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In this letter we describe our novel photon regeneration experiment using a x-ray beam with a photon energy of 50.2 keV and 90.7 keV, two superconducting magnets of 3 T over a length of 150 and 97 mm, and a Ge detector with a high quantum efficiency. A counting rate of regenerated photons compatible with zero has been measured. The corresponding limits on the axion-two photons coupling constant is presented as a function of the axion mass. Our setup widens the energy window of purely terrestrial experiments devoted to axion search by coupling with two photons. It opens a new domain of experimental investigation of photon propagation in magnetic fields.

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Photon propagation in magnetic fields is a long standing domain of research for QED test [1] and for particle searches beyond the standard model [2]. All the experiments performed up to now have used a photon energy of the order of 1 eV (see [3] and Refs. within). Higher photon energies have been proposed to increase the signal to be measured, in particular γ rays [4] for QED test, or to increase the parameter space window for particle searches, in particular x-rays [5, 6].

As far as particle searches are concerned, photon regeneration experiments [7–9], also called "light shining through the wall" experiments, are an important tool in the search for massive particles that couple with photons in the presence of magnetic fields. Such particles are predicted by many extensions of the standard model. A very well known example is the standard axion, a pseudoscalar spinless and chargeless boson, proposed by Peccei and Quinn [10] to solve the strong CP problem i.e. the difference between the value of the neutron electric dipole moment predicted by QCD and its experimental value [11].

The principle of a photon regeneration experiment is to send a polarized photon beam through a region where a transverse magnetic field is present, and then to stop photons by a wall. Since they hardly interact with matter, axions generated in the magnetic region upstream of the wall can pass through it. Behind the wall, a second magnetic field region allows to convert back axions into photons. Several photon regeneration experiments have been performed [12–18]: none of them has ever detected regenerated photons. They have therefore set limits on the axion-two photons coupling constant g and the axion mass m_a. The best limits can be found in Ref. [18].

Limits are usually given for masses $m_\mathrm{a} \ll \omega$ [19], where ω is the photon energy, but a detailed theoretical analysis of axion-photon and photon-axion conversion amplitudes valid for $m_\mathrm{a} \leq \omega$ can be found in Ref. [20]. Again, for all the photon regeneration experiments performed up to now, ω is of the order of 1 eV. Experiments searching for axions of astrophysical origin, such as ADMX [21] and CAST [22], provide better limits than the purely terrestrial ones. ADMX looks for galactic cold dark matter μeV axion conversion into microwave photons in a resonant cavity immersed in a static magnetic field, while CAST looks for axions generated in the core of the sun. These axions travel to earth and are converted back into photons of a few keV in a static laboratory magnetic field. Due to the higher photon energy, the CAST limits extend up to masses on the order of a few eV [22]. These limits, however, depend on the model used to calculate the flux of axions to be detected. The critical sensitivity to these models is exposed by the recent proposal of an axion with a 17 meV mass which could explain the observed spectral shape of the x-ray solar emission [23]. In this case axions coming from the sun's interior would be reconverted into photons near the sun's surface, thus escaping the detection by CAST.

Increasing the photon energy in photon regeneration experiments allows to test new regions of the m_a and g parameter space. The use of soft x-rays has been proposed in Ref. [5], namely at the VUV-FEL free electron laser at DESY, providing photons of energy between 10 eV and 200 eV. The use of hard x-rays from a synchrotron light source has been proposed in Ref. [6]. Synchrotron light sources provide photons with energy of several tens of keV, much higher than the photon energy available nowadays at free electron lasers.

In this letter we describe our photon regeneration experiment using x-ray beams with a photon energy of 50.2 keV and 90.7 keV, carried out at the European Synchrotron Radiation Facility (ESRF), France, on beamline ID06. Our setup consists of two superconducting magnets that provide magnetic fields of 3 T over a length of 150 and 97 mm respectively, and a Ge detector with a high quantum efficiency for the stated photon energies. This configuration widens the energy domain probed by purely terrestrial axion searches. A counting rate of regenerated photons compatible with zero has been mea-

