In Search Of Axions: The CAST Experiment

George K. Fanourakis
(For the CAST Collaboration[1])

Institute of Nuclear Physics, NCSR "Demokritos"
Neapoleos & Patr. Grigoriou, 15310 Ag. Paraskevi Attikis, Greece

Abstract. The CERN Axion Solar Telescope (CAST) experiment uses a decommissioned LHC test magnet in conjunction with three different technology X-ray photon detectors and tracks the sun to look for the elusive axion. Axions or axion-like particles with a two-photon interaction can be produced in the Sun by the Primakoff process, according to the theory. In a laboratory magnetic field they can be transformed into X-rays with energies of a few keV. CAST has been running for about 6 months during 2003 and most of 2004. The first results from the analysis of the 2003 data are presented here. No signal above background was observed, implying an upper limit to the axion to photon coupling $g_{\alpha\gamma\gamma} < 1.16 \times 10^{-10}$ GeV^{-1} at 95% CL for $m_\alpha \leq 0.02$ eV. This limit is comparable to the limit from stellar energy loss arguments and considerably more restrictive than any previous experiment in this axion mass range.

Keywords: axions, dark matter, X-ray detection, Micromegas.
PACS: 95.35.+d; 14.80.Mz; 96.60.Vg; 07.85Nc; 84.71Ba.

INTRODUCTION

The Lagrangian of Quantum Chromodynamics (QCD), the gauge theory of the strong interactions of quarks and gluons, is constructed with the requirement that it is Lorentz as well as local gauge invariant. Denoting the fermion matter fields (quarks) by ψ_n, N the number of quark flavors, the gauge fields (gluons) by A^α, g the strong

[1] The CAST Collaboration:
S. Andriamonje[2], V. Arsov[13], S. Aune[2], D. Autiero,[1] F. Avignone[3], K. Barth[1], A. Belov[11], B. Beltran[6], H. Brauninger[5], J. M. Carmona[6], S. Cebrian[6], E. Chesi[1], J. I. Collar[7], R. Creswick[3], T. Dafni[4], M. Davenport[1], T.Decker[16], L. Di Lella[1], C. Eleftheriadis[8], J. Englhauser[5], G. Fanourakis[9], H. Farach[3], E. Ferrer[2], H. Fischer[10], J. Franz[10], P. Friedrich[5], T. Geralis[9], I. Giomataris[2], S. Gninenko[11], N. Goloubev[11], M. D. Hasinoff[12], F. H. Heinsius[10], R. Hill[16], D.H.H. Hoffmann[4 I], I.G. Irastorza[2], J. Jacoby[13], D. Kang[10], K. Koenigsmann[10], R. Kotthaus[14], M. Krcmar[15], K. Kousouris[9], M. Kuster[4,5], B. Lakic[15], C. Lasseur[1], A. Liolios[8], A. Ljubicic[15], G. Lutz[14], G. Luzon[6], D. W. Miller[7], A. Morales[6], J. Morales[6], M. Mutterer[4], A. Nikolaidis[8], A. Ortiz[6], T. Papaevangelou[1], M. Pivovaroff[16], A. Placci[1], G. Raffelt[14], J. Ruz[6], H. Riege[4], M. L. Sarsa[6], I. Savvidis[8], W. Serber[14], P. Serpico[14], Y. Semertzidis[4], R. Soufli[16], L. Stewart[1], K. Van Bibber[16], J. D. Vieira[7], J. Villar[6], L. Walckiers[1], K. Zachariadou[9], and K. Zioutas[8].
[1]European Organization for Nuclear Research (CERN), Geneve, Switzerland. [2]DAPNIA, Centre d' Etudes Nucleaires de Saclay (CEA-Saclay), Gif-sur-Yvette, France, [3]Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA, [4]GSI-Darmstadt and Institut fur Kernphysik, TU Darmstadt, Darmstadt, Germany, [5]Max-Planck-Institut fur Extraterrestrische Physik, Garching, Germany, [6]Instituto de Fisica Nuclear y Altas Energıas, Universidad de Zaragoza, Zaragoza, Spain, [7]Enrico Fermi Institute and KICP, University of Chicago, Chicago, IL, USA, [8]Aristotle University of Thessaloniki, Thessaloniki, Greece, [9]National Center for Scientific Research "Demokritos", Athens, Greece, [10]Albert-Ludwigs-Universitaet Freiburg, Freiburg, Germany, [11]Institute for Nuclear Research (INR), Russian Academy of Sciences, Moscow, Russia, [12]Department of Physics and Astronomy, University of British Columbia, Vancouver, Canada, [13]Johann Wolfgang Goethe-Universitaet, Institut fur Angewandte Physik, Frankfurt am Main, Germany, [14]Max-Planck-Institut fur Physik (Werner-Heisenberg-Institut), Munich, Germany, [15]Rudjer Boskovic Institute, Zagreb, Croatia, [16]Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA94550, USA.

