Tanner Dean's Scholar Summer Program 2017

Kaiwen Zheng, 18'

Physics

"An Investigation of the Magnetic Sensitivities of Transition Edge Sensors"

I. Abstract

Observations of the comic microwave background (CMB) are critical to the study of cosmology and astrophysics. Current CMB surveys are conducted by utilizing sensitive detectors called transition edge sensors (TESes). TESes can be influenced by external magnetic fields like the Earth's magnetic field which can result in inaccurate results. One way to avoid this problem is to use expansive magnetic shields to block troublesome external fields. However, scientists often do not know the amount of shielding required in advance because the behavior of TESes under magnetic fields is not currently well understood theoretically. In order to determine the magnetic shielding requirements for more sensitive future CMB experiments, we must measure the magnetic sensitivity of TESes that will be used.

My project focuses on characterizing the behavior of existing TESes under the influence of magnetic fields. I will do this by first cooling down the TESes to much below 1 degree Kelvin above absolute zero using a special refrigerator called a dilution refrigerator. Once cold, I will apply a uniform magnetic field to the TESes and measure various important TES properties using available electronics. Repeated measurements under different magnetic fields will enable me to describe the influence of the magnetic field on these TESes quantitively. Moreover, I will compare the magnetic sensitivity of different TESes to help determine the best TES design for future CMB experiments. The results will contribute to our understanding of the physics of how TESes work and will enable scientists to better build next generation CMB telescopes and at lower cost.

II. Biographical Sketch

When I played with a spinning top as a child, I was enthralled by its motion. Why did its axis rotate from side to side? After some searching, I discovered that the self-rotation of the earth was exactly the same motion. I was amazed by how the same law of motion could relate both to a small top and the giant Earth, and I wanted to study the science behind it. This semester, in the junior mechanics class, I finally learned the motion that had intrigued me: precession. However, as I studied, more questions emerged, some of which have no available answers despite centuries of research. I want to join the enthusiastic explorers who endeavor to answer these questions, by conducting research during the semester, this summer and after graduation. The various research opportunities available here in Cornell will give me valuable experience in studying one question in depth, and will be a stepping stone to my PhD program in physics.

In addition to my interest in physics, I am active in different kinds of art. I spend most of my spare time drawing in the Slope Studio. I am especially fond of realistic drawings, and often spend weeks on a portrait. I am also enthusiastic about music. I started singing my sophomore year. Right now, I am an alto in Cornell Chorale and am taking individual instruction in classical singing from the music department. My choir gives me a different perspective on my Cornell life, where I can devote myself to beautiful music without distraction.

Arts and science provide me with different ways to appreciate the world, and I believe both are essential for me to become a well-rounded person. I have enjoyed taking advantage of the incredible academic and artistic opportunities at Cornell, and I will carry this enthusiasm with me in the future.

III. Statement of Purpose

My summer project in Cornell will be in the field of observational cosmology. In particular, I will test the superconducting sensors and readout electronics used in cutting edge cosmological experiments in order to characterize their performance under the influence of magnetic fields.

Cosmology is the science of the origin and evolution of the universe. The universe is thought to have begun with a Big Bang. After the Big Bang, the Universe underwent a mysterious period of early faster-than-light-speed expansion called inflation. Just after inflation, the temperature of the universe was too high for atoms to form, so the universe at first consisted of photons and a hot plasma of nuclei and electrons. In this early period, the photons were trapped in this plasma, making the universe opaque. As the universe expanded, however, the temperature of this plasma dropped, until eventually electrons and protons could combine to form atoms.[1] Once free electrons combined with protons to form neutral atoms, the photons in the early universe were released and free to propagate. These photons are still traveling through the universe today. This light was stretched by the expansion of the universe which shifted its frequency down to microwave wavelengths, which is why it is called the Cosmic Microwave Background (CMB). The exciting discovery of the CMB in the last century provided landmark evidence for the Big Bang model and ruled out the static universe model.

The CMB is vital to the study of cosmology because it carries information about the very early universe. Since the conditions in the early universe were too hot and dense to be practically recreated in the lab, the only known way to study the physics of the very early universe is through the observation and analysis of the CMB. In particular, the faint, observed fluctuations of the temperature and polarization of the CMB over the sky are believed to have been created by cosmic inflation, which occurred in the first 10^{-32} seconds after the Big Bang.[2] These fluctuations gave rise to everything we observe today, including galaxy clusters, galaxies, and even the Earth. Measurements of the CMB also have the potential to help improve our understanding of particle physics, including by determining the masses of neutrinos.