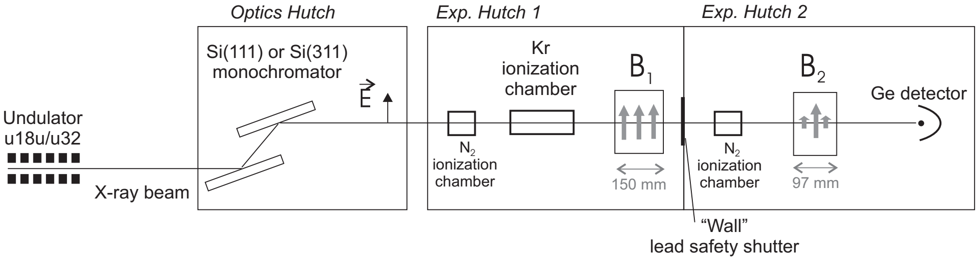

FIG. 1: Experimental Setup. The double crystal monochromator is adjusted to select the desired photon energy. The first experimental hutch corresponds to the axion generation area with the transverse magnetic field B_1. The second experimental hutch contains the second magnetic field B_2 which allows to reconvert axions to photons. These photons are detected by a liquid nitrogen cooled Ge detector with a high quantum efficiency. Ionization chambers placed along the beam path measure the incident flux or serve for alignement purposes. The synchrotron x-rays are polarized parallel to the magnetic fields.

sured. We present the corresponding limits on the axion-two photons coupling constant as a function of the axion mass. Thanks to the high photon energy, our limits extend to a parameter region where no model independent limits had been set so far. In particular our experimental results provide limits on the existence of 17 meV axions.

Our experimental setup is shown in Fig. 1. We use two different photon energies, $\omega = 50.2\,\text{keV}$ and 90.7 keV, corresponding to slightly different settings of the x-ray beamline. For 50.2 keV (resp. 90.7 keV), a Si(111) (resp. Si(311)) double crystal monochromator is adjusted to select x-rays emitted by the 5^{th} (resp. 9^{th}) harmonic of the cryogenic permanent magnet multipole undulator source U18 closed to a gap of 6.0 mm [24]. The energy bandwidth is 7.3 eV (resp. 6.8 eV). For both energies, the size of the beam is $2 \times 2\,\text{mm}^2$ and the synchrotron x-rays are horizontally polarized. The beam direction is stabilized by a feedback loop adjusting the pitch of the second monochromator crystal to ensure a position stability better than 0.1 mm at the entrance of the second magnet.

Most of the beam path is under vacuum in order to avoid air absorption. The incident flux is measured thanks to ionization chambers filled with 1 bar of Nitrogen or Krypton. Different ionization chambers placed along the beam path let us check for any photon loss due to beam misalignment for example. During data acquisition, the 30 cm long Krypton filled ionization chamber, located just before the first magnet, is used to precisely monitor the incident flux. During data acquisition, the beamline has delivered about 1.2×10^{12} photons per second at 50.2 keV and 3.1×10^{10} photons per second at 90.7 keV.

The magnetic fields are provided by two superconducting magnets with the field direction parallel to the x-ray polarization. Their diameter aperture is about 2 cm and the pressure inside the magnets is less than 10^{-4} mbar. Both magnets have been manufactured by Oxford Instruments. The first one has provided a maximum magnetic field $B_1 = 3\,\text{T}$ which can be regarded as uniform along the beam path over a length of $L_1 = 150\,\text{mm}$. The second magnet was lent to us by the DUBBLE beamline (BM26) [25] at the ESRF. It has also delivered $B_2 = 3\,\text{T}$. The shape of its magnetic field along the beam direction can be approximated by a triangular shape with a half base length of $L_2 = 97\,\text{mm}$, the maximum of 3 T being at the center of the magnet.

The magnets are located in the two lead shielded experimental hutches, EH1 and EH2 respectively, of the beamline. The closed lead safety shutter between EH1 and EH2 serves as the wall to block the x-ray beam. It consists of a 50 mm thick lead block. Similarly, the x-ray regeneration and detection section is shielded by the radiation hutch EH2. The complete enclosure of the primary x-ray beam in EH1 and the additional shielding of EH2 lead to a comfortably low level of x-ray background radiation dominated by cosmic events.

The detection system is based on a 5 mm thick Ge detector (Canberra GL0055) cooled with liquid nitrogen. The sensitive area is 6 mm large in diameter. X-ray photons arriving on the detector create electric charges proportional to the photon energy, which are amplified (Canberra 2024) and filtered by a single channel analyzer (Ortec 850) to reject events that do not correspond to the photon energy selected by the monochromator. This detection system combines an acceptable quantum efficiency of $\approx 99.98\%$ at 50.2 keV and $\approx 84\%$ at 90.7 keV, with a reasonably low dark count rate. This background count rate was measured at $(7.2 \pm 0.7) \times 10^{-3}$ photons per second while the x-ray beam was turned off, as shown on the first line of Table I.

