CHARACTERIZATION OF SUPERCONDUCTING AND MAGNETIC MATERIALS WITH MUON SPIN ROTATION AND NEUTRON SCATTERING

COMBINED

Progress Report
March 1996 - August 1997
&
Final Report
June 1988 - August 1997

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Final Report
June 1988 - August 1997

Research Activities

This report represents the culmination of over nine years of research activity in the study of superconducting and magnetically ordered materials using the muon spin rotation (μSR) and neutron scattering techniques on the part of physics faculty and students of Virginia State University and supported by the United States Department of Energy through its Division of Basic Energy Sciences/Materials Sciences Division. Because all the activities that took place up until March 1996 have been covered in previous annual reports, this final report includes only a brief overview of activities prior to that date, and concentrates on the period from March 1996 through August 1997.

The primary activity undertaken in this project has been studies of high-temperature superconductors and their close chemical relatives (which, for the most part, display anti-ferromagnetic or spin glassy behavior at sufficiently low temperatures) with the μSR technique. These experiments extend from early work done with a relatively primitive muon beam at the AGS of Brookhaven National Laboratory and large polycrystalline samples of the earliest known high-Tc materials to studies of very small high-purity single crystals of the best high-Tc materials currently available using the highest quality surface muon beams and specially-designed low-background spectrometers at the Tri-University Meson Facility (TRIUMF) in the past three years.

During the period since the last annual report five μSR experiments were done at TRIUMF with DOE support (plus two more with new support from the Air Force Office of Scientific Research). A study of single-crystal high-temperature superconductors was done in July 1996. The VSU team on this experiment consisted of C.E. Stronach, D.R. Noakes, and graduate student M.F. White, Jr., and it was done in collaboration with the University of British Columbia team headed by J.H. Brewer. A study of the quasicrystal materials Gd₅Mg₄Zn₅₀ and Tb₅Mg₄Zn₅₀ was done by D.R. Noakes in collaboration with G.M. Kalvius of the Technical University of Munich and R. Wäppling of Uppsala University (Sweden) during the first week of December 1996. During the second week of December 1996 a study of the cryocrystals CH₄ and CF₄ (both in the solid phase) was done by D.R. Noakes in collaboration with S. Storchak of Moscow State University and J.H. Brewer of the University of British Columbia. A study of high-Tc superconductors (Y₀.₈Ca₀.₂-123 crystal ,optimally doped; Y₀.₈Ca₀.₂Cu₃O₆₆, underdoped; YBa₂Cu₄O₈ ) was done at TRIUMF during the third week of December 1996 by C.E. Stronach and D.R. Noakes, plus C. Bernhard of the Max...
Planck Institute - Stuttgart and M. Heuberger, a graduate student at the University of Konstanz. In February 1997 Stronach and Noakes joined A. Kratzer of the Technical University of Munich and R. Wäppling in a study of GdMn$_2$, hexagonal CeCuSn, and the spinel Mn$_{0.4}$Zn$_{0.6}$Fe$_2$O$_4$.

Thesis Projects Completed by Students

Since the last annual report three VSU graduate students have completed their M.Sc. Degrees with thesis projects done under the ægis of this DOE-supported program:

- **Jacob R. Brankley** (May 1996): *Muon Spin Relaxation Studies of Praseodymium Cuprate High-Temperature Superconductors*
- **Muhammad M.K. Sarker** (May 1997): *Muon Spin Relaxation Study of Cd$_{1-x}$Mn$_x$Te*
- **Xuewen Wan** (May 1997): *ZF-μSR Study of the Interplay between Antiferromagnetism and Superconductivity in Low-Carrier-Density Regime Y$_{1-x}$Ca$_x$Ba$_2$Cu$_4$O$_6$.*

Previously, thirteen VSU graduate students completed their M.Sc. degrees under the advisement of Stronach and Noakes, ten of them with DOE support:

