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4. TITLE AND SUBTITLE Final Report: Spin-Orbit Coupled Bose-Einstein Condensates			5a. CONTRACT NUMBER W911NF-09-1-0257		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 611102		
6. AUTHORS Victor Galitski			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of Maryland - College Park Office of Research Administration 3112 Lee Building 7809 Regents Drive College Park, MD 20742 -5141			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		
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14. ABSTRACT This ARO research proposal entitled "SPIN-ORBIT COUPLED BOSE-EINSTEIN CONDENSATES" (SOBECs) explored properties of the fundamentally new class of coherent states of quantum matter that had been predicted by the PI and subsequently experimentally realized with cold atoms. A unique feature of the SOBECs is a topologically protected spin-orbital degeneracy of the ground state that results in a variety of fascinating, previously unseen phenomena, which can be exploited for ultra-sensitive quantum interferometry, gravimetry, and fault-tolerant					
15. SUBJECT TERMS superfluids, spin-orbit coupling, optical lattices, topological states					
16. SECURITY CLASSIFICATION OF:		17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT			c. THIS PAGE	Victor Galitski
UU	UU	UU	UU	19b. TELEPHONE NUMBER	
				301-405-6107	

Report Title

Final Report: Spin-Orbit Coupled Bose-Einstein Condensates

ABSTRACT

This ARO research proposal entitled "SPIN-ORBIT COUPLED BOSE-EINSTEIN CONDENSATES" (SOBECs) explored properties of the fundamentally new class of coherent states of quantum matter that had been predicted by the PI and subsequently experimentally realized with cold atoms.

A unique feature of the SOBECs is a topologically protected spin-orbital degeneracy of the ground state that results in a variety of fascinating, previously unseen phenomena, which can be exploited for ultra-sensitive quantum interferometry, gravimetry, and fault-tolerant topological quantum computing. The PI has developed a quantum-mechanical description of the new phases and designed specific experimental schemes to realize them. The PI also generalized the new concepts to interacting spin-1/2 bosons in optical lattices and described a superfluid-to-Mott insulator transition in spin-orbit-coupled systems.

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>
08/30/2011	1.00 Brandon Anderson, Jacob Taylor, Victor Galitski. Interferometry with synthetic gauge fields, Physical Review A, (03 2011): 0. doi: 10.1103/PhysRevA.83.031602
08/30/2011	5.00 Tudor Stanescu, Victor Galitski, S. Das Sarma. Topological states in two-dimensional optical lattices, Physical Review A, (07 2010): 0. doi: 10.1103/PhysRevA.82.013608
08/30/2011	4.00 Kai Sun, Christopher Varney, Marcos Rigol, Victor Galitski. Interaction effects and quantum phase transitions in topological insulators, Physical Review B, (09 2010): 0. doi: 10.1103/PhysRevB.82.115125
08/30/2011	3.00 Christopher Varney, Kai Sun, Victor Galitski, Marcos Rigol. Kaleidoscope of Exotic Quantum Phases in a Frustrated XY Model, Physical Review Letters, (08 2011): 0. doi: 10.1103/PhysRevLett.107.077201
08/30/2011	2.00 Andrew Robertson, Victor Galitski, Gil Refael. Dynamic Stimulation of Quantum Coherence in Systems of Lattice Bosons, Physical Review Letters, (04 2011): 0. doi: 10.1103/PhysRevLett.106.165701
11/08/2013	22.00 G. R. Boyd, V. Galitski, V. M. Yakovenko. Detecting d-wave pairing and collective modes in fermionic condensates with Bragg scattering, Physical Review A, (06 2012): 0. doi: 10.1103/PhysRevA.85.063619
11/08/2013	20.00 Ryan Barnett, G. R. Boyd, Victor Galitski. SU(3) Spin-Orbit Coupling in Systems of Ultracold Atoms, Physical Review Letters, (12 2012): 0. doi: 10.1103/PhysRevLett.109.235308
11/08/2013	21.00 J. Radi?, A. Di Ciolo, K. Sun, V. Galitski. Exotic Quantum Spin Models in Spin-Orbit-Coupled Mott Insulators, Physical Review Letters, (08 2012): 0. doi: 10.1103/PhysRevLett.109.085303
11/08/2013	23.00 Brandon M. Anderson, Gediminas Juzeli?nas, Victor M. Galitski, I. B. Spielman. Synthetic 3D Spin-Orbit Coupling, Physical Review Letters, (06 2012): 0. doi: 10.1103/PhysRevLett.108.235301
11/08/2013	24.00 So Takei, Chien-Hung Lin, Brandon M. Anderson, Victor Galitski. Low-density molecular gas of tightly bound Rashba-Dresselhaus fermions, Physical Review A, (02 2012): 0. doi: 10.1103/PhysRevA.85.023626
11/08/2013	25.00 Victor Galitski, Ian Spielman. Spin-orbit coupling in quantum gases, Nature, (02 2013): 49. doi:
TOTAL:	11

