Microwave Kinetic Inductance Detectors and Their Implications for Dark Energy

Emily Macuk
McHenry County College
8900 U.S. 14
Crystal Lake, Illinois 60012

Juan Estrada and Karen M. Kephart
Detector Development and Operations Department
Fermi National Accelerator Laboratory
Batavia, Illinois 60510

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Abstract

Microwave kinetic inductance detectors (MKIDs) are superconducting photon detectors first developed at the California Institute of Technology and NASA's Jet Propulsion Laboratory in 2003, by Drs. Jonas Zmuidzinas and Rick LeDuc. Fermilab is collaborating with the University of California, Santa Barbara on the research and development of these detectors. MKIDs have time resolution capabilities and are able to identify the energy of individual photons. To fully understand and characterize the properties of the MKID device, tests were run using different wavelengths of light, changing the temperature of the cryogenic refrigerator, and analyzing the critical temperature from a plot of frequency versus temperature. Observations were performed using wavelengths between 360 and 700 nm. To find the critical temperature of each pixel, wide sweep scans were taken of the detector at different temperatures, beginning at 60 mK and ending at 223 mK. The data from the wide sweep was then plotted on a graph of temperature versus frequency and fit to an equation that included both variables. After fitting the data from the plot, the critical temperature of each pixel was extrapolated from the data. After fitting the graph, it was found that the critical temperature is the same for every pixel on the device. Promising results reaffirm the potential of the MKID detectors. Improving the MKIDs and understanding how they work aids the effort to make them operational. Moving forward, it is the goal of Fermilab to use the MKID detectors in combination with the Dark Energy Camera to further explore the universe and effectively measure the redshift of the galaxies.

1. Introduction

1.1 Fermilab and Microwave Kinetic Inductance Detectors

Drs. Jonas Zmuidzinas and Rick LeDuc first developed the microwave kinetic inductance detectors at the California Institute of Technology and NASA's Jet Propulsion Laboratory in 2003 [9]. MKIDs have the ability to take measurements across the electromagnetic spectrum [2]. As research on MKIDs continues to flourish, Dr. Ben Mazin of the University of California, Santa Barbara, continues to test and develop these detectors, adapting them for the ultraviolet, optical, and near-IR regions of the spectrum [13].

Fermilab is working in partnership with UCSB on the research and development of these detectors. The focus at Fermilab is to fine-tune the performance of these devices with the intent of installing and testing this new technology on the Southern Astrophysical Research (SOAR) telescope in Chile. Currently, Fermilab's Detector Development and Operations Department is testing these detectors at different wavelengths, temperatures, and attenuations, to create a better understanding of how they operate and what steps can be taken to improve the detector array's performance.

1.2 Dark Energy Summary

Feeding of the energy from the Big Bang, the universe expands perpetually. For the first nine million years, gravity has slowed the expansion of the universe. Dark energy is the antithesis of gravity. Working against its forces, dark energy causes the acceleration of the expansion of the universe [7].

Scientists Saul Perlmutter, Brian Schmidt and Adam Reiss uncovered the phenomenon of dark energy. Working for their respective projects, either the Supernova Cosmology Project or the High-Z Supernova Search team, these men explored supernovae in distant galaxies. In a joint effort, these scientists discovered that dark energy causes the acceleration of the expansion of the universe. By studying distant supernovae, they found that large stars that were further away appeared dimmer than they should have been. After taking careful measurements, Perlmutter, Schmidt and Reiss found that these "standard candles" were not as bright as they should have been. The scientists concluded that there must be a different force at work counteracting gravity. This force was dubbed "Dark Energy."

Dark energy has come to the forefront of modern cosmological studies and is a prevalent area of research in astronomy. Dark energy refers to "a hypothetical form of energy that permeates space and exerts a negative pressure, which would have gravitational effects to account for the differences between the theoretical and observational results of gravitational effects on visible matter" [14]. Dark energy accounts for approximately sixty-eight percent of the universe [3].

1.3 The Dark Energy Survey (DES)

In response to the discovery of dark energy, the concept Dark Energy Survey emerged. The Dark Energy Survey is an effort to measure the expansion of the universe with high precision. Over one hundred and twenty scientists from twenty-three different institutions are collaborating on this project. This team of scientists worked to build the Dark Energy Camera

(DECam), which is mounted on the Blanco telescope in Chile. This telescope is taking a survey of the southern skies, collecting data that can be used to uncover the mysteries we seek to understand.

The DECam is a wide-field charge-coupled device (CCD) imager mounted on the Blanco Telescope at the Cerro Tololo Inter-American Observatory in Chile. DECam includes seventy-four science CCDs. A CCD is a device for the movement of electric charge. CCDs work by counting the number of photons that incident off their pixels during a certain amount of time [6].

