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 reflecting-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 of great interests. 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 [1–4]. 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 [5]. Many varieties of ALP search experiments based on this mechanism have been proposed and been done [6, 7]. 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. An interesting phenomenon due to the strong crystalline field is the channeling of charged particle in crystal. It is found that a charged particle incident on a crystal with a small angle to a crystallographic plane or an axis is influenced by strong and almost continuous electric field. For example, positrons can be trapped in a potential well of depth $\sim 10^2$ V between two crystallographic planes with lattice distance ~ 0.1 nm and are channeled between two parallel crystallographic planes. The electric field between two crystallographic planes is estimated $\sim 10^{10} - 10^{11}$ V/cm which corresponds to magnetic field $\sim 10^4 - 10^5$ T. We expect that significant conversion of ALP and photon can be induced by the strong crystalline field.

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

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

$$\vec{R} = l_1 \vec{a}_1 + l_2 \vec{a}_2 + l_3 \vec{a}_3, \quad (1)$$

where $\vec{a}_i$ is 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 the crystal. Using the reciprocal lattice vector $\vec{q}$ the potential and the electric field can be Fourier transformed and be expressed as

$$U(\vec{x}) = \sum_{\vec{q}} U_{\vec{q}}\, e^{-i\vec{q}\cdot\vec{x}}, \quad (2)$$

$$\vec{E}(\vec{x}) = \sum_{\vec{q}} \vec{E}_{\vec{q}}\, e^{-i\vec{q}\cdot\vec{x}}, \quad (3)$$

where $\vec{E}_{\vec{q}} = -i\vec{q}\, U_{\vec{q}}$. $\vec{q} = 2\pi \sum_{i=1}^{3} n_i \vec{b}_i$ 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 (010) 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.

For a charged particle incident on a crystal with a direction almost parallel to a crystallographic plane or coinciding with a crystallographic axis, the strong electric field of nuclei add constructively so that a macroscopic and continuous electric field is obtained. In a good approximation the electric field can be considered constant in the longitudinal direction and periodic in the transverse direction. For example, the plane continuum potential can be expressed as [8]

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

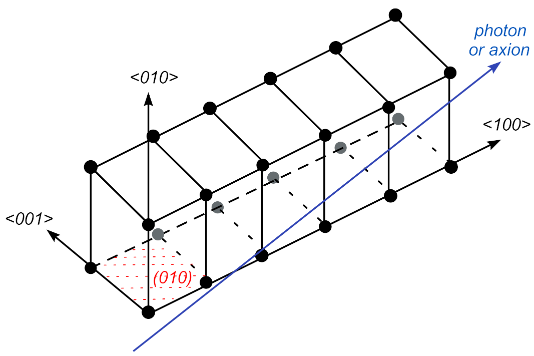

FIG. 1: Crystal lattice

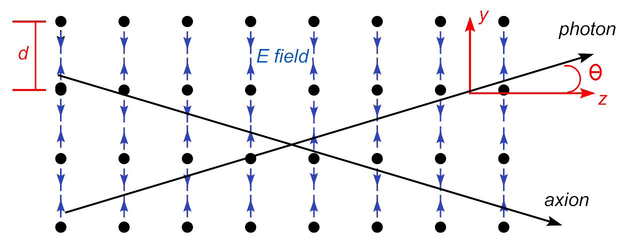

FIG. 2: ALP-photon conversion in intense crystalline field. Planar continuum electric field in y direction is plotted.

where $s = 2|y'|/d$ and $|s| \leq 1$. d is the interplanar distance and $y' = y - y_{mid}$ the transverse coordinate relative to the middle between two neighboring planes y_{mid}. η, V, δ 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 (4). One can see that the corresponding electric field is extremely strong.

The channeling of a charged particle in crystal happens when the transverse kinetic energy is smaller than the transverse potential energy in the crystalline field. In this case the transverse motion of the charged particle is significantly modified by this strong electric field. For example, a positron or an ion can be trapped in the potential well between two neighboring planes and is restricted to move between the neighboring planes. On the other hand, electron can be attracted by the electric field of the nuclei in a crystallographic axis and restricted to move along this axis when its transverse kinetic energy is smaller than the transverse potential energy. Electron can also be attracted to move around a single plane which is called planar channeling. Charged particle oscillate in the transverse direction when channeling in crystal. The oscillating motion in transverse direction can produce coherent radiation which has been intensively explored theoretically and experimentally [9]. Many other aspects of the interaction of high energy charged particle with crystalline field have been explored [8, 9]. 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 [9] since the radiation and the pair-production processes are closely related by the crossing symmetry. This is an example of the quantum process of high energy photon in the crystalline field. It's natural to expect other quantum process of photon, such as the Primakoff type effect of photon and ALP, to happen in the crystalline field.

