Precision measurements of scattering lengths in ^{87}Rb

M. Egorov, B. Opanchuk, V. Ivannikov, B. V. Hall, P. Drummond, P. Hannaford, A. I. Sidorov
Ausrtralian Research Council Centre of Excellence for Quantum-Atom Optics and
Centre for Atom Optics and Ultrafast Spectroscopy, Swinburne University of Technology, Melbourne, Australia

Introduction

Collisional interactions between ultracold atoms play an important role in physics of Bose-Einstein condensates and in dynamics of matter-wave interferometry [1, 2]. The strength of interactions is characterised through an s-wave scattering length. Accurate knowledge of scattering length values is important for dynamics of BEC interferometry, spin squeezing of condensates, miscibility of superfluids and studies of drifts of fundamental constants [3].

We developed an effective $1D$ description of dynamics of a two-component condensate and demonstrate that collective oscillations can be used for precision measurements of inter- and intra-species scattering lengths.

Collective oscillations in 2-component BEC

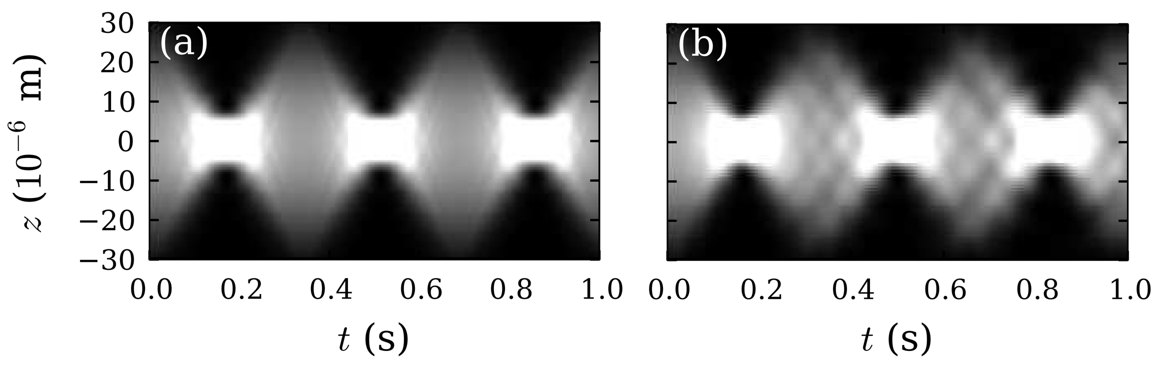


Fig. 1: Linear density evolution of state $|2\rangle$ simulated with $1D$ theory (a) and $3D$ GP equations (b).

A pulse of MW/RF radiation prepares a 2CBEC in a non-equilibrium state, triggering collective oscillations of both components. For $N_2 \ll N_1$ we developed an effective $1D$ treatment of the condensate dynamics. We factorize the order parameter using Gaussian radial trial wavefunctions [4] and obtain the effective equation for $1D$ wavefunction of state $|2\rangle$:

$$i\hbar\frac{\partial}{\partial t}f_2 = \left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2} + \frac{m\omega_{\rm eff}^2 z^2}{2} + \mu_{\rm eff}\right] f_2, \qquad (1)$$

where

$$\omega_{\rm eff} = \frac{2}{\sqrt{3}}\sqrt{1-\sqrt{a_{12}/a_{11}}} \times 2\pi f_z, \qquad (2)$$

$$\mu_{\rm eff} = \frac{\mu}{3}\left(4\sqrt{a_{12}/a_{11}} - 1\right), \qquad (3)$$

$$\mu = \left(135 N a_{11} \hbar^2 \omega_r^2 \omega_z \sqrt{m}/2^{11/2}\right)^{2/5}. \qquad (4)$$

Collective oscillations as a measure of a_{12}

We tested the dependence of the frequency of oscillations on different parameters (a_{12}, a_{22}, the atom number N and the area of the preparation pulse θ). The criteria for that (preparation pulse area $\theta \ll \pi/2$ and large N) are checked against GPE simulations.

