

First Search for Axion Dark Matter with a MADMAX Prototype

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This Letter presents the first search for dark matter axions with mass in the ranges 76.56 to 76.82 μeV and 79.31 to 79.53 μeV using a prototype setup for the MAGnetized Disk and Mirror Axion eXperiment (MADMAX). The experimental setup employs a dielectric haloscope consisting of three sapphire disks and a mirror to resonantly enhance the axion-induced microwave signal within the magnetic dipole field provided by the 1.6 T Morpurgo magnet at CERN. Over 14.5 days of data collection, no axion signal was detected. A 95% CL upper limit on the axion-photon coupling strength down to $|g_{a\gamma}| \sim 2 \times 10^{-11} \text{ GeV}^{-1}$ is set in the targeted mass ranges, surpassing previous constraints, assuming a local axion dark matter density ρ_a of 0.3 GeV/cm^3 . This study marks the first axion dark matter search using a dielectric haloscope.

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Introduction—Axions have become prominent candidates for cold dark matter (DM) [1–4]. They were originally introduced to explain the absence of CP -violating effects in quantum chromodynamics (QCD) through the Peccei-Quinn (PQ) mechanism [5–8]. In the well-motivated postinflationary PQ-symmetry breaking scenario the axion mass required to match the observed DM density is expected to be in the range $m_a \sim 26$ to 500 μeV for axion models with short-lived domain walls [9–12] or even higher for other models [13,14]. In the following, the term

“axion” will refer to both QCD axions and axionlike particles.

In an external magnetic field $\mathbf{B}_e$, axions convert to photons and source an oscillating current with frequency corresponding to m_a , given by $\mathbf{J}_a = g_{a\gamma} \mathbf{B}_e \dot{a}$ [15] as an additional term to be added to Maxwell’s equations, with $g_{a\gamma}$ the axion-photon coupling strength and $\dot{a}$ the temporal derivative of the axion field. Cavity searches are a promising approach to detect axions [16]. They are designed to convert axions from the DM halo into microwave photons using a resonator in a magnetic field. Several cavity searches [17–26] have already put significant constraints on $|g_{a\gamma}|$ for $1 \mu\text{eV} \lesssim m_a \lesssim 26 \mu\text{eV}$, with first efforts being underway to test higher m_a [27–36], which are challenging to probe with cavity experiments as their size must be adjusted to match the wavelength of the generated photon. At higher m_a values, corresponding to higher frequencies of the generated photon, this results in a reduced volume for

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resonant axion-photon conversion, thereby decreasing sensitivity.

The MAGnetized Disk and Mirror Axion eXperiment (MADMAX) [37–39] makes use of the dielectric haloscope concept to access the well-motivated mass range $m_a > 26 \mu\text{eV}$. This concept, based on the magnetized mirror axion DM search idea [40], uses a “booster” composed of a set of parallel dielectric disks and a metallic mirror to enhance a potential axion signal, effectively decoupling the conversion volume from the wavelength and thereby overcoming the limitation of typical cavity experiments toward higher masses.

Because of the large de Broglie wavelength of the considered nonrelativistic DM axions of $\mathcal{O}(10 \text{ m})$, $\mathbf{J}_a$ is assumed to be uniform over the extent of the booster. This leads to an oscillating electric field uniform across a single medium with dielectric permittivity ϵ . The field $\mathbf{E}_a$ exhibits discontinuities at the boundaries of different media, resulting in the emission of traveling waves with frequency corresponding to m_a ensuring the continuity of the electric field. The signal power P_{sig} due to the coherent emission from multiple surfaces in relation to the power emitted by an ideal magnetized mirror, P_0 , is enhanced by the frequency-dependent boost factor $\beta^2 = P_{\text{sig}}/P_0$. By adjusting the disk positions its center frequency and width can be tuned. This makes it possible to boost the potential DM axion signal compared to the magnetized mirror concept [40] in dedicated mass ranges. The sensitivity of a MADMAX prototype setup to $|g_{a\gamma}|$ for a specific signal to noise ratio (SNR) can be estimated as [15]

