Axion mass estimates from resonant Josephson junctions

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Recently it has been proposed that dark matter axions from the galactic halo can produce a small Shapiro step-like signal in Josephson junctions whose Josephson frequency resonates with the axion mass [C. Beck, PRL 111, 231801 (2013)]. Here we show that the axion field equations in a voltage-driven Josephson junction environment allow for a nontrivial solution where the axion-induced electrical current manifests itself as an oscillating supercurrent. The linear change of phase associated with this nontrivial solution implies the existence of a large magnetic field in a tiny surface area of the weak link region of the junction which makes incoming axions decay into microwave photons. We derive a condition for the design of Josephson junction experiments so that they can act as optimum axion detectors. Four independent recent experiments are discussed in this context. The observed Shapiro step anomalies of all four experiments consistently point towards an axion mass of $(110 \pm 2) \mu eV$. This mass value is compatible with the recent BICEP2 results and implies that Peccei-Quinn symmetry breaking was taking place after inflation.

About 95% of the energy contents of the universe appears to be of unknown origin, in the form of dark matter and dark energy. While there is a lot of astrophysical evidence for the existence of dark matter and dark energy, a deeper understanding of the physical nature of these main ingredients of the universe is still lacking. Clearly it is important to design new experiments on earth that could have the potential to unravel some of the unknown physics underlying dark matter and dark energy.

At the particle physics level, there are two main candidates what dark matter could be. These are WIMPS (weakly interacting massive particles) [1] and axions [2–5]. WIMPS are motivated by supersymmetry, whereas axions are motivated by the solution of the strong CP problem in QCD. Various experimental searches to detect WIMPS [6] and axion-like particles [9–12] on the earth are currently going on.

Very recently, there have been three new suggestions how one could possibly detect dark matter axions in laboratory experiments on the earth [13–15]. All three proposals have in common that they are based on relatively small devices and that they suggest to look for small oscillating electric currents induced by axion flow, with a frequency given by the axion mass. Proposal 1 [13] is based on a technique similar to nuclear magnetic resonance (NMRI), known from medical imaging. Proposal 2 [14] is based on resonance effects in Josephson junctions. Proposal 3 [15] suggests to use LC circuits cooled down to mK temperatures.

In this paper we present a detailed calculation describing the physics of proposal 2, starting from the field equations of axion electrodynamics in a Josephson environment. In contrast to axions in vacuum, in a Josephson junction the axion has the possibility to induce electric supercurrents, rather than just ordinary currents. Our main result presented in this paper is that, besides the trivial solution where the axion passes through the Josephson junction without interaction, there is a nontrivial solution to the axion field equations due to these supercurrents. We show that the nontrivial solution implies the existence of a huge (formal) axion-flow generated magnetic field in a tiny surface area of the weak-link region of the junction, which makes incoming axions decay into microwave photons. The axion flow from the galactic halo through the junction then leads to a small measurable excess current of Cooper pairs, for which we will derive a concrete formula. The experimental consequence of this are Shapiro steps [16, 17] generated by axion flow, which are small but observable provided certain conditions on the design of the Josephson junction are satisfied. We will derive these conditions explicitly.

An experiment by Hoffmann et al. based on S/N/S Josephson junctions [18], discussed in detail in [14], provided evidence for an axion mass of 110 $\mu eV$ and an axionic dark matter density of about 0.05 GeV/cm$^3$ if interpreted in this way. Here we will discuss the results of four different experiments [18–21]. In all four cases small Shapiro step-like anomalies have been observed that, if interpreted within our theory, point towards an axion mass of $m_a c^2 = (110 \pm 2) \mu eV$.

The predicted axion mass value has profound cosmological implications. If this value is confirmed by further experiments, it means that the Peccei-Quinn symmetry breaking took place after inflation [22]. Employing the recent results of [22, 23] our result implies that the fractional contribution $\alpha_{dec}$ to the cosmic axion density from decays of axionic strings and walls is $\alpha_{dec} = 0.66 \pm 0.05$.

