A Search for Alternative Electronic Order in the High Temperature Superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ by Scanning Tunneling Microscopy

by

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B.A. (Harvard University) 1999
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Professor J. C. Séamus Davis, Chair
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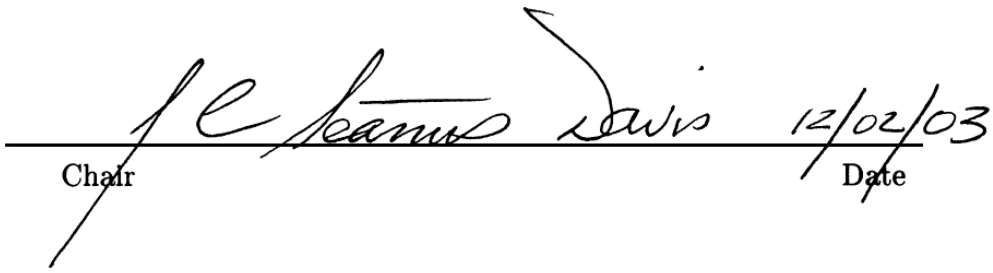

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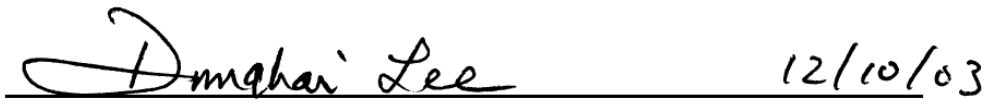

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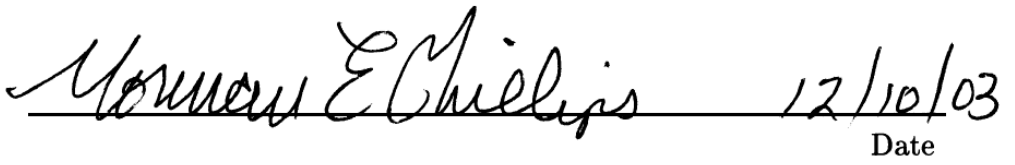

Date

University of California, Berkeley

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Abstract

A Search for Alternative Electronic Order in the High Temperature Superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ by Scanning Tunneling Microscopy

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Doctor of Philosophy in Physics

University of California, Berkeley

Professor J. C. Séamus Davis, Chair

High temperature superconductors were discovered in 1986, but despite a frantic pace of research, resulting in some 10^4 publications per year for the last 16 years, these materials remain poorly understood. Because their electronic structure is both inhomogeneous and highly correlated, a full understanding will require knowledge of quasiparticle properties both in real space and momentum space. These materials also exhibit a rich three-dimensional phase diagram parameterized by temperature, magnetic field, and carrier concentration. Despite numerous theoretical predictions for exotic phases, large regions of parameter space remain unexplored due to experimental limitations.

In this thesis, I will present the first application of Fourier-transform scanning tunneling spectroscopy (FT-STS) to a high temperature superconductor, $Bi_2Sr_2CaCu_2O_{8+\delta}$. For the first time, a single experiment can simultaneously probe the real space and momentum space properties of the quasiparticles. FT-STS shows that the quasiparticles in optimally doped BSCCO at 4.2 K and zero applied field can be described by a *d*-wave superconducting phase, without the need to invoke any exotic order parameters.

I will also present scanning tunneling microscopy (STM) studies of nanoscale features in BSCCO. With such a local probe, we may take advantage of spatial inhomogeneity to gain insight into phases inaccessible to bulk experiments. Crystal inhomogeneity allows the use of single atom defects to probe nanoscale domains of very underdoped BSCCO, sug-

gesting that the electronic structure there is very different from that in the superconducting state. Field inhomogeneity, because BSCCO is a type-II superconductor, allows the study of magnetic vortices, another kind of nanoscale domain where superconductivity is destroyed. Remarkably, in vortices I find evidence of a four-unit-cell periodic "checkerboard"-like electronic structure. This may be the first local glimpse into the structure of the mysterious "pseudogap" phase whose bulk properties are exhibited by all high temperature superconducting materials outside of the superconducting dome.

J C Séamus Davis

Professor J. C. Séamus Davis
Dissertation Committee Chair

To my husband,

Daniel Todd Larson

who can always find a way to make me laugh.

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Acknowledgments

Without the support of many people in many places, this thesis could not have been written. I'd like to thank first of all my emotional support network: my husband Daniel Larson who helped me to laugh through all the obstacles which appeared in my path during graduate school, and my parents Edward & Caroline Hoffman who were always only a phone call away. Graduate school included many frustrations as well as triumphs, but I was lucky to have kind and patient listeners. Thanks also to the running partners and soulmates whom I was so lucky to find during my last year at Berkeley: Jenni Buckley and Joey & David Kimdon.