$$|g_{a\gamma}| = 3.5 \times 10^{-11} \text{ GeV}^{-1} \sqrt{\frac{2 \times 10^3}{\beta^2}} \sqrt{\frac{T_{\text{sys}}}{300 \text{ K}}} \times \left(\frac{0.1 \text{ m}}{r}\right) \left(\frac{1 \text{ T}}{B_e}\right) \left(\frac{2.2 \text{ days}}{\Delta t}\right)^{1/4} \sqrt{\frac{\text{SNR}}{5}} \times \left(\frac{m_a}{80 \mu\text{eV}}\right)^{5/4} \sqrt{\frac{0.3 \text{ GeV/cm}^3}{\rho_a}}, \quad (1)$$

with system temperature T_{sys} , radius r of the disks and mirror, effective data-taking time Δt , and the local axion DM density ρ_a .

The MADMAX Collaboration has made significant progress in advancing the development of a future large-scale dielectric haloscope [41–48]. Small-scale setups have successfully validated the dielectric haloscope approach in dark photon DM searches [49,50], specifically with a broadband MADMAX prototype [50]. This work for the first time demonstrates that a tunable dielectric haloscope can be used to search for axion DM.

Experimental setup—The Closed Booster 200 (CB200) MADMAX prototype is used. As illustrated in Fig. 1, it consists of an aluminum mirror and three sapphire disks of 1 mm thickness, each with a diameter of 200 mm and distanced by separation rings enclosed in an aluminum casing, a Rexolite[®] microwave lens, and an aluminum taper, all controlled at $\mathcal{O}(10 \mu\text{m})$ precision. In contrast to the design used in [50] and envisioned for the final MADMAX design, the prototype is enclosed by conductive boundaries, resulting in fixed boundary conditions, such that only a limited number of cylindrical wave-guide modes within a given frequency range exists inside the booster. This significantly simplifies modeling of the electromagnetic response and allows us to determine β^2 with fewer dedicated measurements. Approximately 84% of the axion-induced power couples to the fundamental transverse electric TE_{11} mode as calculated by the modal overlap formalism considering the mode of propagation in a wave guide, which is absorbed in the calculation of β^2 . The emitted TE_{11} power emissions are coupled into the receiver chain by a lens and a specifically designed taper via a 50Ω transmission line. The power output of the system is coupled to a heterodyne receiver system, consisting of a series of low noise amplifiers (LNAs) and filters, and a Rohde & Schwarz FSW43 real-time spectrum analyser, which streams time-domain data with $\sim 0.11 \text{ s}$ coherent integration time to a computer where it is Fourier transformed on GPUs to power spectra. Subsequently, 8047 single power spectra are averaged to individual files with

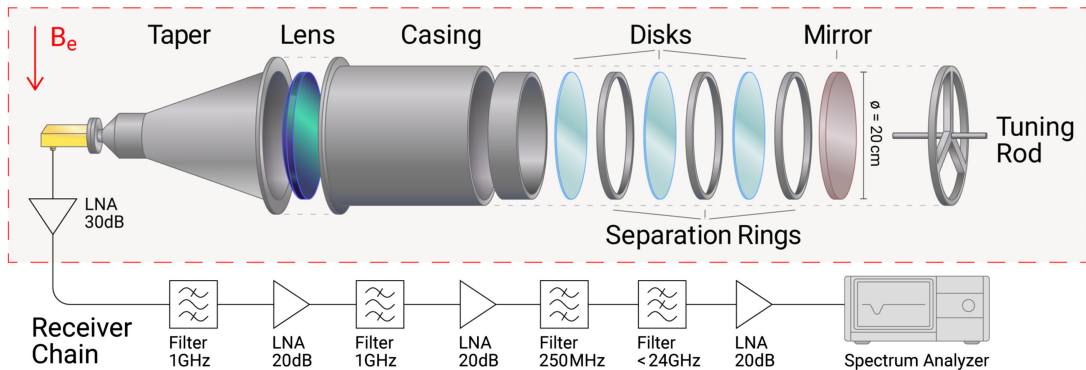


FIG. 1. Exploded schematic view of the MADMAX prototype CB200 and the receiver chain. The shaded region represents the components exposed to the $\mathbf{B}$ field.