Let us consider the classical field equations of axion electrodynamics [3, 4, 24, 25] in a Josephson junction (JJ) [14, 16, 17, 20]. $\theta = a/f_a$ denotes the misalignment angle of the axion field $a$, $\delta$ the electromagnetic phase difference in the JJ. In SI units one has

\begin{equation}
\ddot{\theta} + \Gamma \dot{\theta} - c^2 \nabla^2 \theta + \frac{m_a c^4}{\hbar^2} \sin \theta = -\frac{g_a}{4\pi^2} \frac{1}{f_a^2} c^3 e V \ddot{B} \quad (1)
\end{equation}

\begin{equation}
\nabla \times \vec{B} - \frac{1}{c^2} \frac{\partial \vec{E}}{\partial t} = \mu_0 \vec{j} + \frac{g_a c}{\pi \epsilon_0} \left( \vec{E} \times \nabla \theta - \vec{B} \dot{\theta} \right) \quad (2)
\end{equation}

\begin{equation}
\nabla \times \vec{E} = \frac{\rho}{\epsilon_0} + \frac{g_a}{\pi} \alpha c B \nabla \theta \quad (3)
\end{equation}

\begin{equation}
\ddot{\delta} + \frac{1}{RC} \dot{\delta} + \frac{2eI_c}{hc} \sin \delta = \frac{2e}{hc} (I + I_a) \quad (4)
\end{equation}
Here $m_a$ denotes the axion mass, $f_a$ is the axion coupling constant, $\Gamma$ is a tiny damping constant, $\vec{E}$ is the electric field, $\vec{B}$ is the magnetic field, $g_\alpha$ is a coupling constant of order 1 ($g_\alpha = -0.97$ for KSVZ axions \cite{27, 28}, $g_\gamma = 0.36$ for DFSZ axions \cite{29, 30}), $\alpha$ is the fine structure constant, $I_e$ is the critical current of the junction, $I$ an external driving current, $I_a$ is a small axion-induced electric current in the junction, $R$ is the normal resistance of the junction, and $C$ its capacity. As usual, $\vec{j}$ and $\rho$ denote electric current and charge densities.

The expected mass of the QCD dark matter axion is in the region $\mu eV$ to $meV$ due to astrophysical and cosmological constraints; the corresponding Compton wave length is much larger than the typical size of a JJ. Thus we may neglect spatial gradient terms $\nabla \theta$ in the above equations and consider the axion field as being approximately spatially homogeneous. The most important axion contribution for detection purposes comes from the last term in eq. \ref{eq:1}: In a magnetic field $\vec{B}$, temporal changes $\dot{\theta}$ of the axion angle imply an axion-induced electric current density $\vec{j}_a$ given by

$$\mu_0 \vec{j}_a = -\frac{g_\alpha}{\pi c} \vec{B} \dot{\theta}. \quad (5)$$

Note that this current is in the direction of the magnetic field $\vec{B}$, and not orthogonal to it, as in ordinary electrodynamics.

Dark matter axions correspond to an oscillating solution of eq. \ref{eq:1} with $\vec{E} \vec{B} = 0$ and $\Gamma$ negligible, given by

$$\theta(t) = \theta_0 \cos(\omega_ar t + \text{const}). \quad (6)$$

The frequency $\omega_ar = 2\pi \nu_ar = m_ac^2/\hbar$ is given by the axion mass. The dark matter energy density due to axions, $\rho_a$, is related to the amplitude $\theta_0$ of the oscillations by

$$\rho_a = \frac{1}{\hbar^3 c^3} \frac{1}{2} m_a^2 c^2 f_a^2 \theta_0^2. \quad (7)$$

This can be used to eliminate $\theta_0$ as

$$\theta_0 = \sqrt{\frac{2c^5 \hbar^3 \rho_a}{f_a m_a c^3}}. \quad (8)$$

$\theta_0$ is very small: The astrophysical estimates of dark matter density in the halo \cite{31} give something of the order $\theta_0 \sim 10^{-19}$.

