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14. ABSTRACT
This research program explored matter wave optics and rotating Bose-Einstein condensates (BECs). High sensitivity inertial sensors based on matter waves may benefit greatly from the coherence properties of condensates. We explored rotating BECs using Bragg spectroscopy and uncovered a new mechanism for measuring rotation. We realized a conical lens, or "axicon", for matter waves by tailoring the expansion of a BEC using a far-detuned, intense, focused laser beam. We devised a new scheme for generating flexible, configurable optical traps for atoms

15. SUBJECT TERMS
persistent current, superfluid, Bose-Einstein condensate, matter wave, atom optics, atom interferometry

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Chandra Raman
UU	UU	UU	UU		19b. TELEPHONE NUMBER 404-894-9062

Report Title

Persistent Currents in a Bose-Einstein Condensate

ABSTRACT

This research program explored matter wave optics and rotating Bose-Einstein condensates (BECs). High sensitivity inertial sensors based on matter waves may benefit greatly from the coherence properties of condensates. We explored rotating BECs using Bragg spectroscopy and uncovered a new mechanism for measuring rotation. We realized a conical lens, or "axicon", for matter waves by tailoring the expansion of a BEC using a far-detuned, intense, focused laser beam. We devised a new scheme for generating flexible, configurable optical traps for atoms using a two-axis scanning acousto-optic modulator, and applied this to realize a BEC in a toroidal potential. Finally, we discovered a mechanism for pumping vorticity into a Bose-Einstein condensate using time-varying magnetic fields, and therefore for the realization of quantum correlated states of large angular momentum.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

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

1. Z. F. Xu, P. Zhang, C. Raman and L. You, Continuous vortex pumping into a spinor condensate with magnetic fields. Phys. Rev. A 78, 043606 (2008).

2. S. R. Muniz, D. S. Naik, M. Bhattacharya and C. Raman: Dynamics of rotating Bose-Einstein condensates probed by Bragg scattering, Journal of Mathematics and Computers in Simulation, Volume 74, Issues 4-5 , 30 March 2007, Pages 397-404.

3. S. R. Muniz, S. D. Jenkins, T. A. B. Kennedy, D. S. Naik, and C. Raman: Axicon Lens for Coherent Matter Waves, Optics Express, Vol. 14, Issue 20, pp. 8947-8957 (2006).

4. S. R. Muniz, D. S. Naik and C. Raman: Bragg Spectroscopy of Vortex Lattices in Bose-Einstein condensates. Rapid Communication in Phys. Rev. A 73, 041605(R) (2006).

Number of Papers published in peer-reviewed journals: 4.00

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

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

1. Rotating Bose-Einstein Condensates: A View into Topological States. SIAM Conference on Nonlinear Waves and Coherent Structures, Seattle, Washington, September 9th, 2006.
2. Topological Effects with Matter Waves: A New Twist on BEC. Annual Meeting of the Society for Industrial and Applied Mechanics (SIAM) Conference on Analysis of Partial Differential Equations, Boston Massachusetts, July 10-12, 2006.
3. Topological Effects in Matter Waves. Workshop on Strong Correlations in Ultra-Cold Fermi Systems, Aspen Center for Physics, Aspen, Colorado, January 15-21, 2006.
4. The Topology of Matter Waves: A story in twists and turns. Topical Conference on Atomic, Molecular and Optical Physics, Indian Society of Atomic & Molecular Physics (ISAMP), Kolkata, India, December 13 - 15, 2005.
5. Magnetic Manipulation of Matter Waves: Vortices, Sinkholes, and Rings. Workshop on Low Dimensional Systems in Quantum Optics, Centro Internacional de Ciencias, Cuernavaca, Mexico, September, 12th - 30th 2005.
6. Nonlinear Dynamics with Bose-Einstein Condensates. The Fourth IMACS (International Association for Mathematics and Computers in Simulation) International Conference on Nonlinear Evolution Equations and Wave Phenomena, Athens, GA, April 11-14 , 2005.