1.4 Redshift

Dark Energy causes the expansion of the universe to accelerate. One way to characterize the effects of Dark Energy is to measure the redshift of the galaxies. Redshift occurs when "light or other electromagnetic radiation from an object is increased in wavelength, or shifted to the red end of the spectrum" [17]. Essentially, as the galaxies expand outwards, their light source moves farther away from the observer. This elongates and shifts their wavelengths to the red end of the spectrum. Redshift is an extremely useful property in regards to the Dark Energy Survey. When measured, redshift could provide scientists with the information needed to find the acceleration of the universe [16].

1.5 CCDs and Spectroscopy

Scientists have come up with two ways to measure the redshift of the galaxies. Both of these techniques have their own unique limitations. The first, and the technology currently being used by the Dark Energy Survey, is wide-band imaging using the charge-coupled device (CCD). The CCD is an integrated circuit that contains many different pixels. The CCD is a semiconductor that has the ability to count the number of photons that hit its pixels during a certain time period. With this information, scientists can create an image showing the intensity of the light during the time period [19].

The first limitation of a CCD detector occurs when the photon hits a pixel. A CCD has the capability of showing which pixel was hit, not the specific time or energy of said photon; because the energy of individual photons cannot be tracked by these detectors, different color filters must be used to create the images of light patterns. To create the full image, several different observations must be run with different color filters. In the end, these images must be superimposed to create one full image of the light pattern. This is somewhat inefficient. Another limitation of CCD is its failure to track at what time the photons make contact with the pixels. Although it can track how many photons hit in a certain amount of time, it lacks the accuracy needed to show at what specific time they hit. Because of this limitation, only two-dimensional images of copies of the light patterns can be created from the data.

The second way redshift can be determined is through high-resolution spectroscopy. A spectrograph has the ability to take waves of light and to break them down into specific wavelengths creating a high-resolution image of the light. Using CCDs, spectrographs break up the light into a color spectrum that hits the CCDs at the end. Spectrographs allow scientists to determine the redshift of objects with higher resolution; it can only look at a relatively small fraction of objects at once (currently the DESI spectrograph is being constructed for 5 000 objects [15].

The microwave kinetic inductance detector has the ability to revolutionize astronomical studies because it does not suffer from either of these limitations.

2. Progress

2.1 Microwave Kinetic Inductance Detectors

Microwave kinetic inductance detectors, or MKIDs, are superconducting photon detectors that operate at cryogenic temperatures close to absolute zero. The superconducting nature of the MKID changes the surface properties of the pixels including eliminating the electrical resistance and the magnetic field [1]. Due to these two properties, the MKID can track the actual arrival time and energy of each photon as it hits a pixel.

The MKID consists of thousands of pixels that contain an inductor and a capacitor. When a photon hits a pixel, it causes Cooper pairs to break and create quasiparticles, which in turn increases the density in the inductor. This causes a phase shift, which exposes the time at which the photon has hit the pixel, and the energy of the photon itself.

Another advantage of the MKID is its ability to be multiplexed. This means that thousands of pixels can be read from the same single microwave feed line. This allows the MKID to have a larger field of vision and makes its images highly accurate. Where the CCDs have reached the height of their potential, MKIDs have the ability to improve exponentially the more processing power that computers gain [10].

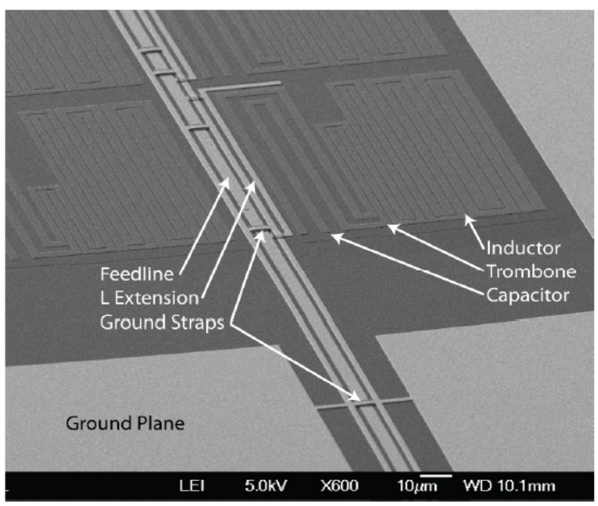

Figure 1. MKID – Single pixel.

