

Abstract

The QCD axion is an hypothetical particle introduced to solve the strong CP problem of standard model of particle physics and is of interest as a possible component of cold dark matter. In the axion scenario, J.E. Moody and F. Wilczek showed that a new macroscopic long-range force, mediated by axion exchange, acts on electron spins, and that such force can be described in terms of an effective magnetic field. The QUAX- $g_p g_s$ experiment, carried out at INFN Laboratori Nazionali di Legnaro, is designed to search for the effects on magnetized samples of the effective field produced by unpolarized mass sources. As this field is macroscopic, it can be detected by measuring the change of magnetization of a paramagnetic Gadolinium silicate (GSO) crystal cooled at liquid helium temperature. The axion effective field induced magnetization can be detected with a SQUID magnetometer. By varying the position of the of source masses, the induced GSO magnetization is modulated at acoustic frequencies. Although the full QUAX- $g_p g_s$ sensitivity has not been yet exploited, we are able to measure a magnetization of 10^{-17} T at few tens of Hz. With this sensitivity we expect to further improve the upper limit of the coupling of the predicted long-range force in the 10^{-3} to 1 m interval.

The QUAX- $g_p g_s$ experiment to search for monopole-dipole Axion interaction

N. Crescini¹, C. Braggio, G. Carugno

*INFN, Sezione di Padova and Dipartimento di Fisica e Astronomia, Via Marzolo 8,
I-35131 Padova (Italy)*

P. Falferi

*Istituto di Fotonica e Nanotecnologie, CNR—Fondazione Bruno Kessler, and
INFN-TIFPA, I-38123 Povo, Trento (Italy)*

A. Ortolan, G. Ruoso

*INFN, Laboratori Nazionali di Legnaro, Viale dell'Università 2, I-35020 Legnaro, Padova
(Italy)*

Keywords: Axion searches, Paramagnetic crystals, Long-range forces, Dark
matter

1. Introduction

In particle physics, a spontaneously broken symmetry implies the existence of a Nambu-Goldstone boson [1]. If the symmetry is exact, the resulting boson is always massless, and couples with fermions with a coupling constant of $g_p = m_f/F$, where m_f is the mass of the fermion and F is the energy scale of the spontaneously broken symmetry. On the other hand, massive bosons are produced by symmetries which are not exact, like QCD pions for the chiral symmetry, and their mass is $m_b = \Lambda^2/F$ (where Λ is the explicit symmetry-breaking scale of the effective Lagrangian).

The search of broken symmetries at extremely high energies can be performed through the search of such exotic pseudo-Goldstone bosons, which mediates long-range ultraweak forces. The detection of a new force will account

¹crescini@pd.infn.it

for the presence of a boson and, therefore, of a broken symmetry; the axion is a pseudo-Goldstone boson arising from the breaking of the Peccei-Quinn symmetry [2] and it could mediate forces which are dependent on its coupling.

The allowed couplings between particles is determined by the vertices of the spin-0 bosons: the pseudoscalar interaction is always spin-dependent, while, in the non-relativistic limit, the scalar interaction can be treated as spin-independent (see Fig. 1). Thus, in a multipole expansion, the two fields are described by the "dipole" (pseudo-scalar coupling g_p) and "monopole" (scalar coupling g_s) moments, respectively.

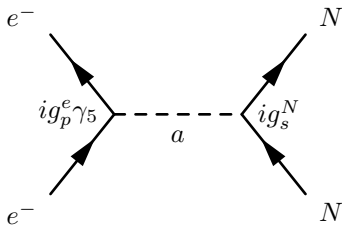


Figure 1: Interaction diagram of a scalar-pseudoscalar coupling between a nucleus N and an electron e^- . N is unpolarized and interacts at the scalar vertex with the coupling constant g_s^N , whereas e^- is polarized and interacts at the pseudoscalar vertex with the coupling constant g_p^e . The mediator is the axion a and the interaction strength is proportional to $g_s^N g_p^e$.

The different axion models ([3–5]) do not provide a unique value for the coupling constants g_p and g_s . The axion mass is determined by the values of F , the energy scale at which the Peccei-Quinn symmetry is broken. In addition, the presence of an axion vacuum angle expectation $\theta \neq 0$ allows for monopole-dipole coupling. The values of the couplings as a function of the mass of the axion m_a reads

$$g_p g_s = \frac{\theta \sigma}{F^2} \frac{m_u m_d}{(m_u + m_d)^2} m_a, \quad (1)$$

where m_u and m_d are the masses of the up and down quarks [6]. The angle θ in the conservative Kobayashi-Maskawa model, is expected in the 10^{-14} range and the pion-nucleon σ term is taken to be 60 MeV [11]. It is worth noticing that this value of θ is a limit from below, and that other models suggest much higher values, up to $\theta \simeq 10^{-8}$, increasing the monopole-dipole coupling of several

orders of magnitude. Cosmological and astrophysical considerations suggest a preferred value of $F \simeq 10^{12}$ GeV [7–10]; in this case axions would account for the missing mass of the universe. Moreover, F must be $< 10^{13}$ GeV, otherwise, axion would overdominate the evolution of the Universe (overclosure problem). The values of θ , σ and F set the axion window in the coupling-mass space [12].

