1. REPORT DATE (DD-MM-YYYY) 03-02-2016
2. REPORT TYPE Final Report
3. DATES COVERED (From - To) 15-Aug-2012 - 14-Feb-2014
4. TITLE AND SUBTITLE Final Report: Acquisition of He3 Cryostat Insert for Experiments on Topological Insulators.

5a. CONTRACT NUMBER W911NF-12-1-0359
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER 611103
5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

6. AUTHORS Nai Phuan Ong

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES Princeton University
   PO Box 0036
   87 Prospect Avenue - 2nd floor
   Princeton, NJ 08544 -2020

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
   U.S. Army Research Office
   P.O. Box 12211
   Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S) ARO
11. SPONSOR/MONITOR'S REPORT NUMBER(S) 61458-PH-RIP.4

12. DISTRIBUTION AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
    The award enabled the PI to acquire a complete cryogenic system with a 9-Tesla superconducting magnet. The equipment facilitated transport experiments on topological insulators and Dirac and Weyl semimetals. These experiments resulted in several notable achievements and novel findings during the period 2013-2015. These include successful tuning of the chemical potential by liquid ion gating in Bi2Te2Se to access the n = 1 Landau level, discovery of non-saturating magnetoresistance in WTe2, initial findings on the chiral anomaly in the Dirac semimetal Na3Bi. Recently, the cryogenic system has been used for Fraunhofer measurements on ferromagnets.

15. SUBJECT TERMS Cryogenic equipment with 9 Tesla magnet, low temperature experiments

16. SECURITY CLASSIFICATION OF: 
   a. REPORT UU 
   b. ABSTRACT UU 
   c. THIS PAGE UU 

17. LIMITATION OF ABSTRACT

18. NUMBER OF PAGES

19a. NAME OF RESPONSIBLE PERSON N. Phuan Ong
19b. TELEPHONE NUMBER 609-258-4347
Report Title
Final Report: Acquisition of He3 Cryostat Insert for Experiments on Topological Insulators.

ABSTRACT
The award enabled the PI to acquire a complete cryogenic system with a 9-Tesla superconducting magnet. The equipment facilitated transport experiments on topological insulators and Dirac and Weyl semimetals. These experiments resulted in several notable achievements and novel findings during the period 2013-2015. These include successful tuning of the chemical potential by liquid ion gating in Bi2Te2Se to access the n = 1 Landau level, discovery of non-saturating magnetoresistance in WTe2, initial findings on the chiral anomaly in the Dirac semimetal Na3Bi. Recently, the cryogenic system has been used for Fraunhofer measurements on ferromagnet-superconducting SQUID junctions.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper


02/03/2016 2.00 Mazhar N. Ali, Jun Xiong, Steven Flynn, Jing Tao, Quinn D. Gibson, Leslie M. Schoop, Tian Liang, Neel Haldolaarachchige, Max Hirschberger, N. P. Ong, R. J. Cava. Large, non-saturating magnetoresistance in WTe2, Nature, (09 2014): 205. doi:


TOTAL: 3

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:
Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received  Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received  Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received  Paper

TOTAL:
<table>
<thead>
<tr>
<th>Number of Manuscripts:</th>
<th>Books</th>
</tr>
</thead>
<tbody>
<tr>
<td>Received</td>
<td>Book</td>
</tr>
</tbody>
</table>

TOTAL:

<table>
<thead>
<tr>
<th>Received</th>
<th>Book Chapter</th>
</tr>
</thead>
</table>

TOTAL:

<table>
<thead>
<tr>
<th>Patents Submitted</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Patents Awarded</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Awards</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Graduate Students</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>NAME</th>
<th>PERCENT_SUPPORTED</th>
</tr>
</thead>
</table>

FTE Equivalent:
Total Number:

<table>
<thead>
<tr>
<th>Names of Post Doctorates</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>NAME</th>
<th>PERCENT_SUPPORTED</th>
</tr>
</thead>
</table>

FTE Equivalent:
Total Number:
Names of Faculty Supported

<table>
<thead>
<tr>
<th>NAME</th>
<th>PERCENT_SUPPORTED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FTE Equivalent:
Total Number:

Names of Under Graduate students supported

<table>
<thead>
<tr>
<th>NAME</th>
<th>PERCENT_SUPPORTED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FTE Equivalent:
Total Number:

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ...... 0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields: ...... 0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields: ...... 0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale): ...... 0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering: ...... 0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ...... 0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: ...... 0.00

Names of Personnel receiving masters degrees

<table>
<thead>
<tr>
<th>NAME</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total Number:

Names of personnel receiving PHDs

<table>
<thead>
<tr>
<th>NAME</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total Number:

Names of other research staff

<table>
<thead>
<tr>
<th>NAME</th>
<th>PERCENT_SUPPORTED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FTE Equivalent:
Total Number:

Sub Contractors (DD882)
Inventions (DD882)

Scientific Progress

Acquisition of the cryogenic system with a 9-Tesla superconducting has provided a strong boost to the productivity of Ong’s group at Princeton in their research on the transport properties of topological insulators and Dirac and Weyl semimetals (supported by Army Research Office Grants W911NF-12-1-0461 and W911NF-11-1-0379). The three main findings facilitated by the cryogenic system are:

i) In-situ low-temperature tuning of the chemical potential in the topological insulator using ionic liquid gating. The intense electric field applied results in band bending that moves the Fermi energy of the surface states. In a 14-Tesla magnetic field, the $n = 1$ Landau level was accessed. The index plot determined the pi-phase shift of the quantum oscillations expected from Dirac states.

ii) A very large magnetoresistance (MR) was discovered in the candidate topological material WTe2. At 4 Kelvin, the MR increased as $B^2$ to over a million percent showing no sign of saturation up to fields of 65 Tesla. This is possibly the first non-saturating MR observed to such high fields. It possibly arises because of the perfect compensation (electron and hole populations) protected by topological properties of the electronic bands.

iii) In the Dirac semimetal Na3Bi, a very unusual negative, longitudinal magnetoresistance was observed at 4 K. By varying the field direction relative to the applied current it was confirmed that the LMR is the long-sought chiral anomaly (predicted in 1983). The anomaly arises from the mixing between Weyl states of opposite chiralities induced by applying parallel magnetic and electric fields. It was first discovered theoretically in the study of the rapid decay of neutral pion particles.

Technology Transfer
Acquisition of the cryogenic system with a 9-Tesla superconducting has provided a strong boost to the productivity of Ong's group at Princeton in their research on the transport properties of topological insulators and Dirac and Weyl semimetals (supported by Army Research Office Grants W911NF-12-1-0461 and W911NF-11-1-0379). The three main findings facilitated by the cryogenic system are

i) In-situ low-temperature tuning of the chemical potential in the topological insulator using ionic liquid gating. The intense electric field applied results in band bending that moves the Fermi energy of the surface states. In a 14-Tesla magnetic field, the n = 1 Landau level was accessed. The index plot determined the pi-phase shift of the quantum oscillations expected from Dirac states.

ii) A very large magnetoresistance (MR) was discovered in the candidate topological material WTe2. At 4 Kelvin, the MR increased as B^2 to over a million percent showing no sign of saturation up to fields of 65 Tesla. This is possibly the first non-saturating MR observed to such high fields. It possibly arises because of the perfect compensation (electron and hole populations) protected by topological properties of the electronic bands.

iii) In the Dirac semimetal Na3Bi, a very unusual negative, longitudinal magnetoresistance was observed at 4 K. By varying the field direction relative to the applied current it was confirmed that the LMR is the long-sought chiral anomaly (predicted in 1983). The anomaly arises from the mixing between Weyl states of opposite chiralities induced by applying parallel magnetic and electric fields. It was first discovered theoretically in the study of the rapid decay of neutral pion particles.

iv) Recently, the cryogenic station has enabled a new series of experiments which explores SQUID junctions in which a supercurrent is injected from a superconductor Al into a ferromagnetic film Ni. Previous attempts observed that the supercurrent decays after a few 0.1 nm. By inserting a thin intervening layer of a spiral magnet (Ho), we have confirmed that the singlet supercurrent can be converted to a triplet supercurrent that exists for several 100 nm in Ni (this confirms a previous report by Robinson et al., Science 2010). Extending their results, Ong’s group has shown that it is possible to rotate the plane of the spins of the triplet pair. These ongoing experiments seem very promising for investigating triplet supercurrents in both ferromagnets and Weyl metals.

**Publications facilitated by Award**