corresponding $8047 \times 0.11 \text{ s} = 14.75 \text{ min}$ measurement time each. The receiver system has a bandwidth of $\sim 250 \text{ MHz}$, which is approximately centered around the respective β^2 peak, a resolution of 9 Hz , and provides negligible dead time. It was configured for each run to acquire data around the frequency of the expected maximum β^2 . The gain of the receiver chain was calibrated by the Y-factor method [51] using a calibrated noise diode. T_{sys} is dominated by the $\sim 230 \text{ K}$ added noise of the LNA. Additional information on the setup and the methodology used can be found in [52].

Two different disk spacing “configurations” leading to β^2 peaks in a $\sim 10 \text{ MHz}$ range were used to search for axions: configuration 1 is designed to be sensitive around 18.55 GHz and configuration 2 around 19.21 GHz , corresponding to axion masses around 76.72 and $79.45 \mu\text{eV}$, respectively. Frequency adjustment is done by proper choice of the width of separation rings between adjacent disks and between mirror-facing disk and mirror: $12.52, 12.25$, and 8.38 mm (from left to right in Fig. 1) for configuration 1 and $11.89, 12.25$, and 8.02 mm for configuration 2. The widths are optimized for a resonance of the TE_{11} mode between mirror and adjacent disk. A $\mathcal{O}(\mu\text{m})$ change in separation between mirror and closest disk results in $\mathcal{O}(\text{MHz})$ frequency shift of the β^2 distribution. The peak frequencies for both configurations were precisely tuned for different runs to different values by applying mechanical force to the mirror using an adjustable tuning rod. Three “physics runs” around 18.55 GHz and two around 19.21 GHz were performed, sensitive to different frequency ranges with peak frequencies separated by $\sim 10 \text{ MHz}$.

Measurements of CB200 power spectra with a total measurement time of 14.5 days have been performed inside the Morpurgo dipole magnet [54] at CERN. The magnet was operated at field strengths from 1.00 ± 0.01 to $1.58 \pm 0.02 \text{ T}$.

Boost factor determination—The boost factor β^2 , which is strongly correlated to the reflectivity S_{11} of the system

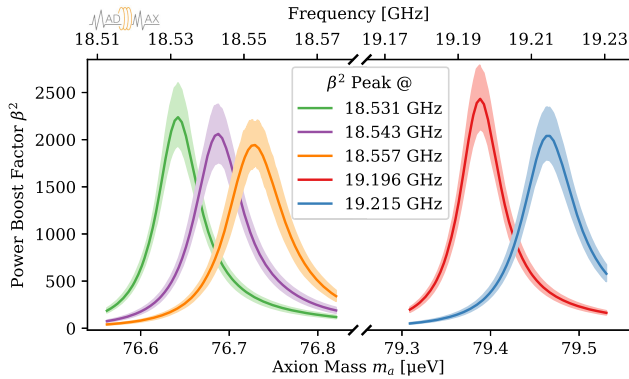


FIG. 2. Modeled β^2 distributions for the five physics runs. Lines denote mean β^2 and shaded regions give $\pm 1\sigma$ intervals.

[15], and its corresponding uncertainties are determined using a single-mode booster model [52] implemented in advanced design system [55]. The model is fitted to S_{11} measurements of the booster. Disk positions, thicknesses, dielectric losses, and permittivity are extracted. Losses due to the lens and three-dimensional effects, such as tilts, are modeled by effective dielectric losses.

Identification of the TE_{11} booster mode is done for each configuration by measuring the shape of the E field between mirror and closest disk, using a bead-pull method [45]. It follows the expected shape. S_{11} measurements confirm the separation of the TE_{11} modes from parasitic modes.

