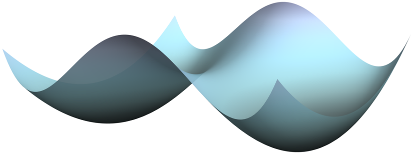
Condensate Properties for a Strongly Repulsive BEC in a Double Well

Joel C. Corbo, Jonathan DuBois, K. Birgitta Whaley

UC Berkeley



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BACKGROUND

First BEC in alkali atoms in 1995.[1,2]

Since then, explosion of theoretical & experimental work into understanding BEC.

Feshbach resonances have opened the door to experimental study of strongly interacting BECs by allowing the BEC's scattering length to be tuned over as many as seven orders of magnitude[3]. Our work makes computational predictions in this strongly-interacting regime.

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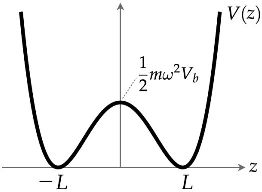
[1] M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman and E. A. Cornell, Science **269**, 198 (1995)

[2] K. B. Davis, M.-O. Mewes, M. R. Andrews, N. J. van Druten, D. S. Durfee, D. M. Kurn, W. Ketterle, Phys. Rev. Lett. **75**, 3969 (1995)

[3] S. E. Pollack, D. Dries, M. Junker, Y. P. Chen, T. A. Corcovilos and R. G. Hulet, Phys. Rev. Lett. **102**, 090402 (2009)

THE SYSTEM

BEC with repulsive interactions in a double well



$$\hat{H} = \sum_{i=1}^{N} \left(\frac{\mathbf{p}_i^2}{2m} + V_{ext}(\mathbf{r}_i) \right) + \sum_{i<j}^{N} V_{int}(\mathbf{r}_i, \mathbf{r}_j)$$

$$V_{ext}(\mathbf{r}) = \frac{1}{2} m\omega^2 \left(x^2 + y^2 + V_b \left(\left(\frac{z}{L} \right)^2 - 1 \right)^2 \right)$$

$$V_{int}(\mathbf{r}_i, \mathbf{r}_j) = \begin{cases} 0 & |\mathbf{r}_i - \mathbf{r}_j| < a \\ \infty & |\mathbf{r}_i - \mathbf{r}_j| > a \end{cases}$$

a = s-wave scattering length $\propto$ interaction strength

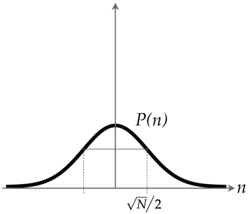
NUMBER SQUEEZED STATES

$$\hat{n} = \frac{1}{2}(\hat{n}_L - \hat{n}_R)$$

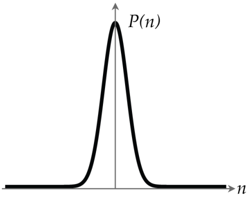
$$\sigma_n = \sqrt{\langle \hat{n}^2 \rangle - \langle \hat{n} \rangle^2} = \sqrt{\langle \hat{n}^2 \rangle}$$

Generally, stronger repulsive interaction $\rightarrow$ more squeezing (i.e., bigger $a \rightarrow$ smaller σ_n)

Squeezed states useful for improved accuracy of atom interferometers (measurement uncertainty: $N^{-1/2} \rightarrow N^{-1}$)[4]



No interaction: $\sigma_n = \sqrt{N}/2$



Squeezed state: $\sigma_n < \sqrt{N}/2$

[4] J. A. Dunningham and K. Burnett, Phys. Rev. A **70**, 033601 (2004)

OUR METHODOLOGY

We use **path integral ground state** (PIGS) quantum Monte Carlo

- Uses imaginary time propagation to project exact many-body ground state from a trial wave function:

$$e^{-\tau\hat{H}}\left|\psi_T\right\rangle \rightarrow \left|\psi_{gs}\right\rangle$$

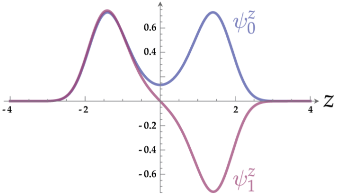
- Allows calculation of many ground state properties (E, σ_n, OBDM, …)
- Does not require mean-field approximation for interaction potential
- Very challenging to to sample configurations with different $n_L - n_R$ for high barrier or high particle density due to inefficiency of moving particles across the barrier

MODELS FOR COMPARISON

Models to study squeezing rely on expanding the many-body ground state in a truncated basis of single particle states:

- **2-mode model**: Uses single-particle ground and first excited states:

$$\psi_g(\mathbf{r}) = \psi_0^{HO}(x)\psi_0^{HO}(y)\psi_0^z(z)$$
$$\psi_e(\mathbf{r}) = \psi_0^{HO}(x)\psi_0^{HO}(y)\psi_1^z(z)$$

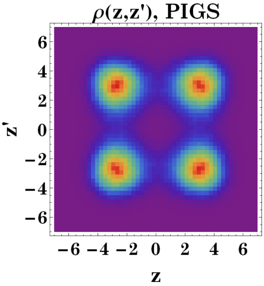


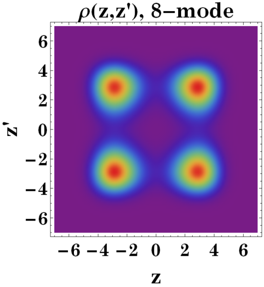
- **8-mode model**[5]: Uses lowest 8 single-particle energy eigenstates.