The Lagrangian of the photon and the ALP is

$$\begin{aligned}\mathcal{L} \quad &= \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 \\ &-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{4}g_\phi\phi F_{\mu\nu}\tilde{F}^{\mu\nu},\end{aligned} \tag{5}$$

where ϕ is the field of ALP, m_ϕ the mass of ALP, $F^{\mu\nu}$ the field strength of photon and $\tilde{F}^{\mu\nu} = \frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}F^{\rho\sigma}$. g_ϕ is the coupling constant.

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

$$\begin{aligned}\sigma \quad &= \frac{1}{2E_i v_i}\int \frac{d^3k_f}{(2\pi)^3}\frac{1}{2E_f}2\pi\delta(E_i - E_f) \\ &\times \left| \int_\Omega d^3x \; g_\phi \; (\vec{k}_\gamma \times \vec{E}) \cdot \hat{\epsilon} \; e^{i(\vec{k}_i - \vec{k}_f)\cdot\vec{x}} \right|^2,\end{aligned} \tag{6}$$

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 which is taken as the speed of the light, $\vec{k}_i$ and $\vec{k}_f$ the initial and final momenta, $\vec{E} = \vec{E}(\vec{x})$ the electric field in the crystal, $\vec{k}_\gamma$ the momentum of the photon, $\vec{\epsilon}$ the polarization vector of photon: $\epsilon^\mu = (0, \vec{\epsilon})$. Ω is the volume of the crystal. One can clearly see in Eq. (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.

Implementing Eq. (3) into Eq. (6) one can see that if for a particular $\vec{q}_T$ the following condition is satisfied:

$$\vec{k}_i - \vec{k}_f - \vec{q}_T = 0, \tag{7}$$

the component $\vec{E}_{\vec{q}_T}$ associated with $\vec{q}_T$ in (3) add coherently and give an resonant enhancement to the cross-section. When this resonant enhancement happens the cross-section is proportional to

$|\vec{E}_{\vec{q}_T}|^2$. $E_{\vec{q}}$ associated with all other reciprocal vectors effectively contribute zero after integration over space.

If $\vec{q}_T$ happens to be the reciprocal vector perpendicular to a crystallographic plane, the corresponding electric field is perpendicular to the plane and is the plane continuum electric field as described above. In the following we consider this case and use the plane continuum potential which is periodic in y direction and constant in x and z direction, as shown in Fig.2. The relevant reciprocal vector is $\vec{q}_T = q_T\hat{y}$ with $q_T = 2\pi n_T/d$ where d is the interplanar distance and $n_T \neq 0$ is an integer. The condition (7) says that in the y direction

$$k_i^y - k_f^y - q_T = 0. \tag{8}$$

If the path length in crystal is a constant the cross-section can be expressed as $\sigma = SP$ where S is the geometric cross section of the target crystal and P is the probability of ALP-photon conversion in the crystal. Using (8) we find in relativistic limit

$$P_{a\to\gamma} = \frac{1}{4}g_\phi^2|E_T|^2L^2\sin^4\varphi_\gamma\frac{\sin^2(\Delta L/(4E))}{(\Delta L/(4E))^2}, \tag{9}$$

where $E = E_i = E_f$, L is the path length in crystal as shown in Fig. (3). φ_γ is the angle between $\vec{k}_\gamma$ and $\vec{E}$. In the case we are considering $\varphi_\gamma = \frac{\pi}{2} - \theta_\gamma$ where θ_γ is the angle between photon direction and z axis as shown in Fig. 2. Δ is

$$\Delta = \omega_p^2 - m_\phi^2 + 2q_T(k_i^y - \frac{1}{2}q_T), \tag{10}$$

where ω_p is the plasma frequency of photon in the crystal and is around tens eV. $E_T = -iq_TU_{q_T}$ is the Fourier transform of the electric field in y direction. Using (4) E_T is expressed as

$$E_T = -iq_T\frac{1}{d}\int_0^d dy\ U(y)e^{iq_Ty}. \tag{11}$$

For example, for (110) plane of W crystal and $q_T = 2\pi/d$ we find $|E_T| = 1.7\times10^{11}$ V/cm. For (110) plane of the Ge crystal and $q_T = 2\pi/d$ we find $|E_T| = 4.0\times10^{10}$ V/cm. The probability $P(\gamma\to\phi)$ can be similarly obtained which coincides with (9). We see that when $|\Delta L/(4E)| > 1$ the conversion probability is oscillatory as a function of L with an amplitude $4g_\phi^2|E_T|^2E^2\sin^4\varphi_\gamma/\Delta^2$. When $\Delta L/(4E) \to 0$ the probability approaches $\frac{1}{4}g_\phi^2|E_T|^2L^2\sin^4\varphi_\gamma$.