CP848, *Recent Advances in Astronomy and Astrophysics,*
7th International Conference of the Hellenic Astronomical Society, edited by N. H. Solomos

coupling constant and by t^{α} the generators of the $SU(3)_c$ color algebra of the rotations of the quark fields in the color space, $\psi_n \rightarrow \exp\{i\alpha^a(x)\, t^a\}\psi_n$ with $\alpha(x)$ an x-dependent parameter, which satisfy the relation: $[t^a,t^b] = if^{ab}{}_c\, t^c$, with a, b, c = 1,…,8, and $f_{\alpha bc}$ the structure constants of this algebra, the Lagrangian can be written as:

$$L = \sum_{n=1}^{N} \overline{\psi}_n \left(i\gamma^{\mu}\partial_{\mu} - g\gamma^{\mu} A_{\mu}^{a} t^{a} - m_n \right)\psi_n - \frac{1}{4} G^{a\mu\nu} G_{\mu\nu}^{a} \qquad (1)$$

With $G_{\mu\nu}^{a}$ the kinetic term of the gluons, $G_{\mu\nu}^{a} = \partial_{\mu} A_{\nu}^{a} - \partial_{\nu} A_{\mu}^{a} - g f_{abc} A_{\mu}^{b} A_{\nu}^{c}$ (2)

The inherent local gauge symmetry of QCD is not spontaneously broken so that the gluons remain massless at all scales. The non Abelian character of this theory introduces non linear phenomena which result in a non trivial topological structure of the vacuum. In fact the true vacuum is actually a linear combination of an infinite number of degenerate vacua, denoted by |n>, the so-called θ vacuum:

$$\left|\theta\right\rangle = \sum_{n=-\infty}^{\infty} e^{in\theta} \left|n\right\rangle \qquad (3)$$

The parameter θ is an observable and as a consequence it must be included in the QCD Lagrangian in an additional effective term which is CP violating:

$$L_{\theta} = \frac{g^2 \theta}{32\pi^2} G_{\mu\nu}^{a} \widetilde{G}^{a\mu\nu} \qquad (4)$$

The QCD Lagrangian, in the limit of zero up and down quark masses, has a large global symmetry described by the group $U(2)_V$**X**$U(2)_A$. For small masses this is approximately true. Indeed experimentally we know that $U(2)_V=SU(2)_V$**X**$U_V(1)$ which is the Isospin**X**Baryon symmetry is true and results in the (p,n) and (π^{+-},π^0) multiplets in the hadron spectrum. However, the axial symmetry $U(2)_A$ is spontaneously broken and one would expect four light mesons. Only three pions are observed though and this is known as the $U(1)_A$ problem. The resolution of this problem comes again from the complexity of the QCD vacuum which makes $U(1)_A$ not a quantum symmetry of QCD even though it is a classical symmetry in the limit of zero quark masses.

