4 Axions and Large Extra Dimensions

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Abstract. Theories including extra space dimensions offer a possible solution to the hierarchy problem of particle physics. An additional effect of these theories is the possibility for axions to propagate in the higher-dimensional space. We explore the potential of the CERN Axion Solar Telescope (CAST) for testing the presence of large extra dimensions.

4.1 Introduction on Extra Dimensions

One of the most puzzling problems in nature is the hierarchy problem of particle physics, i.e., the large separation between the electroweak scale $\sim 10^3$ GeV and the Planck scale $M_{\rm Pl} = 1.22 \times 10^{19}$ GeV. One possible solution is the introduction of n extra space dimensions. Recent theories involve the idea that the standard-model fields are confined to our (3+1)-dimensional subspace (brane) of a higher-dimensional space (bulk), while only gravity may propagate throughout the bulk. The hierarchy is generated by the geometry of the additional dimensions.

While our knowledge of the weak and strong forces extends down to scales of order 10^{-15} mm, we have almost no knowledge of gravity for distances smaller than roughly a millimeter. It is thus conceivable that at small distances gravity behaves differently from the inverse-square force law. However, gravity obeys Newton's law at distances greater than a millimeter and therefore behaves as if there are only 3 spatial dimensions. There are several different scenarios[1] to achieve this.

1. Arkani-Hamed, Dimopoulos and Dvali (ADD) suggested that the extra dimensions are compactified and the geometry of the space is flat. The hierarchy is generated by a large volume of the extra-dimensional space (large extra dimensions) [2].
2. Randall and Sundrum assumed that the hierarchy is generated by a large curvature of the extra dimensions (warped extra dimensions) [3].

[1] An additional possible scenario is with TeV^{-1} sized extra dimensions [1] which allows also the standard-model particles to propagate in the bulk. This scenario cannot solve the hierarchy problem.

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It is the relation of these models to the hierarchy which yields testable predictions at the TeV scale.

4.1.1 Large Extra Dimensions

Large extra dimensions aim to stabilize the mass hierarchy by producing the hugeness of the Planck mass M_{Pl} via the relation

$$M_{\mathrm{Pl}}^2 \approx M_D^{n+2} R^n, \tag{4.1}$$

where R is the (common) compactification radius of the extra dimensions and M_D is the fundamental higher-dimensional scale. In this scenario, it is assumed that the extra dimensions are flat and thus of toroidal form. In order to eliminate the hierarchy between the Planck and electroweak scale, M_D should be of order TeV. In this case R ranges from a sub-millimeter to a few fermi for $n = 2$–6. The case of $n = 1$ is excluded since the corresponding compactification radius ($R \approx 10^{11}$ m) is such that deviations from Newton's law could be observed on solar-system scales. Due to the large size of the extra dimensions, the standard-model fields have to be constrained to the brane.

After compactification of the n additional dimensions, all fields propagating in the bulk are decomposed into a complete set of modes, the so-called Kaluza-Klein (KK) tower of states, with mode numbers $\mathbf{k} = (k_1, k_2, \ldots, k_n)$ labeling the KK excitations. The momentum of the bulk field is quantized in the n compactified dimensions, $\mathbf{p}_n^2 = \mathbf{k} \cdot \mathbf{k}/R^2$. For an observer on the brane, each allowed momentum in the compactified volume appears as a KK excitation of the bulk field with mass $m_{\mathbf{k}}^2 = \mathbf{p}_n^2$. The result is a KK tower of states where each KK excitation has identical spin and gauge quantum numbers.

Experimental constraints on the radius of the extra dimensions, for the case of two flat dimensions of equal radii, are given by [4]

- direct tests of Newton's law ($1/r^2 \to 1/r^{2+n}$ for $r < R$)

$$R < 0.15\,\mathrm{mm}\ ,$$

- collider signals (direct production of KK gravitons)

$$R < 210\text{–}610\,\mu\mathrm{m}\ ,$$

- and astrophysics (limits depend on technique and assumption)

supernova cooling	$R < 90$–$660\,\mathrm{nm}$
neutron stars	$R < 0.2$–$50\,\mathrm{nm}$

4.2 Axions in Large Extra Dimensions

In the ADD model, extra dimensions are felt only by gravity while the standard-model fields are confined to a (3+1)-dimensional subspace of a higher-dimensional space. In addition to gravity, one can assume that fields that are singlets under the standard-model gauge group could also propagate in the higher-dimensional space. As such, one might consider axions.