The single particle *monopole-dipole* coupling (e.g. of electronic spin with nuclei) can be described by the potential

$$V_{md} = \frac{\hbar g_p^e g_s^N}{8\pi m_e c} \left[(\hat{\boldsymbol{\sigma}} \cdot \hat{\mathbf{r}}) \left(\frac{1}{r\lambda_a} + \frac{1}{r^2} \right) \right] e^{-\frac{r}{\lambda_a}}, \quad (2)$$

where λ_a is the Compton wavelength of the axion, g_p^e and g_s^N are the coupling constants of the Yukawa interaction, c is the speed of light in vacuum, m_e is the mass of the electron, $\hat{\boldsymbol{\sigma}}$ is the vector of Pauli spin matrices, and r and $\hat{\mathbf{r}}$ are the distance and unit vector between the monopole and the dipole, respectively [1, 6, 13]. This potential describes the interaction between two single particles and the axion Compton wavelength determines the range of the interaction. Since $\lambda_a = h/m_a c$ is macroscopic, we have a long-range force.

Thanks to the presence of the Pauli matrices vector term, this interaction can be written in the form of an effective magnetic field. We can estimate the amplitude of this field using the formula of the potential energy of an electron in an external magnetic field \mathbf{B}

$$U = \mu_e \hat{\boldsymbol{\sigma}} \cdot \mathbf{B}, \quad (3)$$

where $\mu_e = e\hbar/2m_e$ is the Bohr's magneton and $\mu_e \boldsymbol{\sigma}$ is the spin magnetic moment of an electron. By recasting Eq.(2) as Eq.(3) we get the explicit expression of this field

$$\mathbf{B}_{\text{eff,md}} = -\frac{g_p^e g_s^N}{4\pi e c} \hat{\mathbf{r}} \left(\frac{1}{r\lambda_a} + \frac{1}{r^2} \right) e^{-\frac{r}{\lambda_a}}. \quad (4)$$

Even if the coupling between single particles is weak, a macroscopic sample, with the order of 10^{23} atoms, could produce a light coherent bosonic field that can be measured. From the integration of this equation over the volume of the source, we can calculate the amplitude of the equivalent measurable field. However, this field is not an ordinary magnetic field, since it couples to the spin of

the fermion, and is independent of fermion magnetic moment, electric charges,
45 moving charges and angular momentum. As the interaction potential is gen-
erated by pseudoscalar exchange rather than by vector gauge boson exchange,
this field does not satisfy the Maxwell's equations.

The plan of the paper is as follows. In section 2 we describe the experimental
apparatus, consisting of source, detector and readout. Section 3 is devoted to the
50 magnetic properties of the GSO sample, section 4 reports noise measurements,
and the expected sensitivity of the experiment is calculated in section 5 in
terms of the measured sensitivity of our SQUID magnetometer. Conclusions
are eventually drawn in section 6.

2. Experimental Apparatus

55 The effective field in Eq.2 interacts with electron spins of matter, and it can
be detected by measuring the induced changes of matter magnetization. First
efforts to measure spin-dependent forces using ferromagnets and SQUIDs are
reported in ref. [14]. Our approach is similar but we substitute the ferromagnet
sample with a paramagnetic crystal, in order to avoid domain wall noise. Aim
60 of the experiment is to detect a magnetization signal which is not produced
by a magnetic field but by a material with high nuclear density. The periodic
modulation of the signal is achieved by varying the source-detector distance.
Figure 2 shows a schematic of the main components of the QUAX- $g_p g_s$ (QEst
for AXion) experiment. A rotating toothed wheel allows for a source mass
65 with a variable distance, while a cryostat houses the detector, placed as close
as possible to the moving source. Hereafter we give some details about the
experimental setup.

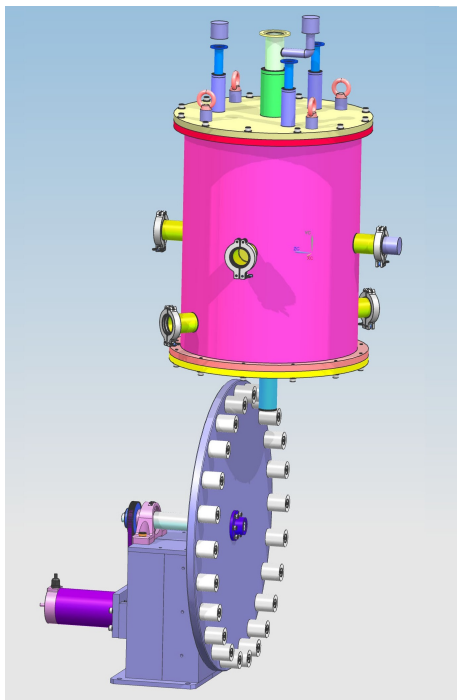


Figure 2: A schematic showing the QUAX- g_p - g_s apparatus for measuring the strength of $g_p g_s$ interaction. The cryostat houses the GSO crystal (detector). The rotating toothed wheel (unpolarized source) modulates in time the monopole-dipole interaction.

