Photoproduction of Pseudoscalar in Static Magnetic Field

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Introduction

In the low-energy frontier of particle physics there exists a study on a group of hypothetical invisible particles which have extremely weak interactions with various other visible particles. This study falls in energies below 100 GeV which is just below the electroweak scale. An example would be the axions or axion-like-particles (ALPs). This study is an extension of the Standard Model in particle physics and is useful in applications to dark matter and in cosmological observations such as stars.

The following experiment setup provides a method of photoproduction to search for ALPs. And, hopefully, be complementary to other methods. However, using accelerators for photoproduction of ALPs will be challenging.

Parity

Parity is the flip in sign of all spatial coordinates in a system; +x,+y,+z → -x,-y,-z. Parity is conserved for the electromagnetic force and strong force which means they have the same strength in right- and left-handed orientations. Parity is violated for the weak force due to asymmetry between right- and left-handed lepton production.

A pseudoscalar is a physical quantity that acts like a scalar but changes sign under a parity inversion, P = -1, where P is parity. The scalar triple product for example: A · (B X C). Multiplying a pseudoscalar by an ordinary vector gives a pseudovector. A pseudovector is a physical quantity that acts like a vector but does not change sign under a parity inversion, P = +1. Take the cross product for example: A X B. Normal scalars have P = +1 and normal vectors have P = -1.

The electric field is a vector so it has P = -1. The magnetic field is a pseudovector so it has P = +1.

The electromagnetic four-vector potential is a 4-vector function of the form (V,Ax,Ay,Az) where Ax,y,z are components of the magnetic vector potential A and V is the electric field potential. The electric field E can be expressed as the gradient of V, and the magnetic field can be expressed as the curl of A.

$$\mathbf{P}:\begin{pmatrix}x\\y\\z\end{pmatrix}\mapsto\begin{pmatrix}-x\\-y\\-z\end{pmatrix}\qquad \mathbf{E}=-\nabla V\qquad \mathbf{B}=\nabla\times\mathbf{A}$$

Interaction Lagrangian Term

An axion, is a hypothetical pseudoscalar elementary subatomic particle postulated in attempt to resolve the strong CP problem in quantum chromodynamics and is a possible dark matter candidate. In our case the pseudoscalar property of axions are very important. Axions are generated through photoproduction, the process can be extended to that of a photon interacting in the presence of a strong magnetic field..

A crucial part of ALPs is the ALP field coupling to two photons which has the following forms, as well as an expression for the coupling between the electromagnetic field tensor F in matrix form (F~ is the dual electromagnetic field tensor constructed by fully contracting F with the levi-civita symbol):

$$\begin{aligned}\mathcal{L}_{\phi(-)\gamma\gamma} &= -\frac{g_-}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}\phi(-)\\ \mathcal{L}_{\phi(+)\gamma\gamma} &= -\frac{g_+}{4}F_{\mu\nu}F^{\mu\nu}\phi(+)\end{aligned}$$

$$F^{\mu\nu} \equiv \partial^\mu A^\nu - \partial^\nu A^\mu = \begin{pmatrix}0 & -E_x & -E_y & -E_z\\ E_x & 0 & -B_z & B_y\\ E_y & B_z & 0 & -B_x\\ E_z & -B_y & B_x & 0\end{pmatrix}$$

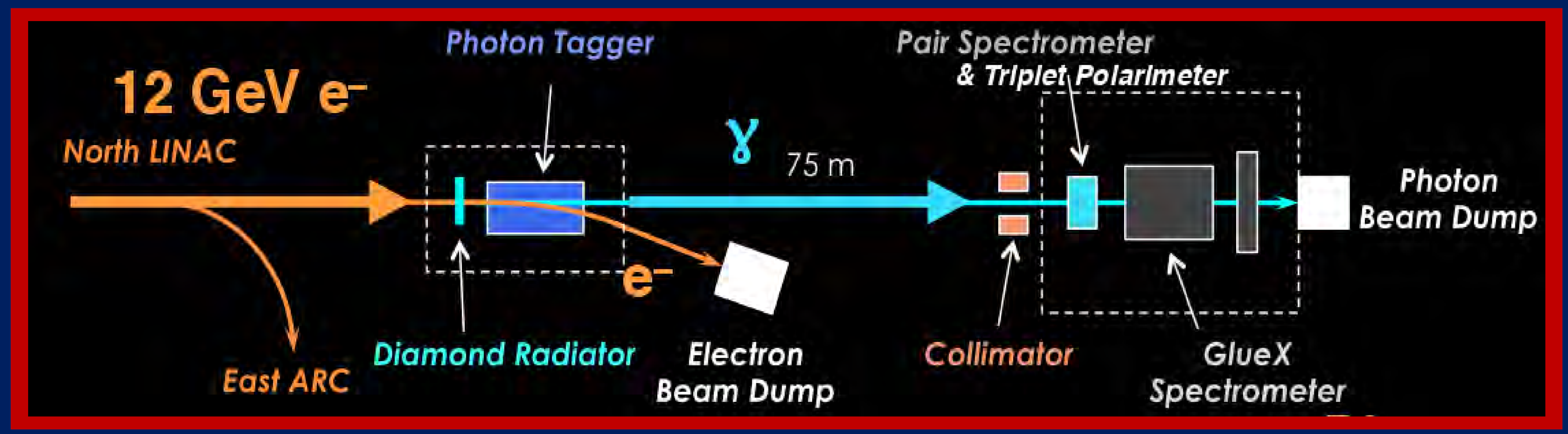
Φ(+) and Φ(-) are the pseudoscalar axion fields being coupled with F and F~. Where Φ(-) is a pseudoscalar of P = -1 which couples to E·B, and Φ(+) is a scalar of P = +1 which couples to E·E + B·B. Note: Parity is not violated in the interaction.

