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Phenomenology and Production Mechanisms of Axion-Like Particles via Photon Interactions: A Theoretical and Numerical Review

N.N. Xuan[1], V.T. Thang[2]

[1]Faculty of Physics – Chemical Engineering, Le Quy Don Technical University, Hanoi, Vietnam
[2]Faculty of Basic Science, Ngo Quyen University, Binh Duong, Vietnam

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Abstract ***— Axion-Like Particles (ALPs) are theoretical pseudoscalar particles proposed in various extensions of the Standard Model, with potential implications for dark matter and solutions to the strong CP problem. This paper presents a concise review of two principal mechanisms for ALP production: photon-photon fusion and the Primakoff effect. Through quantum field theoretical calculations, we derive and analyze the corresponding scattering cross-sections, highlighting their dependence on ALP mass, coupling constants, and center-of-mass energy. Numerical simulations using realistic parameters demonstrate how ALP production varies across energy regimes and under different experimental conditions. The sensitivity of detection is evaluated, with particular emphasis on experimental setups involving high-energy proton beams and fixed nuclear targets. We also discuss the challenges in isolating ALP signals from background processes and propose directions for enhancing experimental sensitivity. This study aims to provide a comprehensive yet accessible framework for understanding ALP phenomenology and contributes to the broader efforts in probing physics beyond the Standard Model.*

Keywords— ALPs, photon fusion, Primakoff effect, scattering cross-section, beyond Standard Model

I. INTRODUCTION

Axion-Like Particles (ALPs) are hypothetical pseudoscalar particles that arise in many extensions of the Standard Model, including theories involving dark matter and solutions to the strong CP problem. ALPs interact weakly with photons and are characterized by their mass m_a and coupling constant $g_{a\gamma\gamma}$. Two primary mechanisms for generating ALPs experimentally are photon fusion and the Primakoff effect. These processes provide different pathways to probe ALPs over a range of masses and couplings [1].

Photon fusion is a process where two photons annihilate to produce an ALP [2]. This mechanism can occur in high-energy environments with a large photon flux, such as in colliders or astrophysical sources [3].

In photon fusion, the cross-section $\sigma(\gamma\gamma \to a)$ for ALP production depends on the photon flux and the ALP mass. Theoretical models predict that the cross-section increases with photon energy up to a certain point but becomes suppressed as the ALP mass approaches the center-of-mass energy [4].

The cross-section can be derived from Feynman diagrams where two photons interact, exchanging virtual particles and producing an ALP. This interaction term is governed by the effective coupling $g_{a\gamma\gamma}$. Calculations typically use quantum field theory and involve integrating over all relevant photon momentum states, leading to dependence on the ALP mass and energy scale.

Experimental constraints on photon fusion processes often come from collider experiments, such as LEP, LHC, and Belle II [5,6], which set limits on ALP production through photon interactions. These experiments have improved sensitivity to ALPs by detecting associated photon signals and examining missing energy signatures, which indicate the presence of weakly interacting particles like ALPs. Results indicate that photon fusion is a promising method for probing ALP masses in the range of 1 MeV to 1 GeV. However, experimental detection is challenging due to the low cross-section at low coupling constants and the difficulty in distinguishing ALP signals from background noise.

The Primakoff effect is another major mechanism for ALP production, where a photon interacts with a nucleus or other charged particle, producing an ALP in the process [7]. This interaction is possible because ALPs couple to the electromagnetic field of charged particles.

The Primakoff effect can be understood as the interaction of a photon with the Coulomb field of a nucleus, leading to the emission of an ALP. The cross-section for this process depends on the nuclear charge Z and is typically proportional to Z^2, making heavy nuclei more effective targets for ALP searches.

The Primakoff effect has been investigated in dedicated ALP search experiments as well as in high-energy collider settings. These experiments place constraints on ALP properties by examining photon-ALP interactions with high-energy protons or heavy nuclei. For instance, constraints from the CERN Axion Solar Telescope (CAST) and experiments like NA62 have set limits on $g_{a\gamma\gamma}$ For ALP masses below 1 eV [8].