Thanks to my labmates, who doubled as friends and teachers. To Kyle McElroy for laughs and sarcasm and heated discussions of physics. To Joan Hoffmann for more sarcasm, much empathy in issues both personal and academic, and innumerable chocolate emergency missions. To Kristine Lang and Eric Hudson who have been big sister and big brother to me and have answered many of my dumb questions both about physics and life. To Krishna Swamy who somehow tolerated a year and a half of sharing a lab with me, and retaught me the value of teamwork in science. To Sudeep Dutta, Christian Lupien, Barry Barker, and Rob Johnson for laughter, advice, and shared memories. To Peter Hamel for being smart and independent, and for often doing the dirty work, if not cheerfully, at least capably. To Annie Endozo and Lorraine Sadler for hugs and the comfort and support of another female presence in the physics department at stressful times.

Thanks to many of the people who made my work so much easier. To Anne Takizawa who was always willing to drop everything in order to listen to a problem or find an impossible solution impossibly quickly. To Donna Sakima and Claudia Trujillo who always had smiles and often candy to go along with their frequent help as I struggled to run SWPS and then teach physics 141.

Thanks to the guys in the machine shop who spent so much time giving me advice and critiquing my designs: Tom Pedersen, Dave Murai, Pete Thuesen, Steve Butler, and Marco Ambrosini. Thanks also to Pat Bonnefil in the electronics shop for his advice and patience especially during my last few frantic months.

Thanks to Lynne Pelosi for a few last minute Friday afternoon purchases which wouldn't have gone out on time without special attention. Thanks to Laura Ng for a smile and personal greeting every time I stepped into the physics library. And thanks especially to Eleanor Crump, who knows everything about everything about the workings of Birge and LeConte and always managed to find a few seconds to share her smile, her personal concern

for my well-being, and her tricks for getting emergency construction projects done quickly.

Thanks to Kathryn Moler for her patience as I struggled to complete this thesis while ramping up as a post-doc in her lab. I wish I could have put 100% effort into both responsibilities simultaneously. Thanks also to the rest of the Moler group for their friendship and inclusiveness during this stressful semester.

A special thanks to my surrogate advisors at Berkeley. To Richard Packard who helped me to launch fearlessly into a construction project which turned out to be both harder and more rewarding than I had imagined, and which now forms a cornerstone of my self confidence that I can do anything in lab that I set my mind to. To John Clarke who was endlessly supportive and frequently popped his head into my lab just to check how I was doing at the end of the day. Teaching with him was one of the most rewarding experiences of graduate school: I learned from him new ways to understand solid state physics, but more importantly how to be a clear and patient teacher. Thanks especially to Dung-Hai Lee who provided the brilliant theoretical insights behind the most exciting discoveries I was fortunate enough to play a role in during graduate school. His patience in explaining simple concepts was wonderful, and his enthusiasm for beautiful explanations was absolutely contagious. I hope that we can continue to work together for a long time.

Finally, by far my biggest debt of gratitude is to my advisor, Séamus Davis. Without him, none of this would be possible. We have at times tried each other's patience, but I have again and again benefited from his calm and imperturbability. He has taught me quite a lot of physics, but perhaps even more importantly he has taught me a whole way of thought: how to break a goal down and think both tactically and strategically about it, then just get the job done.

I would also like to acknowledge the Fannie and John Hertz Foundation, which provided me with two years of generous financial support during graduate school.

Jennifer E. Hoffman

Curriculum Vitae

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Education

Dec. 2003	Ph.D. Physics (experimental condensed matter), University of California, Berkeley
May 2001	M.A. Physics, University of California, Berkeley
June 1999	B.A. Physics, Magna Cum Laude, Highest Honors in Physics, Harvard University

Research and Teaching Positions

2003–04	Stanford University, Postdoctoral Research Associate, K. A. Moler Group
1999–2003	UC Berkeley, Graduate Student Research Assistant, J. C. Davis Group
1999, 2002–03	UC Berkeley, Graduate Student Instructor, Physics Department
Summer 1999	UC Berkeley and Fermi National Accelerator Laboratory, Graduate Student Research Assistant, Y. K. Kim Group
1996–98	Harvard University, Research Assistant, E. Mazur Group

Fellowships and Awards

2003	Outstanding Graduate Student Instructor, University of California, Berkeley
2001–03	Hertz Graduate Fellowship, Fannie & John Hertz Foundation
2001	NSF Graduate Fellowship (declined), National Science Foundation
2001	National Defense Science and Engineering Graduate Fellowship (declined), Department of Defense
2001	Mentored Research Award (declined), University of California
1999–01	Physics Department Fellowship, University of California, Berkeley
1998–99	Goldwater Fellowship, Barry Goldwater Foundation
1996–99	Robert Byrd Scholarship, State of Connecticut Department of Higher Education
1996	National Merit Scholarship, National Merit Scholarship Corporation

Publications

[1] "Relating atomic-scale electronic phenomena to wave-like quasiparticle states in superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$," K. McElroy, R.W. Simmonds, J.E. Hoffman, D.-H. Lee, J. Orenstein, H. Eisaki, S. Uchida, J.C. Davis, *Nature* **422**, 592 (2003).