2.2 Adiabatic Demagnetization Refrigerator

Since the MKIDs work at cryogenic temperatures, scientists must provide a vehicle for their functionality. In this case, the adiabatic demagnetization refrigerator (ADR) is used to cool down the detectors. Adiabatic refers to a system or process in which heat does not enter or leave the system; in this way the ADR effectively cools down the detectors to below 1 $^{\circ}$K. This creates a superconducting environment that takes away resistance and allows the detectors to be efficient. The ADR works by using properties of heat and the magnetic properties of molecules in salts. The cool down of the ADR consists of several stages. In the first stage of the cool down, the system uses compressed helium; the compressed helium enters the system and expands, absorbing the energy. After this stage of the cool down is complete, the ADR is down to 45 °K. The next stage involves the lower half of the ADR. The ADR contains a salt pill, which is a block of a paramagnetic substance, two magnets, a thermal sink, and a heat switch. The salt pill is encased in a container and is thermally attached to the MKID device. When the salt pill is placed in a strong magnetic field, it causes the molecules to realign. If the strength of the magnetic field is decreased, the molecules will realign again using their thermal motion. Their thermal energy is thus transferred into magnetic energy, which in turn cools down the salt pill. Because the salt pill is thermally connected to the detectors, the detectors are cooled down in tandem with the salt pill. This is how the superconducting state is achieved. At Fermilab and UC Santa Barbara, the ADR is used to cool down the MKID detectors.

2.3 Attenuator and Temperature Testing

Taking data of a photon's effects on the MKID device is a process. A detailed list of the components of the process was created to ensure that anyone could test the pixels for resonators. First, the environment variables for the scan are set. Next, the resonators are tested by performing a wide sweep of frequencies that are then observed on a plot of Q vs. I. Last, scans are taken with the lamp off and with the lamp on, so that the difference between photons hitting the device and dark exposures can be observed. After taking these scans at different wavelengths and with and without light, histograms are made to discern the difference it made on the results.

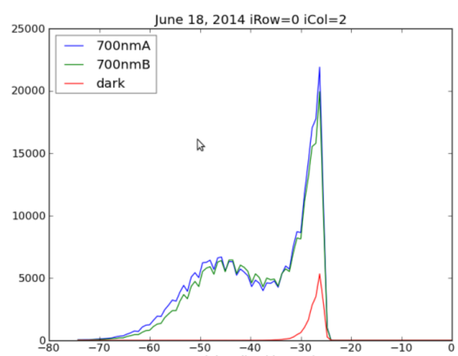

Figure 2. Channel Two – 700 nm.

Figure 2 above shows the results of two tests run with 700 nm wavelengths. The results show multiple photons between the -70 and -30 range. These are good results and clearly show the photon incidents on the MKID device.

Another quality test done with the MKIDs involves changing the temperature of the ADR, and in turn the MKID itself, to see if it performs better at colder or warmer temperatures. Testing temperatures ranging from 60–223 mK, it was clear to see that the performance increased at colder temperatures.

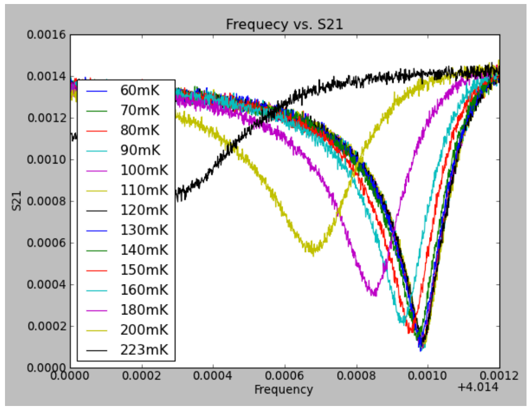

Figure 3. Plot of Frequency vs. S21.

2.4 Fitting for Critical Temperature

One of the issues that the MKID device presented was the consistency of superconducting film across the detector. It was believed that each pixel had its own individual critical temperature due to manufaturing imperfections. To test this theory, the temperature data taken ranging from 60–223 mK was used to create a graph of frequency versus temperature. Using the equation that relates these two variables are fit of the graph was made. One of the parameters of the fit on this graph is critical temperature. Finding the critical temperature of each pixel provides information at what temperature each pixel becomes superconducting. Likewise, there is a relationship between critical temperature and bond energy. The lower the critical temperature of the pixel, the lower the bond energy. The data revealed that every pixel had the same critical temperature.

3. Future Work

3.1 MKIDs and SOAR

At Fermilab, the goal with the MKID project is to mount it to a camera which will in turn be placed on the telescope to take images of the sky. Currently, the Detector Development and Operations Department is working on a proposal to test the MKIDs at the Southern Astrophysical Research (SOAR) telescope in Chile. The proposal includes several projects that Fermilab would like to execute using the MKID devices. An example of one of these projects is MegaZ. MegaZ, or the MKID Extra-Galatic Redshift Survey, is a project that will use MKIDs to map the sky and measure the redshift of many different galaxies.

4. Impact on Laboratory Missions

The research of dark energy and the development of dark energy experiments and tools is a mission of Fermilab. The Dark Energy Survey is one of the Department of Energy's top prioties. Because MKIDs have the potential to revolutionize astronomical studies, they create promising research for Fermilab and for the Department of Energy itself.

5. Conclusion

The future is promising for this detector techonology. The microwave kinetic inductance detector has the ability to revolutionize the field of astronomy, improving the efficiency of observations and creating more capability in range of distance.

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