論文の内容の要旨

Search for Axion Like Particles using Laue-case Conversion in a Single Crystal (単結晶中におけるラウエ型変換を用いたアクシオン様粒子の探索)

氏名　山道智博

This thesis proposes and performs an X-ray Light Shining through a Wall (LSW) search for Axion Like Particles (ALPs) using a Laue-case conversion within a crystal. ALPs are particle predicted by theories Beyond the Standard Model (BSM). ALPs have properties similar to a pseudo-scalar unknown particles, axion, as their name suggests. Axion is a pseudo-scalar particle predicted in association with a puzzle referred to as 'strong CP problem', the fine-tuning problem of the neutron EDM. A BSM theory introducing an additional U(1) symmetry, $U(1)_{PQ,}$ was introduced to resolve the problem. The spontaneous symmetry breaking of $U(1)_{PQ}$ generates inevitably a neutral pseudo-Nambu-Goldstone boson referred to as axion.

The axion can interact with two photons via an anomaly diagram of exotic fermions with $U(1)_{PQ}$ charges. The interaction mediates a mixing of axions and photons in external electromagnetic fields, which is referred to as the Primakoff effect. The coupling constant is proportional to the axion mass. Axion Like Particles (ALPs) are pseudo-Nambu-Goldstone bosons with properties similar to the original axion. Although ALPs have properties similar to the standard axion, the proportionality between ALPs' mass, m_a, and ALP-two photon coupling constant, $g_{a\gamma\gamma}$, are no longer related to each other. Searches for ALPs should cover the whole $m_a - g_{a\gamma\gamma}$ plane without restrictions. In addition to the theoretical point of view, ALPs are also of astronomical interest. ALPs are viable candidates for dark matter and they can provide possible explanation for various astrophysical phenomena such as solar coronal heating (m_a=0.1-1.0 keV).

Extensive searches have been performed so far to observe the invisible axion and ALPs. The most stringent limits on ALPs have been obtained by model-dependent searches: the observation of stellar evolution and telescope experiments. Although the most stringent limits on ALPs in a broad mass range has been obtained by astronomical observations, their limits inevitably depend on models of stellar evolution and cosmological systems. Telescope experiments are less model-dependent because ALPs are directly detected. However, these experiments have also uncertainties on production of ALPs. Upper limits obtained by these experiments can be relaxed by possible reduction effects. ALPs flux from stellar systems can be reduced when ALPs mass and couplings depend on environmental parameters in stellar systems, such as temperature and matter densities. The uncertainty of solar axion searches is considered to be much smaller than other searches since the solar activity is better understood by Standard Solar Model (SSM). However, solar axions can be detected only when they can actually escape from the sun.

The experimental scheme referred to as 'Light-Shining-through-a-Wall' has been utilized by purely laboratorial searches in order to search ALPs model-independently. LSW experiments measure photons passing through a photon-shielding wall under external magnetic fields. Injected photons from artificial sources are converted into ALPs by the

Primakoff effect in an external magnetic field. These ALPs pass through an opaque wall without absorption due to weak couplings to matters. Then ALPs are subsequently reconverted into detectable photons by an inverse process. The conversion in an external magnetic field can be described as an oscillation between photons and ALPs similar to neutrino oscillation. The conversion probability has resonant ALPs' mass limited to the plasma frequency of the media on the photon path, which is up to ~40 eV in previous LSW experiments. The sensitivity to ALPs heavier than the resonant mass is strongly reduced and unreliable due to the rapid oscillation of the conversion probability.

The photon-ALP conversion can take place also under an electric field such as an atomic electric field within a crystal. It is well known that atomic electric fields in crystals are as high as ~ 10^{11} V/m, which corresponds to magnetic fields of ~ 10^3 T. The effective magnetic fields are much higher than currently available magnets. These high electric fields can provide an additional conversion scheme for LSW experiments. The feasibility to use the electric field has been explored by *Buchm¨uller/Hoogeveen* and *Liao*. *Buchm¨uller/Hoogeveen* firstly study the conversion of nearly massless ALPs by the Bragg-case reflection. Solar axion searches using the crystal fields have been proposed and performed. These experiments use a crystal detector itself as a converter from solar axions into X rays. However, LSW experiments using atomic electric fields have not been performed because Bragg-case diffraction in crystals reduces the X-ray penetration length L_B ~ 1 μm and the production efficiency of ALPs significantly. It was also suggested by them that the conversion is more effective when reflecting lattice planes are perpendicular to crystal surfaces (Laue-case). Later, *Liao* takes into account nonzero ALPs' mass by approximating crystals as periodic electric field. The study showed that ALPs in the keV range can be continuously searched by scanning incident angles of X rays. This study approximate crystals as a periodic electric field and ignores X-ray absorption, scattering and diffraction in a realistic crystal. A rigorous calculation including these effects is required to conduct a new-type LSW experiment.

Yamaji studies the Laue-case conversion within a crystal by taking into account X-ray diffraction and the relation between ALPs' mass and the detuning angle at the same time. The effective conversion lengths are much longer (O($10^{2\text{-}3}$)) than the X-ray penetration length of Bragg-case conversion under the Bragg condition. It can be said that the Laue-case conversion is suitable to convert and reconvert ALPs in a LSW experiment since the conversion probability of the Laue-case conversion is also $10^{2\text{-}3}$ higher than the Bragg-case one.

