**Generation and search of axion-like light particle using intense crystalline field**

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Intense electric field \( \sim 10^{10} - 10^{11} \) V/cm in crystal has been known for a long time and has wide applications. We study the conversion of axion-like light particle and photon in the intense electric field in crystal. We find that the conversion of axion-like particle and photon happens for energy larger than keV range. We propose search of axion-like light particle using the intense crystalline field. We discuss the solar axion search experiment and a variety of shining-through-wall experiment using crystalline field. Due to the intense crystalline field which corresponds to magnetic field \( \sim 10^4 - 10^5 \) Tesla these experiments are very interesting. In particular these experiments can probe the mass range of axion-like particle from eV to keV.

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The search of axion-like particle (ALP) has attracted a lot of interests after the axion was invented in a mechanism solving the strong CP problem in the Standard Model \([1,2]\). The search of ALP is based on a mechanism that ALP and photon can transform to each other in external electromagnetic field, e.g. in external magnetic field \([3]\). Many varieties of ALP search experiments based on this mechanism have been proposed and been done \([4,5]\). So far, no evidence of ALP has been found. One of the crucial difficulties in laboratory search of ALP is that the external magnetic field is maximally around a few Tesla in laboratory.

It is well known for a long time that extremely strong electric field exists in crystal. For a charged particle incident on a crystal with a direction almost parallel to a crystallographic plane the strong electric field of nuclei add constructively so that a macroscopic and continuous electric field, the plane continuum electric field, is obtained. As a consequence, positrons can be trapped in a potential well of depth \( \sim 10^2 \) V between two crystallographic planes with lattice distance \( \sim 0.1 \) nm and are channeled between two parallel crystallographic planes. The plane continuum electric field is estimated \( \sim 10^{10} - 10^{11} \) V/cm which corresponds to magnetic field \( \sim 10^4 - 10^5 \) T.

Charged particles when channeling in crystal oscillate in the transverse direction and can produce coherent radiation which has been intensively explored theoretically and experimentally \([6,7]\). A high energy photon (\( \gtrsim \) GeV) incident on a crystal is also expected to be affected by the strong crystalline field and to produce electron-positron pairs \([8]\) since the radiation and the pair-production processes are related by the crossing symmetry. It’s natural to expect other quantum process of photon, such as the Primakoff type effect of photon-ALP conversion, to happen in the crystalline field.

In this Letter we study the ALP-photon conversion in intense crystalline field and propose to do laboratory search of ALP using the crystalline field. We first briefly review the intense electric field in crystal. We study the ALP-photon conversion in crystalline field. We propose to do ALP search experiment using intense crystalline field.

The structure of a single crystal is described by the Bravais lattice

\[
\vec{R} = l_1 \vec{a}_1 + l_2 \vec{a}_2 + l_3 \vec{a}_3,
\]

where \( \vec{a}_i \) is a primitive vector and \( l_i \) an integer. The crystal is periodic, e.g. the atomic density \( \rho(\vec{x} + \vec{R}) = \rho(\vec{x}) \). The same is true for the electric field and the potential in crystal. Using the reciprocal lattice vector \( \vec{q} \) the potential and the electric field can be Fourier transformed and be expressed as

\[
U(\vec{x}) = \sum_{\vec{q}} U_{\vec{q}} e^{-i\vec{q} \cdot \vec{x}}, \tag{2}
\]

\[
\vec{E}(\vec{x}) = \sum_{\vec{q}} \vec{E}_{\vec{q}} e^{-i\vec{q} \cdot \vec{x}}, \tag{3}
\]

where \( \vec{E}_{\vec{q}} = -i \vec{q} \times \vec{U}_{\vec{q}} \). \( \vec{q} = 2\pi \sum_{i=1}^{3} n_i \vec{b}_i \) where \( n_i \) is an integer, \( \vec{b}_i = \frac{1}{2} \epsilon_{ijk} (\vec{a}_j \times \vec{a}_k) / (\vec{a}_1 \cdot (\vec{a}_2 \times \vec{a}_3)) \) and \( \vec{a}_i \cdot \vec{b}_j = \delta_{ij} \). In Fig. 1 we give a plot for the cubic lattice. A crystallographic plane labeled \( \langle 010 \rangle \) is shown in the plot. The plane is parallel to the \( \langle 100 \rangle \) and \( \langle 001 \rangle \) axis and perpendicular to \( \langle 010 \rangle \) axis.

