We propose a new scheme aimed at cooling nanostructures to microkelvin temperatures, based on the well established technique of adiabatic nuclear demagnetization: we attach each device measurement lead to an individual nuclear refrigerator, allowing efficient thermal contact to a microkelvin bath. On a prototype consisting of a parallel network of nuclear refrigerators, temperatures of \( \sim 1 \) mK simultaneously on ten measurement leads have been reached upon demagnetization, thus completing the first steps toward ultracold nanostructures.

The ability to reach low millikelvin or even microkelvin temperatures in nanoscale samples would open up the possibility to discover new physics in a variety of systems. For example, an intriguing nuclear spin ferromagnetic phase transition in a GaAs interacting 2D electron gas (2DEG) has been predicted to occur around \( \sim 1 \) mK \( B = 0 \), constituting a novel type of correlated state. Nuclear spin fluctuations would be fully suppressed in this ferromagnetic phase, eliminating the main source of decoherence for GaAs spin qubits. Further, full thermodynamic nuclear polarization is possible at temperatures \( T \lesssim 1 \) mK in an external magnetic field of \( B \sim 10 \) T. Other systems benefiting from ultralow temperatures include fractional quantum hall states with small gaps \( \Delta \), in particular the \( \nu = 5/2 \) state, which is currently considered for topological quantum computation.

The majority of quantum transport experiments to date, such as those in GaAs 2DEGs or any other nanoelectronic devices on insulating substrates, have been carried out at electron temperatures \( T_e \) significantly greater than that of the host \( ^3\text{He}-^4\text{He} \) dilution refrigerator (DR). Since only metals provide significant thermal conduction at temperatures well below 1 K, nanostructures are thermally connected to and cooled by the DR primarily through their electrical leads. Since these leads need to be electrically isolated, some insulator will still inhibit efficient cooling. The main challenges for cooling such samples below 1 mK include overcoming poor thermal coupling between electrons in the leads and the refrigerator, providing sufficient attenuation of high frequency radiation, and reducing low frequency interference such as ground loops. To our knowledge, the minimum temperature reported is 4 mK, with sintered silver heat exchangers attached to sample wires in a \( ^3\text{He} \) cell. Similarly, Pomeranchuck cooling with sintered Pt and \( \sim 10 \) mK, generating as large a thermal contact coefficient as possible. Sec-

![FIG. 1. (Color) (a) Schematic of parallel nuclear refrigerator network. Only six NRs are shown for simplicity. (b) Cooling scheme, with different colors denoting potentially different temperatures under steady state conditions.](image-url)
ond, thermal contact between the DR and NR is cut off by a superconducting heat switch and the field is adiabatically reduced by a large factor, e.g. $x = B_i/B_f \sim 100$. Ideally (perfect adiabaticity), the nuclei are cooled by the same factor such that $T_f = T_i/x$. Finally, experiments are performed at microkelvin temperatures for a finite time, typically days or even weeks. The heat leaking into the system plays an important role since it increases $T_e$ in the NRs above the nuclear spin temperature and is absorbed by the nuclei until the polarization is lost and the NRs heat up to or above DR temperatures.

We propose to cool nanostructures to microkelvin temperatures using a parallel network of NRs. Each NR constitutes part of the electrical connection from room temperature down to the sample. Semiconductors and insulators, commonly used in nanosamples, are not practical as NRs since it is difficult to sufficiently precool their nuclei. Still, one might consider as NRs devices with large conducting regions containing nuclear spins, such as GaAs 2DEGs with a highly doped, metallic back gate (or similar). However, their nuclear heat capacity would be drained all too quickly given realistic heat leaks. Therefore, our strategy is to incorporate the most widely used material for NRs: Cu, an excellent conductor with nuclear spin $3/2$. In this system the nuclear hyperfine interaction couples the nuclei at temperature $T_f$ to the electrons at temperature $T_e$ with a characteristic nuclear spin relaxation time $T_1$ that obeys the Korringa law, $T_eT_1 = \kappa \approx 1 \text{ K s}$ [8, 9]. The effective thermal equilibration time is reduced from $T_1$ by the very large ratio of nuclear and electronic heat capacities, resulting in strong, fast cooling even at $T_e < 100 \mu \text{K}$ [15]. However, conducting sample sections may be thermally isolated from other degrees of freedom at low enough temperatures.

We now turn to the discussion of the prototype NR network (see Fig. 1). Each NR consists of a Cu plate situated in the center of a demagnetizing field, connected with high conductivity wires on one side to a home built chip carrier made from 2850 FT Stycast epoxy [16], and on the other side through a heat switch [17] to the mixing chamber (MC) of a DR. Twelve parallel NRs are tied to a sacrificial NR with dental floss, using small teflon spacers ensuring electrical (and thermal) isolation, giving a total of thirteen NRs. The sacrificial Cu piece is glued into an araldite [18] beam extending from the MC and holds a teflon touch guard in place, which keeps the NRs from contacting the radiation shield.