Source. - The source consists of large unpolarized masses that provides the monopole part of the interaction. Each mass is a lead disk, 2.5 cm thick,
 70 9.5 cm in diameter and 1.95 kg in weight. In the first experimental setup, 4 masses evenly spaced are placed on a rotating wheel having controllable angular velocity; this configuration allows us to modulate the interaction at a given frequency. A higher frequency signal modulation is suitable to improve the apparatus sensitivity. To this aim, a measurement with 24 masses on the wheel
 75 is planned.

Detector. - The paramagnetic sample is a cubic crystal of gadolinium oxyorthosilicate Gd_2SiO_5 (GSO) of volume $V = 1 \text{ cm}^3$ [15]. The monopole-dipole interaction, acting on the electron spins in the crystal, causes a change in the magnetization of the sample and induces a change of the magnetic flux collected

80 by a coil surrounding the GSO. To reduce thermal fluctuations, the crystal is cooled down to cryogenic temperature ($T \simeq 4\text{K}$). The distance between source and detector is 3.7 cm.

SQUID readout. - To measure the GSO magnetization induced by the source we use a Magnicon C6XXL1W dc-SQUID based magnetometer. With reference
85 to Fig. 3, the coil L_p picks up the magnetic flux generated by GSO magnetization; L_p is connected to the SQUID input coil L_i . Optimal work conditions of the SQUID require $L_p \simeq L_i$.

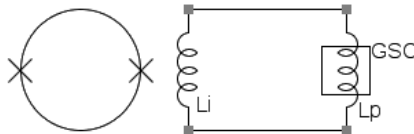


Figure 3: Lumped element model of the apparatus. $L_i = 1.8 \mu\text{H}$ is the input coil of the SQUID, $L_p \simeq 1.8 \mu\text{H}$ is the pick-up coil around the GSO crystal.

To further increase the sensitivity of the apparatus, the signal can be amplified with a resonant RLC circuit, tuned at the signal frequency. In the resonant
90 readout configuration, the signal is increased by the Q -factor of the resonant circuit.

It is worth noticing that B_{eff} is not subjected to Maxwell's equations. Therefore we can shield the apparatus from electromagnetic noise sources without affecting the signal. We use two MgB_2 superconductive shield, that remove external noise of an expected factor 10^{12} . In addition, the apparatus is placed in
95 a μ -metal cylinder that reduces the magnetic fields of an expected factor of the order of 10^2 .

3. GSO magnetic properties

We are interested in properties of GSO crystals that affect signal and noise, i.e. magnetic susceptibility χ and spin relaxation time τ_M . If $k_B T \gg g\mu_B H$,

where H is the external magnetic field, the susceptibility of a set of identical ions of angular momentum $J = L + S$ is given by Curie law. When the free ions are part of a lattice in a solid structure, e.g. ions with partially filled electronic f -shells in insulating crystals, the generalized Curie law of paramagnetic susceptibility reads [16]

$$\chi_0(T) = \mu_0 \frac{N}{V} \frac{\mu_B^2}{3} \frac{p_{\text{eff}}^2}{k_B T}, \quad (5)$$

where μ_0 is the vacuum magnetic permeability, k_B is Boltzman's constant, T is the temperature, N/V is the number of ions for unit of volume, μ_B is Bohr's magneton and p_{eff} is the effective number of Bohr magnetons. Here $p_{\text{eff}} = g\sqrt{J(J+1)}$, where g is the Landé factor $g(J, L, S) = \frac{3}{2} + \frac{1}{2} \left(\frac{S(S+1) - L(L+1)}{J(J+1)} \right)$ taking the electron g_0 -factor to be exactly 2. Referring to [15], the reported value of the effective Bohr magnetons number for a GSO crystal is $p_{\text{eff}} = 8.02$. This parameter, together with the values in table 1, gives $\chi_0(4\text{K}) = 0.72$ in good agreement with reference [15].

