c^2\nabla^2\theta + \frac{m_a^2 c^4}{\hbar^2}\sin\theta = -\frac{g_\gamma}{4\pi^2}\frac{1}{f_a^2}c^3 e^2 \vec{E}\vec{B} \qquad (1)$$

$$\nabla \times \vec{B} - \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t} = \mu_0 \vec{j} + \frac{g_\gamma}{\pi}\alpha\frac{1}{c}\vec{E} \times \nabla\theta - \frac{g_\gamma}{\pi}\alpha\frac{1}{c}\vec{B}\dot{\theta} \qquad (2)$$

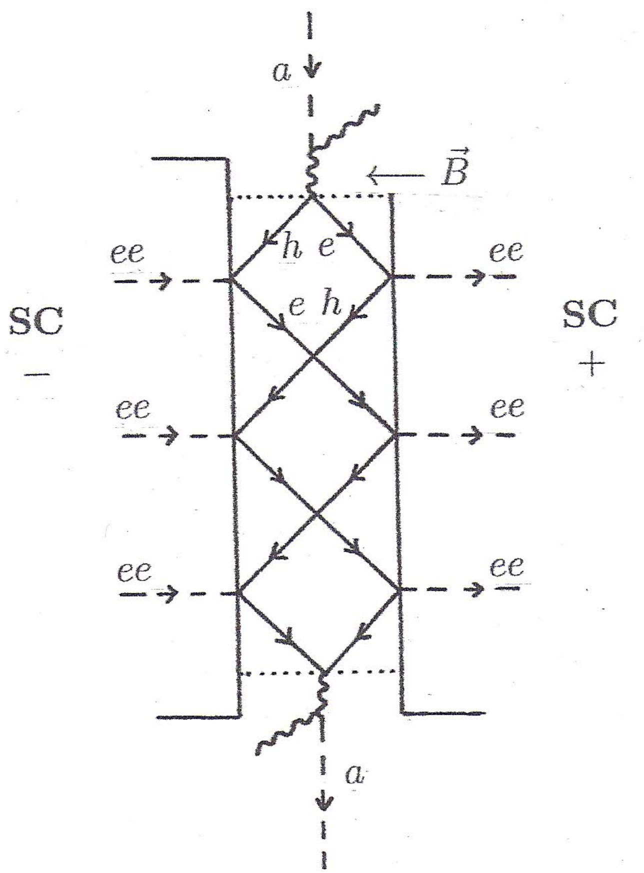
$$\nabla\vec{E} = \frac{\rho}{\epsilon_0} + \frac{g_\gamma}{\pi}\alpha c\vec{B}\nabla\theta \qquad (3)$$

$$\ddot{\delta} + \frac{1}{RC}\dot{\delta} + \frac{2eI_c}{\hbar C}\sin\delta = \frac{2e}{\hbar C}I \qquad (4)$$

$$P_{a\to\gamma} = \frac{1}{16\beta_a}(g_\gamma\ Bec\ L)^2\frac{1}{\pi^3 f_a^2}\frac{1}{\alpha}\left(\frac{\sin\frac{qL}{2\hbar}}{\frac{qL}{2\hbar}}\right)^2 \qquad (5)$$

m_a axion mass, f_a axion coupling constant, $\beta_a = v_a/c$ axion velocity, $\vec{E}$ electric field, $\vec{B}$ magnetic field, $g_\gamma = -0.97$ for KSVZ axions, $g_\gamma = 0.36$ for DFSZ axions, q momentum transfer, $P_{a\to\gamma}$ probability of axion decay, I_c critical current of junction.

3 Field equations allow for an Axion — Andreev pair interaction



C. Beck, PRL 111, 221801 (2013)

Microscopic model of what happens in an S/N/S junction.
Axion tunnels through junction and triggers
(by multiple Andreev reflections)
the transport of n Cooper pairs

Experimentally observable consequence of this effect:

- A Shapiro step (a tiny step (or wiggle)) in the I-V curve that occurs at a position where the Josephson frequency ω_J resonates with the axion mass m_a:

  $\hbar\omega_J = 2eV = m_a c^2$

  (C. Beck, PRL 2013)

- Effect of axion flow is similar to the existence of a second Josephson junction with critical current

  $I_c^a = \sqrt{\frac{\rho_a v_a}{h\alpha}} w \cdot 2e \sim 10^{-8}$A

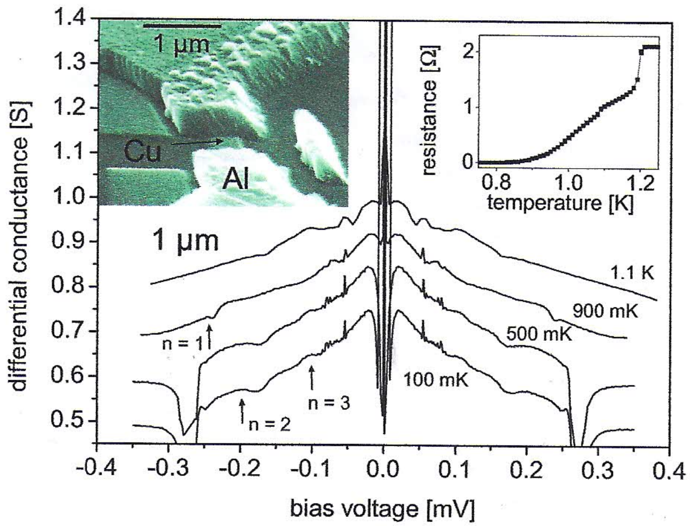
  ρ_a: axion density, v_a: axion velocity, w width of Josephson junction, $h = 2\pi\hbar$

  (C. Beck, Physics Dark Universe 2015)

- Expect from galactic axion flow a small but perfectly measurable effect: A little peak-like structure in the differential conductance $G = dI/dV$ occuring at the voltage $V_a = m_a c^2/(2e)$.