Primakoff production has also been a significant component in astrophysical ALP searches, such as in supernovae and solar emissions, providing indirect constraints on ALP properties by modeling ALP production rates in stellar cores.

However, Precise calculations of ALP production cross-sections via photon fusion and the Primakoff effect are difficult, particularly in accounting for complex interactions in nuclear fields. Additionally, as the ALP mass approaches the energy scale of the interaction, corrections become necessary to ensure accuracy. Theoretical models predicting ALPs often involve assumptions about coupling constants and energy dependence, which might differ in extended theories in beyond the standard model. There are challenges in generalizing results to a broader parameter space while remaining consistent with known physics.

II. THE CROSS SECTION FOR AN ALP GENERATION VIA PHOTON FUSION

The cross-section for the process $e^-(p_1)+e^+(p_2)\to\gamma(k_1)+a(k_2)$, where p_1,p_2,k_1,k_2 are momentum of electron (e^-), positron (e^+), photon (γ), and ALP (a) respectively. This involves calculating the cross-section for an electron-positron annihilation into a photon and an Axion-Like Particle (ALP) using the relevant Feynman rules. The ALP-photon interaction arises from an effective Lagrangian:

$$\mathcal{L}_{\text{int}}=\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}\,. \tag{1}$$

This Lagrangian implies that the ALP couples to two photons with a coupling strength $g_{a\gamma\gamma}$. To calculate the total cross-section, we start by writing down the matrix element ($\mathcal{M}$) for the process $e^+e^-\to\gamma a$. The relevant Feynman diagram consists of the electron-positron annihilation vertex and the interaction vertex between the photon and the ALP.

The amplitude for the process can be written as:

$$\mathcal{M}=\bar{v}(p_2)(-ie\gamma^\mu)u(p_1)\epsilon_\mu^*(k_1)\frac{i}{q^2}\left(g_{a\gamma\gamma}\epsilon^{\mu\nu\rho\sigma}k_{1\nu}q_\rho k_{2\sigma}\right), \tag{2}$$

Here, $\bar{v}(p_2)$ and $u(p_1)$ are the spinors for the positron and electron, respectively; γ^μ is the gamma matrix corresponding to the interaction vertex for photon emission, $\epsilon_\mu^*(k_1)$ is the polarization vector of the outgoing photon, $q=p_1+p_2$ is the total momentum of the incoming electron-positron pair (or the momentum transferred), $\epsilon^{\mu\nu\rho\sigma}$ is the Levi-Civita symbol.

We need to square the amplitude $|\mathcal{M}|^2$, sum over final-state spins, and integrate over the available phase space.

The differential cross-section is given by:

$$d\sigma=\frac{1}{4E_{\text{CM}}^2}|\mathcal{M}|^2\,d\Pi_2\,, \tag{3}$$

where $E_{\text{CM}}=\sqrt{s}$ is the center-of-mass energy and $d\Pi_2$ is the two-particle final-state phase space element.

The two-particle phase space element $d\Pi_2$ in the center-of-mass frame is:

$$d\Pi_2=\frac{d^3k_1}{(2\pi)^3 2E_{k_1}}\frac{d^3k_2}{(2\pi)^3 2E_{k_2}}(2\pi)^4\delta^4(p_1+p_2-k_1-k_2) \tag{4}$$

The squared matrix element includes summing over the polarizations of the photon and averaging over the spins of the electron and positron.

Must pay attention, sum over photon polarizations $\sum_{\text{polarizations}}\epsilon_\mu^*(k_1)\epsilon_\nu(k_1)=-g_{\mu\nu}$ in the Lorentz gauge.

For the electron-positron spinors, we use spin summation identities $\sum u(p)\bar{u}(p)=\not{p}+m$ and $\sum v(p)\bar{v}(p)=\not{p}-m$.

The result for the squared matrix element is: $|\mathcal{M}|^2 \propto e^2 g_{a\gamma\gamma}^2 \dfrac{(s-m_a^2)^3}{s}$, where s is the Mandelstam variable (total energy in the center-of-mass frame squared).