In a good approximation the plane continuum electric field can be considered constant in the longitudinal direction and periodic in the transverse direction. For example, the plane continuum po-
potential can be expressed as

$$U(y) = V[cosh(\delta(\sqrt{1+\eta^2} - \sqrt{s+\eta^2})) - 1],$$  \(4\)

where \(s = 2|y'|/d\) and \(|s| \leq 1\). \(d\) is the interplanar distance and \(y' = y - y_{\text{mid}}\) the transverse coordinate relative to the middle between two neighboring planes \(y_{\text{mid}}\). \(\eta, V, \delta\) are parameters. For example, \(\delta = 3.85\), \(V = 6.4\) \(V\), \(\eta^2 = 0.0007\), \(d = 0.119\) nm for the (110) plane of the W crystal at room temperature \(8\). The potential height \(U_0\) is around 130 V. For (110) plane of the Ge crystal, \(\delta = 3.2\), \(V = 4.5\) \(V\), \(\eta^2 = 0.0052\), \(d = 0.2\) nm, \(U_0 = 40\) V. The plane continuum electric field can be derived from \(8\).

The Lagrangian of the photon and the ALP is

$$\mathcal{L} = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{4} m^2_{\phi} \phi^2 - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \frac{1}{4} g_{\phi} \phi F_{\mu\nu} F^{\mu\nu},$$ \(5\)

where \(\phi\) is the field of ALP, \(m_\phi\) the mass of ALP, \(F^{\mu\nu}\) the field strength of photon and \(F_{\mu\nu} = \frac{1}{2} \varepsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}\). \(g_\phi\) is the coupling constant.

For a uniform incident flux the cross section for the ALP-photon conversion in crystal is

$$\sigma = \frac{1}{2 E_i v_i} \frac{d^3 k_f}{(2\pi)^3} \frac{1}{2 E_f} 2\pi \delta(E_i - E_f)$$

$$\times \int \int d^3 x \ g_\phi (\vec{k}_i \times \vec{E}_f) \cdot \hat{\epsilon} e^{i(\vec{k}_i - \vec{k}_f) \cdot \vec{x}}^2,$$ \(6\)

where \(E_i\) and \(E_f\) are the energies of the initial and final particles respectively, \(v_i\) the velocity of the initial particle relative to the crystal detector, \(\vec{k}_i\) and \(\vec{k}_f\) the initial and final momenta, \(\vec{E} = \vec{E}(\vec{x})\) the electric field in the crystal, \(\vec{E}_f\) the momentum of the photon, \(\hat{\epsilon}\) the polarization vector of photon: \(\hat{\epsilon} = (0, \hat{\epsilon})\). \(\Omega\) is the volume of the crystal. One can clearly see in \(6\) that photon polarized normal to the plane of \(\vec{k}\) and \(\vec{E}\) involve into the transformation with ALP. Photon polarized in the plane of \(\vec{k}\) and \(\vec{E}\) does not interact with ALP.

If the path length in crystal is a constant the cross-section can be expressed as \(\sigma = SP\) where \(P\) is the probability of ALP-photon conversion and \(S\) is the geometric cross section of the target crystal. A complete expression of \(P\) should sum contributions of all \(\vec{E}_q\) in crystal. For simplicity we concentrate on the case that ALP interact efficiently with a plane electric field which is periodic in \(y\) direction and constant in \(x\) and \(z\) direction, as shown in Fig. 2. The relevant reciprocal vector is perpendicular to the crystallographic plane: \(\vec{q} = q_y \hat{y}\) where \(q_T = 2\pi n_T / d\) where \(n_T \neq 0\) is an integer.