Number of Papers published in peer-reviewed journals:

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

Received

Paper

11/08/2013 26.00 Chris Varney, Kai Sun , Victor Galitski, Marcos Rigol. Quantum phases of hard-core bosons in a frustrated honeycomb lattice,
Invited review for special issue "Focus on Quantum Spin Liquids, New Journal of Physics 14, 115028 (2012) , (11 2012): 115028. doi:

TOTAL: 1

(c) Presentations

1. Invited speaker at the conference, "Frontiers of Condensed Matter Physics," organized by the Royal Swedish Academy of Sciences in Stockholm, Sweden (January, 2011). Title: "Quantum Dynamics and Quantum-to-Classical Correspondence"
2. Invited Physics Department Colloquium at the University of Melbourne, Australia; Title of the Colloquium: "Exotic quantum phenomena and topological phases in spin-orbit-coupled systems" (March, 2011)
3. Invited speaker at the international Workshop, "Physics of Cold Trapped Atoms" (LPHYS'11) Sarajevo, Bosnia and Herzegovina, (July, 2011). Title: "Spin-orbit-coupled Bose-Einstein condensates" (March, 2011)
4. Invited talk at the program on topological insulators held in the Kavli Institute for Theoretical Physics, Santa Barbara, CA (September - December, 2011). Title: "Dual Approach to Nonequilibrium Quantum Mechanics and Topological Dynamical Systems"
5. Co-organizer and speaker at the Workshop and Winter school, "New Spin 2," held in Texas A & M University in January, 2012. Title of the talks: "Introduction to the theory of spin-orbit-coupled systems in solids and cold-atoms," (school) and "Theory of Spin-Orbit-Coupled Cold-Atom Systems" (Workshop)
6. Invited talk at the statistical physics seminar at the Institute for Physical Science and Technology, College Park, MD (January, 2012). Title: "Dual Approach to Time-Dependent Quantum Mechanics and Topological Dynamical Systems"
7. Invited talk at the Workshop "Frontiers of quantum condensed matter physics: light, matter and unusual devices out of equilibrium," New York, NY (March, 2012). Title: "Dual Approach to Time-Dependent Quantum Mechanics and Topological Dynamical Systems"
8. Invited talk at the Symposium "Frontiers of Quantum Matter" at the Center for Quantum Science, George Mason University, Fairfax, VA (June, 2012); Title: "Floquet topological insulators"
9. Invited talk at the International Conference, "Dubna -Nano 2012," at the Joint Institute for Nuclear Research, Bogoliubov Laboratory for Theoretical Physics, Dubna, Russia (July, 2012) Title: "Floquet topological insulating states"
10. Invited talk at the 21th International Laser Physics Workshop, University of Calgary, Calgary, Canada (July, 2012). Title: "Floquet topological insulators"
11. Invited talk at the KITP conference, "Dynamics and Thermodynamics in Isolated Quantum Systems," Kavli Institute for Theoretical Physics, Santa Barbara, CA (August, 2012). Title: "Stimulation of Quantum Phases by Time-dependent Perturbations"
12. Invited condensed matter seminar at Penn State University, (September, 2012). Title: "Quantum fluctuation phenomena in low-dimensional superfluids"
13. Invited Departmental Colloquium at the University of Minnesota, Minneapolis, MN (September, 2012). Title: "Exotic Quantum Phenomena and Topological Phases in Spin-Orbit-Coupled Systems"
14. Invited condensed matter seminar, William I. Fine Theoretical Physics Institute, University of Minnesota, Minneapolis (September, 2012). Title: "Stimulation of Quantum Phases by Time-dependent Perturbations"
15. Invited CUA seminar at the Harvard-MIT Center for Ultracold Atoms (CUA), Cambridge, MA (October, 2012). Title: "Stimulation of Quantum Phases by Time-dependent Perturbations"
16. Invited physics Colloquium at PennState University, University Park, PA (December, 2012), Title: "Exotic Quantum Phenomena and Topological Phases in Spin-Orbit-Coupled Systems"
17. Invited physics Colloquium at Monash University, Melbourne, VIC, Australia (January, 2013), Title: "Exotic Quantum Phenomena and Topological Phases in Spin-Orbit-Coupled Systems"
18. Invited seminar at the University of Massachusetts, Amherst, MA (April, 2013), Title: "Spin-orbit coupling in cold atoms"