Finally, we integrate the squared matrix element over the phase space to get the total cross-section.

For $e^+e^- \to \gamma a$, the cross-section in the center-of-mass frame is given by:

$$\sigma(e^+e^- \to \gamma a) = \frac{\alpha g_{a\gamma\gamma}^2}{32\pi s}\left(1-\frac{m_a^2}{s}\right)^3 \qquad (5)$$

The cross-section scales with $g_{a\gamma\gamma}^2$, the square of the coupling constant between ALP and photons. It also depends on the factor $\left(1-\frac{m_a^2}{s}\right)^3$, which suppresses the cross-section near the threshold for ALP production, $s \approx m_a^2$.

The energy s is the center-of-mass energy of the electron-positron pair, meaning that higher-energy collisions will have a larger cross-section unless the ALP mass is close to the center-of-mass energy.

To visualize the dependence of the scattering cross-section on the mass of the ALP under three different energy regimes (low, high, and ultra-high energy), we can plot the expression for the cross-section (5) in three energy regimes:

- Low-Energy Case (LE): $g_{a\gamma\gamma} = 10^{-10}\,\mathrm{GeV}^{-1}$, $s = 10^4\,\mathrm{GeV}^2$.

- High-Energy Case (HE): $g_{a\gamma\gamma} = 10^{-11}\,\mathrm{GeV}^{-1}, s = 10^6\,\mathrm{GeV}^2$

- Ultra High-Energy Case (UHE): $g_{a\gamma\gamma} = 10^{-7}\,\mathrm{GeV}^{-1}, s = 10^6\,\mathrm{GeV}^2$

The factor $\left(1-\frac{m_a^2}{s}\right)^3$ suppresses the cross-section for values of m_a close to $\sqrt{s}$, especially at low energies.

Vary m_a (ALP mass) from a small value (e.g., 10^{-3}MeV) to a larger fraction of $\sqrt{s}$.

For each case, calculate the cross-section and plot σ as a function of m_a

Fig. 1 is the graph showing the dependence of the scattering cross-section on the ALP mass m_a for three different energy regimes:

- In LE: The cross-section drops rapidly as m_a approaches $\sqrt{s}$, resulting in a sharp decrease for heavier ALPs. It is extremely small $\sim 4.97\times10^{-18}\,\mathrm{GeV}^{-2}$. This implies that ALP production via photon fusion is very rare at lower energies with such a weak coupling.

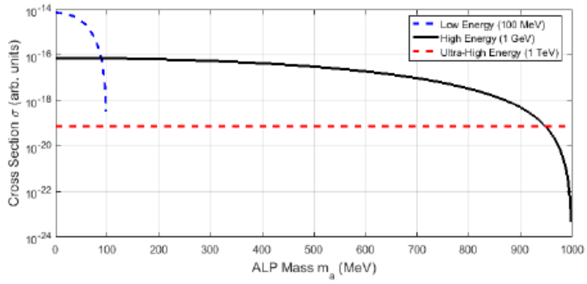

Fig.1: Cross Section vs. ALP Mass for Different Energy Regimes

- In HE: The cross-section remains relatively constant for lower ALP masses but decreases as m_a nears the energy scale. It remains small $\sim 4.97\times10^{-18}\,\mathrm{GeV}^{-2}$.

- In UHE: The cross-section is nearly constant over a wide range of ALP masses, only dropping at very high values of m_a. It becomes significantly larger $\sim 4.97\times10^{-10}\,\mathrm{GeV}^{-2}$. This suggests that for stronger couplings and higher energies, ALP production via photon fusion can become more probable.

These examples illustrate how the cross section varies with the coupling constant and the center-of-mass energy, providing a sense of the expected magnitudes in different scenarios. As expected, the behavior of the cross-section is highly dependent on the energy scale s and the mass of the ALP, with heavier ALPs suppressing the cross-section more significantly in lower energy regimes.