To calculate the thermodynamic fluctuation of the magnetization, we resort to the fluctuation-dissipation theorem [17], which reads

$$S_M(\omega) = \frac{2k_B T}{\mu_0 \omega V} \text{Im}(\chi(\omega)), \quad (6)$$

where $S_M(\omega)$ is the spectrum of the magnetization noise, and $\text{Im}(\chi(\omega))$ is the imaginary part of the Fourier transform of the susceptibility. In the Debye approximation [18], and assuming $\omega\tau_M \ll 1$ we have

$$\text{Im}(\chi(\omega)) = \text{Im}\left(\frac{\chi_0}{1 + i\omega\tau_M}\right) \simeq \chi_0 \omega \tau_M. \quad (7)$$

Hence, the mean square fluctuation of the magnetization, integrated over a frequency band $\Delta\nu$, is

$$\sigma_M^2 = \int_{\Delta\nu} S_M(\nu) d\nu = \frac{4k_B T \chi_0 \tau_M (\Delta\nu)}{\mu_0 V}. \quad (8)$$

To evaluate this quantity, the spin relaxation time τ_M of GSO was measured through an EPR spectrum, obtained with a ELEXSYS 580 Bruker instrument, equipped with a dielectric cavity at 80 K. The measurement gives a linewidth

110 $\Delta H_{pp} = 0.48$ T. Considering the gyromagnetic ratio of the electron γ_e , we get
 $\delta\nu = \gamma_e \Delta H_{pp} = 13.5$ GHz. Since $\gamma_e/2\pi = 28.0$ GHz/T and $\tau_M = 1/(\pi\delta\nu)$, the
spin relaxation time is 7.4×10^{-11} s.

Volume	$V = 1 \text{ cm}^3$
Density	$\rho = 6.71 \text{ g/cm}^3$
Molar weight	$\rho_{\text{mol}} = 422.58 \text{ g/mol}$
Number of moles	$N_{\text{mol}} = 0.015 \text{ mol}$
Spin relaxation time	$\tau_M = 7.4 \cdot 10^{-11} \text{ s}$
Effective number of μ_B	$p_{\text{eff}} = 8.02$

Table 1: Summarized features of the used GSO crystal.

Assuming no variation of τ_M from 80K to 4K the value of the noise depends
only on the temperature; in our case $T \simeq 4\text{K}$, and using the previously calculated
115 $\chi_0(4\text{K})$, the level of magnetization noise is $S_B^{1/2}(\omega) = 1.2 \times 10^{-16} \text{ T}/\sqrt{\text{Hz}}$.

4. Magnetic noise measurements

Referring to figure 3, the spectral density of the equivalent flux noise at the
pickup coil of the SQUID is given by

$$S_B^{(p)}(\omega) = \frac{1}{(n\pi r^2)^2} \frac{(L_i + L_p)^2}{M_i^2} S_\phi(\omega), \quad (9)$$

where n and r are the number of turns and the radius of the pick-up coil re-
spectively, L_p is the pick-up coil inductance, L_i is the internal inductance of
the SQUID, and $M_i = k\sqrt{L_s L_i}$ is the mutual inductance between L_i and the
120 loop inductance of the SQUID L_s . The intrinsic SQUID flux noise level is
 $S_\phi^{1/2}(\omega) \simeq 0.81\mu\phi_0/\sqrt{\text{Hz}}$ [19], since $M_i = 8.8$ nH and $\phi_0 \simeq 2 \times 10^{15}$ Wb, using
Eq.9 and calibrating the magnetic flux through our pick-up coil, the calculation
yields $S_B^{(p)}(\omega)^{1/2} \simeq 7.3 \times 10^{-16} \text{ T}/\sqrt{\text{Hz}}$.

Noise spectra has been measured at frequencies $f > 0.1$ Hz (i.e. above the
125 $1/f$ noise knee of the SQUID [19]), and are reported in figure 4. As can be

seen, there exist frequency bands where the background is compatible with the SQUID noise.

The spectra are shown in the frequency bands of planned $g_p^e g_s^N$ measurements, i.e. around 10 Hz and 500 Hz.

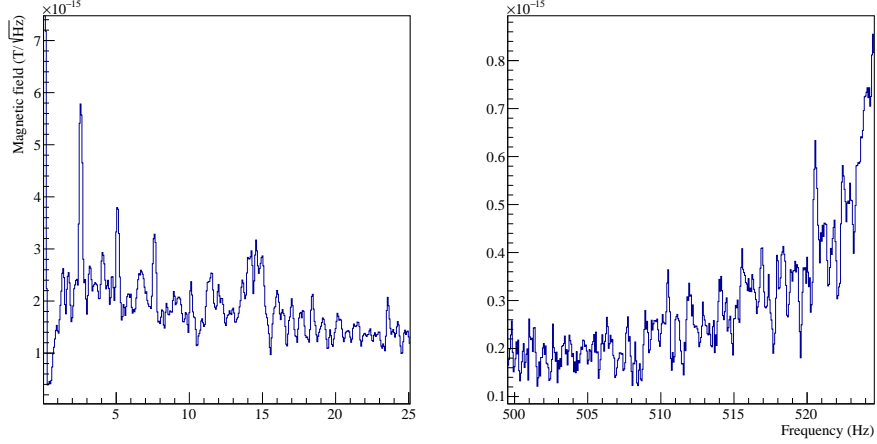


Figure 4: Square root of magnetic noise power density in the frequency bands of $g_p^e g_s^N$ measurements.