- **Howard P. Cooke** (May 1992): *Muon Spin Rotation Studies of YBa$_2$Cu$_3$O$_7$ Doped with Iron*
- **Melvin U. Spurlock** (May 1992): *Muon Spin Relaxation Studies of Titanium Hydride*
- **Keith C. Hepburn-Wiley** (July 1992): *Muon Spin Rotation Studies of YBa$_2$Cu$_3$O$_7$ Doped with Nickel and Zinc*
- **Michael R. Davis** (May 1993): *Muon Spin Rotation Study of Magnetic Ordering in Nd$_{2-x}$Ce$_x$CuO$_{4-y}$*
- **Peter E. Radcliff, Jr.** (May 1993): *Muonium and Muonated Radical Formation in Pure and Doped Fullerenes*
- **Adnan N. Ismail** (July 1993): *Muon Spin Relaxation Studies of Quasicrystals*
• Randolph S. Cary (May 1995): Development of Programs in FORTRAN to Analyze Muon Spin Rotation Data

• Vaughn B. McMullen (July 1995): Simulation of Magnetic Field Distributions in Dilute Materials

• Timbangen Sembiring (July 1995): Studies of the Flux-Penetration State in High-
  $T_c$ Superconducting Materials Containing Bismuth and Mercury by Muon Spin Relaxation

• Mary-Ann Blankson-Mills (July 1995): Muon Spin Rotation Studies of Superconducting Doped (Y,Ca)Ba$_2$Cu$_3$O$_{6+\delta}$ Compounds

• Hassan J. Llewellyn (May 1993, support from a NASA grant): Photomultiplier Tests for the CEBAF Large Acceptance Spectrometer Time-of-Flight System

• Peter Chow (July 1993, support from a NASA grant): Track Finding with Neural Networks

• Jane G. Fowler (July 1995, support from a NASA grant): Analysis of the Spectrum of De-excitation Gamma Rays Following the Interaction of 720-MeV Alpha Particles with Calcium Nuclei

Recent Publications

Since the submission of the last annual report the following papers have been published by the VSU investigators supported by this program, with their collaborators from other institutions (a cumulative list of all publications for the duration of the support period, June 1988 through August 1997, is included as an appendix to this report):

The influence of impurities and alloying in the Kondo semimetal CeNiSn as seen by $\mu$SR
Texture effect on vortex-state TF-μSR in Bi-2223 high-$T_c$ superconductors


Hyperfine Interactions 105 (1997) 95.

A μSR study of the superconducting condensate density in high-temperature superconductors


Hyperfine Interactions 105 (1997) 139.

Muons and muonium in Zn spinels


Concentration dependence of critical scattering from Cr(V) alloys above the Néel temperature

D.R. Noakes, E. Fawcett and T.M. Holden


Magnetic field dependence of the London penetration depth in the vortex state of YBa$_2$Cu$_3$O$_{6.95}$


μSR magnetic response of CeNiSn on impurity content


μSR studies of magnetic correlations in Pt- and Cu-doped CeNiSn


μSR studies of the doping dependence of the magnetic response of the Kondo semimetal CeNiSn


μSR measurement of the fundamental length scales in the vortex state of YBa$_2$Cu$_3$O$_{6.60}$


Physical Review Letters, accepted for publication.

The following papers were co-authored by members of the VSU group that received support from this DOE grant. These papers are not on topics relevant to the grant-supported research and the work done by the VSU personnel was not supported with funds from this grant (a small grant from NASA did provide support). They are listed to provide completeness in terms of the research activities of the involved VSU personnel:

Heavy fragment production cross sections from 1.05-GeV/nucleon $^{56}$Fe in C, Al, Cu, Pb and CH$_2$ targets


Pion-nucleus single charge exchange induced by stopped negative pions


Several additional papers based on work supported by this grant from the DOE are in the process of being written. They will be sent to the DOE in supplemental reports as they are accepted for publication.
Summary

Several major accomplishments have resulted from this work done by VSU investigators (and their collaborators) and supported by the DOE. Among the most noteworthy are:

- The results of a number of the μSR experiments done on high-$T_c$ superconductors and their close chemical relatives provided much of the early evidence for a d-wave component to the condensate electron pairs in these materials, and have provided additional evidence of an exotic nature to the pairing mechanism.