III. THE SCATTERING CROSS SECTION OF THE PRIMAKOFF PRODUCTION

The Primakoff effect is the production of ALPs from photon interactions with an external electromagnetic field, such as the Coulomb field of a nucleus. When high-energy protons impinge on a fixed target, the virtual photons from the proton's electromagnetic field interact with the external field, producing ALPs.

Here, we will present how to calculate the Primakoff scattering cross-section of ALPs in a proton beam, emphasizing the dependence on the scattering angle.

The process for the Primakoff effect is: $p + \mathrm{Target} \to p + a$.

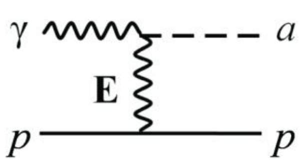

Fig.2: Feynman diagram for Primakoff effect

This is a photon-induced process where a virtual photon from the proton's electromagnetic field interacts with the Coulomb field of the target nucleus, producing an ALP.

The Primakoff process can be treated as $\gamma \to a$ conversion in the external electromagnetic field. The matrix element $\mathcal{M}$ for this process is proportional to the ALP-photon coupling:

$$\mathcal{M} \propto g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} \tag{6}$$

The external field contribution comes from the electromagnetic field of the target nucleus, and this introduces a dependency on the momentum transfer *q*, which relates to the ALP production angle.

In the high-energy limit, the production of ALPs from a proton beam can be analyzed in the laboratory frame where the target nucleus is at rest. The virtual photon from the proton interacts with the target nucleus, and the ALP is produced at an angle θ.

The differential cross section for the Primakoff process is related to the photon flux and the photon-ALP conversion cross section in the Coulomb field. The photon flux $d\mathcal{F}$ from the proton is given by the Weizsäcker-Williams approximation, which can be improved by including the realistic form factors for both the proton and target nucleus:

$$d\mathcal{F} = \frac{Z^2\alpha}{\pi}\frac{dq^2}{q^2}\left(1-\frac{q^2}{Q_{\max}^2}\right)F^2(q) \tag{7}$$

where Z is the atomic number of the target, α is the fine structure constant, and $Q_{\max}$ is the maximum momentum transfer determined by the ALP mass and the kinematics.

The cross section for ALP production is proportional to the square of the ALP-photon coupling $g_{a\gamma\gamma}^2$ and the electromagnetic form factor *F(q)*, which describes the interaction with the target nucleus:

$$\frac{d\sigma}{d\Omega} = \frac{g_{a\gamma\gamma}^2 Z^2\alpha}{q^4}|F(q)|^2 \cdot \frac{1}{(1+\theta^2/\theta_c^2)^2}, \tag{8}$$

where θ is the characteristic scattering angle related to the energy of the incoming photon; $|F(q)|^2$ is the form factor of the nucleus (e.g., for a point nucleus, *F(q)*=1).

The form factors modify the flux by accounting for the internal structure of the interacting particles. For a nucleus, the form factor can be parameterized as:

$$F(q) = \frac{1}{(1+q^2/\Lambda^2)^2}, \tag{9}$$

Where Λ is related to the size of the nucleus, typically $\Lambda \sim 770\,\text{MeV}$ for a proton.

For heavy nuclei (e.g., lead with Z=82), the form factor is more complex due to nuclear effects but can often be approximated by a similar dipole form with a modified Λ depending on the nucleus's size.

The total photon flux $\mathcal{F}$ is obtained by integrating over the momentum transfer q^2 up to $Q_{\max}^2$:

$$\mathcal{F} = \frac{Z^2\alpha}{\pi}\int_0^{Q_{\max}^2}\frac{dq^2}{q^2}\left(1-\frac{q^2}{Q_{\max}^2}\right)F^2(q) \tag{10}$$

This integral requires knowledge of *F(q)* and the upper bound $Q_{\max}^2$, which depends on the beam energy E_p and ALP mass m_a. For light ALPs (sub-eV to MeV), the upper bound can be approximated as:

$$Q_{\max}^2 \approx 2E_p^2\left(1-\frac{m_a^2}{E_p^2}\right) \tag{11}$$

Once the photon flux is computed, the ALP production cross section σ_{ALP} is:

$$\sigma_{\text{ALP}} = \mathcal{F}\times\sigma_{\gamma\to a}, \tag{12}$$

where $\sigma_{\gamma\to a}$ is the ALP production cross section from photon interactions, given by:

$$\sigma_{\gamma\to a} \propto g_{a\gamma\gamma}^2\frac{(q^2-m_a^2)}{s} \tag{13}$$