Axions are hypothetical particles associated with the spontaneously broken Peccei-Quinn (PQ) symmetry that can solve the strong CP problem in QCD [5]. Besides, axions are serious candidates for the dark matter of the Universe. An effective axion Lagrangian is of the form

$$L_{\mathrm{eff}} = L_{\mathrm{QCD}} + \frac{1}{2}\partial_\mu a \partial^\mu a + \xi \frac{g_s^2}{32\pi^2}\frac{a}{f_{\mathrm{PQ}}} G^b_{\mu\nu}\tilde{G}^{b\mu\nu}\,, \tag{4.2}$$

where f_{PQ} is the PQ symmetry breaking scale and ξ is a model-dependent parameter. The axion-photon coupling strength is given by the relation

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_{\mathrm{PQ}}}\left(\frac{E}{N} - 1.93 \pm 0.08\right), \tag{4.3}$$

where E/N is a model-dependent parameter. The mass[2] of the axion m_{PQ} is related to f_{PQ} by

$$m_{\mathrm{PQ}} = 6\,\mathrm{eV}\frac{10^6}{f_{\mathrm{PQ}}/1\,\mathrm{GeV}}\,. \tag{4.4}$$

The most stringent constraints on f_{PQ} (or equivalently on m_{PQ}) are set by astrophysical and cosmological considerations: $10^9\,\mathrm{GeV} \le f_{\mathrm{PQ}} \le 10^{12}\,\mathrm{GeV}$.

As already stressed, a singlet higher-dimensional axion field could also propagate into the bulk. Also, according to astrophysical and cosmological considerations, the Peccei-Quinn scale f_{PQ} could be much greater than the fundamental scale M_D. To avoid a new hierarchy problem, axions should propagate in the extra dimensions. Then the higher-dimensional scale $\bar{f}_{\mathrm{PQ}}$ can be lowered by the same mechanism as in the case of gravity

$$f^2_{\mathrm{PQ}} \approx M_S^\delta R^\delta \bar{f}^2_{\mathrm{PQ}}\,, \tag{4.5}$$

where M_S is the string scale, $M_S \sim M_D$. As the phenomenologically allowed region for f_{PQ} is such that $f_{\mathrm{PQ}} \ll M_{\mathrm{Pl}}$, the axion must be restricted to a subspace of the full higher-dimensional space ($\delta < n$), if $\bar{f}_{\mathrm{PQ}}$ is to remain in the TeV range [6]. However, $\delta = n$ is possible for $\bar{f}_{\mathrm{PQ}} \ll \mathrm{TeV}$ [7].

Upon compactification of δ additional spatial dimensions, the higher-dimensional axion field is expanded into a Kaluza-Klein tower of states.

[2] It is common in theories with extra dimensions to denote the ordinary 4-dimensional axion mass by m_{PQ}. The axion mass m_a, corresponding to the lowest state in the KK axion tower, does not have to be identical to m_{PQ}.

KK excitations have an almost equidistant mass spacing of order $1/R$. The lowest KK state specifies the coupling strength of each KK state to matter. A source of axions, such as the Sun, will emit all KK states up to the kinematic limit, i.e., axions with masses of some keV. Another interesting feature arising from the higher-dimensional axionic theories is that the axion mass may decouple from the Peccei-Quinn energy scale (in 4-dimensional theories $m_{\mathrm{PQ}} \sim 1/f_{\mathrm{PQ}}$). In such cases, the axion mass is determined by the compactification radius $m_a \simeq 1/2R$ [6]. This will be shown for the simplest case $\delta = 1$.

