Axion Solutions to the Strong CP Problem in Twin Higgs Scenarios

Project Purpose:

I will be investigating the feasibility of solving the strong CP problem and electroweak hierarchy problem of particle physics with an axion generalization of Twin Higgs models.

Project Importance:

The standard model of particle physics is renowned as one of the most successful theories in the history of science. However, there are some outstanding problems that lead us to believe it is a low energy approximation (or effective field theory) of a more fundamental theory[1]. Much of the current effort in particle physics seeks to develop new theories that address these problems and test them experimentally. We refer to these candidates for a more fundamental theory as extensions of the standard model.

One of the outstanding problems with the standard model, known as the electroweak hierarchy problem, asks why the Higgs mass (as determined by analysis of the bosons of the electroweak force) is so much smaller than the Planck scale, a scale that represents the contributions of gravity to extensions of the standard model. One way this concern has been addressed in the past is by proposing a Twin Higgs model. In this scenario, the Higgs field connects the standard model with a copy of itself in such a way that an approximate symmetry of the theory can explain the hierarchy between the electroweak scale and higher energy states[2]. These Twin Higgs theories can take many different forms and remain a motivated target of experimental searches for new physics[3].

Another outstanding problem is known as the strong CP problem, which asks basically, why a term that ought to exist in the standard model Lagrangian, given our current understanding of effective field theories, has an unusually small order of magnitude, given that one known contribution to the term is quite large[4,5]. One way the problem has been addressed is by postulating the existence of a particle called the axion that is born out of a spontaneously broken symmetry which ensures that the coefficient of the problematic term is dynamically set to zero[4]. Unfortunately, it has been shown that both instantons and the contributions of quantum gravity can ruin the mechanism by which the axion sets the problematic term to zero, reintroducing the problem to the theory[4,5,6]. This is known as the axion quality problem. However, by raising the axion mass, this problem can be avoided[2,7].

I will examine the feasibility of Twin Higgs models with an axion by characterizing the mass of the axion in various twin Higgs models and determining whether the axion quality problem can be avoided in such scenarios. Such a theory would address both the electroweak hierarchy and strong CP problems and provide interesting experimental signals.

Project Overview:

I have already done some initial work on the problem and am working with Dr. Chris Verhaaren to prepare a paper on the application of axions to a family of Twin Higgs scenarios. I will extend this work and provide extensive background on axion solutions and the axion quality problem.

The project is a typical example of a model building research project, and as such, it is a theoretical work, with experimental input. I will be developing a novel manifestation of the twin Higgs framework and performing calculations using data that has already been obtained experimentally. I will also determine the experimental consequences of these models and characterize their dependence on various parameters to constrain what parameters are possible and how these models could be discovered. Some of the experimental input I have come across so far can constrain the models include measurements from supernovae that place a lower limit on the mass of an axion, as well as the measurement of the neutron electric dipole moment that constrains the amount by which the axion vacuum expectation value is allowed to vary from its goal. I will also be reviewing an extensive reservoir of literature on axions, instantons, Twin Higgs models, and effective field theories in order to provide background for the question and perform the needed calculations. I have been introduced to much of this literature and performed some initial calculations they introduce, which I can adjust and apply to the models I am interested in.

Timeline:

August 2025:

- Review literature and provide background for thesis.

September 2025:

- Determine whether small instantons are a problem in Twin Higgs models by reviewing literature and applying calculations to Twin Higgs scenarios.
- Calculate axion mass in Mirror Twin Higgs models.

October 2025:

- Calculate axion mass in Fraternal Twin Higgs model.
- Analysis of viable parameter space for Twin Higgs models.

November 2025:

- Generalize results to other Twin Higgs models.
- Finish writing thesis draft.

December 2025:

- Polish draft and prepare thesis defense.

Investigator qualifications:

I have worked with Dr. Verhaaren over the previous summer to get introduced to our research question and literature. Before that, I took his PHSCS 522 class on particle physics, which gave me an introduction to many of the concepts present in our research. I also worked with Dr. Scott Glasgow of the department of mathematics for one year, where I learned about some of the mathematics of field theories (particularly Yang-Mills theories) and got introduced to quantum field theory concepts and notations.

Thesis Committee:

Advisor: Dr. Chris Verhaaren does research as an assistant professor for the Department of Physics and Astronomy in theoretical particle physics. He has coauthored publications on topics such as supersymmetric top quark partners, Q-balls, dark matter and the Aharanov-Bohm effect, Higgs naturalness, and collider phenomenology. He earned his Ph.D. from the University of Maryland in elementary particle theory in 2016 and worked as a postdoctoral researcher for the University of California from 2016 to 2021. A recent publication of his provides a description of the Fraternal Twin Higgs scenario we are trying to apply an axion to.

Coordinator: Dr. Karine Chesnel is an associate professor in the Department of Physics and Astronomy. She is also the honors coordinator for this department. She does research in condensed matter theory and has taught undergraduate courses in quantum mechanics in previous years. She earned her Ph.D. from University Joseph Fourier, France and has since worked as a post-doctoral researcher at Lawrence Berkeley National Laboratory.

Reader: Dr. David Neilsen is a physics professor here at BYU who does research in general relativity and relativistic astrophysics. He earned his Ph.D. from the University of Texas at Austin in 1999 and has worked as a visiting scientist at the University of Utah, Los Alamos National Laboratory, and the Perimeter Institute for Theoretical Physics. His work in theoretical physics will give him some important background for the cosmological implications of the theory that I will be developing, as well as a foundation understanding of the best practices in this field of research.

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References:

1. B. Batell, M. Low, E. T. Neil, and C. B. Verhaaren "Review of neutral naturalness", (2022). https://doi.org/10.48550/arXiv.2203.05531
2. B. Batell, T. Cochran, L. Page, and C. B. Verhaaren "Extended color twin Higgs", (unpublished).
3. Z. Chacko, H.-S. Goh, and R. Harnik, "Natural electroweak breaking from a mirror symmetry", Physical Review Letters **96**, (2006).
4. A. Hook, "TASI Lectures on the Strong CP Problem and axions" (2023). https://arxiv.org/abs/1812.02669
5. M. Kamionkowski and J. March-Russell, "Planck-scale physics and the Peccei-Quinn mechanism", Physics Letters B **282**, 137 (1992).

6. S. M. Barr and D. Seckel, “Planck-scale corrections to axion models,” Phys. Rev. D 46, 539–549 (1992).
7. K. J. Kelly, S. Kumar, and Z. Liu, “Heavy axion opportunities at the DUNE near detector”, Physical Review D **103**, (2021).