The Primakoff effect is highly forward-peaked, with most ALPs produced at small scattering angles. The angular distribution $d\sigma/d\theta$ is related to the momentum transfer q and photon energy E_γ:

$$q^2 \approx 2E_\gamma^2(1-\cos\theta) \tag{14}$$

At small angles θ, the momentum transfer q is small, and the cross section is maximized. To model the full angular distribution, one can write:

$$\frac{d\sigma}{d\Omega} \propto \frac{g_{a\gamma\gamma}^2}{q^2+m_a^2} \tag{15}$$

This shows how the cross section depends on the angle θ and the mass m_a. Forward scattering dominates, but form factor corrections (due to larger q^2) reduce the cross section at larger angles.

The angular distribution is governed by the factor $(1+\theta^2/\theta_c^2)^{-2}$ in (8), which implies that the ALP production is peaked in the forward direction (small θ).

The characteristic angle θ_c is given by:

$$\theta_c = \frac{m_a}{E_\gamma} \tag{16}$$

The differential cross section is sharply forward-peaked, meaning most of the ALPs are produced at small angles relative to the proton beam direction.

Now, We'll compute the photon flux by integrating the differential photon flux formula derived earlier (10).

To perform this integration, we will use the following parameters [10]: Z = 82 (lead target), $\alpha \approx 1/137, Q_{\max}^2 = 2E_p^2$, with $Ep = 100\text{GeV}$.

Form factor: $F(q^2) = \dfrac{1}{(1+q^2/\Lambda^2)^2}$ with $\Lambda = 0.7\text{GeV}$.

The photon flux depends on the integration over q^2. We'll numerically integrate this expression in the range $0 \le q^2 \le Q_{\max}^2$.

I would use numerical integration functions to compute the flux. Once we have the photon flux, we can calculate the sensitivity of the experiment by determining how many ALPs would be produced for a given $g_{a\gamma\gamma}$ and ALP mass m_a.

The ALP production cross section is proportional to the photon flux $\mathcal{F}$ and the photon-ALP interaction:

$$\sigma_{\text{ALP}} \sim g_{a\gamma\gamma}^2 \mathcal{F} \frac{(q^2 - m_a^2)}{s} \tag{17}$$

For small ALP masses ($m_a \ll E_p$), the cross section simplifies to: $\sigma_{\text{ALP}} \sim g_{a\gamma\gamma}^2 \mathcal{F} \dfrac{q^2}{s}$, with a proton-nucleus collision $s \approx 2E_p m_T$ (with m_T being the target nucleus mass).

The number of ALPs produced in the experiment is given by:

$$N_{\text{ALP}} = I \times T \times \sigma_{\text{ALP}} \times \epsilon, \tag{18}$$

where, I is the proton beam intensity (e.g., 10^{16} protons per second), T is the target thickness (in cm), σ_{ALP} is the ALP production cross section (17), ϵ is the detector efficiency (e.g., 0.8).

With a known $g_{a\gamma\gamma}$, photon flux, and beam energy, we can estimate N_{ALP} by calculating the cross section and then plugging it into the formula (18).

By varying $g_{a\gamma\gamma}$ and m_a, we can study how sensitive the experiment is to different ALP masses and couplings. For a fixed beam intensity and target, the number of ALPs produced will scale with $g_{a\gamma\gamma}^2$, allowing us to set upper limits on $g_{a\gamma\gamma}$ based on experimental results.

I run the Matlab code to compute the photon flux and estimate ALP production. Then, we can extend this by plotting N_{ALP} versus $g_{a\gamma\gamma}$ for different ALP masses to explore the sensitivity range of the experiment.