- The close relation between high-$T_c$ superconductivity and antiferromagnetism has been reconfirmed and found to be a general phenomenon related to these materials.

- Industrial texturing processes used in the fabrication of Bi-2223-based SC cables have been shown to alter the London penetration depth of these materials.

- The formation of muonium and muonic radicals in fullerene compounds has been observed and used to confirm properties of this new class of materials, including the trapping of impurity species in the $C_{60}$ cages.

- Bizarre magnetic effects have been observed in quasicrystal materials such as $I$-Al-Mn-Si, $i$-Tb$_6$Mg$_{42}$Zn$_{30}$ and $i$-Gd$_6$Mg$_{42}$Zn$_{30}$, which have not yet been fully explained.

- Through neutron-scattering measurements it has been found that an unexpected and as yet unexplained discontinuity exists in the incommensurability of Cr(V) and Cr(Re) alloys.

- Through an associated DOE grant program for instrumentation, VSU received funds to purchase a dilution refrigerator, which has been set up at TRIUMF through a memorandum of understanding between the laboratory and VSU, and which will serve both VSU investigators and other TRIUMF users in ultra-low temperature studies.

- With support from this program, thirteen VSU graduate students did their M.S. thesis research on these research topics. This included participation in their thesis experiments at major research facilities (the Alternating Gradient Synchrotron at Brookhaven National Laboratory and the Tri-University Meson Facility) where they worked with both their advisers and the research staff at these laboratories, and were...
Future Work

Fortunately, this research group at Virginia State University has successfully solicited two research grants this past year, one from the Air Force Office of Scientific Research (AFOSR), the other from the Ballistic Missile Defense Organization (BMDO). The AFOSR grant supports studies of superconducting and magnetically-ordered materials with the μSR and neutron-scattering techniques, thus providing a seamless transition from DoE to AFOSR support. The BMDO grant will support fabrication of novel nanoengineered materials by the use of mechanical milling, and will provide funds to bring Dr. A.S. Arrott (recently retired from Simon Fraser University) to VSU as a part-time Distinguished Senior Research Professor.

The problems that will be of primary scientific concern relative to the areas of research supported by the DoE appear to be (1) a survey of underdoped single crystals of high-$T_C$ materials in the search for evidence for or against the SO(5) theory of superconductivity and antiferromagnetism, (2) measurements of penetration depths and searches for phase transitions such as 2D-3D in overdoped high-$T_C$ materials; (Both of these studies should help pin down the pairing mechanism for high-temperature superconductivity.) (3) determination of the incommensurability gap in Cr and its alloys, to be studied with neutron scattering. New areas of research we hope to develop include the nanoengineered materials mentioned previously, plus studies of fatigue and adhesion in both magnetic and non-magnetic materials. We also hope, should funding become available, to organize a small theory group that will study various aspects of superconductivity and magnetic ordering.

Respectfully submitted,

Carey E. Stronach, Ph.D.  
Director & Professor of Physics  
September 30, 1997
Papers Published with Full or Partial US DOE Support

μSR Measurement of the Fundamental Length Scales in the Vortex State of $\text{YBa}_2\text{Cu}_3\text{O}_{6.60}$
Physical Review Letters, accepted for publication.

Magnetic Field Dependence of the London Penetration Depth in the Vortex State of $\text{YBa}_2\text{Cu}_3\text{O}_{6.95}$

A Muon Spin Rotation Study of the Superconducting Condensate Density in High-Temperature Superconductors
Hyperfine Interactions 105 (1997) 139.

Texture Effect on Vortex-State Transverse-Field $\mu^+\text{SR}$ in Bi-2223 High-$T_c$ Materials
Hyperfine Interactions 105 (1997) 95.

