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6. AUTHORS Nai Phuan Ong			5d. PROJECT NUMBER		
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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 Na2Bi. Recently, the cryogenic system has been used for Fourier transform measurements on ferromagnet					
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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)

<u>Received</u>	<u>Paper</u>
02/03/2016	1.00 Jun Xiong, Yuehaw Khoo, Shuang Jia, R. J. Cava, N. P. Ong. Tuning the quantum oscillations of surface Dirac electrons in the topological insulator Bi, Physical Review B, (07 2013): 35128. doi: 10.1103/PhysRevB.88.035128
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 WTe ₂ , Nature, (09 2014): 205. doi:
02/03/2016	3.00 J. Xiong, S. K. Kushwaha, T. Liang, J. W. Krizan, M. Hirschberger, W. Wang, R. J. Cava, N. P. Ong. Evidence for the chiral anomaly in the Dirac semimetal Na ₃ Bi, Science, (09 2015): 0. doi: 10.1126/science.aac6089
TOTAL:	3

Number of Papers published in peer-reviewed journals:

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

<u>Received</u>	<u>Paper</u>
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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):

<u>Received</u>	<u>Paper</u>
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TOTAL:

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

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

<u>Received</u>	<u>Paper</u>
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TOTAL:

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

(d) Manuscripts

<u>Received</u>	<u>Paper</u>
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TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

<u>NAME</u>	<u>PERCENT_SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT_SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME

PERCENT SUPPORTED

FTE Equivalent:

Total Number:

Names of Under Graduate students supported

NAME

PERCENT SUPPORTED

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

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME

PERCENT SUPPORTED

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 π -phase shift of the quantum oscillations expected from Dirac states.

ii) A very large magnetoresistance (MR) was discovered in the candidate topological material WTe_2 . 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 Na_3Bi , 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 π -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

Jun Xiong, Yuehaw Khoo, Shuang Jia, R. J. Cava and N. P. Ong, "Tuning the quantum oscillations of surface Dirac electrons in the topological insulator Bi₂Te₂Se by liquid gating," Phys. Rev. B 88, 035128 (2013) (Editor's suggestion). doi: 10.1103/PhysRevB.88.035128.

Mazhar N. Ali, Jun Xiong, Tian Liang, Steven Flynn, Quinn Gibson, Leslie Schoop, Neel Haldolaarachchige, Max Hirschberger, Jing Tao, N. P. Ong, & R. J. Cava, "Large Magnetoresistance in WTe₂," Nature 514, 205 (2014). doi:10.1038/nature13763

Jun Xiong, Satya K. Kushwaha, Tian Liang, Jason W. Krizan, Max Hirschberger, Wudi Wang, R. J. Cava, and N. P. Ong, "Evidence for the chiral anomaly in the Dirac semimetal Na₃Bi," Science 350, 413 (2015). DOI: 10.1126/science.aac6089