19. "Quantum Floquet Dynamics of the Order Parameter in Fluctuating Superconductors," Aspen Center for Physics, Aspen, CO (June, 2013)

20. "Exotic quantum spin models in spin-orbit-coupled Mott insulators," Invited talk at the 23rd International Laser Physics Workshop, Prague, Czech Republic (July, 2013)

21. "Many-body physics of spin-orbit-coupled quantum gases," Invited talk at the March Meeting 2014 in Denver, Colorado (March, 2014)

22. "Synthetic spin-orbit coupling in cold atom systems," invited seminar at the Institute of Theoretical Physics and Astronomy, Vilnius University, Vilnius, Lithuania (July, 2014)

23. "Moving solitons in fermionic superfluids," presentation at the Workshop "Gauge Fields in Condensed Matter, Ultracold Atoms and Beyond," Aspen Center for Physics, Aspen, CO (August, 2014)

24. "Moving solitons in fermionic superfluids," keynote talk at the Australasian Workshop on Emergent Quantum Matter 2014, Dunwich, Queensland, Australia (November, 2014)

Number of Presentations: 24.00

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:

(d) Manuscripts

<u>Received</u>	<u>Paper</u>
08/30/2011	6.00 Christopher Varney , Kai Sun, Marcos Rigol, Victor Galitski. Topological Phase Transitions for Interacting Finite Systems, Physical Review Letters (submitted) (08 2011)
08/30/2011	7.00 Juraj Radic , Tigran Sedrakyan, Ian Spielman, Victor Galitski. Vortices in spin-orbit-coupled Bose-Einstein condensates, Physical Review A (08 2011)
10/18/2012	9.00 So Takei , Chien-Hung Lin, Brandon Anderson, Victor Galitski. Low-density molecular gas of tightly-bound Rashba-Dresselhaus fermions, Physical Review A (11 2011)
10/18/2012	13.00 J. Radic?, A. Di Ciolo, K. Sun, V. Galitski. Exotic Quantum Spin Models in Spin-Orbit-Coupled Mott Insulators, Physical Review Letters (8 2012)
10/18/2012	8.00 Brandon Anderson, Gediminas Juzeliunas, Victor Galitski, Ian Spielman. Synthetic 3D Spin-Orbit Coupling , Physical Review Letters (12 2011)
10/18/2012	10.00 Victor Galitski, Victor Yakovenko, Greg Boyd. Detecting d-wave pairing and collective modes in fermionic condensates with Bragg scattering, Physical Review A (03 2012)
11/03/2016	11.00 Ryan Barnett, Greg Boyd, Victor Galitski. SU(3) Spin-Orbit Coupling in Ultracold Atoms , Physical Review Letters (07 2012)
11/03/2016	19.00 Victor Galitski, Ian Spielman. Synthetic spin-orbit coupling in cold atomic gases, Nature (09 2012)
TOTAL:	8

Number of Manuscripts:

Books

Received Book

10/18/2012 18.00 Victor Galitski , Boris Karnakov , Vladimir Kogan, Victor Galitski Jr . Exploring Quantum Mechanics: A Collection of 700+ Solved Problems for Students, Lecturers, and Researchers, London, UK: Oxford University Press, (12 2012)

TOTAL: 1

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

1. Named one of the University of Maryland Research Leaders (2013, 2014)
 2. University of Maryland's Board of Visitors Faculty Award
 3. The Richard A. Ferrell Distinguished Faculty Fellowship (2011)
 4. Simons Investigator Award (2013)
 5. Future Fellowship Award from the Australian Research Council (2014)
-

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
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FTE Equivalent:

Total Number:

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
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

<u>NAME</u>
Total Number:

Names of personnel receiving PHDs

<u>NAME</u>
Total Number:

Names of other research staff

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

1. A theory of vortex excitations in spin-orbit-coupled condensates developed.
2. A new kind of non-equilibrium topological insulating states introduced, with possible realization in driven optical lattices.
3. Experimental schemes to realize various synthetic spin-orbit-coupled Hamiltonians designed.
4. A new kind of spin-orbit-coupled Mott insulators introduced.
5. Theory of unconventional Cooper pairing in spin-orbit-coupled Fermi gases developed.
6. Realistic models that host quantum spin liquid states proposed
7. A theory of superfluid-to-topological insulator developed with applications to optical lattices.
8. Generalized inverse scattering methods to describe soliton motion in quantum superfluids.

Technology Transfer