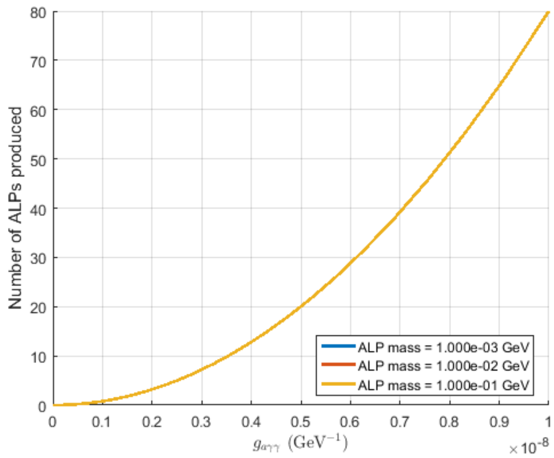

Fig.3: Sensitivity to $g_{a\gamma\gamma}$ for different ALP masses

ALP interactions are typically weak due to the small coupling constants, making signals difficult to distinguish from background noise. High precision detectors and low-noise environments are essential for reliable measurements, especially for small $g_{a\gamma\gamma}$.

Experiments must filter out significant photon backgrounds, particularly in the Primakoff effect, where photon interaction with nuclei might lead to competing processes that mimic ALP signals.

High-energy experiments require advanced detectors with precise energy resolution to differentiate between photon fusion and Primakoff events, especially at higher ALP masses.

Future upgrades in collider luminosity, such as at the High-Luminosity LHC (HL-LHC), will improve photon fluxes and thus increase the probability of ALP detection through photon fusion.

New experimental setups, such as beam dump experiments and dedicated detectors like IAXO (International Axion Observatory), are expected to enhance sensitivity to ALPs, especially at low masses and couplings.

ALP production in astrophysical environments, including the Sun and supernovae, provides indirect methods for setting bounds on ALP properties. Future space-based observatories with high-energy photon detection capabilities could yield additional insights into ALP generation mechanisms.

ALP generation via photon fusion and the Primakoff effect remains a promising area for probing Beyond Standard

Model (BSM) physics. While both processes allow for exploration of a wide parameter space of ALP masses and couplings, they face significant theoretical and experimental challenges. Progress in collider technology, improved theoretical models, and advancements in detector precision are expected to address some of these challenges, making ALP detection increasingly feasible. Continued work in this field will deepen our understanding of ALPs and their role in fundamental physics, with potential implications for dark matter and cosmology.

IV. CONCLUSION

Axion-Like Particles (ALPs) are hypothetical particles proposed in various extensions of the Standard Model of particle physics. They are considered as candidates for dark matter and are characterized by their very light mass and weak interactions with ordinary matter. The primary mechanisms for ALP production include photon-photon fusion and the Primakoff effect.

Photon-photon fusion occurs when two high-energy photons collide, potentially producing an ALP in environments with sufficient energy, such as in astrophysical phenomena or high-energy particle collisions. The Primakoff effect involves the interaction of a photon with a nucleus, leading to the emission of an ALP. Both processes are crucial for understanding how ALPs could be detected in experiments. Experimental constraints on ALP properties have been set by various experiments, such as the CERN Axion Solar Telescope (CAST) and NA62, which have established limits on the coupling constant $g_{a\gamma\gamma}$ for ALP masses below 1 eV. Additionally, collider experiments like LEP, LHC, and Belle II have provided constraints by detecting associated photon signals and examining missing energy signatures indicative of weakly interacting particles like ALPs. These experiments help refine the parameter space for ALP masses and couplings.

Detecting ALPs poses significant challenges due to their weak coupling to standard model particles, resulting in very low production rates and signals that can be easily obscured by background noise. Advanced technologies and experimental setups are required to enhance sensitivity and distinguish ALP signals from other interactions. Ongoing research aims to improve detection methods and explore the implications of ALPs in cosmology and particle physics.

In summary, ALPs represent a compelling area of study in the quest to understand dark matter and the fundamental forces of nature, with ongoing efforts to uncover their properties and potential existence.

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