[2] "Imaging quasiparticle interference in $Bi_2Sr_2CaCu_2O_{8+\delta}$," J.E. Hoffman, K. McElroy, D.-H. Lee, K.M. Lang, H. Eisaki, S. Uchida, J.C. Davis, *Science* **297**, 1148 (2002).

[3] "A four unit cell periodic pattern of quasi-particle states surrounding vortex cores in $Bi_2Sr_2CaCu_2O_{8+\delta}$," J.E. Hoffman, E.W. Hudson, K.M. Lang, V. Madhavan, H. Eisaki, S. Uchida, J.C. Davis, *Science* **295**, 466 (2002).

[4] "Imaging the granular structure of high-T_c superconductivity in underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$," K.M. Lang, V. Madhavan, J.E. Hoffman, E.W. Hudson, H.Eisaki, S. Uchida, J.C. Davis, *Nature* **415**, 412 (2002).

Invited Talks

- "Scanning Tunneling Spectroscopy of High Temperature Cuprate Superconductors." Condensed Matter Seminar, Caltech Physics Department, 23 May 2003.
- "Wavefunction Imaging in High Temperature Cuprate Superconductors." Condensed Matter Seminar, University of California, Los Angeles Physics Department, 21 May 2003.
- "Wavefunction Imaging in High Temperature Cuprate Superconductors." Condensed Matter Seminar, University of California, Berkeley Physics Department, 28 April 2003.
- "Wavefunction Imaging in High Temperature Cuprate Superconductors." Yale University Applied Physics Department, 17 April 2003.
- "Wavefunction Imaging in High Temperature Cuprate Superconductors." Harvard University Physics Department, 3 April 2003.
- "Quasiparticle Interference in $Bi_2Sr_2CaCu_2O_{8+\delta}$." Aspen Center for Physics, conference on Condensed Matter Physics: Complex Quantum Order, Aspen, Colorado, 11 February 2003.
- "Imaging Quasiparticle Interference in $Bi_2Sr_2CaCu_2O_{8+\delta}$." International Conference on Physics and Chemistry of Molecular and Oxide Superconductors (MOS), Hsinchu, Taiwan, 14 August 2002.
- "Incommensurate Conductance Modulations from Quasiparticle Scattering in $Bi_2Sr_2CaCu_2O_{8+\delta}$." Stanford University Applied Physics Department, 15 July 2002.
- "Checkerboards in $Bi_2Sr_2CaCu_2O_{8+\delta}$." Stanford University Applied Physics Department, 28 May 2002.
- "Imaging Quasiparticle Interference in $Bi_2Sr_2CaCu_2O_{8+\delta}$." Condensed Matter Seminar, M.I.T. Physics Department, 17 April 2002.
- "Introduction to the Scientific Community." MATHCOUNTS National Competition, Washington, D.C., May 1998.
- "Networking for Student Success." College Board National Forum, New York, NY, November 1996.

Research

- **UHV-compatible, Scanning Tunneling Microscope Construction, J.C. Davis Group, Physics Department, UC Berkeley, 2001-2003.** I have designed, purchased, assembled, debugged, and operated a cryogenic high-resolution STM system, which achieved atomic resolution on the cuprate superconductor $Bi_2La_xSr_{2-x}Cu0_{4+\delta}$.
- **Scanning Tunneling Microscopy of High-T_c Superconductors, J.C. Davis Group, Physics Department, UC Berkeley, 2000-2003.** I have used a 4 K scanning tunneling microscope with sub-Ångstrom resolution to probe the local density of states of $Bi_2Sr_2CaCu_2O_{8+\delta}$. Specific studies have included: the effect of Ni and Zn impurities and their relation to local superconducting gap magnitude, electronic structure of magnetic vortices, and long-range quasiparticle interference patterns due to disorder scattering. I have applied the technique of Fourier-transform scanning tunneling spectroscopy for the first time to the cuprates, using an STM to provide simultaneous real-space and momentum-space information about the quasiparticles.
- **Branching Fractions in J/Ψ Production, Fermi National Laboratory, Summer 1999.** I wrote code to analyze over one million potential J/Ψ events to determine what fraction of the actual J/Ψ particles resulted from decay of a B-meson.
- **Femtosecond Laser Catalysis of Chemical Reactions on a Platinum Surface, E. Mazur Group, Physics Department, Harvard University, Summer 1996-Winter 1998.** Using a femtosecond laser in a UHV chamber I studied reactions of carbon, oxygen, methyl iodide, and benzene on a platinum surface.

Community Service

- Coordinator, Society for Women in Physical Sciences, UC Berkeley, 2000-2001.
- Mentor, Society for Women in Physical Sciences, UC Berkeley, 1999-2000.
- Counselor, Research Science Institute, MIT, Summer 1997.