Now consider as a suitable axion detector a driven JJ in the voltage stage which contains a constant magnetic field $\vec{B}$ near the surface of the weak link (WL) region that points in the direction of the bias current $I$ of the junction. At the moment we do not discuss the origin of this magnetic field, later we will see that it is self-induced by axion flow as a consequence of the field equations. We denote the distance between the two superconducting electrodes of the junction by $d$, the width of the superconductors by $w$ and their height by $L$, so that the volume of the weak link region is $dwL$. The volume of the region where the magnetic field is present is $dwl_1$, we assume $L_1 << L$, i.e. the magnetic field is only present near the surface of WL. Let us consider axions from the galactic halo that enter WL transversally with velocity $v_a$ through the plane spanned up by $w$ and $d$. The dark matter oscillations \ref{eq:5} yield via eq. \ref{eq:4} an axion-induced current $\vec{i}_a$ which couples into the JJ via eq. \ref{eq:1}. $\vec{i}_a$ is given by

$$\vec{i}_a(t) = \vec{j}_a(t)A = -\frac{Ag_\alpha}{\mu_0 \pi c} \vec{B} \dot{\theta} \quad (9)$$

$$= \frac{Ag_\alpha \omega_a \theta_0}{\mu_0 \pi c} \vec{B} \sin(\omega_ar t + \text{const}). \quad (10)$$

Here $A = L_1w$ is the small surface area through which the magnetic field penetrates. $\vec{i}_a(t)$ is an oscillating current produced by entering dark matter axions coming from outside WL. Inside WL there is a superconducting environment and hence the possibility that the oscillating current \ref{eq:10} manifests itself as a supercurrent in the JJ. This means we can write for $I_\alpha(t) = |\vec{i}_a(t)|$

$$I_\alpha(t) = I_\alpha \sin(\theta(t)), \quad (11)$$

where $I_\alpha$ can be regarded as an axion-generated critical current in the junction, and the phase $\theta(t)$ grows linearly inside WL. Equality between eq. \ref{eq:10} and \ref{eq:11} implies

$$\theta(t) = \omega_ar t + \text{const} \quad (12)$$

and

$$I_\alpha = \frac{Ag_\alpha \omega_a \theta_0}{\mu_0 \pi c}. \quad (13)$$

Apparently, coincidence of the electric currents \ref{eq:11}, \ref{eq:10} produced in a small vicinity inside and outside WL can be achieved if the angle variable $\theta(t)$ switches from harmonic oscillations to linearly increasing behavior modulo $2\pi$ when entering WL, still with the same frequency $\omega_ar$.

The linear change $\dot{\theta} = \omega_ar$ from eq. \ref{eq:12} now couples back into the system via eq. \ref{eq:1}. Suppose the effective damping constant $\Gamma$ in eq. \ref{eq:1} satisfies $\Gamma >> \omega_ar \theta_0$. This is not a very restrictive condition, since for axions with a mass of $O(100\mu eV)$ one has the very small value $\omega_ar \theta_0 \sim 10^{-8}s^{-1}$. If this condition is satisfied then the first, third and fourth term on the left-hand side of eq. \ref{eq:1} can be neglected, and eq. \ref{eq:1} reduces to

$$\Gamma \dot{\theta} = -\frac{g_\gamma}{4\pi^2} \frac{1}{f_a} c^3 e^2 \vec{E} \vec{B}. \quad (14)$$

The linear increase $\dot{\theta} = \omega_ar$ inside WL due to eq. \ref{eq:12} thus induces an axion-generated magnetic field $\vec{B}$ via eq. \ref{eq:14}. Using $E = V/d$, where $V$ is the external voltage applied to the JJ, as well as using the resonance condition $m_ac^2 = 2eV_b$ between axion mass and Josephson frequency $\omega_J = 2eV_b/\hbar = \delta$ (which can be achieved by suitably choosing $V$) we get from eq. \ref{eq:14}

$$B = \frac{8\pi^2 f_a^2 \Gamma_d}{g_\gamma c^2 e \hbar}. \quad (15)$$
We have thus found a nontrivial solution of the field equations [1–4] where there is an axion-generated magnetic field (in the direction of the bias current) given by [15] due to the existence of supercurrents. Depending on what is assumed for Γ, this can be a huge magnetic field (see [14] for some numerical examples), but it is penetrating only through a tiny surface area $A = L_1 w$ so that the flux is reasonably sized. To properly describe axion electrodynamics in a JJ, we also need to take into account the probability of axion decay in a strong magnetic field. From the Primakov effect one has for the decay probability of axions in a magnetic field of strength $B$ [24]

$$P_{a \rightarrow \gamma} = \frac{1}{16\beta_a}(g_\gamma B e c L)^2 \frac{1}{\pi^3 f_a^2} (\alpha \sin \frac{qL}{\pi})^2.$$  \hspace{1cm} (16)

