Ferromagnetic detector of (pseudo-) Goldstone bosons

I. V. Vorob'ev, I. V. Kolokolov, and V. F. Fogel'
Institute of Nuclear Physics, Siberian Branch of the Academy of Sciences of the USSR

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This letter discusses a laboratory experiment on the generation and detection of pseudoscalar Goldstone bosons (the arion, the axion, the majoron, etc.) by means of a coherent arion-photon conversion in a resonant system of magnetized spins of a paramagnetic or ferromagnetic medium.

1. In this letter we discuss a new experiment to search for an exotic long-range effect associated with the exchange of a massless or very light (pseudo-) Goldstone boson (an arion[1,2] or an axion[3]).

An experimental search for such a long-range effect is of interest both from the general physical standpoint (a new long-range force!) and because it could provide (indirect) information about the physics at energies of 10^6–10^{19} GeV, in a region totally inaccessible to accelerators. Methods for searching for exotic interactions and corresponding bosons on the basis of their macroscopic manifestations (e.g., anomalies in interactions of spin-polarized objects) hold promise. An interaction which arises in the exchange of an arion and which was discussed in Refs. 1 and 2 gives rise to quasimagnetic forces which act between polarized objects. Correspondingly, the magnetic interaction can be effectively suppressed by superconducting screens.[4]

There are experimental limitations on G_a, the constant of the fermion-fermion interaction due to the exchange of an arion:

$G_a < 10^{-2}\, G_F$ (Refs. 5 and 6), $G_a < 10^{-3}\, G_F$ (Ref. 4).

2. The Lagrangian of the interaction of an arion (a) with an electron (e) is[1,2]

$$\mathcal{L}_{ae} = q a \bar{e} i \gamma_5 e \ , \tag{1}$$

where q is the dimensionless arion charge ($G_a^{1/2} \sim q/m_e$). In the low-energy limit, this charge generates an effective Lagrangian of the interaction of the arion field with a magnetized medium:

$$\mathcal{L}_{eff} = \kappa \vec{\nabla} a \mathbf{m} \ . \tag{2}$$

Here $\mathbf{m}(\mathbf{r})$ is the magnetization density (more precisely, the variable part of this density), $k = \mu_a/\mu_B g$ is the ratio of the arion magneton to the Bohr magneton and the Landé factor, and $\mu_a = \sqrt{G_a/8\pi}$. Since interaction (2) is similar to an interaction with a magnetic field, $k\nabla a$, an experiment might be formulated in the following way (see the schematic diagram in Fig. 1).

A waveguide resonator in the gap between magnet pole tips is filled with a high-Q ferrite. The frequency of the pump generator and that of the receiver are equal to one of the resonant frequencies of the resonator filled with the magnetic material. A coher-

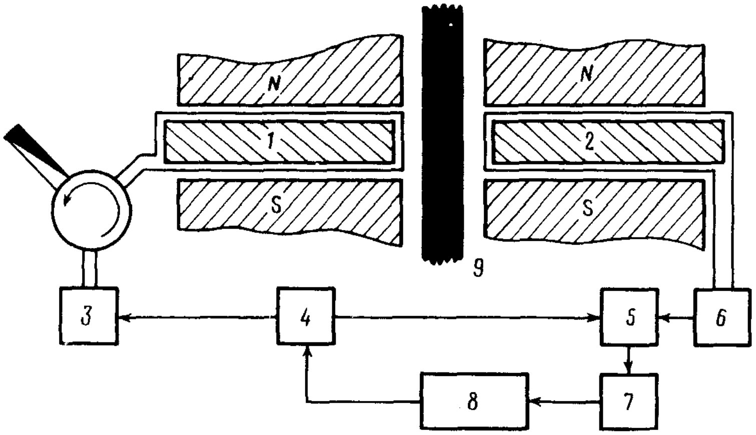

FIG. 1. Experimental layout. 1,2—Waveguide resonator filled with a ferrite; 3—high-power microwave source; 4—master oscillator; 5—synchronous detector; 6—high-sensitivity microwave amplifier; 7—amplitude-to-digital converter; 8—computer; 9—screen.

ent spin wave excited in the ferromagnet by the pump wave generates a coherent axion field. The axion beam, with a narrow directional pattern, passes freely through the waveguide walls and the shielding used to absorb photons and enters a second waveguide, also filled with a magnetized ferrite. The axion wave resonantly excites a coherent precession of the spins, and the latter gives rise to a weak electromagnetic wave which is coupled with the spins. The electromagnetic wave is detected by a sensitive receiver.

The Ω_k dispersion relation for coupled oscillations of the electromagnetic field and the magnetization is[7]

$$\Omega_k^2 = \frac{1}{2\epsilon}\left[k^2 + \tilde{\omega}_m^2 \pm \sqrt{(k^2 - \tilde{\omega}_m^2)^2 + 8k^2\omega_m\tilde{\omega}_m}\,\right], \tag{3}$$

where ε is the dielectric constant of the medium, $\omega_m = 2g\mu_B M_0$, M_0 is the saturation magnetization,

$$\tilde{\omega}_m = \sqrt{\omega_0(\omega_0 + 4\pi\omega_m)},$$

and B_0 is the magnetic field (demagnetizing factors are taken into account here). Since $\varepsilon > 1$, the arion dispersion relation $\Omega_k^a = k$ has a point of intersection with the upper branch from (3) at a certain frequency Ω_0. It is at this frequency that the generator should operate. The amplitude of the oscillations in the first resonator is determined by the energy balance: All of the incoming energy $\mathscr{E}$ is carried off by magnons which relax at a frequency γ. In the second resonator, the amplitude is determined as the amplitude of an oscillator with a damping γ which is at resonance with the external force. Simple calculations lead to the following expression for the energy flux of the electromagnetic radiation at the exit from the second resonator, $\mathscr{E}_f$ (for the conversion coefficient):

$$\frac{\mathcal{E}_f}{\mathcal{E}} = C\kappa^4(kL)\,\frac{\Omega_0\,\omega_m\,(\Omega_0 - \tilde{\omega}_m)^2}{\gamma^3\,\omega_m}\,. \tag{4}$$

Here $C = \text{const}$ is a factor on the order of unity, L is the length of the resonator, and k is the wave vector of the oscillations of frequency Ω_0. In order of magnitude we have

$$\frac{\mathcal{E}_f}{\mathcal{E}} \sim \kappa^4\,(kL)(\Omega_0/\gamma)^3\,. \tag{5}$$

The typical quality factors of the available ferrites are $\Omega/\gamma \approx 10^3$, and at $kL = 10^2$ we would have

$$\mathcal{E}_f/\,\mathcal{E} \approx 10^{11}\kappa^4\,. \tag{6}$$

A direct conversion of a photon into an axion and back to a photon in a transverse magnetic field[8] provides an energy transformation coefficient $\mathscr{E}_f/\mathscr{E} \approx \alpha^4 k^4 (kL)^4$. At the same parameter values, $\mathscr{E}_f/\mathscr{E} \approx k^4$, this quantity would be lower by 11 orders of magnitude.

By varying the pump frequency and the strength of the external field one could arrange coherent excitation and absorption of a massive axion if its mass is smaller than the gap in the magnetic spectrum, i.e., 10^{-4} eV.

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