130 5. Sensitivity calculations

The signal that we want to measure is a change of the GSO magnetization. For a paramagnet, the change of magnetization \mathbf{M} due to an external field \mathbf{H} is given by $\mathbf{M} = \chi_0 \mathbf{H} \equiv \chi_0 \mathbf{B} / \mu_0$, where χ_0 is the magnetic susceptibility. Likewise, the axion effective magnetic field will induce a change in the magnetization
135 $\mu_0 M = \chi_0 B_{\text{eff}}$, that will be collected by the pick-up coil. The noise sources are the magnetization noise and the SQUID noise; however, in our experimental apparatus the dominant noise is due to the SQUID as discussed in sections 3 and 4.

Non-resonant readout - The signal to noise ratio of the magnetization measure is $\text{SNR} = \chi_0 B_{\text{eff}} / \sigma_B$, where $\sigma_B^2 = S_B^{(p)}(\omega) / t$ is the variance of the mea-
140

sure and t is the integration time. The minimum detectable magnetization at unitary signal to noise ratio corresponds to an equivalent field $B_{\text{eff},\text{min}} = S_B^{(p)}(\omega)^{1/2}/(\chi_0 \sqrt{t})$. Substituting for the measured values of χ_0 and $S_B^{(p)}(\omega)$, and assuming an integration time $t \simeq 5$ h, we get $B_{\text{eff},\text{min}} \simeq 10^{-17}$ T. The present configuration of QUAX- $g_p g_s$ should be able to improve the upper limit reported in reference [20] of one order of magnitude.

Resonant readout - To further improve the sensitivity, we exploit a resonant pick-up circuit.

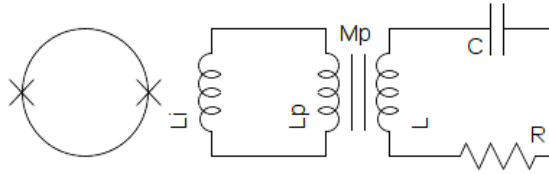


Figure 5: Lumped model of the pick-up circuits coupled with the SQUID. The resistance R is an equivalent resistance accounting for all circuit losses, L is the inductance of the coil, C is the capacity, L_i is the internal inductance of the SQUID, L_p is the pick-up coil, and M_p is the mutual inductance between L_p and L .

Calculations show that the SNR is increased by $2Q$, with Q is the quality factor of the resonant circuit. Using the measured values of the non-resonant readout and $Q \simeq 10^4$, we get $B_{\text{eff},\text{min}} \simeq 10^{-22}$ T.

We summarize in figure 6 the expected sensitivity of our apparatus in terms of the strength of the monopole-dipole interaction, compared with the upper limits already reached by other experiments. The measurements of other authors are reported in references [20–30]. It is worth mentioning that some experiments has been proposed [31, 32] that should be able to reach sensitivities of the same order of magnitude of our experiment.

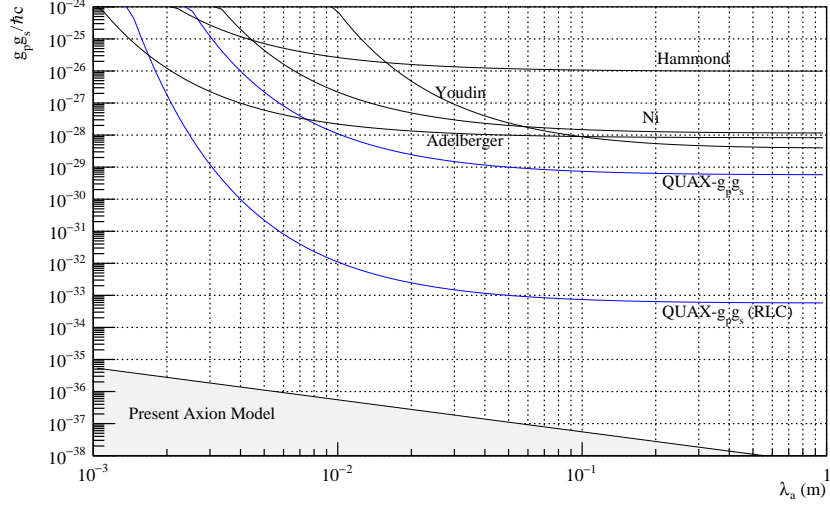


Figure 6: Expected sensitivity of QUAX- $g_p g_s$ with an integration time of 5 h. As can be seen the limit on the $g_p^e g_s^N$ coupling can be lowered of 1 or 5 orders of magnitude in the non-resonant or resonant(RLC) configuration, respectively. We also show the $g_p^e g_s^N$ upper limit already reported in the literature (see text).

6. Conclusions

We proposed a method to measure the $g_p^e g_s^N$ interaction and reported some preliminary results on the magnetic noise of the apparatus.