In order to obtain an effective 4-dimensional theory, one extra spatial dimension has to be compactified, e.g., on a $\mathbf{Z}_2$ orbifold of radius R where the orbifold action is identified as $y \to -y$. This implies that the axion field will have a Kaluza-Klein decomposition of the form

$$a(x^\mu, y) = \sum_{n=0}^{\infty} a_n(x^\mu) \cos\left(\frac{ny}{R}\right) , \tag{4.6}$$

where $a_n(x^\mu)$ are the Kaluza-Klein modes. An effective 4-dimensional Lagrangian is then given by

$$\begin{aligned} L_{\mathrm{eff}} = L_{\mathrm{QCD}} &+ \frac{1}{2}\sum_{n=0}^{\infty}(\partial_\mu a_n)^2 - \frac{1}{2}\sum_{n=1}^{\infty}\frac{n^2}{R^2}a_n^2 \\ &+ \frac{\xi}{f_{\mathrm{PQ}}}\frac{g_s^2}{32\pi}\left(\sum_{n=0}^{\infty} r_n a_n\right) G^b_{\mu\nu}\tilde{G}^{b\mu\nu} , \end{aligned} \tag{4.7}$$

where

$$r_n \equiv \begin{cases} 1 & \text{if } n = 0, \\ \sqrt{2} & \text{if } n > 0. \end{cases} \tag{4.8}$$

We can see from (4.7) that the gauge fields couple not to an individual axion mode a_k, but rather to the linear superposition

$$a' \equiv \frac{1}{\sqrt{N}} \sum_{n=0}^{n_{\max}} r_n a_n = \frac{1}{\sqrt{N}}\left(a_0 + \sqrt{2}\sum_{n=1}^{n_{\max}} a_n\right) , \tag{4.9}$$

where

$$N \equiv 1 + 2n_{\max} , \tag{4.10}$$

and $n_{\max}$ is a cutoff, determined according to the underlying mass scale M_S. The Kaluza-Klein axion states have a drastic effect on the axion mass matrix, given by

$$M^2 = m_{\mathrm{PQ}}^2 \begin{pmatrix} 1 & \sqrt{2} & \sqrt{2} & \sqrt{2} & \cdots \\ \sqrt{2} & 2+y^2 & 2 & 2 & \cdots \\ \sqrt{2} & 2 & 2+4y^2 & 2 & \cdots \\ \sqrt{2} & 2 & 2 & 2+9y^2 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} , \tag{4.11}$$

where we have defined

$$y \equiv \frac{1}{m_{\mathrm{PQ}} R} \tag{4.12}$$

as the ratio of the scale of the extra dimension to the 4-dimensional axion mass m_{PQ}. The usual Peccei-Quinn case corresponds to the upper-left 1×1 matrix, leading to the result $M^2 = m_{\mathrm{PQ}}^2$. Thus, the physical effect of the additional rows and columns is to pull the lowest eigenvalue of this matrix away from m_{PQ}^2. The eigenvalues λ of the mass matrix are the solutions to the transcendental equation

$$\pi R \lambda \cot(\pi R \lambda) = \frac{\lambda^2}{m_{\mathrm{PQ}}^2}. \tag{4.13}$$

The axion linear superposition can be written as

$$a' \equiv \frac{1}{\sqrt{N}} \sum_n r_n a_n = \frac{1}{\sqrt{N}} \sum_\lambda \frac{\lambda^2}{m_{\mathrm{PQ}}^2} A_\lambda \hat{a}_\lambda \;, \tag{4.14}$$

where $\hat{a}_\lambda$ are the normalized mass eigenstates, and A_λ are given by

$$A_\lambda \equiv \frac{\sqrt{2}\, m_{\mathrm{PQ}}}{\lambda} \left(\frac{\lambda^2}{m_{\mathrm{PQ}}^2} + 1 + \frac{\pi^2}{y^2} \right)^{-1/2} . \tag{4.15}$$

The solutions to the transcendental equation (4.13) for the axion zero mode [6] and the first KK excitation [8] are shown in Fig. 4.1. Let us consider the two limiting cases $m_{\mathrm{PQ}} R \ll 1$

$$\begin{aligned} \lambda_0 &\approx m_{\mathrm{PQ}} \\ \lambda_n &\approx \frac{n}{R} \quad \text{with} \quad n = 1, 2, 3, \ldots \end{aligned}$$

and $m_{\mathrm{PQ}} R \gg 1$

$$\lambda_n \approx \frac{2n+1}{2R} \quad \text{with} \quad n = 0, 1, 2, \ldots \; .$$