4 A candidate signal

Small peak of unknown origin observed at voltage $V_a = 55\mu$V by Hoffmann et al. $\Longrightarrow m_a c^2 = 110\mu$ eV and $\rho_a \sim 0.1 GeV/cm^3$ (C. Beck, PRL 2013)



C. Hoffmann, F. Lefloch, M. Sanquer, B. Pannetier, Phys. Rev. B 70, 180503(R) (2004)

A peculiar, unexplained Shapiro step feature of this type pointing to an axion mass of around 110 μeV has been found in 4 independent condensed matter experiments:

C. Beck, Phys. Dark Univ. 7-8, 6 (2015)

- Hoffmann et al. (PRB 2004) $V_a = (55 \pm 1)\mu$V
- Golikova et al. (PRB 2012) $V_a = (52 \pm 5)\mu$V
- He et al. (arXiv 2011) $V_a = (53 \pm 3)\mu$V
- Bae et al. (PRB 2008) $V_a = (55 \pm 1)\mu$V

Taking the average over all 4 independent experimental groups, we get $V_a = (54 \pm 3)\mu$V, which points towards an axion mass prediction in the range

$$m_a c^2 = 2eV_a = (108 \pm 6)\mu\text{eV},$$

taking into account all of these 4 independent observations.

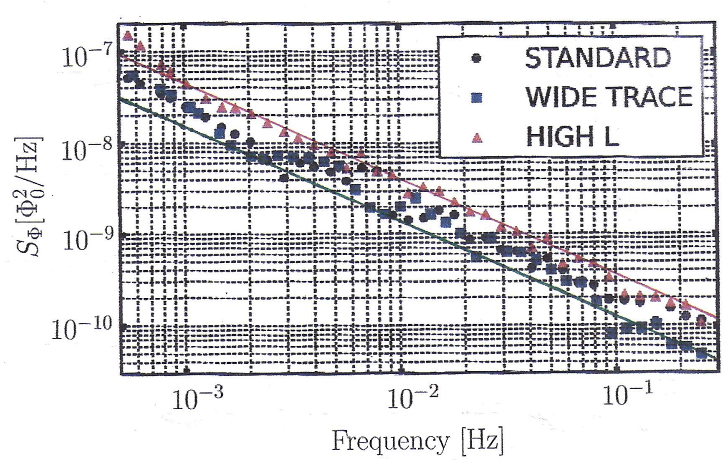
Some recent predictions of the QCD axion mass:

- C. Beck, PRL 111, 221801 (2013)
  $\boldsymbol{m_a = (110 \pm 2)\mu}\text{eV}$
  (based on theoretical assumption of axion-Andreev pair interaction)
- S. Borsanyi et al., Nature 539, 69 (2016)
  $\boldsymbol{m_a = 50....1500\mu}\text{eV}$
  (based on lattice QCD simulations)
- G. Ballesteros, J. Redondo, A. Ringwald, C. Tamarit, PRL 118, 071802 (2017)
  $\boldsymbol{m_a \sim 100\mu}\text{eV}$
  (based on theoretical asumptions of SMASH model)

5 Fluxnoise effects in SQUIDS

ALPs can also produce broadband $1/f$ flux noise effects at very low frequencies:

$$S_\Phi(f) = \frac{\theta_1^2 \Phi_0^2 A_s}{16\pi^2} \left(\frac{f}{v k^*} \right)^{n_s - 1} \frac{1}{f}$$



Measured magnetic flux noise spectrum as measured by Sank et al (PRL 109, 067001 (2012)) and theoretical prediction (straight lines) (C. Beck, Sci. Rep. 6, 28275 (2016))

6 Conclusion

- Nobody really knows what dark matter is... WIMPs? Axions? Something else?
- Axions hitting the weak-link region of S/N/S junctions can trigger the transport of additional Cooper pairs. Leads to small measurable signal in the differential conductivity if axion mass resonates with Josephson frequency.
- Candidate signal of unknown origin has been observed in measurements of Hoffmann et al. Can be interpreted in terms of an axion mass of $\mathbf{(110 \pm 2)}\boldsymbol{\mu}$eV and a local axionic dark matter density of $\sim$ 0.1 GeV/$\boldsymbol{cm^3}$. C. Beck, Phys. Rev. Lett. 111, 231801 (2013) [arXiv:1309.3790]
- Peculiar effect occuring at $\sim$ $\mathbf{55}\boldsymbol{\mu}$V pointing to an axion mass of about $\mathbf{110}\boldsymbol{\mu}$eV has been observed by 4 independent condensed matter groups working with S/N/S Josephson junctions: C. Beck, Phys. Dark Univ. 7-8, 6 (2015) [open access]
- Re-do these kinds of Josephson experiments under isolated conditions!
- Recommendation for any axion haloscope experiment: Search around 110 $\boldsymbol{\mu}$eV first! (Done! See e.g. ORGAN collaboration: B.T. McAllister et al., arXiv:1706.00209)