Novel superconducting states in actinides and other anisotropic superconductors.
Charles C Agosta - PI July 1, 2005 - Jan 31, 2011
Clark University, 950 Main Street, Worcester, MA 01610
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Final Report

The goal of this grant was to use a low temperature high magnetic field apparatus, coupled with a tunnel diode oscillator (TDO) penetration depth measurement system to investigate novel correlated electron phases in anisotropic superconductors. This grant resulted in three distinct scientific advances, the most important being the discovery of an inhomogeneous superconducting state first predicted over 40 years ago, and a number of broader impacts. A synopsis of the products of the grant is that 4 papers were published and an experimental program was established that continues to produce more data. As an example we published a paper in 2012 with the most extensive experimental results on the subject of inhomogeneous superconductors ever published. The broader impacts are that two graduate students received PhDs as a result of this grant, and a major US high magnetic field facility was rebuilt.

The papers published directly due to the activity funded by the grant are:

William A. Coniglio, Laurel E. Winter, Kyuil Cho, and C. C. Agosta, B. Fravel, and L. K. Montgomery, "Unusual phase diagram and FFLO signature in λ -(BETS) $_2$ GaCl $_4$ from RF penetration depth measurements," , *Phys. Rev. B*, **83**, 224507 (2011).
<http://prb.aps.org/abstract/PRB/v83/i22/e224507>

K. Cho, H. Kim, M. A. Tanatar, Y. J. Song, Y. S. Kwon, W. A. Coniglio, C. C. Agosta, A. Gurevich, and R. Prozorov, "Anisotropic upper critical field and possible Fulde-Ferrel-Larkin-Ovchinnikov state in the stoichiometric pnictide superconductor LiFeAs," *Phys. Rev. B*, **83**, 060502(R) (2011). Rapid Communication
<http://prb.aps.org/abstract/PRB/v83/i6/e060502>

T. Coffey, C. Martin, C. C. Agosta, and M. Tokumoto, "A bulk 2D Pauli Limited Superconductor," *Phys. Rev. B*, **82**, 212502 (2010).
<http://prb.aps.org/abstract/PRB/v82/i21/e212502>

K. Cho, B. E. Smith, W. A. Coniglio, L. E. Winter, C. C. Agosta, and J. A. Schlueter, "Upper critical field study in the organic superconductor β "- (ET) $_2$ SF $_5$ CH $_2$ CF $_2$ SO $_3$: Possibility of the Fulde-Ferrell-Larkin-Ovchinnikov state," *Phys. Rev. B*, **79**, 220507(R) (2009). (picked as an Editor's Suggestion)
<http://link.aps.org/doi/10.1103/PhysRevB.79.220507>

A subsequent paper published after the end of the grant but continuing the same scientific thread and using the apparatus developed during the grant.

C. C. Agosta, J Jin, B. E. Smith, K. Cho, W. A. Coniglio, I. Mihut, and C. Martin, S. W. Tozer, T. P. Murphy, and E. C. Palm, J. A. Schlueter, "The FFLO State in κ -(BEDT-TTF)₂Cu(NCS)₂ and A Semi-Empirical Method to Determine the Pauli-Limiting Field," *Phys. Rev. B*, **85**, 214514 (2012).

<http://link.aps.org/doi/10.1103/PhysRevB.85.214514>

The graduate students who were funded by this grant were:

Kyuil Cho, now a postdoctoral associate at the DOE funded AMES research laboratory on the campus of the University of Iowa.

William A Coniglio. A postdocotral associate at the National High Magnetic Field Laboratory in Tallahassee. He is spending part of his time at the pulsed magnetic field laboratory in Los Alamos, a partially DOE supported laboratory.

The discovery of inhomogeneous superconductors is important because they were predicted 42 years ago, and their existence relies on subtle aspects of the understanding of the microscopic theory of the superconducting state. Showing that this exotic superconducting state exists, and measuring its stability tests the limits of the validity of microscopic superconducting theory, and will help predict or even design future superconducting systems. In particular, recent studies have shown that many superconductors can exist with iron as one of the elements. Iron, intrinsically magnetic, was always thought to destroy superconductivity. Inhomogeneous superconductors have tunable magnetic properties that will help us understand the reasons that iron based superconductors, the pnictides, exist. In a similar way organic conductors are very anisotropic, similar to the cuprates. In contrast to the cuprates they are intrinsically clean, that is the quasiparticles have long mean free paths, as compared to the cuprates. Therefore, although the materials we study are very different than the pnictides, or the cuprates, the discovery and detailed measurements of inhomogeneous organic superconductors is a useful to further the understanding of recent superconducting theory.

An early goal of the grant was the development of a high pressure gas sample cell that could be used in pulsed magnetic fields. The idea is to use helium gas to change the pressure in the cell and vary the sample properties, such as the lattice constants and carrier density. Using helium gas allows us to change the sample properties without warming the sample from cryogenic temperatures. The difficulty was making the cell out of non-conductive materials so that we could use it in pulsed magnetic fields, up to 50 tesla in our case. We used ceramic and plastic materials, eventually creating a cell out of Parmax that was able to reach 9000 psi. The weak point was the connection to the helium capillary. We believe 15,000 psi will eventually be possible. The cells contained a 0.6 mm TDO coil for measuring the properties of samples.

During the duration of this grant our building was renovated, which made it necessary to move the laboratory out to a temporary location and back to its previous location over a period of nine months. Adding time for the breakdown and reinstallation of the laboratory and failure of the integrity of the new floor, our main apparatus, our pulsed magnetic field, was not available for about a year. During this time we developed the pressure cells and rebuilt parts of the pulsed magnetic field. All of the digital control electronics were updated with microcontrollers to make the system more robust and versatile. Also during this time, Si Foner donated the contents of his laboratory at MIT to us as he went into retirement. Dr. Foner had arguably the world's leading pulsed magnetic field laboratory, he held the magnetic field record for many years, and having his magnets to analyze and having his advanced high strength magnet wire has already given us access technology that is very hard to recreate.

The apparatus that was rebuilt in our laboratory as part of the grant is unique and powerful. In addition to producing the highest magnetic field outside of Los Alamos, 51 tesla, experiments can be preformed down to 400 mK, and probably lower with technology developed during the grant but not yet tested. Just as important, the software and control of the system was optimized to maximize the data throughput. As an example, in one experiment 195 magnet sweeps in the range of 10 to 50 tesla were done in a period of 9 days, averaging over 20 magnet sweeps a day. This level of data collection is not possible with a dc magnet. In addition, in our system only the sample needs to be cooled with helium, because our magnet is cooled by liquid nitrogen. In these nine days of experiments only 100 liters of liquid helium were used.

The tunnel diode oscillator system that we use for rf penetration depth measurements was also improved during this grant. The signal to noise ratio was reduced by a factor of 10. A good signal to noise ratio is essential to picking out the subtle phase transitions that occur in many condensed matter systems, and rf penetration is very compatible with pulsed magnetic fields. Along with its sensitivity to many physical properties, such as vortices, the London penetration depth, normal skin depth, etc., the tunnel diode system is compatible with pulsed fields because it tends to run at a frequency much higher than the electrical noise produced by the pulsed magnetic field. Therefore it is useful for many kinds of high magnetic field experiments. These attributes have made rf penetration a mainstay of the national pulsed magnetic field facility at LANL.

During this grant we discovered an exotic superconducting state, predicted over 40 years ago, and showed that it will help understand the pairing mechanism of superconductors with magnetic ions. We built a unique and powerful apparatus for studying condensed matter systems at high magnetic fields, and shared the technology with a national laboratory. During this time we also educated graduate and undergraduate scientists.