The Coldest Cubic Meter in the Known Universe

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CUORE is a 741 kg array of TeO$_2$ bolometers that will search for the neutrinoless double beta decay of $^{130}$Te. The detector is being constructed at the Laboratori Nazionali del Gran Sasso in Italy, where it will begin taking data in 2015. The CUORE cryostat will cool several metric tonnes of material to below 1 K and the CUORE detector itself will operate at a typical temperature of 10 mK. At this temperature, the CUORE detector will be the coldest contiguous cubic meter in the known Universe.

I. INTRODUCTION

The Cryogenic Underground Observatory for Rare Events (CUORE) is an experiment being built at the Laboratori Nazionali del Gran Sasso. It is designed to search for Neutrinoless Double Beta Decay ($0\nu\beta\beta$) and is scheduled to begin commissioning in 2015. It is also going to be the coldest cubic meter in the known Universe.

Neutrinoless double beta decay is a second order weak decay in which a nucleus spontaneously converts two of its neutrons into protons and produces two electrons in the process ($(^Z,^A) \rightarrow (^{Z+2},^A) + 2e^-$), without the corresponding electron anti-neutrinos. If observed, this process would indicate a violation of lepton number and have major implications for the nature of the neutrino as well as the fundamental symmetries of the Universe. It could even shed light on the question of the Baryon asymmetry of the universe — the matter/anti-matter mismatch that allowed the formation of stars and galaxies in the first place.

The CUORE detector will search for the $0\nu\beta\beta$ decay of the isotope $^{130}$Te using a cryogenic array of TeO$_2$ bolometers. Each bolometer module consists of a 750 g absorber and an NTD thermistor to measure temperature. When an individual nucleus anywhere inside the absorber undergoes a decay, it releases a small amount of energy which is quickly converted into a rise in temperature of the system, which is detected by the thermistor. Since the energy deposited is so small, — of order a few MeV — seeing a measurable increase in the temperature requires a very small heat capacity and thus an operating temperature near absolute zero. In the case of CUORE, the target operating temperature is 10 mK and the decays of interest cause temperature spikes on the order of hundreds of $\mu$K. The full CUORE detector consists of 988 bolometric modules for a total mass of 741 kg. When operational, this mass, plus an additional 2 metric tonnes of supporting material, will need to be cooled to 10 mK, producing the largest region in the Universe at that temperature.

In this paper, I will briefly discuss the temperature of the Universe and some of the naturally occurring cold places in it. I will introduce the CUORE detector and cryostat and describe the working volume and its temperature. I will also compare the CUORE detector to some of the other large low temperature experiments that are operating or being built.

II. LOW TEMPERATURE REGIONS IN NATURE

In comparison to the CUORE detector, the Universe is actually quite warm. Its temperature is dominated by the Cosmic Microwave Background (CMB) photons that pervade all empty space. This thermal bath of photons exists everywhere throughout the Universe and has a well defined temperature which has been measured with extreme accuracy to be $T_{\text{CMB}} = 2.72548 \pm 0.00057$ K [1].

Many regions of space are heated above $T_{\text{CMB}}$ by structure formation and the radiation this gives off, but there is currently only one known naturally occurring region below $T_{\text{CMB}}$ and that is the Boomerang Nebula [2]. This proto-planetary nebula (PPN) consists of a central star surrounded by an envelope of molecular gas. The Boomerang Nebula is unique among known PPN in that it has produced an extremely massive and rapidly expanding envelope of gas. The high opacity of this envelope absorbs CMB photons in the outer layers, shielding the inner regions and allowing them to cool via adiabatic expansion. By combining radio measurements with radiative modeling, the authors of [2] place the kinematic temperature at about 1 K, but possibly as cold as 0.3 K. This makes the Boomerang Nebula the

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TABLE I: The stages of the CUORE cryostat below 1K and the volumes and masses colder than that temperature. The values are cumulative and should be read as the ‘total volume/mass colder than.’ (Numbers are approximate.)

| Stage                  | Temperature (mK) | Volume (L) | Mass (kg) |
|------------------------|------------------|------------|-----------|
| 4K Stage               | 3.5 K            | 3340       | 16000     |
| Still                  | 850              | 1890       | 14100     |
| Heat Exchange (HEx)    | 50               | 1440       | 5900      |
| Base (no load)         | 10               | 990        | 400       |
| Base                   | 10               | 636        | 2000      |

The largest known object in the Universe outside the laboratory. But here on Earth we routinely achieve temperatures colder than 300 mK.

