Possible resonance effect of axionic dark matter in S/N/S Josephson junctions

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We provide theoretical arguments that dark matter axions from the galactic halo that pass through the earth may generate a small observable signal in resonant S/N/S Josephson junctions. The corresponding interaction process is based on uniqueness of the gauge-invariant axion Josephson phase angle modulo 2π and is predicted to produce a small Shapiro step-like feature without externally applied microwave radiation when the Josephson frequency resonates with the axion mass. A resonance signal of so far unknown origin observed in [C. Hoffmann et al. PRB 70, 180503(R) (2004)] is consistent with our theory and can be interpreted in terms of an axion mass $m_a c^2 = 0.11$meV and a local galactic axionic dark matter density of 0.05 GeV/cm^3. We discuss future experimental checks to confirm the dark-matter nature of the observed signal.

The existence of dark matter in the universe is one of the major puzzles of current research in astrophysics, cosmology, and particle physics. While there is clear evidence for the existence of dark matter from astronomical observations, it is still unclear what the physical nature of dark matter is. Important candidate particles for dark matter are weakly interacting massive particles (WIMPS) [1] and axions [2, 3]. Many experimental searches to detect WIMPS [4] and axion-like particles [5–9] are currently under way. A positive result would be a major breakthrough in our understanding of the matter contents of the universe.

Most experiments searching for axions are based on the Primakoff effect, i.e. the decay of axions into two microwave photons in the presence of a strong magnetic field, as well as the inverse process. For example, in 'Light shining through wall experiments' one looks for photons that convert to axions in a strong magnetic field, travel through a 'wall', and convert back to photons [7, 8]. In other experiments, such as the ADMX experiment [9], one looks for axions that decay into microwave photons in a resonant cavity. New ideas and novel suggestions how to detect axions, axion-like particles and hidden photons are currently developing [10, 11].

In this letter we propose a new approach how to detect QCD-axionic dark matter in the laboratory with high efficiency, exploiting a macroscopic quantum effect. Our proposal is based on S/N/S (Superconductor/Normal Metal/Superconductor) Josephson junctions as suitable detectors [12–15]. We will provide theoretical arguments that axions that pass through the weak link region of such a Josephson junction in the voltage stage may trigger the transport of additional Cooper pairs if the Josephson frequency ω_J coincides with the axion mass $m_a c^2 = \hbar\omega_J$. The effect is resonantly enhanced. For S/N/S junctions the proximity effect plays an important role and the charge transport of Cooper pairs is mediated by multiple Andreev reflections of quasiparticles. For more details on the theoretical and experimental aspects of S/N/S junctions, we refer to [12–16] and references therein.

The theory underlying our proposal will be worked out in detail in the rest of this paper, but the basic theoretical idea can be regarded as being kind of a complement of the 'Light Shining through Walls' (LSW) mechanism [7, 8]. In LSW experiments photons decay into axions in a strong magnetic field, which then pass a 'wall' and decay back into photons, which can be detected. Here we employ the opposite effect where axions convert into photons in a Josephson junction and back into axions when leaving the junction. For brevity we may call this effect ATJ ('Axions tunneling a junction'). The 'wall' for axions in this case is represented by the weak-link region of the biased Josephson junction in the voltage stage.

From an experimental point of view, ATJ predicts a Shapiro-step like feature [17] in the measured I-V curve of the S/N/S junction that occurs *without* externally applied microwave radiation [18–20]. The measured differential conductivity is predicted to exhibit a small peak at Josephson frequency $\hbar\omega_J = 2eV = m_a c^2$, whose intensity depends on the velocity of galactic axions hitting the earth, the size of the weak-link region of the junction, and the local galactic halo density of axions. V is the bias voltage. The width of the peak is not determined by the velocity dispersion of the axions (they are in good approximation monochromatic) but by the line width of the Josephson junction and the number of Andreev reflections. Our calculations in this paper show that the effect of axionic dark matter on the I-V curve is small but observable.

