Snowmass2021 - Letter of Interest

Low-Mass Broadband Electrical Action Sensing Techniques (BEAST)

Thematic Areas: (check all that apply □/■)
■ (CF2) Dark Matter: Wavelike

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Abstract: When axions, $a(t)$, mix with an applied photonic degree of freedom (γ), a photon of different frequency will be produced via a second photonic degree of freedom (γ') through the inverse Primakoff effect, given by $\gamma + a \rightarrow \gamma'$. From the view point of the second photon degree of freedom, γ', this is a non-conservative electrodynamical process due to the creation of photons from an external non-electromagnetic source (namely the first photonic degree of freedom mixing with the axion). If the first photonic degree of freedom is an applied DC $\vec{B}$-field, the modified axion electrodynamical equations become similar to the electrodynamics of an AC voltage source, producing an AC electromagnetic action (or emf, $\mathcal{E}_a(t)$) oscillating at the Compton frequency of the axion. As in standard electrodynamics, $\mathcal{E}_a(t)$ may be modelled as an oscillating effective impressed magnetic current boundary source. This boundary source is present in the axion-photon electrodynamical equations[1;2], however, the relevant term is usually approximated to equal zero, so only a derivative axion-photon coupling remains, consistent with a zero total derivative. In the low-mass limit where the Compton wavelength of the axion is greater than the dimensions of the experiment (quasi-static limit) this approximation is no longer valid and the boundary source terms are the dominant effect. The end result is the realisation of new Broadband Electrical Action Sensing Techniques (BEAST) with a sensitivity linearly proportional to the axion photon coupling[1–3]. Contrary to what has been published by others[4–6], we have subsequently shown our sensitivity calculations are consistent, and calculate that the electric field produced by the axion current in the low-mass limit is suppressed. *Our technique does not detect this suppressed axion induced electric field, $\vec{E}_a(t)$, but directly detects $\mathcal{E}_a(t)$ from the non-conservative process*. This is a much more sensitive technique because it is not suppressed by the mass of the axion and puts axion-photon coupling low-mass experiments on a similar footing to axion-gluon coupling experiments[7;8] such as the CASPEr[9;10] and Sussex-RAL-ILL nEDM experiments[11], which are not suppressed by the axion mass and have also been projected to be sensitive enough to detect QCD axions at low mass ranges below $10^{-8} eV$. This result may be considered controversial, but no one has yet shown how this calculation is wrong! To fully consider this effect in axion electrodynamics, the electrodynamics of standard impressed sources that convert external energy to electromagnetic must be fully understood[12–15].

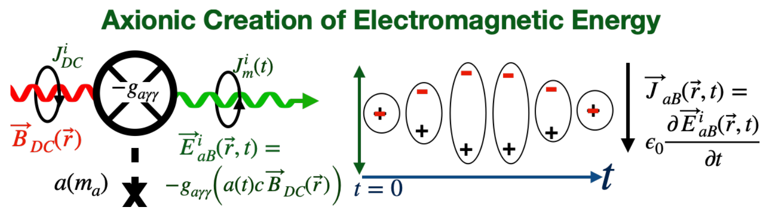

Figure 1: Schematic of the creation of electromagnetic energy through the mixing process between the axion particles, $a(m_a)$ and a DC $\vec{B}$-field, $\vec{B}_{DC}(\vec{r})$, via the inverse Primikoff effect. $\vec{B}_{DC}(\vec{r})$ is created from an impressed DC electric current, $\vec{J}^i_{DC}(\vec{r})$, exciting the coil of an electromagnet (a boundary source for the DC magnetic field). The created electromagnetic energy in the second photon degree of freedom is at a frequency, ω_a, equivalent to the axion mass, m_a, represented by the effective magnetic current boundary source, $\vec{J}^i_m(\vec{r},t)$, which sources an external force per unit charge, represented by an impressed electric field, $\vec{E}^i_{aB}(\vec{r},t)$, with a mixing efficiency of the axion-photon coupling of $g_{a\gamma\gamma}$. The external force per unit charge, $\vec{E}^i_{aB}$, supplied by the mixing process directly oscillates the axion background "Noether" charge, with the derivative equal to the axion displacement current, $\vec{J}_{aB}(\vec{r},t)$. Experiments sensitive to the axion current, $\vec{J}_{aB}(\vec{r},t)$ couple to the derivative to the axion scalar field $\frac{\partial a(t)}{\partial t}$ [16–18], while experiments sensitive to the external force per unit charge, $\vec{E}^i_{aB}$, couple directly to the axion scalar field, $a(t)$ [1–3;19].