Number of Presentations: 6.00

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

1. Tetsuya Ishikawa, Matthew Gibbs, Gustavo Telles and Chandra Raman: Characterization of LIAD loaded sodium MOT, Poster presentation at the 40th Meeting of the Division of Atomic, Molecular and Optical Physics, Charlottesville, Virginia, May 19-23, 2009 (20009 Bulletin of the American Physical Society).
2. Matthew Gibbs, Tetsuya Ishikawa, Gustavo Telles and Chandra Raman: Collision dynamics of magnetically trapped Na and Rb, Poster presentation at the 40th Meeting of the Division of Atomic, Molecular and Optical Physics, Charlottesville, Virginia, May 19-23, 2009 (20009 Bulletin of the American Physical Society).
3. Sergio Muniz, Chandra Raman, Kristian Helmerson, William Phillips: Creating arbitrary potentials to study and manipulate Bose-Einstein condensates, Poster presentation at the 40th Meeting of the Division of Atomic, Molecular and Optical Physics, Charlottesville, Virginia, May 19-23, 2009 (20009 Bulletin of the American Physical Society).
4. G. Telles, M. Gibbs, T. Ishikawa, E. Thieman and C. Raman: Towards Dual BEC of Na and Rb. Poster presentation at the International Conference on Atomic Physics (ICAP 2008, Storrs, Connecticut, July 27-August 1, 2008.
5. G. Telles, M. Gibbs, T. Ishikawa, E. Thieman and C. Raman: Progress Towards a Dual BEC of Na Rb. Contributed talk at the 39th Meeting of the Division of Atomic, Molecular and Optical Physics, State College, Pennsylvania, May 27th-31st. (2008 Bulletin of the American Physical Society).
6. M. Gibbs, G. Telles, A. Seltzman, T. Ishikawa, E. Thieman and C. Raman: Towards Dual BEC: Zeeman Slower Approach. Poster presentation at the 39th Meeting of the Division of Atomic, Molecular and Optical Physics, State College, Pennsylvania, May 27th-31st. (2008 Bulletin of the American Physical Society).
7. G. Telles, M. Gibbs, A. Seltzman, and C. Raman: NaRb Two Species BEC. Poster presentation at the Integrated Atomic Systems Workshop, Atlanta, Georgia, November 5th, 2007.
8. S. R. Muniz, C. Raman: Matter wave lens for Bose-Einstein condensates. The Fifth IMACS (International Association for Mathematics and Computers in Simulation) International Conference on Nonlinear Evolution Equations and Wave Phenomena, Athens, GA, April 17th , 2007.
9. S. R. Muniz, C. Raman: Producing time-averaged arbitrary landscape potentials to manipulate BECs. Poster presentation at the 20th International Conference on Atomic Physics, Innsbruck, Austria, July 16-21, 2006.
10. S. R. Muniz, D. S. Naik, C. Raman: Using Bragg scattering to probe rotating Bose-Einstein condensates. Poster presentation at the 20th International Conference on Atomic Physics, Innsbruck, Austria, July 16-21, 2006.

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 10

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

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
Tetsuya Ishikawa	0.33
FTE Equivalent:	**0.33**
Total Number:	**1**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Sergio Muniz	0.33
FTE Equivalent:	**0.33**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Chandra Raman	0.33	No
FTE Equivalent:	**0.33**	
Total Number:	**1**	

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)

Statement of the problem studied:

This research program explored matter wave optics and rotating Bose-Einstein condensates (BECs). High sensitivity inertial sensors based on matter waves may benefit greatly from the coherence properties of condensates. We explored rotating BECs using Bragg spectroscopy and uncovered a new mechanism for measuring rotation. We realized a conical lens, or “axicon”, for matter waves by tailoring the expansion of a BEC using a far-detuned, intense, focused laser beam. We devised a new scheme for generating flexible, configurable optical traps for atoms using a two-axis scanning acousto-optic modulator, and applied this to realize a BEC in a toroidal potential. Finally, we discovered a mechanism for pumping vorticity into a Bose-Einstein condensate using time-varying magnetic fields, and therefore for the realization of quantum correlated states of large angular momentum.

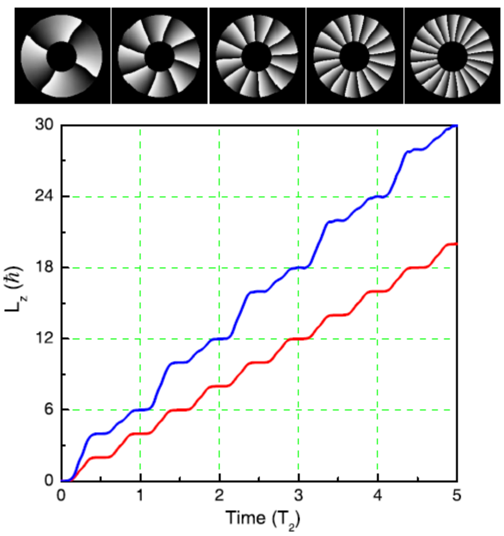
Summary of the most important results:

- **Time Averaged Potentials.** We have devised a new scheme for generating flexible, configurable optical traps for atoms using a two-axis scanning acousto-optic modulator. By rapidly scanning a focused, far off-resonance infrared laser beam atoms can be trapped in a potential which can be arbitrarily configured using computer control. Our preliminary results demonstrated lifetimes of up to 10 seconds in this trap. In order to exert fine control over the potential minimum, we adjusted the laser beam intensity at every scan point. Using this technique we realized a BEC in a toroidal potential. These results were presented at the DAMOP meeting in 2006.