Here $L$ is the length of the detector, $q$ is the axion-photon momentum transfer, and $\beta_a = v_a/c$. In particular, for the length scale $L_1$ within which the axion decays with probability $P_{a \rightarrow \gamma} = 1$ one has (for $qL_1 << h$)

$$L_1 = \frac{\hbar c^2}{f_a \Gamma d} \sqrt{\frac{\beta_a}{4\pi \alpha}}.$$  \hspace{1cm} (17)

Clearly, the axion-generated $\mathcal{B}$ field is only present in the area where the axion still exists and has not yet decayed. This suggests to use for the area $A$ in equation (13) the value $A = L_1 w$, where $L_1$ is given by (17). Putting eq. (15), (17) and (8) into eq. (13) a remarkable simplification takes place and one finally ends up with the simple formula

$$I_c^a = \frac{\rho_a v_a}{\hbar a} w \cdot 2e.$$  \hspace{1cm} (18)

Note that physically unmeasurable quantities like the formal huge magnetic field concentrated in a tiny surface area as well as the unknown constant $\Gamma$ have all dropped out, and the critical current $I_c^a$ is basically determined by the dark matter axion velocity $v_a$ relative to the junction and the axionic dark matter density near the earth $\rho_a$, as well as the fundamental constants $\hbar = 2\pi \hbar$, $\alpha$ and $2e$ (the charge of Cooper pairs).

In a recent preprint [22] it was proposed that axions can have different interactions with Cooper pairs in a superconductor than in the vacuum case, possibly stronger ones, since electron number is not conserved. This is in line with the ideas presented here: In our consideration presented here and in [14], incoming axions decay into microwave photons and trigger at the same time the process of Cooper pairs forming out of ordinary electrons, thus producing additional supercurrents in the voltage-biased junction. The (maximum) additional critical current $I_c^a$ as allowed by axion electrodynamics is given by [15]. This critical current $I_c^a$ is derived from the axion field equation (2) and is a current of ordinary electromagnetic weak link; it is not related to the existence or non-existence of a possible weak link in Peccei-Quinn symmetry as discussed in [22].

As with any critical current, $I_c^a$ represents the maximum electric supercurrent one can expect to see due to axionic dark matter passing through a Josephson junction, an idealized situation, as allowed by the classical field equations. In practice, the current will often be smaller, depending on the experimental situation and the geometry of the Josephson junction used. To work this out further, let us denote by $A^*$ the surface area of WL perpendicular to axion flow, which for orthogonally entering axions is given by $A^* = w d$. So far we did mainly do classical axion electrodynamics. But one also needs to take into account the particle nature of axions and Cooper pairs. Following the ideas of [14], we may assume that each axion entering WL triggers the flow of $N$ Cooper pairs (Fig. 2 in [14]). In an S/N/S junction $N$ is related to the number of Andreev reflections and given by

$$N \approx \frac{2\Delta}{eV} + 1$$  \hspace{1cm} (19)

where $\Delta$ is the gap energy of the superconductor [14][18]. The maximum observable supercurrent is constrained by the geometry of the JJ and given by the number of axions hitting the WL region of surface area $A^*$ per time unit, multiplied by $2eN$:

$$I_c^a = \frac{\rho_a}{m_a c^2} v_a A^* \cdot 2eN.$$  \hspace{1cm} (20)

For an optimum S/N/S axion detector, both formulas [18] and (20) should be valid, i.e. $I_c^a \approx I_c^a$. By equating them we obtain

$$dN \approx \frac{m_a c^2}{\sqrt{\alpha} \rho_a v_a}.$$  \hspace{1cm} (21)

The right-hand side is just determined by astrophysical dark matter properties, whereas the left-hand side yields a relation for the detecting JJ experiment. For the Aluminium junction used by Hoffmann et al. [18], one can readily check that condition (21) is satisfied. This experiment thus provides an optimum axion detector. If one wants to use other S/N/S Josephson junction, say with a higher gap energy $\Delta$, then naturally $d$ must be chosen smaller. For the dark matter parameters advocated in [14], one obtains a characteristic length scale of $dN \approx 6 \mu m$.

