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Superfluid density in strongly underdoped $\mathbf{YBa_2Cu_3O_{6.333}}$

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Current research in high temperature superconductivity focuses on the underdoped cuprates, in the region of the phase diagram where d-wave superconductivity gives way to antiferromagnetism. Important clues for connecting these two states can be found in the evolution of the superfluid density ρ_s with doping. ρ_s is the most fundamental property of a superconductor, measuring its ability to resist perturbations to the phase of the superfluid wavefunction. In addition, the temperature dependence of ρ_s provides a direct probe of the electrical current carried by the quasiparticle excitations. Here we report measurements of ρ_s in ultra-high purity $YBa_2Cu_3O_{6.333}$, over a range of dopings near the boundary of the superconducting phase. We have succeeded in producing samples with sharp superconducting transitions and have harnessed the process of CuO-chain ordering to fulfill a long-held ambition in strongly correlated electron materials — continuous tunability of the carrier density in a *single sample*, with *no* change in cation disorder. We now have preliminary evidence for the production of so-called Ortho III$'$ oxygen order, in which every full CuO chain is separated by two empty chains. The superfluid density measurements are surprising and challenge current theoretical understanding of the underdoped cuprates. ρ_s becomes anomalously small, but there is no vortex unbinding transition. The slope of $\rho_s(T)$ indicates that the current carried by the quasiparticles shrinks smoothly towards zero on approach to the Mott insulator. In addition, the correlation between T_c and ρ_s is sublinear, in disagreement with long-established phenomenology. In the same experiments, microwave spectroscopy of the quasiparticle conductivity has also been used to probe the evolution of the quasiparticle relaxation dynamics on the approach to the superconducting quantum critical point.