The β^2 calculation includes the overlap between the theoretical field shape and the uniform axion current of 84% . This is analogous to a form factor in cavity

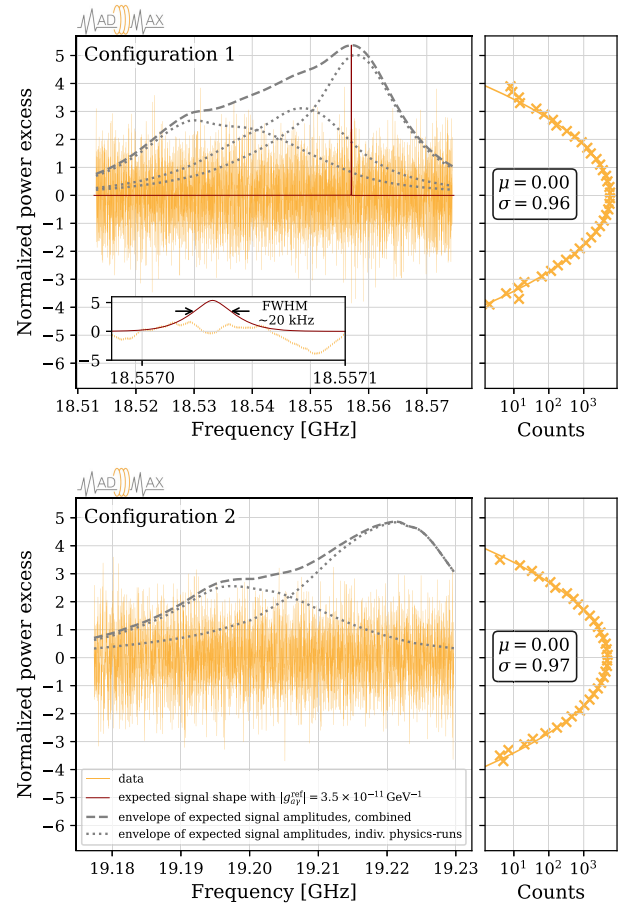


FIG. 3. Grand spectra with 0.9 kHz bin width for both booster configurations. Dashed gray lines indicate the envelope of expected amplitude in each frequency bin for a reference axion signal with photon coupling of $|g_{a\gamma}^{\text{ref}}| = 3.5 \times 10^{-11} \text{ GeV}^{-1}$, combining all physics runs for both configurations. Dotted lines show the expectation for individual physics runs. The expected signal shape of the same coupling strength at peak sensitivity is shown as solid line. The inset shows an enlargement of this mass region. The right panels display histograms of the spectra, overlaid with a best-fit Gaussian distribution with the indicated mean and standard deviation.