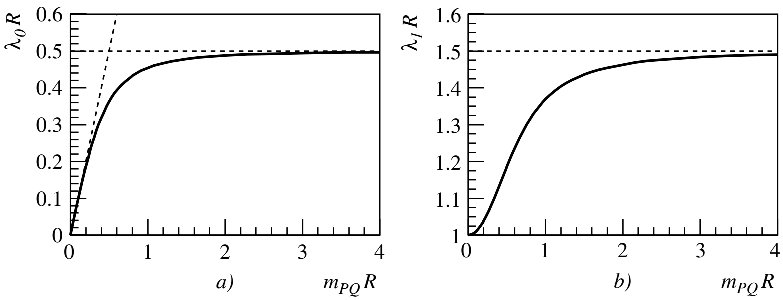

Fig. 4.1. Solutions to the transcendental equation for: (**a**) the axion zero mode; (**b**) the first KK excitation

Two important consequences of (4.13) are:

1. the lightest axion mass eigenvalue is given by

$$m_a \approx \min\left(m_{\mathrm{PQ}}, \frac{1}{2R}\right), \text{ and} \tag{4.16}$$

2. the masses of KK excitations are separated by $\approx 1/R$.

From (4.16) we see that for $m_{\mathrm{PQ}} \geq \frac{1}{2}R^{-1}$, the Peccei-Quinn scale f_{PQ} decouples from the axion mass. As long as $m_{\mathrm{PQ}} \geq \frac{1}{2}R^{-1}$, the axion mass m_a is determined by the radius of the extra space-time dimension, regardless of the specific size of m_{PQ}.

4.3 CAST as a Probe of Large Extra Dimensions

4.3.1 CAST Physics

Axions could be produced in the core of the Sun by the Primakoff conversion of thermal photons in the Coulomb fields of nuclei and electrons in the solar plasma. The expected solar axion flux at the Earth has an approximate spectrum [9]

$$\frac{\mathrm{d}\Phi_a}{\mathrm{d}E_a} = 4.02 \times 10^{10}\left(\frac{g_{a\gamma\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)^2 \times \frac{(E_a/\mathrm{keV})^3}{e^{E_a/1.08\,\mathrm{keV}} - 1}\,\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{keV}^{-1} \tag{4.17}$$

and an average energy of $\langle E_a \rangle \approx 4.2\,\mathrm{keV}$. Axions could be back converted into X-rays in laboratory magnetic field [10]. The expected number of X-rays reaching a detector is

$$N_\gamma = \int \frac{\mathrm{d}\Phi_a}{\mathrm{d}E_a} P_{a\to\gamma}\, S\, t\, \mathrm{d}E_a\ , \tag{4.18}$$

where $P_{a\to\gamma}$ is the axion-photon conversion probability, S is the effective area and t is the measurement time. The axion-photon conversion probability in a gas (in vacuum $\Gamma = 0$, $m_\gamma = 0$) is given by the relation

$$P_{a\to\gamma} = \left(\frac{B g_{a\gamma\gamma}}{2}\right)^2 \frac{1}{q^2 + \Gamma^2/4}\left[1 + e^{-\Gamma L} - 2e^{-\Gamma L/2}\cos(qL)\right]\ , \tag{4.19}$$

where L is the path length, B is the magnetic field and Γ is the inverse absorption length for the X-rays in a gas. The axion-photon momentum transfer q is defined as $q = |(m_\gamma^2 - m^2)/2E_a|$, where m is the axion mass and m_γ is the effective photon mass in a gas (in the case of H_2 and He we have $m_\gamma(\mathrm{eV}) \approx \sqrt{0.02\,P(\mathrm{mbar})/T(\mathrm{K})}$). The coherence condition

$$qL < \pi \Rightarrow \sqrt{m_\gamma^2 - \frac{2\pi E_a}{L}} < m < \sqrt{m_\gamma^2 + \frac{2\pi E_a}{L}} \tag{4.20}$$

restricts the experimental sensitivity to some range of axion masses. For example, the coherence length of $L = 10\,\mathrm{m}$ in vacuum requires $m \leq 0.02\,\mathrm{eV}$ for $E_a = 4.2\,\mathrm{keV}$. For higher axion rest masses, the coherence can be restored for a narrow mass window around $m = m_\gamma$ by the presence of a buffer gas. The CERN Axion Solar Telescope (CAST) experiment [11] is being operated in a scanning mode in which the gas pressure is varied in appropriate steps to cover a range of possible axion masses up to $0.82\,\mathrm{eV}$.