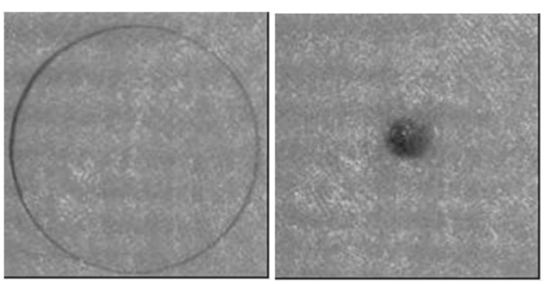
- **Vortex Pump.** We have discovered a mechanism for pumping vorticity into a Bose-Einstein condensate using time-varying magnetic fields, and therefore for the realization of quantum correlated states of large angular momentum. A fundamental connection exists between the geometrical structure of a magnetic field distribution and the quantized circulation of magnetically trapped atoms. We have devised optimal procedures for continuously increasing or decreasing a condensate's vorticity (up to 30 hbar of circulation) by repeating two-step *B*-field manipulation protocols. The attached figure [taken from Z. F. Xu, P. Zhang, C. Raman and L. You, Phys. Rev. A 78, 043606 (2008)] shows the resulting phase distribution as computed using mean-field numerical simulations.

- **Axicon lens for coherent matter waves.** Matter wave optics is a growing field, with applications to sub-micrometer scale particle deposition and lithography. One needs refractive elements to efficiently couple atoms and molecules into guiding structures, particularly to build compact matter wave inertial sensors on an atom chip. In our laboratory, we have realized a conical lens, or “axicon”, for matter waves. We tailored the expansion of a Bose-Einstein condensate using a far-detuned, intense, focused laser beam. The result was a dramatic, ring-shaped output similar to a conical beam of laser light. However, unlike photonic optics, propagation of matter waves is profoundly affected by the interactions between atoms. Our work opened up the possibility for cylindrical atom optics without the perturbing effect of mean-field interactions [See attached figure from S. R. Muniz, S. D. Jenkins, T. A. B. Kennedy, D. S. Naik, and C. Raman: Axicon Lens for Coherent Matter Waves, Optics Express, Vol. 14, Issue 20, pp. 8947-8957 (2006).].

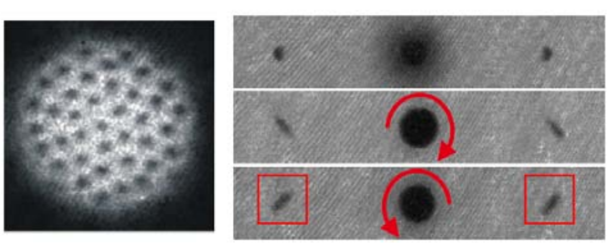
- **Vortex dynamics.** We have examined rapidly rotating BECs, where lattices of quantized vortices can be observed. We have measured both the rotation rate and, importantly, the *sense* of rotation (i.e. counter-clockwise or clockwise) by applying a phase sensitive technique, Bragg scattering of laser light. Our technique, which is complementary to conventional imaging methods, has direct application to mapping the velocity distribution of turbulent superfluids. This work appeared as a Rapid Communication in Physical Review A [Phys. Rev. A 73, 041605(R) (2006)].



Pumping vorticity into a BEC. (Above) The temporal development of the condensate phase in a hexapole magnetic field at times of 30, 70, 110, 150 and 190 ms. (Below) The continuously increasing vorticity of a condensate for combinations of 2D and 3D quadrupole magnetic fields. The time T_2 = 60 ms.



Axicon lens for matter waves. BEC interacts with a conical lens, causing it to expand into an extremely thin ring shape (left). The expansion of a BEC without application of the lens is shown on the right.



Snapshots of a rotating Bose-Einstein condensate. Quantized vortices appear as black holes when a BEC is set into rapid rotation (left). Our Bragg imaging method (right) allowed us to measure the rate and sense of that rotation through the location and tilt angle of the scattered atoms in the red boxes.

Publication List:

1. Z. F. Xu, P. Zhang, C. Raman and L. You, ***Continuous vortex pumping into a spinor condensate with magnetic fields.*** Phys. Rev. A **78**, 043606 (2008).

2. S. R. Muniz, D. S. Naik, M. Bhattacharya and C. Raman: ***Dynamics of rotating Bose-Einstein condensates probed by Bragg scattering,*** Journal of Mathematics and Computers in Simulation, Volume 74, Issues 4-5 , 30 March 2007, Pages 397-404.

3. S. R. Muniz, S. D. Jenkins, T. A. B. Kennedy, D. S. Naik, and C. Raman: ***Axicon Lens for Coherent Matter Waves,*** Optics Express, Vol. 14, Issue 20, pp. 8947-8957 (2006).

4. S. R. Muniz, D. S. Naik and C. Raman: ***Bragg Spectroscopy of Vortex Lattices in Bose-Einstein condensates.*** Rapid Communication in Phys. Rev. A **73**, 041605(R) (2006).