Finally in the process of spontaneously symmetry breaking of the local gauge symmetry in the strong and electroweak interactions, the quarks acquire in general complex masses and in order to obtain real values one has to diagonalize the quark mass matrix M, a fact which inserts another CP violating term in the QCD Lagrangian:

$$L_m = \frac{g^2 Arg(\det M)}{32\pi^2} G_{\mu\nu}^{a} \widetilde{G}^{a\mu\nu} \qquad (5)$$

The total θ parameter is then: $\overline{\theta} = \theta + Arg(\det M)$

If based on this information we calculate the neutron electron dipole moment, we get $d_n \approx 10^{-16}\ \bar{\theta}$ e·cm. Comparing with the experimental limit $d_n < 0.63 \times 10^{-25}$ e·cm, we deduce that θ has the very small value of: $\bar{\theta} \approx 10^{-9}$[1]. Thus the strong CP problem appears as the question of why this parameter coming from the strong and weak sector is so small.

The most elegant solution of the strong CP problem comes from the work of Peccei and Quinn [2] who introduced an additional axial global $U(1)_{PQ}$ symmetry, which is spontaneously broken and it replaces $\bar{\theta} = \theta + \mathrm{Arg}(\det M)$ with $a(x)/f_a$, where a(x) is a new Nambu-Goldstone (NG) field and f_a is the symmetry breaking scale. This axion field has non zero vacuum expectation value <a> and the Lagrangian written in terms of the physical axion $a_{ph}(x)=a(x)-\langle a\rangle$ has no longer the θ-term.

The original model of Peccei and Quinn as supplemented by Weinberg [3] and Wilczek [4] introduced the standard axion, an axion tied with the electroweak symmetry breaking scale. This axion, with near MeV mass and appreciable couplings to matter and radiation, would be easily detectable. However, the PQWW axion was subsequently ruled out by experiment. Later models such as the DFSZ model [5] and the KSVZ model [6] introduced the invisible axions, thus called because they are very weakly interacting since $f_a \gg f_{ew}$. The detection of this type of axion is based on its coupling to two photons and many experiments have been and are being conducted to search for its existence. Two detailed reviews on the evolution of the theory and the axion searches are written by Kim [7] and Cheng [8].

AXION PROPERTIES AND ASTROPHYSICAL ISSUES

The axion, as every NG boson, couples derivatively to matter:

$$L_{a\psi\psi} = \sum_i c_i \frac{1}{f_a}\left(\bar{\psi}_i \gamma^\mu \gamma_5 \psi_i\right)\left(\partial_\mu a\right) \tag{6}$$

The parameters c_i are model dependent parameters, and i stand for the fermion matter fields. The axion is special because it couples to two gluons with a non-derivative term:

$$L_{agg} = \frac{1}{f_a}\frac{g}{8\pi} G^{a\mu\nu}\tilde{G}^a_{\mu\nu} a \tag{7}$$

At low energies this term generates the axion mass:

$$m_a = \frac{f_\pi m_\pi}{f_a}\frac{\sqrt{m_u m_d}}{m_u + m_d} = 0.6\,eV\left(\frac{10^7\,GeV}{f_a}\right) \tag{8}$$

All effective coupling constants of axions with matter and radiation depend on the inverse of the symmetry breaking scale f_a, and are therefore linear in the axion mass. The axion also couples to photons:

$$L_{a\gamma\gamma} = c_\gamma \frac{g}{\pi f_a} F^{\mu\nu} \tilde{F}_{\mu\nu} a = -g_{a\gamma\gamma} \vec{E} \cdot \vec{B} a \tag{9}$$

For the DFSZ axion we have c_γ=0.36 and for the KSVZ c_γ=-0.97. This coupling is very important for the detection of the axions.

One of the main axion production mechanisms, stemming from the two photon interaction thus common to all axion models, is the Primakoff process:

$$Z + \gamma(k) \to Z + a(k_a) \quad or \quad e(p_1) + \gamma(k) \to e(p_2) + a(k_a) \tag{10}$$

Here Z is the nucleus, e=electron, γ=photon, a=axion and the symbols in parentheses represent the initial and final momenta of these particles.