III. THE CUORE CRYOSTAT

The CUORE detector is hosted in one of the largest cryostats ever constructed and is cooled by a $^3$He/$^4$He dilution refrigerator that was designed and built by Leiden Cryogenics and is one of the most powerful in the world. A detailed description of the CUORE cryostat can be found here [4], and a paper describing its commissioning is in preparation. The cryostat is built as a series of nested vessels that step the temperature down from 300 K to $\sim$ 40 K, $\sim$ 3.5 K, $\sim$ 800 mK, $\sim$ 50 mK and finally the detector temperature of 10 mK. Each stage is connected to a cooling unit and has a radiation shield that thermally isolates the enclosed volume.

The largest stage of the cryostat below 1 K is the Still. The temperature of this stage will be adjusted to optimize the temperature of the coldest stage, but it is typically maintained between about $\sim$800-900 mK. It is composed of a radiation shielding copper can 112 cm in diameter by 185 cm in height, mounted to the bottom of the copper Still plate that has a diameter of 133 cm and a thickness of 4.3 cm. The total enclosed volume at or below $\sim$ 1 K is $\sim$1890 L.

Inside the still shield is the next colder stage of the cryostat, the Heat Exchanger. The temperature of this stage will also be adjusted to maintain the base temperature but it is typically maintained at $\sim$50 mK. This stage consists of a radiation shielding copper can of diameter of 103 cm and height of 165 cm, it is mounted to the bottom of a copper plate that has a diameter of 107 cm in diameter and 2.8 cm thick. The total enclosed volume at or below $\sim$ 50 mK is 1435 L.

Inside the Heat Exchanger (HEx) vessel is the coldest stage of the cryostat, the Mixing Chamber (MC) plate, the lead shielding, and the CUORE detector itself. The MC plate is suspended from the Heat Exchanger plate and hosts the final stage of the dilution refrigerator. The plate itself is 98 cm in diameter and 1.8 cm thick and supports a radiation shielding copper vessel below, which is 94 cm in diameter and 130 cm in height. The MC stage is cooled to 10 mK and encloses a volume of 990 L.

However, inside this volume things get slightly complicated. Below the 10mK plate, there will be $\sim$2.6 metric tonnes of lead and copper shielding, which, for reasons of cooling power, is thermalized to 50 mK. This shielding takes up a volume of 235 L inside the 10 mK shielding. So to be conservative, we will take the operating volume at 10mK to be only that of the shielded detector itself, 636 L. These sizes and volumes are summarized in Tab. I.

IV. DISCUSSION

The current record for the coldest cubic meter in the Universe was set in the first of the CUORE cryostat commissioning runs without the lead shielding mounted [paper in preparation]. When the CUORE detector is fully commissioned and running (2015), the detector will be held stably at the operating temperature of $\sim$10 mK for the duration of CUORE data taking – which is expected to be $\sim$ 5 years. During this time, both the 636 L held at 10 mK and the 1435 L held entirely below 50 mK will be the coldest volumes of those respective sizes in the known Universe. This gives CUORE cryostat the distinction of being the Coldest Cubic Meter in the known Universe.

In Tab. II I list a few, but certainly not all, of the larger currently running experiments below 100 mK. I list their approximate cold volumes and operating temperatures. Not surprisingly, the largest coldest experiments are often rare-event searches.
TABLE II: A (non-exhaustive) list of currently running large volume experiments with operating temperatures below 100 mK. The mass represents the target or detector mass, excluding any supporting material or structure. CUORE (HEx) is not a separate experiment, but just the 50 mK stage of the CUORE detector. All numbers are approximate, and only meant to give a sense of scale. \(^a\)Auriga/Nautilus operated at \(T \sim 100\) mK from 1997-99, but are currently taking data at 4.4 K.

| Experiment            | Mass (kg) | Size (L) | Temperature | Physics Goal | Location           | Ref. |
|-----------------------|-----------|----------|-------------|--------------|--------------------|------|
| CUORE                 | 741       | 636      | 10 mK       | \(0\nu\beta\beta\) | Gran Sasso, Italy  | 4    |
| CUORE-0               | 39        | 27       | 12 mK       | \(0\nu\beta\beta\) | Gran Sasso, Italy  |      |
| CRESST-II             | 10        | 24       | 15 mK       | Dark Matter  | Gran Sasso, Italy  |      |
| Edelweiss             | 32        | 50       | 20 mK       | Dark Matter  | Modane, France     |      |
| SuperCDMS             | 10        | 21       | 40 mK       | Dark Matter  | Soudan, SD         |      |
| CUORE (HEx)           | -         | 1435     | 50 mK       | \(0\nu\beta\beta\) | Gran Sasso, Italy  |      |
| Auriga/Nautilus\(^a\) | 2200      | 848L     | 100 mK      | Gravity Wave | Italy              |      |

V. CAVEATS, QUALIFICATIONS, IFS AND BUTS..

There are several caveats and assumptions that should be noted. Many of these are technicalities, but they deserve mentioning:

- The CUORE detector, like everything on Earth, is bathed in a constant flux of neutrinos both from the sun and earth’s core. The solar neutrinos were last thermalized in the core of the sun to temperatures of order \(10^7\) K and neutrinos from the earth’s core were last thermalized to temperatures of order \(10^4\) K. However, neutrinos interact so infrequently — we expect of order 100 solar neutrinos per year to interact in the CUORE detector — that they never reach a thermal equilibrium with anything on Earth (thankfully). However, all of these neutrinos are still technically present inside the volume of the CUORE detector, so I explicitly ignore them here.