Remarkably, a measurement performed by Hoffmann et al. [12] some 10 years ago (aimed at better understanding the noise characteristics of S/N/S junctions) provides experimental evidence for a peak consistent with our theoretical prediction. The authors of the above paper observed a small temperature-independent resonance peak of the differential conductivity at a voltage of 0.055 meV for all temperatures below 1K and remark in their paper that 'the origin of the additional peak is not clear'. We here propose to interpret their measured peak in terms of ATJ, i.e. axions hitting the normal metal region of their S/N/S junction. From this interpretation we obtain a prediction of the axion mass of $m_a c^2 = 0.11$ meV. From the intensity of their observed signal we can also estimate the local halo density of dark matter axions as 0.05 GeV/cm^3, which is in agreement with astrophysical expectations [21]. Axions with the above mass value are expected to account for about 20% of the dark matter contents of the universe.

Let us now develop our theory (based on a coherent field effect [10]) in more detail. Consider an axion field $a = f_a\theta$, where θ is the axion misalignment angle and f_a is the axion coupling constant. If strong external electric and magnetic fields $\vec{E}$ and $\vec{B}$ are present, then the classical equation of motion of the axion misalignement angle is

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

g_γ is a model-dependent dimensionless coupling constant ($g_\gamma = -0.97$ for KSVZ axions [22, 23], whereas $g_\gamma = 0.36$ for DFSZ axions [24, 25]). Γ is a damping parameter. In the early universe, $\Gamma = 3H$, where H is the Hubble parameter, but at a later stage of the universe larger Γ can be relevant, depending on the interaction processes considered [26]. As shown be Sikivie et al. [27], axions at the current stage of the universe are most likely to form of a Bose-Einstein condensate (BEC) which opens up the possibility to exploit macroscopic quantum effects of the axion condensate for detection purposes. The typical parameter ranges that are allowed for QCD dark matter axions are $6 \cdot 10^{-6}eV \le m_a c^2 \le 2 \cdot 10^{-3}eV$ and $3 \cdot 10^9 GeV \le f_a \le 10^{12} GeV$. The product $m_a c^2 f_a$ is expected to be of the order $m_a c^2 f_a \sim 6 \cdot 10^{15}(eV)^2$.

Let us consider as a suitable detector a Josephson junction (JJ) [28], which we initially treat in the approximation of the RSJ model [16] (later we will come to more specificic physics for S/N/S junctions). In the RSJ model the phase difference δ of a Josephson junction driven by a bias current I satisfies

$$\ddot{\delta} + \frac{1}{RC}\dot{\delta} + \frac{2eI_c}{\hbar C}\sin\delta = \frac{2e}{\hbar C}I \tag{2}$$

where I_c is the critical current of the junction, and R and C are the normal resistance and capacity of the junction, respectively.

As pointed out in [19, 20], the equations of motions for axions (1) and JJs (2) are basically the same, and also the numerical values of the coefficients in the equations are of similar order of magnitude (see [19] for some numerical examples). In this formal analogy the axion mass parameter squared essentially corresponds to the critical current I_c, the product $\vec{E} \cdot \vec{B}$ corresponds to the bias current I, and the damping Γ corresponds to $(RC)^{-1}$.

Now let us consider an axion with misalignment angle θ that enters the weak link region of a Josephson junction with phase difference δ (Fig. 1a). Both the axion (as a BEC with an equation of motion identical to a JJ) and the Josephson junction (as a coherent state of two superconductors separated by a weak link region) are macroscopic quantum systems and can be described by a joint macroscopic wave function Ψ. Similar to the case where two Josephson junctions are put together in a SQUID configuration [16] the phase variable φ of the joint axion Josephson junction wave function $\Psi = |\Psi|e^{i\varphi}$