4.3.2 CAST and Large Extra Dimensions

In view of the fact that the CAST experiment is sensitive to axion masses up to $\sim 0.8\,\mathrm{eV}$, it can easily be shown that a possible effect of large extra dimensions can be seen only in the case of $n = 2$ extra dimensions. For the case $n > 2$, the compactification scale $1/R$ becomes greater than the sensitivity region of the CAST experiment and the effect of extra dimensions cannot be observed.

Limits on the Coupling Constant

The total number of X-rays (at the pressure P_i) due to all modes of the KK tower reads for $m_{\mathrm{PQ}}R \ll 1$

$$N_{\gamma i}^{\mathrm{KK}} = \frac{2\pi^{\delta/2}}{\Gamma(\delta/2)} R^\delta \int_0^\infty m^{\delta-1} N_{\gamma i}(m) G(m)\,\mathrm{d}m\ , \tag{4.21}$$

and for the case $m_{\mathrm{PQ}}R \gg 1$

$$N_{\gamma i}^{\mathrm{KK}} = \frac{2\pi^{\delta/2}}{\Gamma(\delta/2)} R^\delta \int_0^\infty m^{\delta-1} N_{\gamma i}(m + 1/2R) G(m + 1/2R)\,\mathrm{d}m\ , \tag{4.22}$$

where $N_{\gamma i}(m)$ is given by

$$N_{\gamma i}(m) = \int \frac{\mathrm{d}\Phi_a(m)}{\mathrm{d}E_a} S t_i P_{a\to\gamma i}(m)\ , \tag{4.23}$$

and the differential axion flux in the case of massive KK axion is given by the relation [7]

$$\frac{\mathrm{d}\Phi_a(m)}{\mathrm{d}E_a} = 4.20 \times 10^{10} \left(\frac{g_{a\gamma\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^2 \times \frac{E_a p^2}{e^{E_a/1.1} - 1}(1 + 0.02m)\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{keV}^{-1}\ . \tag{4.24}$$

The function $G(m)$ is defined as [8]

$$G(m) = \widetilde{m}^4 \left(\widetilde{m}^2 + 1 + \frac{\pi^2}{y^2} \right)^{-2} , \tag{4.25}$$

where $\widetilde{m} \equiv m/m_{\mathrm{PQ}}$. The origin of the function $G(m)$ is the mixing between the KK modes entering the KK decomposition of the bulk axion field and the corresponding normalized mass eigenstates. As already shown in (4.7), standard-model fields couple to the linear superposition of KK axion modes. Due to the mixing, this linear superposition rapidly decoheres. Therefore, the subsequent detection of this particular linear combination is strongly suppressed. As a consequence our results reflect a suppressed coupling $g_{a\gamma\gamma} \sim 1/f_{\mathrm{PQ}}$. In the absence of the decoherence, photons would be coupled to the linear combination with unsuppressed coupling $1/\bar{f}_{\mathrm{PQ}}$.

In order to obtain an upper limit on the coupling constant in the framework of large extra dimensions, we apply the central limit theorem at 3σ level

$$\sum_i N_{\gamma i}^{\mathrm{KK}} \leq 3 \sqrt{\sum_i N_{bi}} \, , \tag{4.26}$$

where N_{bi} is the background of the X-ray detector (with numerical values taken from [12]). For the sake of simplicity, it is assumed that all axions have an average energy of 4.2 keV. We take the largest compactification radius of 0.15 mm as set by direct tests of Newton's law. Combining (4.19) with (4.21)–(4.26), we have derived limits on the axion-photon coupling $g_{a\gamma\gamma}$ as a function of the fundamental PQ mass, as shown in Fig. 4.2.