The first LSW experiment using the Laue-case conversion is proposed and performed in this thesis based on the calculation. The Laue-case conversion within a crystal can provide an alternative scheme of LSW searches for ALPs. This experimental scheme is sensitive to heavier ALPs than previous LSW experiments. There is another advantage of the new conversion scheme: the tenability of the resonant ALPs' mass. The resonant mass of previous LSW experiments cannot be easily tuned because it depends on the photon energy, the conversion length and the plasma frequency of the media on the photon path. By contrast, the Laue-case conversion has resonant ALPs' mass dependent on the detuning angle. The resonant mass can be easily scanned only by rotating the conversion system.

A LSW experiment using the conversion scheme is performed at a third-generation X-ray synchrotron radiation facility, BL19LXU beam line of SPring-8. A novel X ray-ALP conversion system is developed by using a silicon channel-cut crystal with two 600 μ m-thick blades. X rays from the beam line are converted into ALPs by the first blade, and then converted ALPs are subsequently reconverted into detectable X rays by the second blade. No significant signals were observed, and an 90% C.L. upper limit on the ALPs-two photon coupling constant is obtained as follows,

$$g_{a\gamma\gamma} < 4.2 \times 10^{-3}\ \mathrm{GeV}^{-1}\ (m_a < 10\ \mathrm{eV}),$$

$$g_{a\gamma\gamma} < 5.0 \times 10^{-3}\ \mathrm{GeV}^{-1}\ (46\ \mathrm{eV} < m_a < 1020\ \mathrm{eV}).$$

This limit is the most stringent limit on ALPs in the keV region as a model-independent laboratorial search. The experiment is scientifically important in that it searched the new parameter region of ALPs. Although the exclusion region of this experiment is previously searched by helioscope experiments with an upper limit of $g_{a\gamma\gamma}$ ~ 10^{-9} GeV^{-1}, Solar axions can evade the detection of these helioscope experiments if the coupling constant $g_{a\gamma\gamma}$ has a value larger than ~ 5×10^{-3} GeV^{-1}. The obtained result can complement solar axion searches by excluding the evasion in the mass range up to 1 keV. The sensitivity to m_a and $g_{a\gamma\gamma}$ can be enhanced by replacing the silicon crystal with a diamond crystals.

Figure. 1 Laue-case conversion in a single crystal.

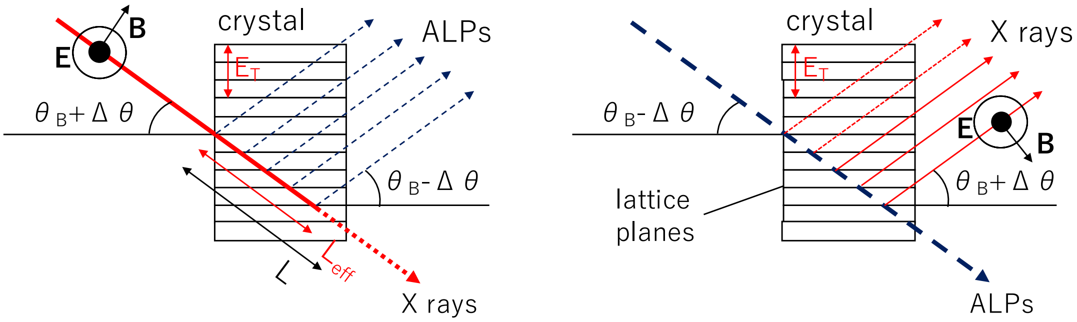

Figure. 2 The conversion-reconversion system

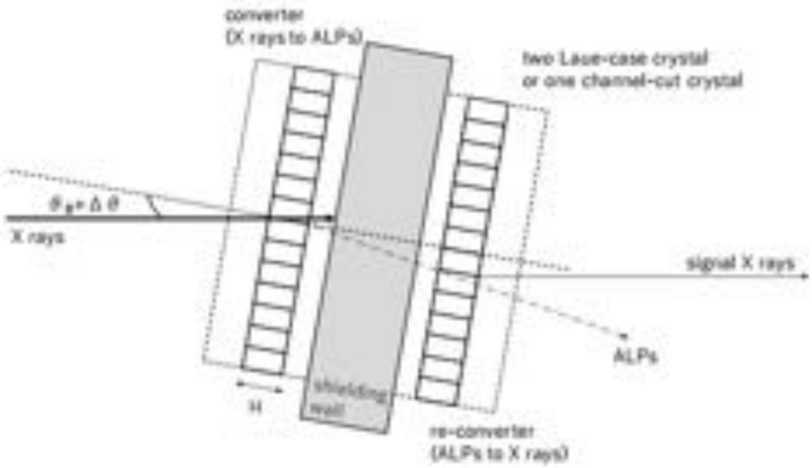

Figure. 3 The exclusion plot on m_a and $g_{a\gamma\gamma}$. The upper limit obtained by this experiment is shown by the blue area. Upper limits obtained by previous laboratorial experiments are also shown by the solid lines and dotted lines.