The importance of the interaction Lagrangian is to describe how the particles interact with one another, including the production of other particles, axions in our case.

Accelerator Setup

The experiment is similar to searching for "Light Shining through a Wall" (LSW) from the quantum oscillations of photons into "Weakly Interacting Sub-Ev Particles" (WISPs) or in our case, axion-like particles (ALPs). This is accomplished by photoproduction to produce a photon beam of momentum p = 9 GeV, into a transverse magnetic field of B = 1.8T, over a short distance of L = 0.96m. The photons gets converted into axions in a magnetic field. For a LSW the axion would get converted back to a photon in another magnetic field that proceeds after.

The proposed experiment setup mimics the actual beam line setup at Jefferson Lab in Virginia, as shown in the figure below.



Probability Calculation for Axion and Pion

The probability equation for photon→axion/pion and axion/pion→photon is shown below in Heaviside-Lorentz natural units where ħ = c = 1. This allows us to calculate the probability of seeing an axion in the photoproduction procedure where all units cancel out.

- $g_{A\gamma\gamma} = 10^{-13}\,GeV^{-1}$ ... coupling constant
- B = 1.8T ... magnetic field
- L = 0.96m ... length of vacuum
- $q = \| k_\gamma - k_A \|$ = GeV ... momentum transfer
- $k_\gamma = \omega$ = 9GeV... photon energy
- $k_A = (\omega^2 - m_A^2)^{1/2}$ in GeV
- m_A = ALP mass = varying

$$P_{\gamma\leftrightarrow A} = \frac{1}{4}(g_{A\gamma\gamma}BL)^2\left(\frac{2}{qL}\sin\frac{qL}{2}\right)^2$$

- Polling rate = 250MHz = $2.50\cdot 10^8$Hz
- m_π = 0.14GeV
- q_π = 0.001GeV
- q_A = varying

Calculations and rationales are as follows:

→$P = A^2 \cdot B^2$ where $A = (1/4)\cdot(g_{A\gamma\gamma}\cdot B\cdot L)$ and $B = \sin(x)/x$
→$\omega = m_A^2/(L\cdot\hbar\cdot c)$
→$q = \omega - \sqrt{\omega^2 - m_{A/\pi}^2}$
→For axions, m_A is very small and q → 0 allowing for sin(x)/x = 1
→$R = P_{\gamma\text{<->}A}\cdot 2.50\cdot 10^8\text{Hz} = 3\cdot 10^{-3}\text{Hz}$
→$R = P_{\gamma\text{<->}A}\cdot R\cdot(3600\text{s/hr})$ = 10.8/hr or roughly 11 axions per hour.
→For pions, m_A is is much larger and q ↛ 0 which means sin(x)/x ≠ 1.
→Pion photoproduction will be killed off due to qL/2 exploding to almost $2.5\cdot 10^{16}$, which results in an enormous photon-beam energy required.

Conclusion

Energies required for pion creation are far too high (for x = small) and tagging rate far too low for axion creation. This proposed experimental setup has end results are not easily achievable. Axion creation would require an untagged photon beam of an incredibly high rate.

The figure on the left shows a summarization of all experiments searching for ALPs. Red are actual experiments on Earth, other colors represent astrophysical explorations. The figure on the right shows the exponential energy required to see axions. Pions would be 10^6 times more difficult.