A worldwide effort is underway to measure the CMB accurately enough to learn about cosmic inflation. Current telescope projects include the South Pole Telescope, the Atacama Cosmology Telescope, the Keck Array, and the Cosmology Large Angular Scale Surveyor. In order to upgrade these telescopes for the next generation of CMB measurements, it is necessary to increase the number of detectors on these telescopes by a factor of 10x or more.[3]

Increasing the number of detectors on these telescopes will be very challenging. The CMB is extremely faint and is only 2.76 degrees (Kelvin) above absolute zero.[4] Therefore, the CMB light is easily overwhelmed by thermal noise. Because of this, a camera at room temperature would not be able to detect the CMB, so we require cameras that work at very low temperatures. Cameras made of arrays of devices called superconducting transition edge sensors (TES) are used to measure the CMB, which work well down to temperatures as low as 0.1 degrees (Kelvin) above absolute zero.[5] The electrical resistance of a TES changes dramatically when exposed to very small fluctuations in temperature. Therefore, by measuring the resistance of TESs exposed to the CMB, we can detect the small temperature differences in the faint measured CMB signal. Current telescopes have around 10,000 TESes for each camera. Next generation experiments plan to increase the number of TESes per camera to 100,000 or more.[6]

However, TESes are extremely sensitive to magnetic fields. External magnetic fields are known to change the correspondence between the temperature and the TES resistance, hence changing how well the TESes are able to measure the CMB. For CMB experiments, external sources of magnetic fields include the magnetic field emitted by the Earth and the fields produced by the electronics in the telescope. Moreover, when the telescope rotates, its motors can produce strong magnetic fields. All of these external fields interfere with our CMB measurements.

One way to block the external magnetic field is to build magnetic shields around the TESes. Nevertheless, the large magnetic shields that would be required for future CMB experiments with 10 times more detectors would be very expensive. Some CMB projects avoid this cost by not using magnetic shields at all, but this risks compromising the performance of their TESes. Since scientists do not fully understand exactly how magnetic fields affect the performance of the TESes, it is hard to determine how much magnetic shielding is actually needed, if any.

It is surprising how little people know about the physics of TESes despite their widespread use. TESes are extremely complicated devices and even now there is no complete theory that can describe how they work perfectly.[7] It is not simple to predict how magnetic fields will affect a TES without making measurements. Therefore, careful measurements are required to understand how much shielding will be needed for next generation CMB projects.

My project this summer will be a continuation of the work I am currently doing to characterize the performance of TESes under the influence of external magnetic fields. I will be conducting research in the lab of Professor Michael Niemack in the Physics department, located on the 3rd floor of the Physical Science Building. Professor Niemack is a leader in several CMB projects including the Atacama Cosmology Telescope, and he is involved in the design of the next generation of CMB telescopes. He and his collaborators are developing designs for TESes to be used in these future CMB experiments. During the summer, I will test the behavior of these TESes and compare their behaviors in order to help decide which are promising for future use.

The Niemack lab will provide all hardware and software needed for this research project. Most importantly, it has a dilution refrigerator. A dilution refrigerator is a special refrigerator that uses liquid helium to cool down to less than 0.1 degrees (Kelvin) above absolute zero. This enables me to cool down the TESes to the low temperatures at which they are designed to work. Once the TESes are cooled, I will change the external magnetic field around them by putting Helmholtz coils around the dilution refrigerator. Our Helmholtz coils are capable of producing a uniform magnetic field inside the dilution refrigerator. I participated in the construction of these Helmholtz coils during the last semester and am able to use them proficiently. I will use existing electronics and software in the lab to measure various properties of the TESes like the critical temperature and the detector noise under applied magnetic fields and compare the behaviors of different designs.

By studying how the TESes react to magnetic fields, we can learn about the physics of how they work. The information we gain will then be used to make better TES sensors in the future, and thus improve future CMB experiments. The next generation of CMB experiments has the potential to radically transform our understanding of fundamental physics, including the unknown physics of cosmic inflation.

Bibliography

[1]Loeb, Abraham. "The Habitable Epoch of the Early Universe". International Journal of Astrobiology. 13 (04): 337–339.

[2]Hawking, Stephen."Supercooled Phase Transitions in the Very Early Universe", Phys .Lett. 110B, 35.

[3]*CMB-S4: Next Generation CMB Telescope.* National Science Fundation, 2017, cmb-s4.org/book.php. Accessed 1 Mar. 2017.

[4] Ryden, Barbara. *Introduction to Cosmology, 2nd Edition.* Cambridge University Press, 2016.

[5] K. D. Irwin and G. C. Hilton. "Transition-edge sensors". *Cryogenic Particle Detection*, ed. C. Enss, Springer. 2005.

[6] Abazajian, Kevork et al. *CMB-S4 Science Book, 1st Edition.* arXiv:1610.02743. Web.

[7] Ullom, Joel and and Douglas A Bennett. "Review of superconducting transition-edge sensors for x-ray and gamma-ray spectroscopy". *IOP Science.* Supercond. Sci. Technol. 28 (2015) 084003 (36pp)