Any light and weakly interacting scalar or pseudoscalar can be produced in hot plasmas and has the potential to cause energy loss in the stellar evolution [9]. Axion emission from stellar objects (red giants, stars in globular clusters, supernova 1987A, etc…) must be weak enough not to change their known evolutionary process. This puts a limit on the scale which, although model dependent, is roughly $f_a > 6*10^9$GeV, corresponding to a mass limit of m_a<0.01eV. On the other hand masses less than about 10 μeV cannot be allowed because so light axions would have abundantly produced in the early universe so that to overcome the closure density. Assuming that the main source of axion radiation is string loops rather than long strings the axions produced abundantly in the Big Bang would be the main candidate for cold dark matter if its mass is roughly in the range of 1μeV - 1 meV [10]. Axions with mass in the sub-eV to eV region could on the other hand be good candidates for the hot dark matter [11].

EXPERIMENTAL TECHNIQUES

Experimental efforts to discover the axion particle have been active since the proposal of the standard axion and continued all along the subsequent theoretical models [12,13]. The new generation axion search includes experiments looking for halo axions of very low masses and experiments looking for solar axions of masses in the allowed region:

The US Large Scale Dark Matter Axion Search experiment (ADMX), employing a large scale microwave cavity at LLNL to search for relic axions in our galactic halo [14]. In the presence of a magnetic field, an axion can decay into a single photon of the same energy, and the conversion probability is resonantly enhanced in a high-Q microwave cavity [15,16]. The technique involves a tunable helium-cooled high-Q cavity placed in the bore of a superconducting solenoid, and the resonant frequency of its lowest TM mode is slowly swept while the cavity output is monitored for excess power from resonant axion conversions. The expected signal is very weak, even with their expected local density of axions, 10^{14} cm^{-3} for a 10 μeV axion, the expected conversion power is extremely weak, ~10^{-23} W, so the physical temperature of the cavity and the intrinsic noise of the electronics must be reduced to minimal values. For the detection of the signal, Heterostructure Field Effect Transistor (HFET) microwave amplifiers are being used achieving total system noise temperatures of ~3 K and representing the world's quietest spectral radio receivers. The experiment is looking for axions with masses between 1.3 μeV and 13 μeV and has already reported null results in the range of 2.1 - 3.3 μeV [13]. An upgrade to ADMX experiment is being pursued in order to improve the signal to noise using SQUID amplifiers.

The University of Kioto experiment (CARRACK), seeks to exploit the extremely low-noise photon counting capability of Rydberg atoms in a Sikivie-type microwave cavity experiment [17]. Rydberg atoms are atomic systems that have been excited to near the ionization limit and in which an electron has been promoted to a level with large principal quantum number n (n~100). Rydberg atoms are quite sensitive as microwave photon detectors because the energy difference between adjacent levels is in the microwave region, they are highly efficient in absorbing these photons and the lifetime of the excited states is appropriate (1ms). This detector would scan the region of 2 to 30 μeV axion masses and results are reported for the 10 μeV [18].

The SOLAX [19] in Sierra Grande, COSME [20] in the Canfrac laboratory and DAMA in Gran Sasso [21], were designed as solar axion experiments which exploit the coherent conversion of axions on the crystalline planes in germanium detectors [22]. Indeed, solar axions could transform efficiently in electric crystal fields when the Bragg condition is satisfied. The obtained limits are not as restrictive as the solar axion experiments based on strong magnets described below.

The recent CERN Axion Solar Telescope (CAST) [23] and the earlier Japanese experiment in Tokyo [24] represent a more sensitive technique to detect solar axions with mass up to ~1 eV. The axion production in the sun's core is obtained by transforming thermal photons in the plasma to axions through the Primakoff process (figure 1a). The expected solar axion flux can be described by the following analytical fit [25,26,27]:

$$\frac{d\Phi_\alpha}{dE} = 6.02\times 10^{10}\left(\frac{g_{\alpha\gamma}}{10^{-10}GeV^{-1}}\right)^2\left(\frac{E}{keV}\right)^{2.481} e^{\left(-\frac{E}{1.205keV}\right)} axions/cm^2/\sec/keV \qquad (11)$$

This expression resembles a Maxwell-Boltzmann with a mean value of ~ 4.2 keV, peaking at about 3.2 keV.

