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# Cryogen-free dilution refrigerator for bolometric search of neutrinoless double beta decay ($0\nu\beta\beta$) in $^{124}$Sn

V SINGH[1,2], S MATHIMALAR[1,2], N DOKANIA[1,2], V NANAL[3,*], R G PILLAY[3] and S RAMAKRISHNAN[4]

[1]Homi Bhabha National Institute, Anushaktinagar, Mumbai 400 094, India
[2]India-based Neutrino Observatory; [3]Department of Nuclear and Atomic Physics;
[4]Department of Condensed Matter Physics and Material Sciences, Tata Institute of Fundamental Research, Mumbai 400 005, India
*Corresponding author. E-mail: nanal@tifr.res.in

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**Abstract.** The feasibility study for searching neutrinoless double beta decay in $^{124}$Sn using cryogenic bolometer has been initiated. For this purpose, a custom-built cryogen-free dilution refrigerator, having a large cooling power of 1.4 mW at 120 mK, has been installed at TIFR, India. This paper describes the design, installation and performance of a cryogen-free dilution refrigerator (CFDR-1200). The performance of CFDR-1200 has been analysed using Takano's model developed for conventional (wet) dilution refrigerators.

**Keywords.** $0\nu\beta\beta$ in $^{124}$Sn; cryogen-free dilution refrigerator.

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## 1. Introduction

Cryogenic bolometers, where the energy of impinging radiation is converted into phonons leading to a measurable temperature rise, have excellent energy resolution and high sensitivity [1]. The intrinsic resolution of a bolometer depends only on its heat capacity and operating temperature [2]. Typically, bolometers are operated at temperatures below 50 mK. Pure insulators as well as superconductors are good candidates for bolometers as their specific heat falls off rapidly at these low temperatures. Further, it is possible to construct bolometers of varying sizes. Large size bolometers with masses ranging from several kilograms to a ton have found attractive application in rare event studies like Dark Matter search [3,4], Neutrinoless Double Beta Decay (NDBD) [5,6] etc. Continuous cooling of these bolometers below 1 K is achieved using dilution refrigerators. Large detector masses put extremely stringent conditions on the cooling power of these dilution refrigerators.

The study of NDBD ($0\nu\beta\beta$) has important implications in understanding the mass and nature of neutrinos. It is perhaps the only experiment which can shed light on the true nature of neutrino (Majorana or Dirac) and its absolute effective mass [7–9]. A feasibility study to search for $0\nu\beta\beta$ in $^{124}$Sn at the upcoming underground facility in India-based Neutrino Observatory (INO) has been initiated [10,11]. $^{124}$Sn has reasonably high $Q$ value (2.28 MeV), moderate isotopic abundance (5.8%) and can be made into a cryogenic bolometer with high energy resolution [12,13].

This paper describes the design and performance of a custom-built M/s Leiden Cryogenics make CFDR-1200 for developing Sn prototype bolometer. Given the long time-scale of the $0\nu\beta\beta$ experiment and remote locations of underground laboratories, the choice of a cryogen-free dilution refrigerator instead of conventional wet system (which requires liquid helium supply), is quite imperative. Furthermore, the cryogen-free dilution refrigerator eliminates the vibrations originating from 1 K pot used in classic dilution refrigerators [14].

## 2. Design of CFDR-1200

It is envisaged that the prototype stage of Tin.Tin (The India's Tin detector) would consist of an array of ∼30 tin (Sn) crystals (natural/enriched $\sim 3 \times 3 \times 3$ cm$^3$ each) arranged in a tower geometry with corresponding read-out sensors. Since the sensitivity of $0\nu\beta\beta$ experiment is crucially dependent on the minimization of background radioactivity, it is essential that the material surrounding the detector elements should be of high radiopurity. In addition, a bulk shielding is highly desirable inside the cryostat to suppress the background events arising from the materials used for the construction of cryostat [15]. Therefore, a provision for additional low activity shielding inside the cryostat is also incorporated in the design. The dilution refrigerator has a cylindrical sample space of 300 mm × 300 mm available below the mixing chamber (MC) which is inside the inner-most 50 mK shield and can support a total mass of ∼100 kg (Sn detector and ∼5 cm thick low activity lead shield).