Assuming an integration time of 5 h, the minimum detectable signal is expected to be $B_{\text{eff,min}} < 10^{-17}$ T, with a resultant limit on the coupling $g_p^e g_s^N / \hbar c < 10^{-29}$. Using a resonant circuit we should improve this upper limit of 5 orders of magnitude.

In order to reach a higher sensitivity it is possible to increase the volume of the detector. This can be done using a number N_c of GSO crystals in series, read by the same SQUID with a resonant pick-up. In this configuration, to reach optimal working conditions of the SQUID one can use a superconducting low-losses matching transformer [33] that allows us to optimally couple N_c pick-up

170 coils to the SQUID input coil. Compared to the single crystal optimally coupled
to the SQUID, this configuration would improve the SNR of $N_c^{3/2}$.

7. Acknowledgment

We wish to thank professor Wei-Tou Ni for helpful discussions concerning
the experiment. The authors also acknowledge Mario Tessaro, Enrico Berto and
175 Fulvio Calaan for help in the realization of the experimental set-up.

References

- [1] S. Weinberg, Approximate symmetries and pseudo-goldstone bosons, Phys. Rev. Lett. 29 (1972) 1698–1701. doi:10.1103/PhysRevLett.29.1698.
URL <http://link.aps.org/doi/10.1103/PhysRevLett.29.1698>
- 180 [2] R. D. Peccei, H. R. Quinn, CP conservation in the presence of pseudoparticles, Phys. Rev. Lett. 38 (1977) 1440–1443. doi:10.1103/PhysRevLett.38.1440.
URL <http://link.aps.org/doi/10.1103/PhysRevLett.38.1440>
- [3] J. E. Kim, Weak-interaction singlet and strong CP invariance, Phys. Rev. Lett. 43 (1979) 103 – 107. doi:10.1103/PhysRevLett.43.103.
185 URL <http://link.aps.org/doi/10.1103/PhysRevLett.43.103>
- [4] M. Dine, W. Fischler, M. Srednicki, A simple solution to the strong {CP} problem with a harmless axion, Physics Letters B 104 (3) (1981) 199 – 202. doi:[http://dx.doi.org/10.1016/0370-2693\(81\)90590-6](http://dx.doi.org/10.1016/0370-2693(81)90590-6).
190 URL <http://www.sciencedirect.com/science/article/pii/0370269381905906>
- [5] M. Shifman, A. Vainshtein, V. Zakharov, Can confinement ensure natural {CP} invariance of strong interactions?, Nuclear Physics B 166 (3) (1980) 493 – 506. doi:[http://dx.doi.org/10.1016/0550-3213\(80\)90209-6](http://dx.doi.org/10.1016/0550-3213(80)90209-6).
195 URL <http://www.sciencedirect.com/science/article/pii/0550321380902096>
- [6] J. E. Moody, F. Wilczek, New macroscopic forces?, Phys. Rev. D 30 (1984) 130–138. doi:10.1103/PhysRevD.30.130.
URL <http://link.aps.org/doi/10.1103/PhysRevD.30.130>
- 200 [7] M. Fukugita, S. Watamura, M. Yoshimura, Light pseudoscalar particle and stellar energy loss, Phys. Rev. Lett. 48 (1982) 1522–1525. doi:10.1103/PhysRevLett.48.1522.
URL <http://link.aps.org/doi/10.1103/PhysRevLett.48.1522>

- [8] J. Preskill, M. B. Wise, F. Wilczek, Cosmology of the invisible axion, Physics Letters B 120 (1-3) (1983) 127 - 132. doi:[http://dx.doi.org/10.1016/0370-2693\(83\)90637-8](http://dx.doi.org/10.1016/0370-2693(83)90637-8).
URL <http://www.sciencedirect.com/science/article/pii/0370269383906378>
- [9] L. Abbott, P. Sikivie, A cosmological bound on the invisible axion, Physics Letters B 120 (1-3) (1983) 133 - 136. doi:[http://dx.doi.org/10.1016/0370-2693\(83\)90638-X](http://dx.doi.org/10.1016/0370-2693(83)90638-X).
URL <http://www.sciencedirect.com/science/article/pii/037026938390638X>
- [10] M. Dine, W. Fischler, The not-so-harmless axion, Physics Letters B 120 (1-3) (1983) 137 - 141. doi:[http://dx.doi.org/10.1016/0370-2693\(83\)90639-1](http://dx.doi.org/10.1016/0370-2693(83)90639-1).
URL <http://www.sciencedirect.com/science/article/pii/0370269383906391>
- [11] M. E. Sainio, Chiral Dynamics: Theory and Experiment: Proceedings of the Workshop Held at MIT, Cambridge, MA, USA, 25-29 July 1994, Springer Berlin Heidelberg, Berlin, Heidelberg, 1995, Ch. Pion-nucleon sigma term, pp. 212-223. doi:10.1007/3-540-59279-2_77.
URL http://dx.doi.org/10.1007/3-540-59279-2_77
- [12] G. Raffelt, Limits on a cp -violating scalar axion-nucleon interaction, Phys. Rev. D 86 (2012) 015001. doi:10.1103/PhysRevD.86.015001.
URL <http://link.aps.org/doi/10.1103/PhysRevD.86.015001>
- [13] S. L. Cheng, C. Q. Geng, W.-T. Ni, Axion-photon couplings in invisible axion models, Phys. Rev. D 52 (1995) 3132-3135. doi:10.1103/PhysRevD.52.3132.
URL <http://link.aps.org/doi/10.1103/PhysRevD.52.3132>
- [14] P. Vorobyov, Y. Gitarts, A new limit on the arion interaction constant, Physics Letters B 208 (1) (1988) 146 - 148.