Background

In standard electrodynamics the common idea is that the motion of a charge carrier is only due to the Lorentz Force, $\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$. However there are other non-electrical causes by which a force on an electron can manifest, or current can flow through a conductor, known as an "impressed force"[15]. If, formally, we write this as the product of the carrier charge, q, and an "impressed field", $\vec{E}^i$, so that $\vec{F}^i = q\vec{E}^i$, the impressed field can then be inputted to Maxwell's equations through an extended constitutive relation, which is defined by an equivalent total field, given by $\vec{E}^T = \vec{E} + \vec{E}^i$ [12–14]. An example of this is an AC voltage source, where $\vec{E}^i$ is an external non-electromagnetic source with an effective electric vector potential, which can drive an oscillating photonic degree of freedom through an electrical action or "electromotive force" (emf)[12–15].

In contrast, axion modified electrodynamics represents the equations of motion from the point of view of two photonic degrees of freedom (γ and γ') and one axion degree of freedom, $a(t)$. Analogous to the voltage source, recently it was shown that the equations of motion can be described by non-conservative electrodynamics, where the axion dynamics enters as a forcing function to standard electrodynamics through an extension of the constitutive relations[1;2]. Here, the forcing functions are mixing terms between the axion and the applied photon, which present as a product of the axion scalar field, $a(t)$, with either the electric field, $\vec{E}$, or magnetic field, $\vec{B}$, of the applied photonic degree of freedom, γ. Fig.1 shows the case when γ is an applied static magnetic field, $\vec{B}_{DC}(\vec{r})$. In this case, $a(t)$ mixes with $\vec{B}_{DC}(\vec{r})$. to create an axionic "impressed force per unit charge" of $\vec{E}^i_{aB}(\vec{r},t) = -g_{a\gamma\gamma}a(t)\vec{B}_{DC}(\vec{r})$, which drives the second photonic degree of freedom, γ', at the Compton frequency of the axion (here we can also define $\vec{E}^T = \vec{E} + \vec{E}^i_{aB}$).

It has been standard within the axion dark matter community to argue that as the axion mass $m_a \to 0$, the scalar axion field, $a(t)$, cannot directly enter the equations as described by axion modified electrodynamics. However, solutions in[1;2] show that the axion field is in fact a physical observable, so how could this be possible? The answer of course is already known, any equations of motion do not describe the system without specifying the boundary conditions, and for non-conservative systems this necessarily includes impressed boundary sources, which act as forcing functions and drive the system from an external energy source. Moreover, the axion-photon system consists of two photonic degrees of freedom, which causes non-trivial boundary conditions as both degrees of freedom must have their boundary conditions satisfied. The effect here is analogous to the well-known Witten's effect, when the axion parameter, $\theta = g_{a\gamma\gamma}a$, becomes a physical observable in the presence of non-trivial boundary conditions as explained in[19]. The non-trivial boundary conditions come from the fact that the process is a non-conservative one with respect to the second oscillating photonic degree of freedom, and like an AC voltage source in standard electrodynamics, there exist an oscillating effective impressed magnetic current boundary source[12–14],which is proportional to the impressed electrical DC current boundary source, $\vec{J}^i_{DC}(\vec{r})$ that drives the first photonic degree of freedom.