Implementing \(3\) into \(4\) and integrating over \(x\) and \(y\) coordinate we find that coherent ALP-photon conversion happens for

$$k_f^y = k_i^y = 0, k_i^x - k_f^y - q_T = 0.$$ \(7\)

Then after integration over \(z\) coordinate we find

$$P = \frac{1}{2} g_\phi |E_T| L \cos \theta_\gamma \cos \theta_i^T G^2 \sin^2(\Delta L / (4|\vec{k}_i|)) \left(\Delta L / (4|\vec{k}_i|)\right)^2,$$ \(8\)

where \(L\) is the path length in crystal as shown in Fig. 3. \(\theta_\gamma\) is the angle between photon direction and \(y\) axis as shown in Fig. 2. \(\theta_i^T\) is the angle of the initial particle. For \(\gamma \rightarrow \phi\) process, \(\theta_i = \theta_\gamma\). \(\Delta\) is

$$\Delta = m_f^2 - m_i^2 - 2 q_T (k_i^y - \frac{1}{2} q_T),$$ \(9\)

where \(m_f\) and \(m_i\) are masses of the final and initial particles. For \(\gamma \rightarrow \phi\) process, \(m_f = m_\phi\) and \(m_i = \omega_p\) where \(\omega_p\) is the plasma frequency of photon in crystal and is around tens eV. \(G = 1 - \omega_p^2 / E^2\) where \(E\) is energy. \(G\) can be taken as one for \(\omega_p \ll E\). \(E_T = -iq_T U_{q_T}\) is the Fourier transform of the electric field in \(y\) direction. Using \(4\) \(E_T\) is expressed as

$$E_T = -i q_T \frac{1}{d} \int_0^d dy \ U(y) e^{iq_T y}.$$ \(10\)

For example, for (110) plane of W crystal and \(q_T = 2\pi / d\) we find \(|E_T| = 1.7 \times 10^{11}\) V/cm. For (110) plane of the Ge crystal
We see that due to the periodic electric field in crystal the final particle is reflected by the crystal. The resonant conversion requires $|\Delta L/(4E)| < 1$ and we find accordingly that the width of resonance in energy and incident angle is: $|\delta E| \lesssim 2|\vec{k}_i| L^{-1}/(q_T \sin \theta_i)$ and $|\delta \theta_i| \lesssim 2EL^{-1}/(q_T |\vec{k}_i| \cos \theta_i)$.

Note that in the limit $(\omega_p, m_\phi) \ll (q_T, E)$ or if $m_\phi \approx \omega_p$, (14) and (15) are reduced to the Bragg scattering angle:

$$\sin \theta_i = \frac{q_T}{2|\vec{k}_i|}, \quad \sin \theta_f = -\frac{q_T}{2|\vec{k}_f|}. \quad (16)$$

In general case (14) and (15) are required to be away from the Bragg scattering angle.

We stress that according to (14) and (15) a careful arrangement of the incident angle with energy is required for resonant ALP-photon transformation to happen. Another condition is that the energy $E$ should be larger than $q_T/2$:

$$E > \frac{\pi}{d} = 3.09 \text{ keV} \times \frac{0.2 \text{ nm}}{d}. \quad (17)$$

Solar axions have average energy $\langle E \rangle \approx 4.2 \text{ keV}$ and have a significant fraction of flux with $E > 3 \text{ keV}$. So crystal detector, e.g. making use of (110) plane in Ge crystal described above, can be used to detect solar axion. The experiment can be done by carefully arranging the crystal target such that the solar axion flux incident on the crystal with a specific angle to a chosen crystallographic plane. Due to the condition (14), for a chosen angle only axions of selected energy contribute to the resonant ALP-photon conversion. The spectrum of solar axion can be scanned by adjusting the angle of crystal target to solar axion flux. Note that for a different crystallographic plane the resonance condition may also be satisfied for a different energy. Since the spectrum of solar axion is continuous many crystallographic planes can contribute to the resonant ALP-photon conversion. Detailed proposal of solar axion search experiments using crystalline field should take all possible planes into account. This is beyond the scope of this Letter.