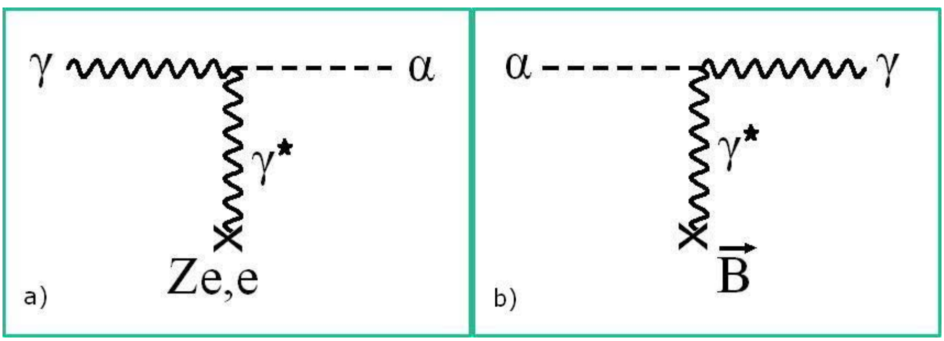

FIGURE 1. a) The axion production through the Primakoff process. b) The axion detection in a magnetic field through the inverse Primakoff process.

If the axions are allowed to enter a transverse magnetic field region, they can convert back to X-ray photons, which retain the original direction of axions, via the inverse Primakoff process (figure 1b) with a probability of:

$$P_{a\to\gamma} = \left(\frac{g_{\alpha\gamma} B}{q}\right)^2 \sin^2\left(\frac{qL}{2}\right) \qquad (12)$$

With B the magnetic field strength, L the path length and q the axion-photon momentum difference which in the vacuum is: $q = m_\alpha^2/2E$. For $qL \ll 1$ this becomes $P_{\alpha\to\gamma} = (g_{\alpha\gamma}BL/2)^2$, so the X-ray flux does not explicitly depend on the axion mass:

$$\Phi_\gamma = 0.51 cm^{-2} day^{-1} \left(\frac{g_{\alpha\gamma}}{10^{-10} GeV^{-1}}\right)^4 \left(\frac{L}{9.26m}\right)^2 \left(\frac{B}{9.0\,T}\right)^2 \qquad (13)$$

If, however, $qL \geq 1$ the axion-photon oscillation length is less than L the rate is reduced because of the axion-photon momentum mismatch. In this case one can use a low-Z gas in order to provide a refractive photon mass m_γ so that $q=|m_\gamma^2-m_\alpha^2|/2E$. If $m_\gamma \approx m_\alpha$ (as accomplished by adjusting the gas pressure), then the X-ray flux is restored to the above rate.

THE CAST EXPERIMENT

Experimental Details

The CAST experiment was designed to dramatically improve the sensitivity to the axion detection [23]. A 9.26m long decommissioned superconducting test LHC magnet was made operational again providing a 9 Tesla field and cross sectional area of 2x14.5 cm^2. The magnet is mounted on a rotating platform and is able to track the sun for about 1.5 hours during sunrise and 1.5 hours during sunset with an accuracy of better than 0.01^o. In order to control the systematics, the experiment uses three different technology detectors to search for the X-rays expected by the axion conversions inside the two magnet bores. A conventional Time Projection Chamber (TPC) is mounted on one side of the magnet covering both bore openings and looks for sunset axions. At the other end two more X-ray detectors are looking for the sunrise axions. One novel Micromegas (Micromesh Gaseous) detector with X-Y readout strip structure [28,29] covers one bore and a Charge Coupled Device (CCD) detector [30], used in conjunction with an X-ray mirror telescope [31], covers the second bore. The X-ray telescope can produce an 'axion' image of ~ 6 mm^2 on the CCD, greatly reducing the effective background of the device. All detectors are made of low background materials and external shielding is used, when required, to keep the overall background rate to a minimum.

All three CAST detectors are recording 'axion' data during their corresponding tracking time while the rest of the time they are devoted to background (mostly) and calibration data taking. Figure 2 shows the CAST experiment in action.

FIGURE 2. View of the CAST experiment. The TPC, mounted at the left end of the magnet, searches for sunset axions whereas the Micromegas and CCD detectors, at the right end, look for sunrise axions.

