Vortices in a Highly Rotating Bose Condensed Gas

by

I. R. Coddington

B.A., Reed College, 1998

A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

Department of Physics

2004

This thesis entitled:
Vortices in a Highly Rotating Bose Condensed Gas
written by I. R. Coddington
has been approved for the Department of Physics

____
Eric Cornell

____
Leo Radzihovsky

Date ______________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Coddington, I. R. (Ph.D., Physics)

Vortices in a Highly Rotating Bose Condensed Gas

Thesis directed by Prof. Eric Cornell

Superfluids, with their dissipationless flow and exotic topologies, have puzzled researchers in diverse fields of physics for almost a century. One of the hallmark features of superfluids is their response to rotation, which requires the fluid to be pierced by an array quantized singularities or vortices. Over the past few years, vortices and the lattices they organize into have become one of the major fields of experimental research with dilute gas Bose-Einstein condensates.

This thesis explores the physics of vortices and vortex lattices in the dilute gas Bose-Einstein condensate while drawing connections to other superfluid systems. In addition to characterizing several equilibrium vortex effects, this work also studies several excitations. By removing atoms from the rotating condensate with a tightly focused, resonant laser, the density can be locally suppressed, creating aggregate vortices containing many units of circulation. These so called "giant vortices" offer insight into the dynamical stability of density defects in this system. Using similar techniques we can excite and directly image Tkachenko waves in the vortex. These low frequency modes are a consequence of the small but nonvanishing elastic shear modulus of the vortex-filled superfluid.

Finally, by working at extremely high rotations we can create a Bose-Einstein condensates in the lowest Landau level. In this regime, which requires rotation rates greater than 99% of the centrifugal limit for a harmonically trapped gas, we are able observe several expected and unexpected shifts in the physical properties of the condensate.

In conclusion the dilute gas Bose-Einstein condensates offers a rich system in which to study vortex physics, and explore dynamical effects common to all rotating

superfluids.

Dedication

To Odele for her love and support, and to my grandfather for getting me thinking about the world.

Acknowledgements

First I would like to thank my advisor, Eric Cornell, for his support and guidance over the last five years. His infectious enthusiasm and depth of knowledge never ceased to amaze me and both were a constant source of my own growth and understanding.

Also, I would like to thank Debbie Jin for her hands on approach and guidance that first year. I learned a lot in a very short period of time. We never ended up needing that stripe laser but I also never stopped using the skills I learned, either.

In the last five years it has been my pleasure share the lab with several other graduate students including Volker Schweikhard, Paul Haljan, and most recently Shih-Kuang Tung. It would be hard to ask for a brighter or more dedicated group of individuals. Even more exceptionally, this group has always been humorous and fun to work with no matter how arduous or frustrating the experiment became. Of course, no discussion of the lab group would be complete without acknowledging our ring leader and post doc Peter Engels. Over the last several years Peter has been both a great mentor as well as a personal friend, and I wish him luck in his new job. He may not believe me, but there is no doubt in my mind that Peter will grow to love his new appointment at Washington State.

This experiment has also benefited considerably from the assistance of a number of theorists. It has been an absolute pleasure to work with and learn from people like Leo Radzihovsky, Dan Sheehy, Gordon Baym, Allen MacDonald and Marco Cozzini.

Support services at JILA are of course outstanding and I could not even begin to count all the ways that the machine shop, electronics shop and computing staff have made this thesis more successful. I would especially like to thank Hans Green and James Fung-A-Fat for their mentorship and patience. Also, I am eternally indebted to Jim McKown for tolerating, what I am sure were, inane questions about the inner workings of Windows and then miraculously making the problems go away.

Thanks, also, to the Cornell-Wieman-Jin group for an excellent working atmosphere and to the “Sloggies” Dave, Nate, Dan, and Andrew for an excellent living atmosphere.

Finally, thanks to the coffee girl and Burnt Toast for making such a good cup of coffee. Thanks to Mike Ziemkiewicz and to a lesser extent John Stewart of The Daily Show for making the last four years of presidential politics bearable.

Contents

Chapter

Tables

Table

Figures

Figure