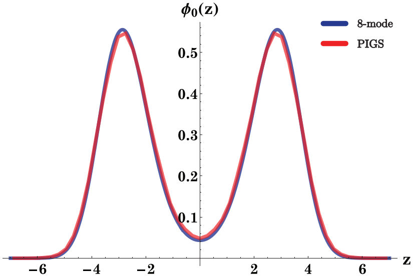
$\dim \hat{H} \sim N^{n_{modes}-1} \rightarrow$ comparison with 8-mode requires small N

[5] M. A. Garcia-March, D. R. Dounas-Frazer and L. D. Carr, Frontiers of Physics **7**, 131-145 (2012)

OBDM & Natural Orbitals ($N = 8, a = 10^{-3}\, a_{ho}$)

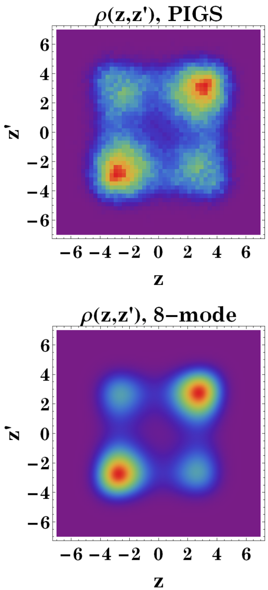


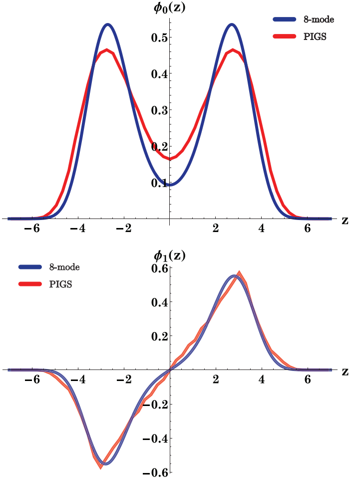




Good agreement between 8-mode and PIGS for small a.

OBDM & Natural Orbitals ($N = 8, a = 0.5\, a_{ho}$)

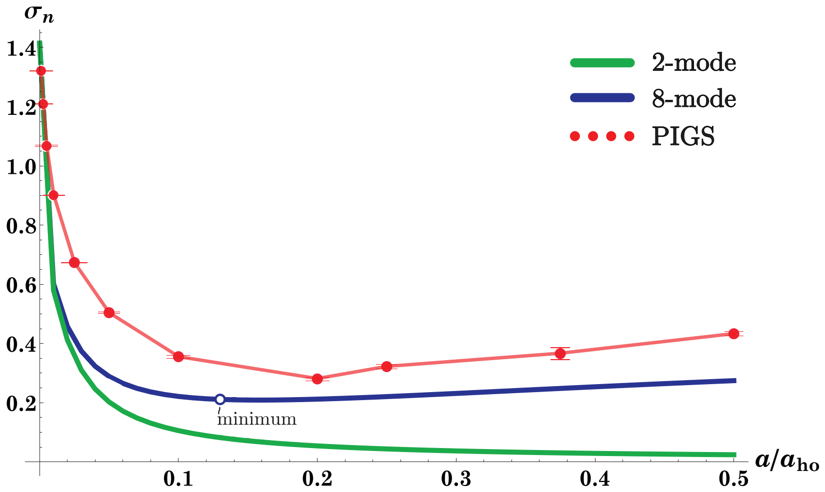




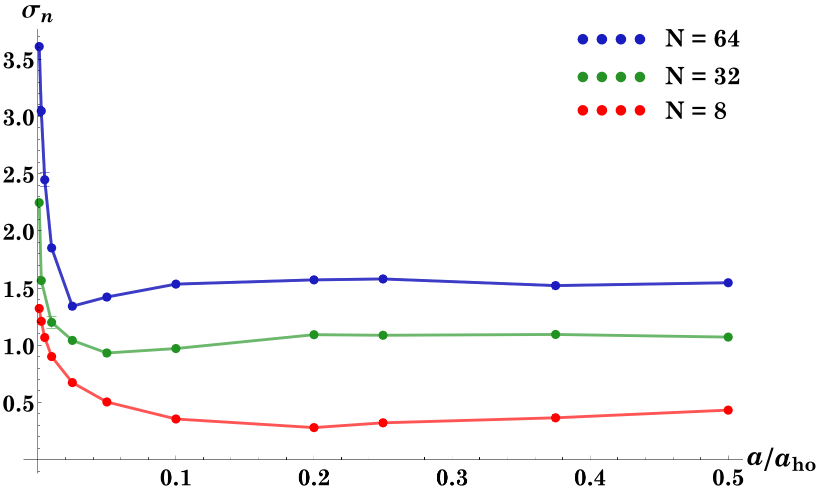
8-mode model breaks down for large a.

SQUEEZING RESULTS FOR $N = 8$

Recall: $\sigma_n = \sqrt{\langle \hat{n}^2 \rangle}$



Squeezing Results for $N = 8, 32, 64$



Note: Minimum σ_n moves to smaller a for larger N

CONCLUSION & OUTLOOK

- We have observed non-monotonic squeezing behavior as a function of a.
- We will extend our results to larger N and different trap geometries.
- Ultimately, we would like to develop a complete understanding of the relationship between squeezing, fragmentation among macroscopically-occupied natural orbitals, and depletion.