doi:[http://dx.doi.org/10.1016/0370-2693\(88\)91220-8](http://dx.doi.org/10.1016/0370-2693(88)91220-8).

URL [http://www.sciencedirect.com/science/article/pii/0370269388912208](http://www.sciencedirect.com/science/article/pii/S0370269388912208)

235

- [15] B. Baiboussinov, C. Braggio, A. Cardini, G. Carugno, F. Congiu, S. Gain, G. Galeazzi, A. Lai, A. Lehman, P. Mocci, A. Mura, F. Quochi, M. Saba, B. Saitta, G. Sartori, An active electron polarized scintillating GSO target for neutrino physics, Nuclear Instruments and Methods in Physics Research A 694 (2012) 335–340. doi:10.1016/j.nima.2012.08.075.

240

- [16] N. Ashcroft, N. Mermin, Solid State Physics, Cengage Learning, 2011.

URL https://books.google.it/books?id=x_s_YAAACAAJ

- [17] L. Landau, E. Lifshitz, Statistical Physics, no. v. 5, Elsevier Science, 2013.

URL <https://books.google.it/books?id=VzgJN-XPTRsC>

245

- [18] W. Bialek, J. Moody, F. Wilczek, Macroscopic t nonconservation: Prospects for a new experiment, Phys. Rev. Lett. 56 (1986) 1623–1626. doi:10.1103/PhysRevLett.56.1623.

URL <http://link.aps.org/doi/10.1103/PhysRevLett.56.1623>

- [19] MAGNICON, 1-stage Current Sensor C6XXL1W Data Sheet.

250

URL <http://www.magnicon.com/>

- [20] W.-T. Ni, A Scheme for a spin coupling experiment in space using magnetic materials with a DC SQUID, Class. Quant. Grav. 13 (1996) A135–A141. doi:10.1088/0264-9381/13/11A/018.

- [21] S. A. Hoedl, F. Fleischer, E. G. Adelberger, B. R. Heckel, Improved constraints on an axion-mediated force, Phys. Rev. Lett. 106 (2011) 041801.

255

doi:10.1103/PhysRevLett.106.041801.

URL <http://link.aps.org/doi/10.1103/PhysRevLett.106.041801>

- [22] G. D. Hammond, C. C. Speake, C. Trenkel, A. P. Patón, New constraints on short-range forces coupling mass to intrinsic spin, Phys. Rev. Lett. 98

- 260 (2007) 081101. doi:10.1103/PhysRevLett.98.081101.
URL <http://link.aps.org/doi/10.1103/PhysRevLett.98.081101>
- [23] W.-T. Ni, S.-s. Pan, H.-C. Yeh, L.-S. Hou, J. Wan, Search for an axionlike spin coupling using a paramagnetic salt with a dc squid, Phys. Rev. Lett. 82 (1999) 2439–2442. doi:10.1103/PhysRevLett.82.2439.
265 URL <http://link.aps.org/doi/10.1103/PhysRevLett.82.2439>
- [24] A. N. Youdin, D. Krause, Jr., K. Jagannathan, L. R. Hunter, S. K. Lamoreaux, Limits on spin-mass couplings within the axion window, Phys. Rev. Lett. 77 (1996) 2170–2173. doi:10.1103/PhysRevLett.77.2170.
URL <http://link.aps.org/doi/10.1103/PhysRevLett.77.2170>
- 270 [25] R. C. Ritter, L. I. Winkler, G. T. Gillies, Search for anomalous spin-dependent forces with a polarized-mass torsion pendulum, Phys. Rev. Lett. 70 (1993) 701–704. doi:10.1103/PhysRevLett.70.701.
URL <http://link.aps.org/doi/10.1103/PhysRevLett.70.701>
- [26] B. J. Venema, P. K. Majumder, S. K. Lamoreaux, B. R. Heckel, E. N. Fortson, Search for a coupling of the earth’s gravitational field to nuclear spins in atomic mercury, Phys. Rev. Lett. 68 (1992) 135–138. doi:10.1103/PhysRevLett.68.135.
275 URL <http://link.aps.org/doi/10.1103/PhysRevLett.68.135>
- [27] E. Fischbach, C. Talmadge, The Search for Non-Newtonian Gravity, AIP-
280 Press S, Springer New York, 1998.
URL <https://books.google.it/books?id=G7wZtGHPiCEC>
- [28] D. J. Wineland, J. J. Bollinger, D. J. Heinzen, W. M. Itano, M. G. Raizen, Search for anomalous spin-dependent forces using stored-ion spectroscopy, Phys. Rev. Lett. 67 (1991) 1735–1738. doi:10.1103/PhysRevLett.67.1735.
285 URL <http://link.aps.org/doi/10.1103/PhysRevLett.67.1735>