Figure 1 shows the complete schematics of the dilution unit. The dilution unit consists of a still, a 50 mK cold plate, a MC and a series of heat exchangers, integrated with a pulse tube cooler [16]. The dilution unit is protected against radiation heat load using shields at 50 K, 3 K, the still and 50 mK. The 50 K and 3 K stage shields are fabricated from aluminum wrapped in multilayer mylar insulation and are cooled by the two stages of the pulse tube cooler. The shields at the still and the 50 mK stage are made of gold-plated copper and are cooled by the dilution refrigerator. The 3 K shield also serves as an inner vacuum chamber (IVC). The external vessel of the cryostat which acts as the outer vacuum can (OVC) is at room temperature. A charcoal-loaded cryopump is mounted on the 50 K and 3 K stages to adsorb any residual gas in OVC and IVC, minimizing heat load due to gas conduction.

The cooling in the pulse tube (PT) cooler is achieved using a closed loop helium expansion cycle. The pulse tube cooler consists of a compressor unit and a cold head unit. The compressor unit compresses the pure helium ($^4$He) gas and the heat of compression is removed via a water-cooled heat exchanger. The compressed helium is then fed to the cold head where adiabatic expansion of helium takes place allowing the system to cool

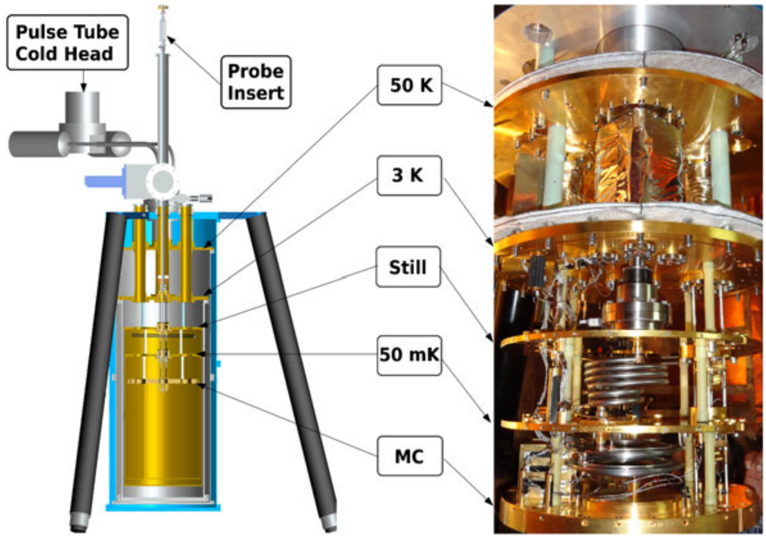


**Figure 1.** Schematics of CFDR-1200 dilution unit at TIFR. The image on the right shows the actual unit.

down to cryogenic temperatures. The pulse tube cooler (Cryomech-PT415 with remote valve motor option [17]) has a typical cooling capacity of 1.5 W at 4.2 K. The valve control unit, which incorporates a stepper motor and controls the gas flow, is detached from the PT-cooler by a 65 cm flexible single hose and is mounted on a vibration dampner. This reduces the vibrations transmitted to the cryostat. The compressor is installed outside the experimental room to reduce acoustical noise. The cold head is connected to the compressor by means of two 20 m long flexible lines.

For achieving temperature lower than 3 K, the $^3$He/$^4$He mixture is condensed using a Joule–Thomson heat exchanger which is installed between the 3 K plate and the still. The amount of $^3$He used in CFDR-1200 ($\sim$45 l) is significantly smaller compared to $^3$He used in wet dilution refrigerator ($\sim$175 l). A turbomolecular pump having a pumping speed of 1850 l/s in series with a 800 m$^3$/h dry roots pump constitute the pumping system on the still line. This high throughput system provides substantial circulation rate (maximum flow rate of $\sim$1900 $\mu$mol/s beyond which the system becomes unstable). However, the excess flow rate is a source of heat load on the MC and limits the cooling power at very low temperature. A tube-in-tube continuous heat exchanger followed by a silver sinter heat exchanger is used between the still and the 50 mK plate. The unit has a couple of continuous silver sinter heat exchanger installed between 50 mK plate and the MC. The latest proprietary designs of Leiden Cryogenics have been used in the construction of MC, the still and the above heat exchangers to minimize the viscous heat load arising from high flow rate. The high cooling power of CFDR-1200 is essential for cooling the massive detector and shield elements to 10 mK.

The CFDR-1200 also has an additional option of a top-loading probe which gets connected to the mixing chamber. The probe has a cylindrical sample space of 40 mm $\times$ 80 mm and is inserted using one of the three clear shot tubes provided in the dilution unit which facilitates easy sample changes in cold condition. The probe is thermally anchored at the 3 K, the still, the 50 mK and the MC stages of the dilution unit to minimize the heat load due to conduction. However, it does introduce a small heat load on the main MC at the base temperature.