To ensure proper operation of the NRs, we note some important details. Each measurement wire begins with 1.6 m of Thermocoax acting as a microwave filter between room temperature and the MC cold finger. It then passes through a silver epoxy microwave filter [19] and is transferred to a bare Ag wire that is fed directly into the plastic MC. For efficient thermalization of the Cu during precooling the thermal resistance between the NR and MC must be minimized. We therefore use annealed, high purity Ag wire with 1.27 mm diameter and residual resistivity ratio $\geq 1500$, which are spot welded to the Cu pieces and, in the MC, sintered to Ag nanoparticles (yielding surface areas of $\sim 3 \text{ m}^2$ per wire used to overcome the Kapitza resistance $R_{Kap}$). The heat switches are “C”-shaped pieces of annealed, high purity Al fused to the Ag wires on both ends. The small critical field of 10 mT allows easy switching with a home built magnet. The ratio of thermal conductivities in the closed state (Al normal) to the open state (Al superconducting) exceeds $10^4$ below 20 mK. Al pieces are placed carefully to minimize differences in the stray $B$-field from the solenoid, adding additional complexity for a network of NRs.

The entire stage is removable at a plastic cone seal at the MC, allowing samples to be directly wire bonded to polished Ag wires. Probably the weakest thermal/electrical link between the device and the NR occurs at the Schottky barriers of the metal-semiconductor contacts, integrated on chip. In steady state, parasitic heat leaking into the device will equal the heat leaving it through its thermal links to the NRs, setting the lowest achievable temperature. Metallic nanostructures will benefit from comparatively higher conductivity metal-
Characterization of the NRs has been carried out by monitoring $T_e$ of the various Cu plates. Five RuO$_2$ chip resistors, labeled A-E, were mounted on the chip carrier (see Fig. 2(a) inset) and electrically connected to ten of the thirteen NRs, with each chip using a pair of NRs as its leads. The resistance reading in these cases reflects an “average” temperature of each pair. Two more chips, F and S, were directly mounted onto individual NRs (S on the sacrificial Cu plate), with the second contact of each electrically connected to – but thermally isolated from – the outside world by a bare NbTi superconducting wire. The final plate was left unmonitored, serving as electrical ground (G) for chip capacitors across A and B. It is well known that RuO$_2$ thermometers can suffer from rather long time constants and saturate below 10 mK. However, in the demagnetized state we can extrapolate the NR temperatures below 10 mK based on warm up curves, as will be described below.

We first calibrate the RuO$_2$ thermometers between 12 and 120 mK. Figure 2(a) shows the resistance of the seven RuO$_2$ chips at $B = 0$ as a function of mixing chamber temperature $T_{MC}$ with Al switches closed. $T_{MC}$ was measured by a cerium magnesium nitrate (CMN) thermometer bolted to the cold finger. Before measuring each data point, an appropriate amount of time for thermalization was allowed. There is no apparent saturation down to $T_{MC} = 12$ mK for thermometers A-F, which all exhibit qualitatively the same temperature dependence. Moreover, on two separate cooldowns a second CMN was mounted directly onto one of the NRs (first A, then F), verifying that $T_e$ measured by the RuO$_2$ chips is indeed equal to $T_{MC}$. We therefore use the data in Fig. 2(a) as electron temperature calibrations for NRs A-F. The sacrificial plate thermometer S displays some saturation for $T_{MC} \leq 30$ mK, presumably due to some heat leak. Upon ramping the magnet to $B = 8$ T, the massive nuclear heat of magnetization significantly elevates the NR temperatures (varying somewhat for individual plates depending on stray field conditions at the corresponding heat switches), but they cool within 15 h to $T_i = T_e \leq 15$ mK (see Fig. 2(b) left inset).

Next, we measure the parasitic heat leak to the NRs. Figure 2(b) shows the NR temperature $T_e$ as a function of applied power at $B = 0$ and with the Al switches open. The heat flowing into the Cu is ultimately drained away by the MC, with the superconducting Al piece as the primary impedance. Its thermal conductance is dominated at low temperature by phonon-dislocation scattering processes, obeying the relation $P_{app} = n A (T_e^3 - T_{MC}^3) - P_0$, where $P_{app}$ is the applied power, $n = 0.57$ mol of Cu, $A$ is a prefactor, and $P_0$ is the intrinsic heat leak to the NR. For $T_e > 70$ mK, parallel channels of heat flow become accessible. Fits (dashed curves) are in very good agreement with the data and allow us to extract $P_0$, which improved over time as indicated by the decrease in $T_e$ (true for all chips A-F) as $P_{app} \to 0$ in the power curves obtained 3, 6, and 18 days after cooling down (top to bottom curves). We conclude that the typical intrinsic heat leak to the NR stage at $B = 0$ is $P_0/n \lesssim 1$ nW mol$^{-1}$, sufficiently low but clearly above the state of the art value of < 5 pW mol$^{-1}$ [15]. Heat leaks measured at $B = 1$ T are also at the nanowatt level and similar for all NRs.