Data Analysis And Results

CAST operated for a total of about 6 months in 2003 and the data taken are already analyzed and published [32]. The data from the experiment running in 2004 are at the final analysis stages. An important feature of the CAST data treatment, for the TPC and Micromegas data, is that the detector backgrounds are measured with about ten times longer exposure during the non tracking periods. The use of these data to estimate and subtract the true experimental background during sun tracking data is the most sensitive step in the CAST analysis. A more sensitive analysis is obtained with the CCD. The CCD measures the background and potential signal at the same time, since the signal is expected at the focusing area of the telescope, so an axion signal will be seen as excess of events in this area. It is worth mentioning the low background levels which can be reached by the CAST detectors after the filtering of the events. As an example the Micromegas detector, during 2003, reached a level of 2.0×10^{-5} events/keV/cm^2/s with better than 85% software efficiency [29].

The three detectors are analyzing their data independently, so in order for an observed excess of events over the background to be considered as a credible signal of axions it must be seen by all detectors. Each detector after filtering the tracking and the background data performs a comparison of the two sets. In the no-excess, no-signal case each analysis comes up with an individual result on the axion-photon coupling by either chi-square minimization (TPC and Micromegas) or the use of Likelihood method (CCD). Input for this analysis is the knowledge of the axion induced photon spectrum for fixed m_α, multiplied with the detector efficiency curves. The final answer is produced by combining the individual results.

As no axion signal was observed, the conclusion from the 2003 data analysis was a greatly improved limit for the axion-photon coupling $g_{\alpha\gamma}$. In the mass range of $m_\alpha \leq$ 0.02eV and with a confidence level of 95%, the CAST experiment obtained [32]:

$$g_{a\gamma\gamma} < 1.16 \times 10^{-10} GeV^{-1} \qquad (14)$$

Figure 3 shows the obtained limit in comparison with the limits obtained from other experiments in the same axion mass range and also shows the limits imposed by astrophysical considerations. The results from the 2004 data analysis are expected to reach the planned sensitivity of the experiment.

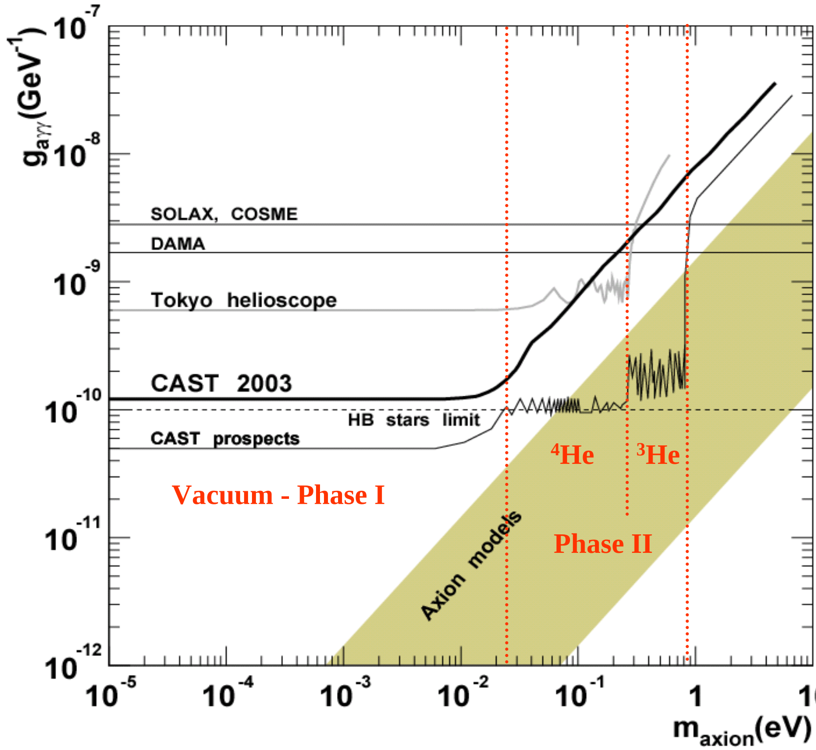

FIGURE 3. Exclusion limit (95% CL) from the CAST 2003 data compared with other constraints discussed in the text. The shaded band is the best motivated by typical theoretical models [33] to search for axions. Also shown is the future CAST sensitivity as foreseen in the experiment proposal.