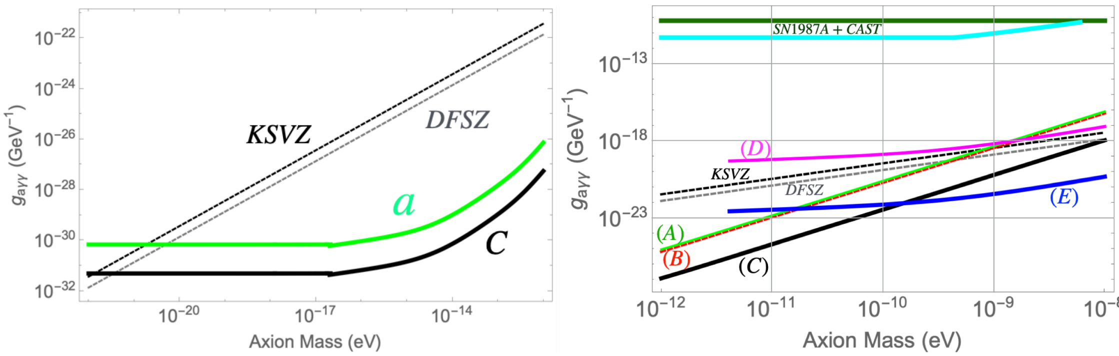

Figure 2: Sensitivity estimates of the Broadband Electrical Action Sensing Technique, compared to KSVZ and DFSZ axions and supernova and CAST limits. **Right**: (A) Solenoid and (B) toroid magnets of order $10cm$ in size, configured with a single coil winding to read out the short circuit current generated by the axion, with one hour and nine minutes of data and equivalent parameters. (C) Increasing the sensitivity of (A) by implementing the ORGAN 14 Tesla solenoid magnet[20] and collecting data for 1.5 months. In this case we can achieve the QCD axion limit for the whole axion masses range of 10^{-12} to 10^{-8} eV. (D) Solenoid magnet of (A) configured with a multiple coil toroid winding readout, to directly measure the emf generated by the axion. (E) Increasing the sensitivity of (D) by implementing the ORGAN 14 Tesla solenoid magnet[20] and collecting data for 1.5 months. This setup is better than the short circuit single winding readout for axion masses above $10^{-10}eV$. **Left**: Extrapolation of the sensitivity of the short circuit current technique to ULDM axions assuming 4 years of data. Below an axion mass of $3.3 \times 10^{-17}eV$ the measurement time is less than the inverse of the axion bandwidth.

Preliminary Work

Our preliminary work is based on three papers[1–3], which show that in the low-mass quasi-static limit a voltage will manifest across a lumped element. This could be a special configuration of an inductor, capacitor or resistor. For example, we calculated the current induced in a straight conducting wire (electric dipole antenna) in the limit where the DC $\vec{B}$-field can be considered as spatially constant and show that it has a sensitivity proportional to the axion mass. Following this we extended the topology by making use of the full extent of the spatially varying DC $\vec{B}$-field of the electromagnet. This was achieved by transforming the 1D conducting wire to a 2D winding with inductance, to fully link the effective impressed magnetic current boundary source, which defines $\vec{E}^{i}_{aB}$,and hence couple to the full axion induced electrical action (or electromotive force). We investigated two different topologies: The first used a single winding, and coupled to the effective short circuit current generated in the winding, which can be optimally read out using a sensitive low impedance SQUID amplifier: The second technique used multiple windings, with every turn effectively increasing the induced voltage, which is proportional to the winding number. The read out of this configuration may be optimised by implementing a cryogenic low-noise high input impedance voltage amplifier. The end result is the realisation of new Broadband Electrical Action Sensing Techniques with orders of magnitude improved sensitivity over current low-mass axion experiments, with a sensitivity linearly proportional to the axion photon coupling and capable of detecting QCD dark matter axions in the mass range of $10^{-12} - 10^{-8}eV$ and below, with the results summarized in Fig.2. Because this technique is not directly dependent on size, a very sensitive low-mass is possible, which is proportional to the current in the coil of the electromagnet, which is linked by the inductor windings.

Research Plans

Using this technique it is also possible to show that a low-frequency voltage will be picked up by a capacitor in a DC magnetic field, with a sensitivity proportional to the axion scalar field $a(t)$. This sensitivity will be further enhanced when combined with a winding discussed above. Simple experiments will be developed based on these concepts for long term operation as already shown in[2;3]. If the axion is discovered the models as presented in this work will be able to be tested experimentally, so it is important the community develops more than one way to search for axions. We also note that[3] has already set some competitive limits, but is not yet widely accepted, it is our goal to further improve on these bounds in a future experiment.

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