Let us now discuss the experimental consequences of our theory. As previously discussed in [14], the decaying axions produce photons and these produce small axion-induced Shapiro steps, which are measurable for junctions with sufficiently large $A^*$. The main Shapiro step occurs at a voltage given by $V_a = m_a c^2/2e$, other integer multiples of $V_a$ may also occur if the axion-induced Cooper pair flow intensity is high. The typical step size should be given by eq. (20).

First, let us discuss Hoffmann et al.’s experiment [18], based on Cu-Al-Cu S/N/S junctions. Their measurement of a Shapiro step-like feature of unknown origin
at $V_a = 55\mu eV$ in [18] was used in [14] to estimate the axion mass as $m_a c^2 = 2eV_a = 110\mu eV$ and the axionic dark matter density near the earth as being $\rho_a = 0.051 GeV/m^3$, assuming orthogonal axion flow. The velocity $v_a$ of axions traveling through the JJ was assumed to be given by the value $v_a = 2.3 \cdot 10^8 m/s$ (the velocity of the earth relative to the galactic halo). Let us now look at other experiments as well.

In the experiment of Golikova et al. [19], based on Al-(Cu/Fe)-Al microbridges, a double-peak peculiarity of the measured differential resistance is observed (Fig. 4 in [19]), with one rather constant peak occurring at $(52 \pm 5)\mu V$, whereas the other peak position near $75\mu V$ is dependent on the length of the sample and the applied magnetic field. A possible interpretation would be to interpret the first (universal) peak as coming from axions and the second peak as being due to a minigap produced by the proximity effect. Further measurements are needed to check this.

He et al. [20] use W-Au-W S/N/S junctions and report the observation of a large number of fractional Shapiro steps without externally applied microwave radiation. Most Shapiro steps occur in the temperature region 2.8-3.2K, and for this temperature region the strongest steps occur at $(53 \pm 3)\mu V$ (see Fig. 2 in [20]), which is again the axion voltage $V_a$. Since the Wolfram superconductors used by He et al. have a gap energy $\Delta$ that is larger by a factor 5 as compared to the aluminium superconductors used in [18] and [19], the number of Andreev reflections $N$ given in eq. (19) is larger, and hence a higher intensity of Cooper pair flow is induced by the incoming axions. This may be the reason that a larger number of observable Shapiro steps is excited in this experiment. In addition, the minigap structure created by the proximity effect may create further Shapiro steps in this junction.

Finally let us discuss another experiment performed by Bae et al. [21], which is quite different from the previous ones, in the sense that a high-$T_c$ superconductor is used, and that there is also some external forcing with microwaves with a given frequency $\nu_1$. Bae et al. [21] investigated the occurrence of Shapiro steps when irradiating a micron-sized sample of BI-2212, a high-$T_c$ crystal, which contains a stack of about 80 intrinsic tunnel Josephson junctions. The superconducting layers of this crystal are separated by $d = 1.2nm$ from each other. The sample used by Bae et al. had width $w = 5\mu m$, hence in total the area of the WL region is given by $A^* = 80 \cdot dw = 4.8 \cdot 10^{-13} m^2$. This effective area is large enough to produce measurable axion-induced currents via eq. (20). From (20) one obtains the prediction $\tilde{I}_a = 16.4 nA$ if $N = 1$ and $\rho_a = 0.051 GeV/cm^2$ is used.

Bae et al. [21] irradiated their probe by external microwave radiation of frequency $\nu_1 = 5GHz$, 13 GHz, 18 GHz, 23GHz, and 26 GHz, respectively. Note that 26 GHz is $\nu_a$. For all values of $\nu_1$ they observed well-pronounced integer Shapiro steps at voltages $V_n$ given by $2eV_n = nh\nu_1$, as expected from the RSJ model [16], with $n$ integer. However, two unexplained peculiarities occurred (see Fig. 1, data from [21]):

1. While for $\nu_1 = 5, 23, 26$ GHz only the usual integer Shapiro steps were observed, at the frequency $\nu_1 = 18$ GHz also one additional fractional Shapiro step is seen, formally with $n = 3/2$ (see Fig. 1a). This unusual step occurs at a voltage $(55 \pm 1)\mu V$, and the step size is (for increasing voltage) 16.4 nA. While in principle fractional Shapiro steps are possible due to non-sinusoidal contributions in the current-phase relation, it is very unusual to have only one such step (there is none at e.g. $n = 1/2$ and $n = 5/2$, and also none for the other values of $\nu_1$). Our physical interpretation is that this unusual step is due to axion flow through the junction and that it is stabilized due to the commensurate ratio $3\nu_1 = 2\nu_a$. The observed step size 16.4nA agrees with what is expected from eq. (20).