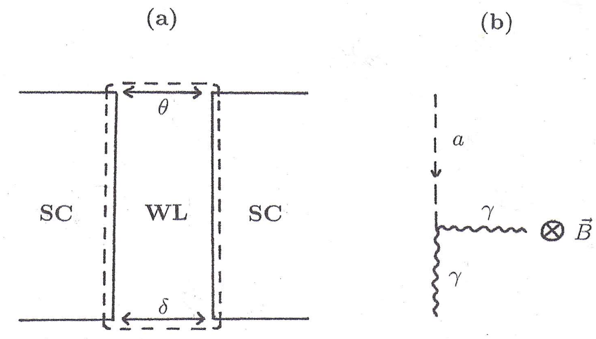

FIG. 1: (a) Closed integration curve (dashed line) over axion and Josephson phase angles in the weak-link region (WL) of a JJ. (b) Feynman graph underlying axion-photon decay in a JJ.

must be single-valued. This means that for a given closed integration curve covering the interior of both superconductors (SC) and the weak link region (WL) one has

$$\int_{SC} \nabla\varphi \cdot d\vec{s} + \delta + \theta = 0 \mod 2\pi \tag{3}$$

(see Fig. 1a). The above condition implies that the Josephson phase difference δ and the axion misalignment angle θ are no longer independent of each other but influence each other. In the presence of a vector potential $\vec{A}$ we may define gauge-invariant phase differences γ_i by

$$\gamma_1 := \delta - \frac{2\pi}{\Phi_0}\int_{weak\ link\ 1} \vec{A} \cdot d\vec{s} \tag{4}$$

$$\gamma_2 := \theta - \frac{2\pi}{\Phi_0}\int_{weak\ link\ 2} \vec{A} \cdot d\vec{s}. \tag{5}$$

$\Phi_0 = \frac{h}{2e}$ denotes the flux quantum. The standard formalism employing uniqueness of the phase φ modulo 2π [16] then yields the relation

$$\hat{\gamma}_1 - \gamma_2 = 2\pi\frac{\Phi}{\Phi_0} \mod 2\pi, \tag{6}$$

where Φ is the magnetic flux through the area enclosed by the chosen closed line of integration, and for convenience we have defined $\hat{\gamma}_1 = -\gamma_1$. If $\Phi << \Phi_0$ or if Φ is an integer multiple of Φ_0 we arrive at the result

$$\gamma_2 = \hat{\gamma}_1 \tag{7}$$

i.e. the gauge-invariant axion misalignment angle γ_2 synchronizes with the gauge invariant phase difference $\hat{\gamma}_1$ of the Josephson junction.

Now consider a JJ in the voltage stage, where a voltage V is maintained between the two superconducting electrodes of the junction. In this case

$$V = R\sqrt{I^2 - I_c^2} \approx RI \quad \text{for } I >> I_c. \tag{8}$$

and the first and third term in eq. (2) can be neglected, so that in good approximation

$$\dot{\delta} = \frac{2eRI}{\hbar} = \frac{2eV}{\hbar} \tag{9}$$

which means δ grows linearly in time, $\delta(t) = \delta(0) + \frac{2eV}{\hbar}t$. There is an oscillating supercurrent $I_c \sin\delta(t)$ and the junction emits Josephson radiation with frequency $\hbar\omega_J = 2eV$.

Eqs. (4), (5), (7) imply that $\theta(t) = \delta(t) + const$ (where the constant depends on the magnetic flux included in the loop), meaning that (classically) the axion misalignment angle evolves in the same way as the Josephson phase difference, up to a constant. In particular, if δ increases linearly in time, then also θ increases linearly in time with the same rate as δ does. We thus get

$$\dot{\theta} = \dot{\delta} = \frac{2eV}{\hbar} \tag{10}$$

from the phase synchronisation condition and

$$\dot{\theta} = \frac{g_\gamma}{\pi}\frac{1}{\Gamma f_a^2}c^3 e^2 \vec{E}\vec{B} \tag{11}$$

from the original equation of motion (1) of the axion, neglecting the first and third term. The joint validity of Eq. (10) and (11) implies that the JJ environment effectively simulates to the axion the existence of a large non-zero product $\vec{E}\cdot\vec{B}$ in the weak-link region. Using $|\vec{E}| = \frac{V}{d}$, where d is the distance between the superconducting electrodes of the JJ, we get from (10) and (11) a *formal* magnetic field given by

$$B = \frac{2\pi\Gamma f_a^2 d}{g_\gamma \hbar c^3 e}. \tag{12}$$

Note that the result (12) is independent of the applied voltage V. The direction of this effective $\vec{B}$-field is in the same direction as that of $\vec{E}$, i.e. it is orthogonal to the superconducting plates the junction.