The following experimental protocol is used before each data acquisition. First, the monochromator is adjusted to select the desired energy while keeping an incident flux as high as possible. Then, the detector is moved about 20 cm sideways from the direct beam position. The safety shutter is opened, allowing the x-ray beam to propagate through both experimental hutches. In this position, the dominant radiation received at the detector are photons elastically scattered by air. This is used to adjust the upper and lower thresholds of the

X-ray beam	Magnets	ω (keV)	$t_{\rm i}$ (s)	$N_{\rm inc}$ (Hz)	Count rate (Hz)	$N_{\rm p}$ (Hz)
OFF	OFF		13913	0	$(7.2 \pm 0.7) \times 10^{-3}$	
ON	OFF	50.2	7575	1.2×10^{12}	$(5.7 \pm 0.9) \times 10^{-3}$	
ON	ON	50.2	7276	1.2×10^{12}	$(6.2 \pm 0.9) \times 10^{-3}$	$(0.5 \pm 2.6) \times 10^{-3}$
ON	OFF	90.7	7444	3.2×10^{10}	$(7.9 \pm 1.0) \times 10^{-3}$	
ON	ON	90.7	7247	3.1×10^{10}	$(8.1 \pm 1.1) \times 10^{-3}$	$(0.2 \pm 3.0) \times 10^{-3}$

TABLE I: Summary of our data acquisition taken with magnets on or off, x-ray beam on or off. The integration time is denoted as $t_{\rm i}$, while $N_{\rm inc}$ is the number of incident photons per second and the count rate is the number of photons detected per second. The error of the regenerated photon rate $N_{\rm p}$ corresponds to 95 % confidence level. No excess count rate above background has been detected.

single channel analyzer such that only photons of the selected energy are counted. Next, the detector is protected by Cu absorbers and it is moved back into the direct beam position to check its geometrical alignment. Finally, before data collection the safety shutter is closed and the Cu absorbers are removed. The procedure is repeated after data collection.

Data are summarized in Table I. They correspond to about 2 hours of data acquisition for each photon energy in two different configurations – with or without the magnetic fields. No excess count above background has been detected. The obtained photoregeneration probability at 95 % confidence level corresponds to the error of the regenerated photon rate $N_{\rm p}$ over the incident photon rate $N_{\rm inc}$. It is $P = 2.2 \times 10^{-15}$ at 50.2 keV, and $P = 9.7 \times 10^{-14}$ at 90.7 keV.

The conversion and reconversion transition rate after propagating in vacuum over a distance z in an inhomogeneous magnetic field B may be written as [26]:

$$p\,(z) = \left| \int_0^z dz' \Delta_g\,(z') \times \exp(i\Delta_{\rm a} z') \right|^2, \tag{1}$$

where $\Delta_g = \frac{gB}{2}$ and $\Delta_{\rm a} = -\frac{m_{\rm a}^2}{2\omega}$. As the first magnet has a magnetic field B_1 that can be considered as constant over a length L_1, Eq. (1) gives a photon to axion conversion probability of:

$$p_1 = \left(\frac{gB_1L_1}{2}\right)^2 \left(\frac{\sin(\frac{\Delta_{\rm osc}}{2}L_1)}{\frac{\Delta_{\rm osc}}{2}L_1}\right)^2, \tag{2}$$

where $\Delta_{\rm osc} = -\Delta_{\rm a}$. For the second magnet, the triangular shape of the magnetic field gives a reconversion probability of:

$$p_2 = \left(\frac{gB_2L_2}{2}\right)^2 \left(\frac{\sin(\frac{\Delta_{\rm osc}}{2}L_2)}{\frac{\Delta_{\rm osc}}{2}L_2}\right)^4. \tag{3}$$

Finally, the expected count rate due to photoregeneration is:

$$N_{\rm p} = \eta N_{\rm inc} p_1 p_2, \tag{4}$$

where η is the detection efficiency. These equations are correct for $m_{\rm a} \ll \omega$.

Using Eq. (4) for the photoregeneration probability and our measurements, we obtain the corresponding limits on the axion-two photon coupling constant g versus the axion mass $m_{\rm a}$. Our limits at 95 % confidence level are plotted in Fig. 2. In particular, g is $< 1.3 \times 10^{-3}\,{\rm GeV}^{-1}$ for masses lower than 0.4 eV, and $< 6.8 \times 10^{-3}\,{\rm GeV}^{-1}$ for masses lower than 1 eV. Our limits could be extended up to 90 keV [20], but because of the loss of coherence they decrease very rapidly when $m_{\rm a} \gg \sqrt{\omega/L_{1,2}}$, thus becoming less interesting. Moreover, for such masses the probability oscillates so rapidly that its actual value depends critically on the exact value of the experimental parameters $L_{1,2}$ and ω. In this case the level of confidence of corresponding limits is mostly limited by the confidence level on these experimental values. We believe that a detailed discussion of this issue is out of the scope of our letter.