2. While for $\nu_1 = 5, 23, 26$ GHz basically all low-$n$ integer Shapiro steps are observed, for $\nu_1 = 13$ GHz only odd-$n$ Shapiro steps are seen ($n = -5, -3, -1, 1, 3, 5$) whereas the even-$n$ Shapiro steps ($n = -4, -2, 0, 2, 4$) are suppressed, so that the voltage difference between neighbored steps is $(55 \pm 1)\mu V$ rather than the expected $27\mu V$ (see Fig. 1b). Due to these double-voltage steps the pattern looks much more similar to a pattern generated by a (phase-shifted) frequency of 26 GHz rather than one of 13 GHz. Our physical interpretation is that at even $n$ the axion-generated Shapiro steps fall onto the ordinary ones generated by the frequency $\nu_1$ and can compensate them, provided they have the same magnitude but opposite sign. The observed zero-crossing step sizes for $n = -3, -1, 1, 3$ are indeed 16.4 nA, which would allow for such a destructive interference.

In summary, all four experiments mentioned contain peculiar Josephson resonance effects associated with the voltage $V_a \approx 55\mu V$, pointing towards an axion mass of $(110 \pm 2)\mu eV$, where we base our error estimate on the data of [18] and [21]. Additional experimental tests are

FIG. 1: Possible signatures of a 110 $\mu eV$ axion in the measurements of Bae et al. [21]: (a) Anomalous Shapiro step (indicated by arrow) occuring at the voltage $V_a = 55\mu V$ ($n = 3/2$) for $\nu_1 = 18$ GHz and (b) anomalous double-size Shapiro steps with voltage differences 55$\mu V$ occuring at odd integers for $\nu_1 = 13$GHz.
of course still needed. A typical axion Shapiro step is predicted to exhibit small daily and yearly periodic oscillations in intensity, similar as in searches for WIMPS \cite{8}. The daily oscillations are expected to come from the fact that the galactic axion flow relative to the earth is directed, the earth rotates but axions produce the strongest signal if they enter the junction transversally. We also emphasize that it is clearly important to extend the search range of other axion search experiments, which are not based on JJs, to the mass region suggested by JJs, $m_a c^2 \sim 0.11 \mu eV$. A recent experimental proposal in this direction is \cite{33}.

Our estimate of the axion mass from Josephson resonances has important cosmological implications. It implies that the Peccei-Quinn symmetry was broken after the end of inflation \cite{22, 23}. Based on the results of \cite{22} (assuming that axions make up all dark matter), the mass value $m_a c^2 = 110 \mu eV$ translates into an axion coupling constant of $f_a = 5.64 \cdot 10^{10} \text{GeV}$, a freeze-out temperature of $T_f = 998 \text{ MeV}$, and for the fractional contribution $\alpha_{\text{dec}}$ to the cosmic axion density from decays of axionic strings and walls we obtain from the formula

$$\alpha_{\text{dec}} = \left(\frac{m_a c^2}{(71 \pm 2) \mu eV}\right)^{7/6} - 1$$

derived in \cite{22} the prediction $\alpha_{\text{dec}} = 0.66 \pm 0.05$.

To conclude, in this paper we have presented a detailed derivation why axions can generate small measurable electric currents in Josephson junctions. This derivation goes beyond the one presented in \cite{14}, because our only assumption is the validity of the field equations of axion electrodynamics, plus the assumption that the axion-induced electric current can manifest itself as a supercurrent. We discussed peculiarities in the Shapiro step patterns measured by four different experimental groups for very different types of Josephson junctions. All four experiments point towards an axion mass of $110 \mu eV$.

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