Putting in typical values for the QCD axion coupling f_a and the distance d, one gets huge numerical values for B, many orders of magnitude higher than what can be achieved by externally producing a B field in the lab. As a numerical example, for a typical tunnel junction $d = 10^{-9}m$ and $RC \sim 10^{-13}s$ [29]. Assuming $f_a \sim 5\cdot 10^{19}eV = 8J$ and $\Gamma \sim (RC)^{-1}$ one gets $B \sim 10^{34}T$, an incredibly large value. Much smaller choices of Γ, of the order of the current Hubble parameter $H \sim 10^{-18}s^{-1}$, still yield a big $B \sim 10^3 T$.

Our conclusion is that a phase-synchronised axion cannot exist in the junction but decays into microwave photons (Fig. 1b). To roughly estimate the probability $P_{a\to\gamma}$ of this to happen, we may use the well-known formula from the Primakoff effect [30]

$$P_{a\to\gamma} = \frac{1}{4\beta_a}(g\ Bec\ L)^2\left(\frac{sin\frac{qL}{2\hbar}}{\frac{qL}{2\hbar}}\right)^2 \tag{13}$$

where q is the axion-photon momentum transfer, $\beta_a = v/c$ the axion velocity, L the length of the detector, and $g := \frac{g_\gamma \alpha}{\pi f_a}$, where α is the fine structure constant. Inserting the formal value of the B-field (12) one obtains for $qL << 2\hbar$

$$P_{a\to\gamma} = \frac{1}{\beta_a \hbar^2 c^4}(\alpha f_a \Gamma d L)^2 \tag{14}$$

In particular, $P_{a\to\gamma} = 1$ corresponds to a very short length scale, namely

$$L = \frac{\hbar c^2}{\alpha}\sqrt{\beta_a}\frac{1}{f_a \Gamma d} \tag{15}$$

For our previous numerical example and an axion velocity of $v = 2.3\cdot 10^5 m/s$ one gets $L \sim 10^{-22}m$, which means that the axion immediately decays at the surface of the weak-link region. Moreover, since $P_{a\to\gamma} = P_{\gamma\to a}$ it can equally likely recombine back into an axion when leaving the weak-link region, thus producing ATJ.

We have thus shown that JJs act like a 'wall' for phase-synchronized axions, and axions are not expected to exist within the weak-link region of a JJ but decay into microwave photons. The total probability of axion decay in the junction is given by $pP_{a\to\gamma}$, where p is the probability that the axion phase synchronizes. There are no astrophysical or cosmological constraints on p since almost all matter of the universe is not in the form of JJs, hence $p \sim O(1)$ is compatible with the astrophysical dark matter status of the axion.

Let us now come to measurable effects to test this theoretical idea. It is well-known that external microwave radiation applied to a Josephson junction leads to distortions in the $I-V$ curve, the well-known Shapiro steps [17]. Within the RSJ model, one can calculate (see, e.g., [31]) that external monochromatic microwave radiation of signal frequency $\hbar\omega_s = 2eV_s$ leads to a distortion I_s in the measured current-voltage curve $I(V)$ given by

$$I_s(V) = \frac{P_s}{4}(RI_c)^2\frac{1}{V^2}\left[\frac{V+V_s}{(V+V_s)^2+(\frac{\delta V}{2})^2} + \frac{V-V_s}{(V-V_s)^2+(\frac{\delta V}{2})^2}\right]. \tag{16}$$

Here P_s is the signal power, and δV is determined by the line width of the Josephson frequency.

