Background Knowledge: Search for Axion Like Particles (ALPs) at the BABAR Experiment

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1 Axions

1.1 Strong CP Problem and the Motivation Behind Axions

We seek to determine why quantum chromodynamics (QCD) seems to preserve CP-symmetry. In the mathematical formulation of QCD, CP (charge-parity) symmetry can be violated in strong interactions. However, no violation of this symmetry has been observed experimentally. There is no known reason in QCD for it to necessarily be conserved, and as a result, this is a "fine-tuning" problem[1]

An **axion** is a hypothetical elementary particle proposed to resolve the strong CP problem. The interaction Lagrangian of QCD is given by:

$$\mathcal{L}_{QCD} = -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} - \frac{g_s^2\theta}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi \tag{1}$$

$$= \frac{\theta_{QCD}}{32\pi^2}TrG_{\mu\nu}\tilde{G^{\mu\nu}} \tag{2}$$

In the above equations G refers to the gluon field strength tensor, $\tilde{G^{\mu\nu}} = \epsilon^{\alpha\beta\mu\nu}G_{\alpha\beta}$ is the dual and the trace runs over the colour $SU(3)$ indices In Equation (1), the terms $G_{\mu\nu}\tilde{G}^{\mu\nu}$ and $i\theta'$ are CP violating. Furthermore, θ and θ' can be interpreted as angles (i.e. $\theta, \theta' \in [0, 2\pi))$). These terms can be combined to form a total effective angle $\bar{\theta}$ Since there is no expermiental evidence of CP violation in the strong interaction, this implies that $|\bar{\theta}| \approx 0$. In an attempt to resolve this problem, Peccei and Quinn (1977) proposed a solution that involves promoting $\bar{\theta}$ to a field through the addition of a new global symmetry (Peccei-Quinn (PQ) symmetry) which is spontaneously broken, which results in a new particle which has been named as the "axion". The introduction of such

[1]The process by which parameters of a model must be adjusted very precisely in order to fit with certain observations

a particle implies that the CP violating terms will be set to zero without the need for any fine tuning.

Five experiments have been conducted in an attempt to search for evidence of axions. However, all of these have yielded negative results

1.2 Axion-Like Particles (ALPs)

The key difference between axions and Axion-Like Particles (ALPs), which result from the aforementioned breaking of the PQ symmetry is that the latter are not as constrained as axions (i.e. their masses and coupling strengths are independent parameters). In addition to this, ALPs couple predominantly to gauge bosons (specifically pairs of bosons, such as $gg, \gamma\gamma, ZZ, W^+W^-, \gamma Z$). In other words, an ALP does not intend to solve the strong CP problem, but its phenomenology is identical to that of an axion. These ALPs are ideal Dark Matter candidates

2 B-Meson Decay Process

The following decay is considered for the subsequent sections

$$B \to K^* A, A \to \gamma\gamma \tag{3}$$

The coupling of the ALPs to weak gauge bosons (i.e. the $W^\pm$) leads to observable signatures. The effective Lagrangian is given by:

$$\mathcal{L} = (\partial_\mu a)^2 - \frac{1}{2} m_a^2 a^2 - \frac{g_{aW}}{4} W_{\mu\nu} \bar{W}^{\mu\nu} \tag{4}$$

One can observe the decay $B \to K^* A, A \to \gamma\gamma$ using B-factories which are desgined to generate and observe B-decays

2.1 B-Factories

B factories were constructed with the intention of testing the CKM (Cabibo-Kobayashi-Maskawa) description of quark mixing and CP violation in the Standard Model. These detectors performed precise measurements of the CKM matrix elements and of several branching ratios of rare B-meson decays. In order to achieve these goals, a B-factory is required to achieve a high luminosity[2]. It is also mandatory to boost the produced $B\bar{B}$ pairs to increase their respective displacement in order to distinguish between them

[2] The luminosity is proportional to the number of collisions that occur in a given amount of time. The greater the luminosity, the more data the experiments can gather to observe rare processes