We see that for $\Delta \to 0$ the probability is coherently enhanced. The condition $\Delta = 0$ requires

$$k_i^y = \frac{1}{2}q_T - \frac{\omega_p^2 - m_\phi^2}{2q_T}, \tag{12}$$

$$k_f^y = -\frac{1}{2}q_T - \frac{\omega_p^2 - m_\phi^2}{2q_T}. \tag{13}$$

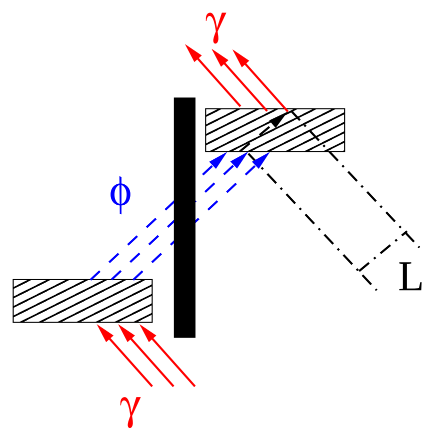

FIG. 3: Reflecting through the wall. Photons are shedded on crystal. Axion-like particles produced in crystal are reflected by the crystal and after passing through the wall generate photons in another crystal target.

(12) and (13) tell us that in the resonance region incident angle and outgoing angle are

$$\sin\theta_i^0 = \frac{q_T}{2|\vec{k}_i|} - \frac{\omega_p^2 - m_\phi^2}{2|\vec{k}_i|q_T}, \tag{14}$$

$$\sin\theta_f^0 = -\frac{q_T}{2|\vec{k}_f|} - \frac{\omega_p^2 - m_\phi^2}{2|\vec{k}_f|q_T}. \tag{15}$$

Note that in the limit $\omega_p, m_\phi \ll q_T, E$, Eqs. (12), (13), (14) and (15) are approximately reexpressed as

$$k_i^y = -k_f^y = \frac{1}{2}q_T, \tag{16}$$

$$\sin\theta_i^0 = \frac{q_T}{2E},\quad \sin\theta_f^0 = -\frac{q_T}{2E}. \tag{17}$$

We see that due to the periodic electric field in the crystal the final particle is reflected by the crystal.

We note that 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 $q_T/2$:

$$E > \frac{\pi}{d} = 3.09\ \text{keV} \times \frac{0.2\ \text{nm}}{d}. \tag{18}$$

Solar axions have average energy $\langle E\rangle \approx 4.2$ keV [10] and have significant fraction of flux with $E \gtrsim 3$ 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 angle and energy condition (14), only axions of selected energy contribute to the resonant ALP-photon conversion. So this type of solar axion search experiment can not use the whole solar axion spectrum at one time. It can scan the spectrum by adjusting the incident angle of solar axion flux. It should be noted that for a different crystallographic plane the resonance condition can also be satisfied at the same time 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.

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 are shedded on 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

$$P = (\frac{1}{2}g_\phi |E_T| L \sin^2\varphi_\gamma)^4 \frac{\sin^4(\Delta L/(4E))}{(\Delta L/(4E))^4}. \quad (19)$$

We can see that this experiment is of great interests. For example, a crystal detector of 1cm length can compete with a detector with 6 Tesla B field and 100 m length if using the (110) plane of W crystal which has $|E_T| = 1.7\times 10^{11}$ V/cm equivalent to B field of 0.57×10^5 Tesla.

A very interesting aspect of ALP search experiment using crystal is that the range of m_ϕ can be scanned by varying the incident angle. This can be seen in (8). For a fixed incident angle θ_i the resonance($\Delta = 0$) happens for m_ϕ:

$$m_\phi^2 = \omega_p^2 + 2q_T(|\vec{k}_i|\sin\theta_i - \frac{1}{2}q_T). \quad (20)$$

A small deviation $\sin\theta_i = \frac{q_T}{2|\vec{k}_i|} + \delta$ results in resonant conversion for $m_\phi^2 = \omega_p^2 + 2q_T|\vec{k}_i|\delta$. m_ϕ range can be scanned in experiment by carefully adjusting the incident angle θ_i.

An important virtue of the ALP search experiment using crystal is that it can probe range of m_ϕ much larger than eV. Using hard X-rays or the solar axion source, ALP search experiments using crystalline field can probe the range of m_ϕ up to keV scale without loss of sensitivity. It is a very good virtue in comparison with previous ALP search experiments.

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_ϕ, from less than eV to keV, by adjusting the incident angle of initial flux to crystal. In particular, these experiments have good sensitivity to the range eV $\lesssim m_\phi \lesssim$ keV when using hard X-ray or using solar axion source in experiments. This range of m_ϕ can not be probed with good sensitivity in previous ALP search experiments.

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