Magnetic Penetration Depth and Condensate Density of Cuprate High-$T_c$ Superconductors Determined by Muon-Spin Rotation Experiments

Anisotropy and Dimensional Crossover of the Vortex State in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ Crystals

Moving Maglev Underground
C. E. Stronach

$\mu^+\text{SR}$ Study of the Effect of Zn Substitution on Magnetism in $\text{YBa}_2\text{Cu}_3\text{O}_x$

$\mu^+\text{SR}$ Study of Zn Substitution in $\text{YBa}_2\text{Cu}_3\text{O}_x$; Is Hole Dynamics Affected?
Penetration Depths and Pinning in (BiPb)-2212 and (TlPb)-1212 - Universal Correlations Revisited
Hyperfine Interactions 86 (1994) 505.

Evidence for Endohedral Muonium in K₂C₆₀ and Consequences for Electronic Structure

Observation of Magnetic Order in the Double-Layer System La₂MCu₂O₇+δ (M = Ca, Sr)

Formation of Muonium and a Muonic Radical in Fullerene

Impurity Species Dependence of Zero-Field Muon Spin Rotation in Chromium Alloys
D.R. Noakes, E. Fawcett, E.J. Ansaldo, C. Niedermayer, C.E. Stronach

Formation of Muonium and a Muonic Radical in Fullerene

Superconductivity and Magnetic Order in Superoxygenezated La₂MCu₂O₇+δ

Muonium in Fullerite
E.J. Ansaldo, C. Niedermayer, C.E. Stronach

Site of the Positive Muon in YBa₂Cu₃O₇
Hyperfine Interactions 63 (1990) 177.

Magnetism in Electron-Doped Copper Oxides
Hyperfine Interactions 63 (1990) 311.
The Superconducting Properties of \( \text{YBa}_2(\text{Cu}_{1-x}M_x)_3\text{O}_y \) for \( M = \text{Zn} \) and \( \text{Ni} \)
Hyperfine Interactions 63 (1990) 81.

Superconductivity and Magnetic Ordering in \( \text{YBa}_2(\text{Cu}_{1-x}\text{Fe}_x)_3\text{O}_y \)

Magnetic Ordering in \( \text{Nd}_2\text{Ce}_n\text{CuO}_6 \)
Hyperfine Interactions 63 (1990) 305.

Magnetic Order and Electronic Phase Diagrams of Electron-Doped Copper Oxide Materials

\( \mu^+ \text{SR} \) Studies of Flux Mobility in the Mixed State of \( \text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8 \)

Muon Motion in Titanium Hydride
J.R. Kempton, K.G. Petzinger, W.J. Kossler, H.E. Schone, C.E. Stronach

Universal Correlation between \( T_c \) and \( n/m^* \) (Carrier Density over Effective Mass) in High-\( T_c \) Cuprate Superconductors

Coexisting Static Magnetic Ordering and Superconductivity in \( \text{CeCu}_2\text{Si}_2 \) Found by Muon Spin Relaxation

\( \mu^+ \text{SR} \) Studies on High-\( T_c \) Superconductivity
Absence of Magnetic Order in (Ba,K)BiO₃

Static Magnetic Ordering of CeCu₂Si₂ Found by Muon Spin Relaxation

Comparison between Muon Spin Rotation and Neutron Scattering Studies on the 3-Dimensional Magnetic Ordering of La₂CuO₄ₓ

Systematic Variation of Magnetic-field Penetration Depth in High-Tc Superconductors Studied by Muon Spin Relaxation


Addendum to Final Report
June 1988 - August 1997

Characterization of Superconducting and Magnetic Materials
with Muon Spin Relaxation and Neutron Scattering

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Additional Publications

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μSR measurement of the fundamental length scales in the vortex state of \( \text{YBa}_2\text{Cu}_3\text{O}_{6.60} \)


Anomalous zero-field muon spin relaxation in highly disordered magnets

D.R. Noakes and G.M. Kalvius

Invited paper: Spin-density-wave antiferromagnetism in the chromium system II: critical and high-temperature fluctuations, spin-glass behavior in \( \text{Cr(Mn)} \)

E. Fawcett, P.C. de Camargo, V.Y. Galkin and D.R. Noakes

Nature of the triple point in chromium alloys: mode-softening of the incommensurate spin density wave.

D.R. Noakes, E. Fawcett, B.J. Sterlnieb, G. Shirane and J. Jankowska