The multiplicity of KK states to which CAST could be sensitive is large ($\sim 10^3$ for $\delta = 1$ and $\sim 10^6$ for $\delta = 2$). Still, one can see from Fig. 4.2 that the upper limit on $g_{a\gamma\gamma}$ is only at most one order of magnitude more stringent than that obtained in conventional theories. This is a result of the fact that CAST is a tuning experiment: for a particular pressure, the coherence condition is satisfied only for a narrow window of axion masses around $m \approx m_{\gamma i}$. Another feature one can observe in Fig. 4.2 is a strong decrease in sensitivity to $g_{a\gamma\gamma}$ for $m_{\mathrm{PQ}}R \geq 20$ if $\delta = 2$ and for somewhat lower values if $\delta = 1$. This is a result of the fact that the function $G(m)$ decreases as fast as $1/(m_{\mathrm{PQ}}R)^8$ in the regime $m_{\mathrm{PQ}}R \gg 1$. In this regime the zero-mode axion mass is determined by the compactification radius, $m_a \approx (1/2)R^{-1} = 6.6 \times 10^{-4}$eV. Contrary to the case of ordinary QCD axions, in theories with large extra dimensions, zero-mode axions with masses outside the favored band arise quite naturally.

Limits on the Compactification Radius

An interesting feature of the CAST experiment is the coherence condition that allows us to detect individual Kaluza-Klein mass states. It is expected

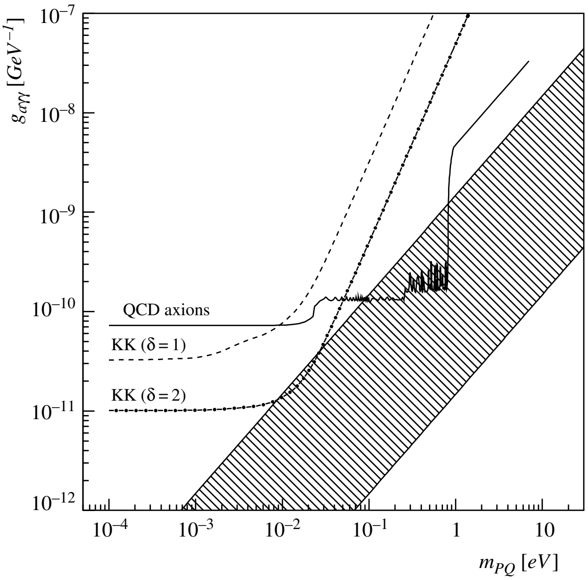

Fig. 4.2. Limits on the axion-photon coupling $g_{a\gamma\gamma}$ as a function of the fundamental PQ mass m_{PQ}. The solid line, corresponding to CAST prospects for QCD axions, is obtained using numerical values from [12]. The dashed region represents the theoretically favoured region in axion models in 4 dimensions. The dashed and dot-dashed lines correspond to CAST prospects for KK axions in the case of two extra dimensions ($R = 0.15\,\mathrm{mm}$) for $\delta = 1$ and $\delta = 2$, respectively

that more than one axion signal may be observed at different pressures of the gas. Therefore, the detection of the corresponding X-rays at least at two pressures may be the signal for the presence of large extra dimensions. Achievable limits on the compactification radius R depend on the mass of the axion zero mode [8]

1. $m_a = 1/(2R) \;\Rightarrow\; m_1 = 3/(2R) \approx 0.8\,\mathrm{eV} \;\Longrightarrow\; R \approx 370\,\mathrm{nm}$
2. $m_a = m_{\mathrm{PQ}} \;\Rightarrow\; m_1 = 1/R \approx 0.8\,\mathrm{eV} \;\Longrightarrow\; R \approx 250\,\mathrm{nm}$

These limits are comparable with the astrophysical limits.

4.4 Conclusion

Theories involving extra dimensions in which gravity propagates offer a possible explanation of the hierarchy problem of particle physics. In addition to gravity, axions too could propagate in the higher-dimensional space. We have explored the potential of the CAST experiment for observing KK axions coming from the solar interior. In theories with two extra dimensions (with $R = 0.15\,\mathrm{mm}$), a sensitivity to $g_{a\gamma\gamma}$ improves at most by one order of magnitude. In addition, the axion mass is decoupled from f_{PQ} and is set by the compactification radius R. We have also demonstrated that the CAST experiment may be sensitive to particular KK axions. Under the requirement to have at least two signals while changing the pressure of the gas, we have found that CAST is capable of probing two large extra dimensions with a compactification radius R down to around 250 nm if $m_{\mathrm{PQ}} < 1/(2R)$ and down to around 370 nm if $m_{\mathrm{PQ}} > 1/(2R)$.

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