- [29] J. Daniels, W.-T. Ni, A torsion balance search for long-range spin-dependent forces using polarized nuclei, *Physica B: Condensed Matter* 194–196, Part 1 (1994) 149 – 150. doi:[http://dx.doi.org/10.1016/0921-4526\(94\)90404-9](http://dx.doi.org/10.1016/0921-4526(94)90404-9).
290 URL <http://www.sciencedirect.com/science/article/pii/S0921452694904049>
- [30] C.-H. Hsieh, P.-Y. Jen, K.-L. Ko, K.-Y. Li, W.-T. Ni, S.-S. Pan, Y.-H. Shih, R.-J. Tyan, The equivalence principle experiment for spin-polarized
295 bodies, *Modern Physics Letters A* 4 (17) (1989) 1597–1603.
- [31] A. Arvanitaki, A. A. Geraci, Resonantly detecting axion-mediated forces with nuclear magnetic resonance, *Phys. Rev. Lett.* 113 (2014) 161801. doi:[10.1103/PhysRevLett.113.161801](https://doi.org/10.1103/PhysRevLett.113.161801).
URL <http://link.aps.org/doi/10.1103/PhysRevLett.113.161801>
- 300 [32] P.-H. Chu, E. Weisman, C.-Y. Liu, J. C. Long, Search for exotic short-range interactions using paramagnetic insulators, *Phys. Rev. D* 91 (2015) 102006. doi:[10.1103/PhysRevD.91.102006](https://doi.org/10.1103/PhysRevD.91.102006).
URL <http://link.aps.org/doi/10.1103/PhysRevD.91.102006>
- [33] L. Baggio, M. Bignotto, M. Bonaldi, M. Cerdonio, L. Conti, P. Falferi,
305 N. Liguori, A. Marin, R. Mezzena, A. Ortolan, S. Poggi, G. A. Prodi, F. Salemi, G. Soranzo, L. Taffarello, G. Vedovato, A. Vinante, S. Vitale, J. P. Zendri, 3-mode detection for widening the bandwidth of resonant gravitational wave detectors, *Phys. Rev. Lett.* 94 (2005) 241101. doi:[10.1103/PhysRevLett.94.241101](https://doi.org/10.1103/PhysRevLett.94.241101).
310 URL <http://link.aps.org/doi/10.1103/PhysRevLett.94.241101>
- [34] P. Falferi, M. Cerdonio, L. Franceschini, R. Macchietto, S. Vitale, J. P. Zendri, A high inductance khz resonator with a quality factor larger than 106, *Review of Scientific Instruments* 65 (9) (1994) 2916–2919. doi:<http://dx.doi.org/10.1063/1.1144639>.

- 315 URL <http://scitation.aip.org/content/aip/journal/rsi/65/9/10.1063/1.1144639>
- [35] A. Vinante, R. Mezzena, G. A. Prodi, S. Vitale, M. Cerdonio, P. Falferi, M. Bonaldi, Dc superconducting quantum interference device amplifier for gravitational wave detectors with a true noise temperature of 16 μ k, Applied Physics Letters 79 (16) (2001) 2597–2599.
320 doi:<http://dx.doi.org/10.1063/1.1408276>.
URL <http://scitation.aip.org/content/aip/journal/apl/79/16/10.1063/1.1408276>
- [36] P. Svrcek, E. Witten, Axions in string theory, Journal of High Energy
325 Physics 2006 (06) (2006) 051.
URL <http://stacks.iop.org/1126-6708/2006/i=06/a=051>
- [37] T. Sleator, E. L. Hahn, C. Hilbert, J. Clarke, Nuclear-spin noise, Phys. Rev. Lett. 55 (1985) 1742–1745. doi:[10.1103/PhysRevLett.55.1742](https://doi.org/10.1103/PhysRevLett.55.1742).
URL <http://link.aps.org/doi/10.1103/PhysRevLett.55.1742>
- 330 [38] J. Clarke, A. I. Braginski (Eds.), The SQUID Handbook: Fundamentals and Technology of SQUIDs and SQUID Systems, Wiley-VCH, 2005.
- [39] A. Papoulis, S. Pillai, Probability, random variables, and stochastic processes, McGraw-Hill electrical and electronic engineering series, McGraw-Hill, 2002.
335 URL <https://books.google.ie/books?id=YYwQAQAIAAJ>