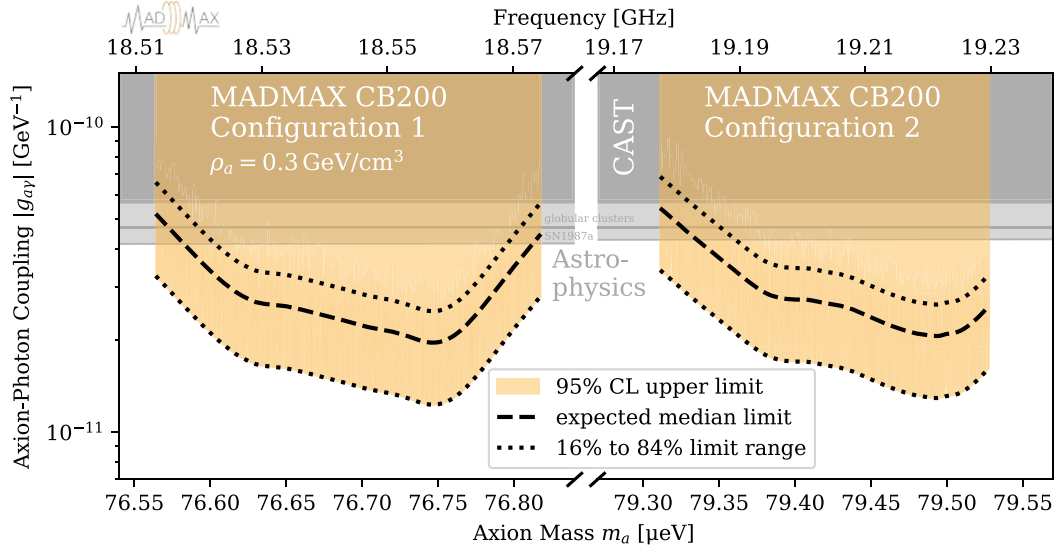


FIG. 4. 95% CL exclusion limits in 0.9 kHz bins (orange) from the 2024 MADMAX axion search with the CB200 prototype using the Morpurgo magnet at CERN assuming a local axion DM density of $\rho_a = 0.3 \text{ GeV cm}^{-3}$. Limits are compared to the helioscope experiment CAST [63] (dark gray) as well as to supernova [64] and globular cluster limits [65] (light gray). The expected median limit and the 16% and 84% quantiles are shown as black dashed and lower and upper dotted lines, respectively. The limits are truncated below the 16% quantile.

experiments. The uncertainty on the overlap of $\pm 12\%$ is determined from the deviation between expected and measured field shape obtained from bead-pull measurements.

When measuring power spectra, the experimentally determined $\sim 41.5 \Omega$ impedance of the first LNA of the receiver chain leads to a mismatch with the transmission line, inducing a standing wave between booster and LNA. This modifies β^2 obtained from S_{11} measurements, depending on the distance between the booster and this LNA. The distance is determined from the broadband oscillation pattern induced by resonance of the LNA noise, similar as in [50]. The modeled frequency behavior of the power spectra, adapted to consider the LNA impedance mismatch, matches the measured ones from the physics runs. Broadband power spectra measurements were taken prior to each physics run. Drifts in T_{sys} or frequency are monitored by comparing the individual 14.75 min long measurements. The variation of the measured booster peak frequencies during physics runs is used to evaluate the systematic uncertainty on β^2 . They follow a Gaussian distribution with a width around 200 kHz for all physics runs, resulting in an additional uncertainty in β^2 for a given frequency of less than 4%.

The extracted boost factors including their uncertainties are shown in Fig. 2. The maximum values for β^2 are around 2000, matching expectations [15] and have uncertainties of 13% to 17%.

Analysis—The analysis procedure for the MADMAX axion DM search [56] is modeled after the framework established by HAYSTAC [57] and adopts their

nomenclature. It combines a set of individual power spectra $P_i(\nu)$, each measured with $\mathcal{O}(14.75 \text{ min})$ averaging time, to a “grand spectrum,” where the full axion signal information is contained in a single bin. The raw fast Fourier transform data are rebinned for analysis to 0.9 kHz, enough to resolve a potential axionlike DM signal.

The spectra $P_i(\nu)$ are filtered using a fourth-order Savitzky-Golay (SG) filter [58] with a window length of $\sim 1 \text{ MHz}$ to extract the baselines $P_{\text{bl},i}(\nu)$, which are subsequently used to obtain the processed spectra $p_{\text{proc},i} = (P_i/P_{\text{bl},i} - 1)$. These processed spectra give local power excesses above the baseline across all frequency bins i . In the absence of an axion signal and assuming ideal baseline removal, the $p_{\text{proc},i}$ are expected to follow Gaussian white noise with zero mean and a standard deviation determined by the averaging time. Studies of the full analysis chain applied to simulated data, including synthetic axion signals, reveal an SNR attenuation due to the SG filter by a factor of $\eta_{\text{SG}} = 0.95$, which is constant in the range $1 < \text{SNR} < 10$.