- Another very interesting source of neutrinos that are also present inside the volume of the CUORE detector is the Cosmic Neutrino Background (C\(\nu\)B). These are the relic neutrinos from the Big Bang, and like the photons in the CMB they are expected to pervade the entire Universe. Unlike the photons in the CMB, these neutrinos interact so infrequently that they have not actually been detected yet. These neutrinos are expected to be warmer than the CUORE detector but like the solar and geo-neutrinos, never come into thermal equilibrium, so I explicitly ignore these as well.

- CUORE will have a significant amount of lead shielding sitting inside the 10 mK shield and thermalized to 50 mK. Lead becomes superconducting around 7 K and as a result, as the temperature drops below \(\sim T_c/10 = 700\) mK, the thermal conductivity becomes very poor and the lead begins to self insulate. It will eventually reach 50 mK, but it is difficult to say on what timescale. Neglecting the lead in the 10 mK volume, the remaining volume at 50 mK is about 1245 L.

- The definition of the cubic meter can be made fuzzy. Here I have considered only a simple contiguous convex volume of space.

- Proving the non-existence of a cubic meter in the Universe colder than CUORE is, of course, an impossible task. I have implicitly restricted the discussion to known or discovered phenomena. But, I admit the possibility of another planet somewhere in an infinite Universe, which is entirely identical to Earth in every way, except that their CUORE collaboration has decided to operate their CUORE detector at 9 mK.

VI. CONCLUSION

The volume inside the CUORE detector will be the largest volume in the Universe below 50 mK and the largest volume at 10 mK. It has already achieved this temperature in its first test cooldown and can now be called the coldest cubic meter in the known Universe. And as such, the CUORE detector has a strong claim to the title of the coldest place in the Universe as well.

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Appendix A: More on the CMB

The CMB sets the standard for what we consider the temperature of the Universe, and in this appendix we consider the possibility of a purely statistical fluctuation of the CMB temperature down to 10 mK somewhere in the Universe. If we broaden our working definition of temperature, we can calculate the probability that the coldest cubic meter in the CMB — according to this interpretation of mean kinetic energy consistent with $\sim 10$ mK. (I should warn, that the following argument will be very approximate.)

Starting from the Planck distribution

$$n(E)dE = \frac{1}{\pi^2 \hbar^3 c^3} \frac{E^2}{e^{E/kT} - 1} dE$$

we can integrate this to find the photon number density at 2.7 K, $n \sim 4 \times 10^8 \text{ m}^{-3}$, the mean photon energy $\langle E \rangle \approx 0.7$ meV, and the RMS $\sigma_E \sim 0.4$ meV. Due to the extremely large number of photons in a given cubic meter, the magnitude of fluctuations of mean kinetic energy is extremely suppressed, $\sigma_{\langle E \rangle} \sim \sigma_E \sqrt{\langle N \rangle} \sim 20 \text{ neV}$. A fluctuation down to a mean kinetic energy consistent with $T \sim 10 \text{ mK}$ (or $\langle E \rangle \sim 2.3 \mu\text{eV}$), amounts to a $\sim 31,000\sigma$ downward fluctuation.

If one were to assume a Gaussian probability distribution, this calculation would imply that the fraction of cubic meters in the Universe that had fluctuated down this far would be about 1 in $\sim 10^{80}$. For reference, there are $\sim 10^{80}$ cubic meters in the observable Universe. However, we are extrapolating this distribution down so far that considering it Gaussian is certainly no longer warranted.

So instead we ask the question what is the coldest cubic meter in the CMB — according to this interpretation of mean energy density. Or in other words, what temperature corresponds to the mean energy density which we expect fewer than 1 in $10^{80}$ cubic meters of space to be colder than. Assuming a Gaussian distribution, this would take us down only 19$\sigma$ — a much more modest distance to extrapolate than 31,000$\sigma$. This corresponds to a fractional difference in temperature of $\frac{\Delta T}{T} \sim 6.1 \times 10^{-4}$. Or in other words, for statistical fluctuations alone, we expect that at any given time the coldest cubic meter anywhere in the CMB is only $\sim 1.6 \text{ mK}$ colder than the average temperature of the CMB.