The MC temperature is monitored using a couple of calibrated carbon speer resistors and a paramagnetic cerium magnesium nitrate (CMN) thermometer. A calibrated platinum resistor (Pt-1000) is mounted on the MC to monitor temperatures above 10 K, during the cool down. The resistance measurements are done using AVS-47B AC-resistance bridge while the inductance of CMN is measured with a digital mutual inductance bridge. In addition to standard diagnostic thermometry, the CFDR-1200 is equipped with read-out wiring for up to 75 sensors (four-probe measurement). The wiring from room temperature to 3 K stage is done using shielded phosphor bronze while shielded NbTi wires are used from 3 K to the MC. The superconducting NbTi wires ensure that the thermal heat load on the MC due to large number of wires is negligible. All the 300 wires are connected with hermetically sealed connectors at 50 K and 3 K stages through two clear shot tubes. This also provides a possibility to mount a pre-amplifier stage for bolometer pulse processing at 50 K, if needed in future. The operation of CFDR-1200 and diagnostic thermometry is controlled using M/s Leiden's control program.

## 3. Performance of CFDR-1200

The cooling power of the CFDR-1200 has been measured for different $^3$He flow rates and is shown in figure 2. The temperature on the MC was controlled by supplying current to a 100 Ω resistor on the MC plate. The flow rate was changed by applying 0 to 40 mA

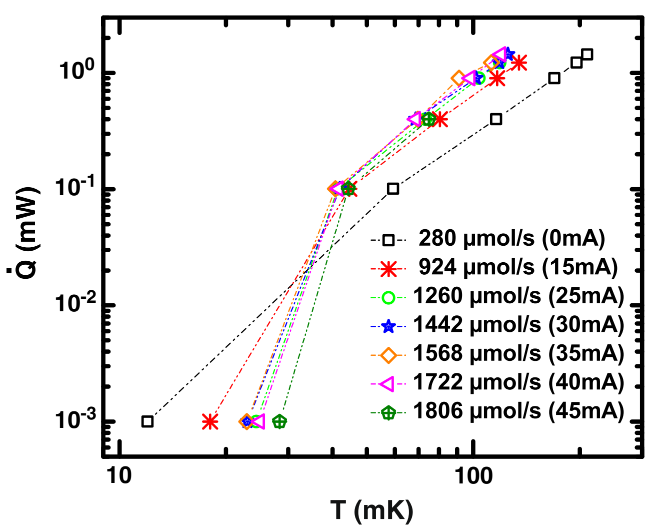


**Figure 2.** The measured cooling power for different flow rates as a function of $T$. Numbers in parenthesis indicate the still heater current. An offset of 1 $\mu$W has been included in $\dot{Q}$ for plotting on log scale.

current to a standard 100 Ω heater inside the still ($I_{\text{still}}$). The lowest minimum temperature of 7 mK, measured with CMN thermometer, was achieved with a flow rate of 280 $\mu$mol/s ($I_{\text{still}} = 0$ mA), without any external heat load on the system. Readings of all calibrated sensors were consistent within ±2 mK at the lowest temperature. As shown in figure 1, at temperatures above 50 mK, there was a substantial gain in cooling power when the flow rate was increased from 280 $\mu$mol/s by increasing $I_{\text{still}}$. However, the flow rate cannot be increased to very large values as the cooling power capacity suffers at very high flow rate. These measurements indicate an optimum flow rate of 1568 $\mu$mol/s for significant cooling power at temperatures above 50 mK. A cooling power of 1.4 mW was measured at 120 mK for the flow rate of 1568 $\mu$mol/s. It should be noted that the base temperature degraded from 12 mK to 30 mK as the flow rate was increased. Moreover, the system has two gas circuit lines for the $^3$He/$^4$He mixture leading to the condenser line. Since the impedances of these lines are different, the flow rate can also be crudely controlled by circulating the gas through any one or both of these lines. The minimum base temperature was achieved when both the lines were open.

The cooling power of a dilution refrigerator is well studied in literature using standard thermodynamics, describing the $^3$He/$^4$He mixture as a Fermi gas [18,19], and is given by

$$\dot{Q}_{\text{m}} = \dot{n}\left(\left(\gamma_{\text{D}} - \frac{\gamma_{\text{C}}}{2}\right)T_{\text{m}}^2 - \left(\frac{\gamma_{\text{C}}}{2}\right)T_{\text{x}}^2\right), \tag{1}$$

where $\dot{Q}_{\text{m}}$ is the cooling power on MC, $\dot{n}$ is the circulation rate of $^3$He, $\gamma_{\text{D}}$ (107 J/mol/K$^2$) and $\gamma_{\text{C}}$ (23 J/mol/K$^2$) are coefficients of heat capacity of $^3$He in dilute and concentrated phases, respectively. $T_{\text{m}}$ is the temperature of the MC and $T_{\text{x}}$ is the temperature of the last heat exchanger from which the $^3$He gas exits before entering the MC. In an ideal heat exchanger of a dilution unit $T_{\text{x}} = T_{\text{m}}$ and the cooling power can be simplified as