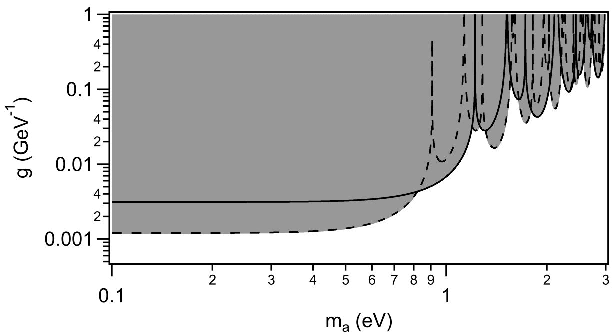

FIG. 2: 95 % confidence level limits on the axion-two photon coupling constant g as a function of the axion mass $m_{\rm a}$. The grey area is excluded. The dashed line represents limits obtained with a photon energy of 50.2 keV while the solid line corresponds to 90.7 keV.

We compare our limits to other best limits obtained with laboratory experiments in Fig.3. Our exclusion region is presented as the grey area. The best limits obtained on a purely laboratory experiment by the ALPS collaboration [18] with a 95 % confidence level is the region above the solid line. The best limits set by the search of extraterrestrial axions are the two hashed areas, namely the 95 % confidence level exclusion region

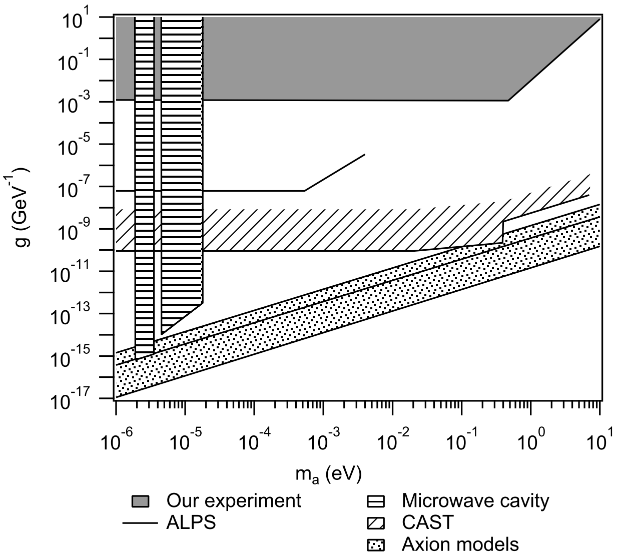

FIG. 3: Limits on the axion-two photon coupling constant g as a function of the axion mass m_a obtained by experimental searches. Our exclusion region is presented as the grey area. See text for more details.

of CAST (diagonally hashed) [22], and the 90 % confidence level exclusion region on microwave cavity experiments (horizontally hashed) [21, 27–29]. Model predictions [30] are also shown as a dotted stripe (line in between: $E/N = 0$ [31, 32]). This figure shows that we have tested a new region of the m_a and g parameter space for purely terrestrial – model independent – experiments.

Our experiment could certainly be upgraded. A longer acquisition time would improve the limits, but an improvement of a factor of 2 requires a 16 times longer acquisition. This also applies for the photon flux and for detector noise rate. The latter could likely be improved by using the x-ray detector in anticoincidence with cosmic ray detectors put around it and/or in coincidence with the electron bunches circulating in the synchrotron ring. Using higher magnetic fields increases limits linearly, which is obviously more interesting. A static 15 T field can be reasonably envisaged. Longer magnets could provide higher limits but only at low masses since longer magnets reduce the coherence length of the photon-axion oscillations and limits at higher masses. The best solution would be to increase the magnetic field B and reduce the magnet length L keeping the product $B \times L$ as high as possible.

Our experiment extends the search of photon oscillations into massive particles in the presence of magnetic fields to higher energies. The observed low background count rate clearly demonstrates the sensitivity of "shining through the wall" experiments with a synchrotron light source. Moreover we studied for the first time the propagation of x-ray photons in magnetic fields opening a new domain of experimental investigations

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