Another interesting experiment is a reflecting-through-wall experiment, a variety of the shining-through-wall experiment [11]. The experimental setup can be arranged as shown in Fig. 3. Photons such as hard X-rays which have large enough penetration depth in crystal are sent to a crystal. Due to the condition of the resonant conversion ALPs produced are reflected by the crystal. After passing through a wall ALPs convert back to photons in crystalline field of another crystal target. This experiment can be done using mono-energetic X-rays with careful angular arrangement of crystal targets and incident angle of X-rays. In a symmetric experimental setup the probability finding
X-rays through the wall is

\[ P = \left( \frac{1}{2} \theta_\phi |E_T| L \cos^2 \theta_\gamma \right)^4 \sin^4 \left( \Delta L/(4E) \right) \left( \Delta L/(4E) \right)^4. \]  

(18)

is estimated as

\[ P = 7.5 \times 10^{-20} \times \cos^4 \theta_\gamma \sin^4 \left( \Delta L/(4E) \right) \left( \Delta L/(4E) \right)^4 \times \left( \frac{|E_T|}{2 \times 10^{11} \text{V/cm}} \right)^4 \left( \frac{g_\phi}{10^{-8} \text{GeV}^{-1}} \right)^4 \left( \frac{l}{5 \text{cm}} \right)^4, \]  

(19)

where \( l = L \cos \theta_\gamma \) is the length of crystal. The event rate is

\[ N = 19.7 \text{ year}^{-1} \frac{W}{10 W} \frac{10 \text{ keV}}{E} \frac{F}{1\%} \frac{P}{10^{-20}}, \]  

(20)

where \( W \) is the power of the X-ray source, \( F \) the efficiency of the coherent conversion of ALP and X-rays. \( F \) arises due to the fact that X-ray source has an angular spread and energy spread and only parts of X-rays can satisfy the condition of resonant conversion: \( |\Delta L/(4E)| \lesssim 1 \). We can see that this experiment is very interesting. If 1% efficiency can be achieved with a X-ray source of 10 W power, a detector using the (110) plane of W crystal with 5cm length can probe \( g_\phi \) to \( 10^{-8} \text{ GeV}^{-1} \). It would be much better than the shining-through-wall experiment using B field [7].

A very interesting aspect of ALP search experiment using crystal is that the range of \( m_\phi \) can be scanned by varying the incident angle. For example, for a fixed incident angle \( \theta_\gamma \), the resonance (\( \Delta = 0 \)) happens for \( m_\phi \):

\[ m_\phi^2 = \omega_p^2 - 2q_T (|k_i| \sin \theta_\gamma - \frac{1}{2} q_T). \]  

(21)

\( m_\phi \) range can be scanned in experiment by carefully adjusting the incident angle \( \theta_\gamma \). This is an important virtue of the ALP search experiment using crystal. Using hard X-rays or the solar axion source, ALP search experiments using crystalline field can probe the range of \( m_\phi \) up to keV scale without loss of sensitivity.

In conclusion we find that coherent ALP-photon conversion can happen in crystalline field if the energy is larger than about keV and a condition of the energy and the incident angle is satisfied. We propose to do ALP search experiments using intense electric field in crystal. These experiments have the following virtues: 1) Since the crystalline field is several orders of magnitude stronger than the magnetic field available in laboratory, ALP search experiment using crystalline field has the potential to reach sensitivity beyond the present experiments based on ALP-photon conversion in magnetic field. 2) ALP search experiments using crystalline field can probe wide range of \( m_\phi \), from eV to keV, by adjusting the incident angle of initial flux to crystal when using hard X-ray or using solar axion source in experiments. This range of \( m_\phi \) cannot be probed with good sensitivity in ALP search experiments using external B field.

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Note added After the submission of this Letter we received Refs. [12-18]. The idea of photon-axion conversion in crystal has been studied in [12, 13] and solar axion search experiments based on [13] have been done [14-18]. We note that the result in this Letter is different from the result in [12, 13]: 1) The probability [8] has a different dependence on the angle \( \theta_\gamma \), than in [12, 13]. 2) The result in this Letter is valid for all possible angles but the result in [12, 13] works only for the Bragg scattering angle which is a special case of our result, as shown in [10]. 3) The resonance condition for non-zero mass case, [14], was not found in [12, 13]. According to result in this Letter previous experiments [14, 18] based on [13] should be re-examined.

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