Given a heat leak sufficiently low for nuclear cooling, we now evaluate the demagnetization process itself, starting from $T_i = 15$ mK and $B_i = 8$ T. The inset of Fig. 2 shows the resistance of several chips during a series of ramps from 8 T to 1 T with open heat switches. The field is decreased linearly in time using three sequential ramps at 1 T h$^{-1}$ from 8 T to 4 T and 4 T to 2 T, and at 0.5 T h$^{-1}$ from 2 T to $B_f = 1$ T. $R$ values increase upon demagnetization, clearly indicating cooling. They continue to increase (at fixed field values of 4 and 2 T) between each field ramp and in fact do so more quickly, reflecting both a thermal lag between the chips and Cu plates as well as a sensitivity to ramp rate. If enough time is allowed after reaching 1 T, $R$ increases further by 5 to 10 kΩ for chips A-E (not shown). Chip F warms up near the end of the demagnetization, while S is nearly constant. It is presently unclear how the stored energy in the Cu nuclei is drained from F, but its performance improves for lower precooling temperatures. For S, the lack of cooling and warming suggest that thermal contact to the environment remains significant.

![Fig. 3](https://example.com/f3.png)

**FIG. 3.** (Color) (a) Systematic heating tests for chip D after demagnetization. Measured $T^{-1}$ (blue curves) and theory for $T^{-1}$ (solid lines) and $T^{-1}$ (dashed lines) vs. $t$ for the applied powers indicated. Inset: cooling of chips during demagnetization. $R$ of thermometer D is plotted against the right axis for comparison in (b).
We extract $T_f$ and $T_e (\gtrsim T_f)$ of the NRs reached after demagnetizing to $B_f$ by recording the time $t$ necessary for a Cu plate to “completely” ($T_e^{-1} \rightarrow 0$) warm up under an applied power, using $t = n\Lambda B_f^2/(P_{app} T_f)$ and $T_e = T_f(1 + \kappa P_{app}/n\Lambda B_f^2)$, where $\Lambda$ is the nuclear Curie constant for Cu. In Fig. 3(a) we plot time traces of $T_e^{-1}$ for chip D (not calibrated above 0.08 mK$^{-1}$) for $P_{app} = 25, 50$, and 100 nW. The other thermometers give consistent results, except for F, which appears to overestimate $T_e$. Thus, a base temperature of $0.1$ mK ($\approx 0.32$ T) starting at $13.3$ mK is dominated by the inhomogeneity of the NRs reached after the power is turned on since $P_{app} \ll P_e$. With this, we obtain $T_f(0) = 3.0 \pm 0.3$ mK for all three $P_{app}$, demonstrating the reliability of achieving a particular minimum temperature for a set demagnetization parameters. The uncertainty in $T_f(0)$ is dominated by the inhomogeneity of $B_f$. We note that in the temperature range explored here, $T_e(0) \approx T_f(0)$ before the power is turned on since $P_0 < P_{app}$.

The final test from the present work (see Fig. 3(b)) is a demagnetization from $8$ T to $0.32$ T starting at $13.3$ mK and cooling to $1.2 \pm 0.1$ mK (extracted using the method described above), demonstrating a reduction in temperature upon demagnetization by a factor of ten. The other chips perform similar to D, thus substantiating the overall cooling scheme proposed here for reaching submillikelvin temperatures on multiple measurement leads.

Ideally, $T_f$ of the Cu nuclei will be reduced by the same factor $x$ as the $B$-field. To characterize the demagnetization process, we introduce the efficiency $\xi_{B_f} = T_i/T_f \div B_i/B_f$, and find $\xi_{RT} = 88 \pm 3\%$, $\xi_{RT} = 80 \pm 3\%$, $\xi_{RT} = 63 \pm 3\%$, and $\xi_{3RT} = 42 \pm 2\%$. $\xi < 100\%$ signifies nonadiabaticity, presumably due to a spurious heat leak. The lower efficiency at smaller $B_f$ probably reflects the reduction in stored energy of the nuclei. The dominant loss mechanism is presently unclear and under investigation. Parasitic coupling between NRs has been seen from power curves, thus emphasizing one of the many technical challenges of building a parallel NR network.

In conclusion, we have laid out a method that enables the direct and simultaneous cooling of the electrical leads to a nanoscale device. Its strength is that it short circuits the two main bottlenecks of cooling electrons: thermal boundary resistance and electron-phonon coupling. We have addressed the technical challenges of constructing a parallel NR network, yielding a prototype that achieves a base temperature of $\sim 1$ mK. Future efforts will reduce the intrinsic heat leak and address the presently low efficiency (securing temperatures well within the microkelvin regime), further demonstrate ultralow temperatures directly in nanoscale devices, and add an independently controllable magnetic field for the sample.

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