Future Prospects

CAST, as seen in figure 3, has not reached the axion model band as yet. It is expected to enter this region in the already approved second phase of the experiment, in which search for higher mass axions is to be conducted. This phase is scheduled to start in October 2005 and involves filling the magnet bores with helium gas so that to obtain zero momentum difference between axion and photon. The vapor pressure of He^4 at 1.8^o K, is such that a maximum axion mass of 0.26 eV can be reached. The pressure settings will be incremented in steps to achieve maximum sensitivity for different mass values. Using He^3 that has a higher vapor pressure, one can reach a higher axion mass of up to 0.8 eV. For even higher masses an isolating gas cell in the bore will be required where He^3 at 5.4^o K would allow reaching a mass of 1.4 eV.

An important upgrade of the Micromegas detector is planned, for phase II. The contribution of the Livermore group, a member of the CAST collaboration, involves the design and construction of an X-ray focusing telescope for use with a scaled down version of the Micromegas detector. This development combined with the addition of shielding around the Micromegas detector is expected to improve the background level of this detector by two orders of magnitude. Figure 4 shows the layout of the new Micromegas line.

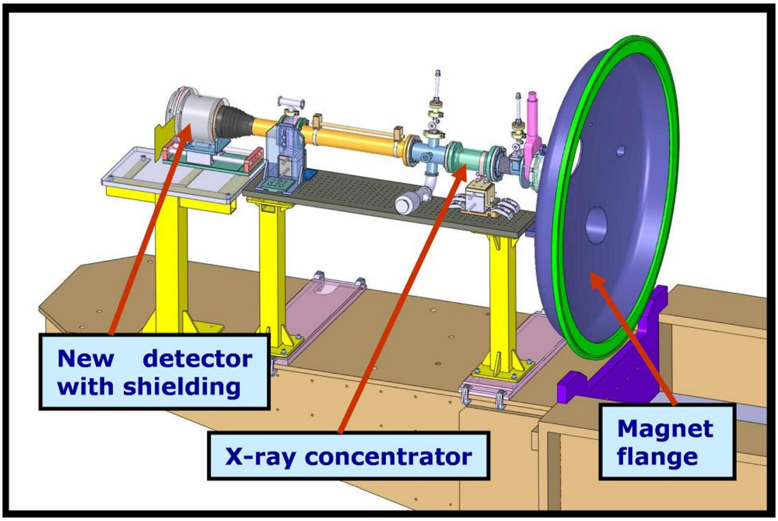

FIGURE 4. The schematic of the new Micromegas detector line for phase II of the CAST experiment is shown. The CCD line (next to Micromegas) is not shown for clarity.

CONCLUSIONS

A new generation of experiments is active and its detector arsenal continuously improving with the purpose to become more efficient for the search of the elusive axions. Axions constitute the most elegant solution to the strong CP problem and the theory will greatly benefit in predictive power and self consistency when this kind of particle is discovered.

The CAST experiment has been looking for axions of mass under 0.02eV during the 2003 and 2004 data taking periods. The result is an enormous improvement of the previous axion-photon coupling limit. During the second phase of the CAST experiment the axion mass region of at least up to 0.8 eV will be explored, by filling with appropriate helium gas the magnet bores. This way CAST enters the axion model region of figure 3, a region which is favored by theoretical modes.

ACKNOWLEDGMENTS

We thank CERN for hosting the experiment and the enormous help of CERN's technical and scientific personnel on practical matters. We acknowledge support from NSERC (Canada), MSES (Croatia), CEA (France), BMBF (Germany), GSRT (Greece), RFFR (Russia), CICyT (Spain), and NSF (USA). Work at LLNL was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48. We also acknowledge support from the European RTN under contract No. HPRN-CT-2002-0029.

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