$$\dot{Q}_{\text{m}} = 84\,\dot{n}\,T_{\text{m}}^2 \text{ J/mol/K}^2. \tag{2}$$

Figure 3 shows the plot of $\dot{Q}/\dot{Q}_{\text{m}}$ as a function of $T_{\text{m}}/T_{\text{b}}$, where $T_{\text{b}}$ is the lowest base temperature achieved. It can be seen that the measured $\dot{Q}$ is consistent with eq. (2) for

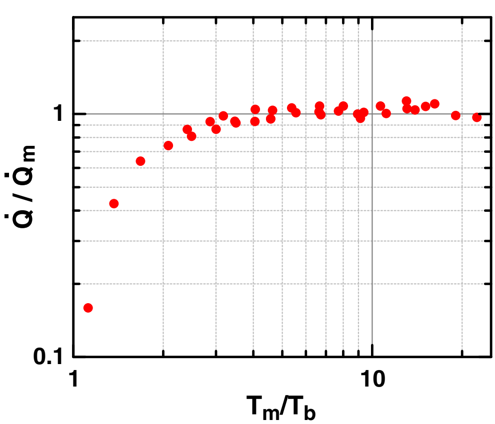


**Figure 3.** Normalized cooling power as a function of normalized temperature (see text for details).

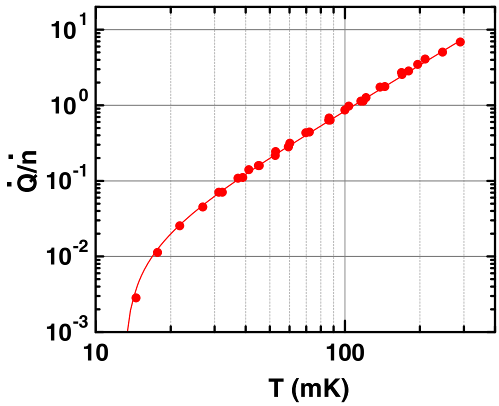


**Figure 4.** Cooling power of CFDR-1200 in the presence of heat load. The solid line is the best fit to the data using Takano's formula [21] (see text for details).

$T_m/T_b \geq 3$. For $T_m < 3T_b$, the incoming $^3$He flow acts like a heat load on the MC. Thus, the heat exchangers are unable to cool down the incoming $^3$He to MC temperature $T_m$ and the assumption $T_x = T_m$ is not valid. This has also been observed in conventional dilution refrigerators [20].

A more critical limit on the performance of the dilution refrigerator is determined by the intrinsic heat load on the MC. The base temperature achieved without the probe was 7 mK. However, when the probe was inserted into the MC, the base temperature was raised to 12 mK because of the heat load brought in by the thermal conduction of the probe.

Takano [21] has suggested an empirical formula for the cooling power of a dilution refrigerator with an intrinsic heat leak, $\dot{Q}_0$ present in the system,

$$\dot{Q} = \dot{n}(\gamma_D - \gamma_C)(T_m^2 - T_0^2), \tag{3}$$

where $T_0$ is the lowest temperature in the presence of $\dot{Q}_0$. The relation between $T_0$ and the ultimate base temperature, $T_b$, is approximated by

$$T_0{}^2 = T_b^2 + \frac{\dot{Q}_0/\dot{n}}{(\gamma_D - \gamma_C)}. \tag{4}$$

The standing heat load of Probe insert $\dot{Q}_0$ in this case is estimated to be 3 $\mu$W at 12 mK by fitting data with eq. (4) and is shown in figure 4. This formula can also be employed to estimate the heat load when a larger detector array is mounted on the MC.

## 4. Summary

A custom-built cryogen-free dilution refrigerator, CFDR-1200, with a high cooling power of 1.4 mW at 120 mK, has been successfully installed and tested at TIFR, Mumbai, India. The minimum base temperature of <10 mK has been measured using calibrated CMN thermometer and a carbon speer resistor. After optimizing the operating conditions (flow rate), the performance of CFDR-1200 has been found to be consistent with the Takano's model for conventional refrigerator. The higher flow rate has resulted in a greater cooling power with a significantly smaller quantity of $^3$He as compared to standard wet dilution refrigerator. This CFDR-1200 will be used for developing a prototype tin cryogenic bolometer for $0\nu\beta\beta$ study.

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