When the Josephson frequency $\hbar\omega_J = 2eV$ resonates with the axion mass $m_a c^2$ we may assume that all axions hitting the weak-link region synchronize and decay ($p = 1$), hence the expected signal power P_s is given by

$$P_s = \rho_a v A. \tag{17}$$

Here ρ_a is the Halo axionic dark matter energy density close to the earth, v is the velocity of the earth relative to the galactic center, and A is the area of the weak-link region perpendicular to the axion flow. The velocity v is

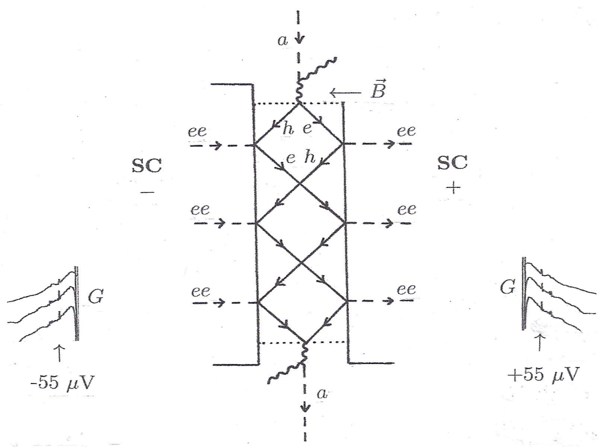

FIG. 2: Axion triggering the transport of n Cooper pairs ee in an S/N/S junction by multiple Andreev reflections, here shown for the example $n = 3$. The dotted line corresponds to the normal metal surface. The left and right insets show the shape of the differential conductivity curve $G(V)$ as measured by Hoffmann et al. [12] for $T = 0.9K, 0.5K, 0.1K$ (top to bottom), with a peak occuring at $\pm 0.055mV$.

known to be $2.3 \cdot 10^5 m/s$, with a yearly modulation of about 10% around its mean value [4, 32].

For a typical tunnel junction [28, 29], the distance between the superconducting electrodes is $d \sim 1nm$ and hence $A \sim 1nm \times 1\mu m \sim 10^{-15} m^2$, whereas S/N/S junctions [12–15] allow for a much larger area of the weak link region, $A \sim 1\mu m \times 1\mu m \sim 10^{-12} m^2$, since for these junctions $d \sim 1\mu m$ is much larger. Thus we expect for S/N/S junctions an axion signal that is stronger by a factor 1000, and which in addition can be further amplified by multiple Andreev reflections. We are thus pointed towards S/N/S junctions as being particularly suited for axion detection.

We propose as a specific microscopic model underlying the interaction of axions with resonant S/N/S junctions the process sketched in Fig. 2. An axion entering the weak link region with a transversal velocity component decays close to the normal metal surface into two microwave photons, one with $q \approx 0$ and the other one with frequency $\hbar\omega_s \approx m_a c^2 = 2eV_s$. The $q \approx 0$ photon interacts with a hole-electron pair in the weak-link region (holes h and electrons e can enter from the surrounding superconductors with energy $-\Delta$, where Δ is the gap energy). The hole and the electron perform multiple Andreev reflections in the usual way [12, 13], meaning the hole is reflected at the S/N interface as an electron and annihilates in this process a Cooper pair, whereas the electron is reflected at the other S/N interface as a hole, creating in this process a Cooper pair. In total, there are n Andreev reflections, with

$$n \approx \frac{2\Delta}{eV} + 1 \tag{18}$$

[12]. At the end of this process, when both the electron and hole energy exceed the gap energy Δ they either just leave the weak-link region or annihilate back into a low-energy photon, which together with another photon of Josephson frequency $\hbar\omega_J = 2eV_s = m_a c^2$ can recombine back into an axion, which leaves the detector unharmed. In total, there is an ATJ process and each incident axion triggers the transport of n Cooper pairs. These additional Cooper pairs produce a signal $G_s = dI_s/dV$ in the measured differential conductivity $G(V)$ of the junction at the signal voltage $V_s = m_a c^2/(2e)$. The total signal current produced by axions is given by

$$I_s = \int G_s dV = \frac{N_a}{\tau} \cdot n \cdot 2e = \frac{\rho_a}{m_a c^2} vA \cdot n \cdot 2e \tag{19}$$

where N_a/τ is the number of axions hitting the normal metal region per time unit τ. Since $2eV_s = m_a c^2$ we get

$$\rho_a = \frac{I_s V_s}{vAn}. \tag{20}$$

This can be used to experimentally estimate the axion dark matter density ρ_a from an experimental measurement of V_s and I_s.