The baseline of the recorded power spectra unexpectedly fluctuates on the scale of $\sim 9 \text{ kHz}$, which introduces unwanted correlations between the processed spectra. This sinusoidal fluctuation is removed by applying a digital notch filter on the inverse Fourier transforms of the $P_i(\nu)$. The filter has negligible influence on both amplitude and line shape of any potential axion signal, while being effective at eliminating the fluctuation artifact. In combination with the SG filter, this process ensures uncorrelated $p_{\text{proc},i}$. The $p_{\text{proc},i}$ are scaled and combined using weights that take the axion sensitivity depending on the B-field

TABLE I. Summary of systematic uncertainties on $|g_{a\gamma}|$. Minimum and maximum uncertainties among the frequency range for all physics runs are reported as first and second values (when necessary). The uncertainty from each physics run is considered individually when included in the limit estimation.

Effect	Uncertainty in $ g_{a\gamma} $
Y-factor power calibration	3 to 5%
Receiver chain power stability	$\leq 2\%$
Axion field—TE ₁₁ overlap	6%
Boost factor determination (excluding overlap)	$< 5\%$
Frequency stability of TE ₁₁ mode	$< 2\%$
Total	5 to 10%

strength in individual runs into account. The resulting combined spectrum is then cross-correlated with the expected Maxwell-Boltzmann axion line shape [59,60] to yield the grand spectrum. A local DM velocity dispersion $\sigma_v = 156$ km/s [61] and a velocity of the laboratory relative to the DM halo $v_{\text{lab}} = 242$ km/s [62] are used, resulting in an FWHM of the expected line shape of ~ 20 kHz.

The grand spectrum is unitless and, in the absence of an axion signal, expected from simulation to have zero mean and a standard deviation of 0.96, slightly below one due to correlations induced by the SG filter [57]. Grand spectra for both configurations are presented in Fig. 3. The gray dashed line shows the envelope of the expected amplitude of excesses, reflecting the SNR of an axion signal with $|g_{a\gamma}^{\text{ref}}| = 3.5 \times 10^{-11}$ GeV⁻¹. Its frequency dependence is determined by a combination of T_{sys} and β^2 . An axion signal would appear as a narrow localized excess with FWHM of ~ 20 kHz, corresponding to 22 bins at a frequency given by m_a as shown in the inset. The largest grand spectrum excess observed in both configurations has a local significance of 4.0σ , which is consistent with statistical expectations. The probability of an equal or larger excess occurring across the entire dataset assuming no axion signal is $p = 0.08$.

Since no evidence of DM axions is found, an upper limit on the axion-photon coupling $|g_{a\gamma}|$ is derived at 95% confidence level (CL) for each 0.9 kHz bin as shown in Fig. 4. The individual uncertainty contributions on $|g_{a\gamma}|$ shown in Table I are propagated into the total uncertainty taking correlations into account. For the β^2 determination this is done using Monte Carlo simulation.

The resulting limits on DM axions exceed previous results from the CAST helioscope [63] and astrophysical considerations [64,65].

Conclusion—Searching for axions with a dielectric haloscope, as proposed by the MADMAX Collaboration, facilitates accessing the “heavy” axion mass region favored by postinflationary PQ-symmetry breaking scenarios. A

novel boost factor determination method was developed and applied to derive first results from a prototype operated in CERN’s Morpurgo magnet, using the intrinsic advantages offered by the MADMAX approach. Detailed understanding of the radio frequency response of a booster system with closed boundary conditions was demonstrated. The booster could be quickly tuned and recalibrated to different frequencies demonstrating in principle the opportunity for future larger-range frequency scans. The data from the prototype test campaign using a small booster system inside a modest B field allow probing for axion dark matter in previously uncharted territory. The achievements presented here and in [50] provide a firm basis for the future research and development program toward a competitive dielectric haloscope, which will include the development of boosters with more and larger dielectric disks, the demonstration of the calibration and operation of boosters at cryogenic temperatures, and the implementation of tuning mechanisms via motorized disk position controls [42,47,48]. With ongoing development of a future, unique, large-bore 9 T dipole magnet [46,66], the MADMAX Collaboration is on a very promising track toward probing dark matter QCD axions in the 100 μeV mass region.

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Data availability—The data that support the findings of this article are openly available [67]; embargo periods may apply.

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