In [12] Hoffmann et al. have observed a signal of unknown origin that is consistent with our theoretical expectations. Independent of the temperature (which is varied from 0.1K to 0.9K) they consistently observe a small peak in their measured differential conductivity $G(V)$ at the voltage $V_s = \pm 0.055mV$ (see insets of Fig. 2, data from [12]). Their measurements provide evidence for a signal current feature of size $I_s = (8.1 \pm 1.0) \cdot 10^{-8} A$, which is obtained by integrating the area under the observed signal peak of the differential conductivity. Their noise measurements also indicate that every quasi-particle performs $n = 7$ Andreev reflections [12]. The area of the metal plate of their junction is $A = 0.85\mu m \times 0.4\mu m = 3.4 \cdot 10^{-13} m^2$. From $2eV_s = ma_c^2$ we thus obtain an axion mass prediction of $m_a c^2 = 110\mu eV$ (equivalent to $f_a \sim 5.5 \cdot 10^{10} GeV$), and eq. (20) yields the prediction $\rho_a = (0.051 \pm 0.006) GeV/cm^3$.

Astrophysical observations suggest that the galactic dark matter density ρ_d near the earth is about $\rho_d = (0.3 \pm 0.1) GeV/cm^3$ [21]. But this includes all kinds of dark matter particles, including WIMPS. Generally, axions of high mass will make up only a fraction of the total dark matter density of the universe, which can be estimated from cosmological considerations to be about $\rho_a/\rho_d \approx (24\mu eV/m_a c^2)^{7/6}$ [3]. For $m_a c^2 = 110\mu eV$ we thus expect an axionic dark matter density that is a fraction $(24/110)^{7/6} \approx 0.17$ of the total dark matter density, giving $\rho_a \approx 0.17 \cdot \rho_d = (0.051 \pm 0.017) GeV/cm^3$. The experimental results of Hoffmann et al. together with our theoretical prediction (20) are thus in perfect agreement with what is expected from astrophysical observations.

To either refute or confirm our hypothesis that the signal seen in [12] is produced by dark matter axions, further measurements are needed. Clearly one should test if the signal survives careful shielding of the junction from any external microwave radiation. A signal produced by axions cannot be shielded. Moreover, one might look for a possible small dependence of the measured signal intensity on the spatial orientation of the metal plate relative to the galactic axion flow (a precise directional measurement would be extremely helpful). Finally, and most importantly, the velocity v by which the earth moves through the axionic BEC of the galactic halo exhibits a yearly modulation of about 10%, with a maximum in June and a minimum in December (as already used in early searches for WIMPS [32]). If the JJ signal is produced by axions, then its intensity should show the same 10% modulation effect over a period of a year. This can be tested in future experiments. In [12] also some fine structure of $G(V)$ near 0.08mV is observed, which might be a hint for further axion-like particles with different mass.

To conclude, in this letter we have described a macroscopic quantum effect in Josephson junctions that may help to prove the existence of axionic dark matter in future measurements. Phase-synchronised axions cannot exist in the weak-link region of JJs due to a (formal) huge magnetic field that is simulated to them by the driven JJ environment in the voltage stage. Axions are expected to decay when entering the weak-link region of the junction and trigger the transport of additional Cooper pairs. This leads to a small measurable signal for the differential conductivity (a Shapiro step-like signal without externally applied microwave radiation) if the axion mass resonates with the Josephson frequency. The effect is particularly strong in S/N/S junctions which have a much larger weak-link region than tunnel junctions and where the Cooper pair transport is amplified by multiple Andreev reflections. A candidate signal of unknown origin has been observed in measurements of Hoffmann et al. [12], which interpreted in this way points to an axion mass of 0.11 meV and a local axionic energy density of 0.05 GeV/cm^3.

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