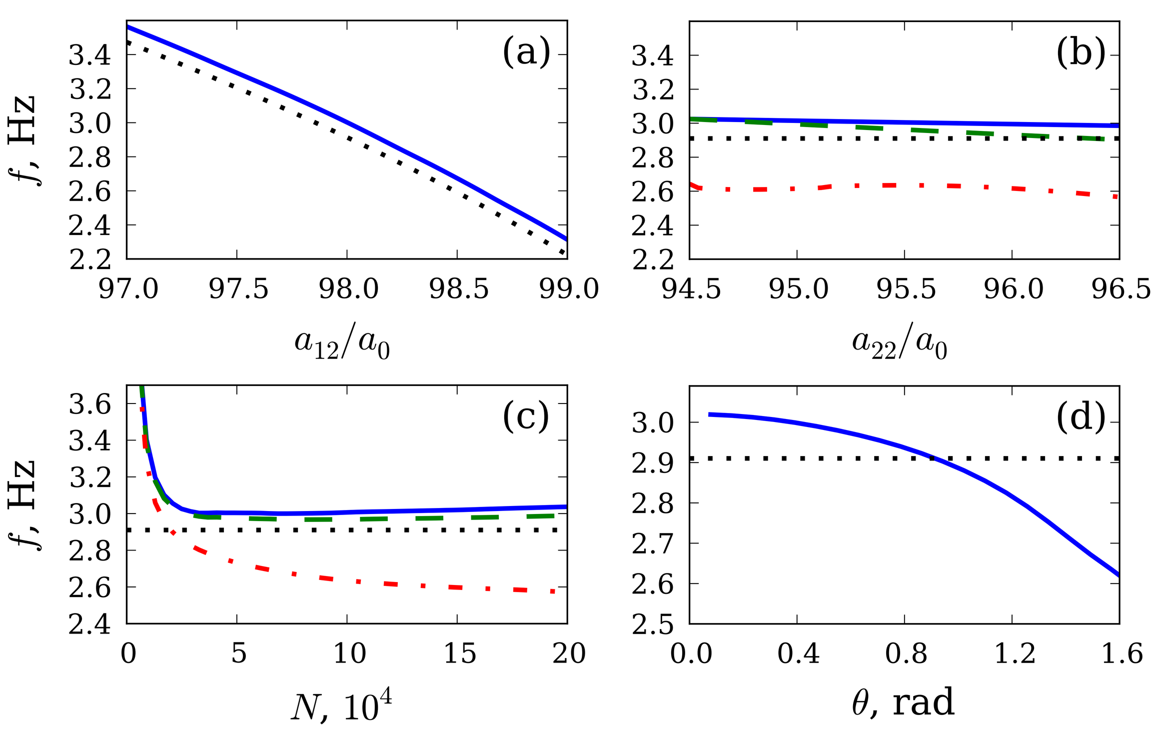


Fig. 2: Analytical predictions of Eq. 1 (dotted lines). GPE simulations for $\theta = \pi/10$ (solid lines), $\theta = \pi/5$ (dashed lines) and $\theta = \pi/2$ (dashed-dotted lines).

Trapped two-component BEC of ^{87}Rb

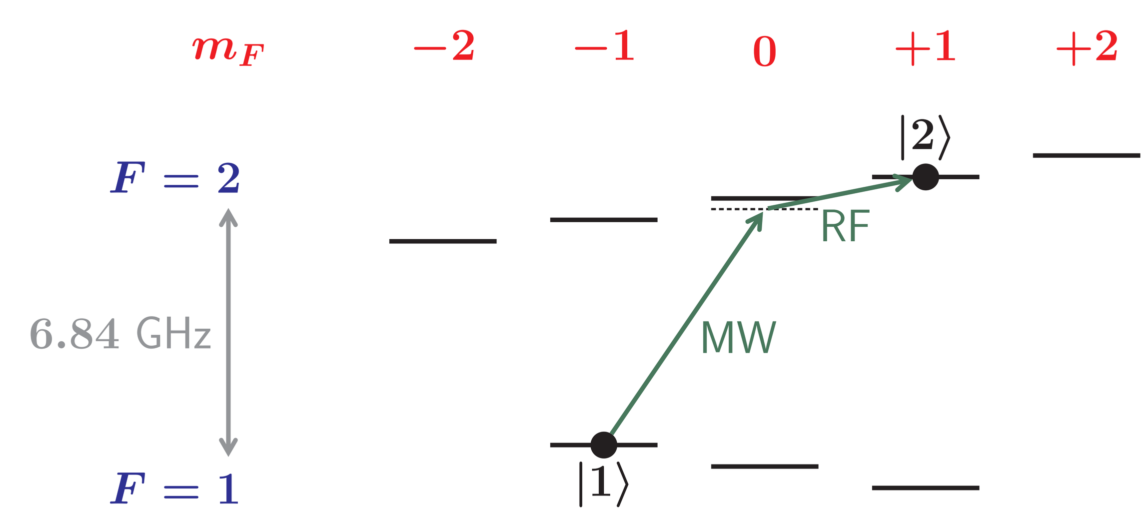


Fig. 3: Preparation of the two-component BEC for studies of collective oscillations and Ramsey interferometry

Experimental setup

We prepare BEC in state $|1\rangle$ [1, 2] in a magnetic trap on a chip (**3.228** G at trap bottom). The trap frequencies are $f_z = 11.507(7)$ Hz, $f_x = 98.23(5)$ Hz, $f_y = 101.0(5)$ Hz.. We transfer a small fraction of $|1\rangle$ to $|2\rangle$ with a pulse of theta area.

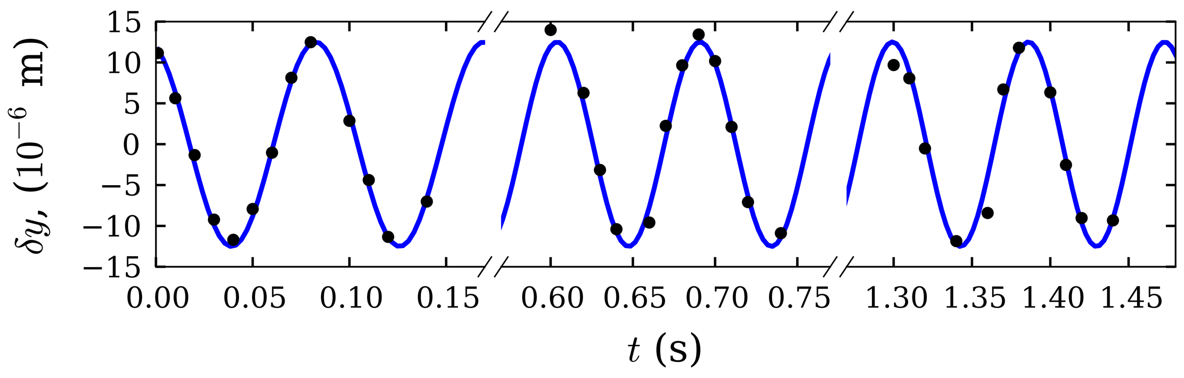


Fig. 4: Measurements of f_z using dipole oscillations.

Converging sequence of measurements

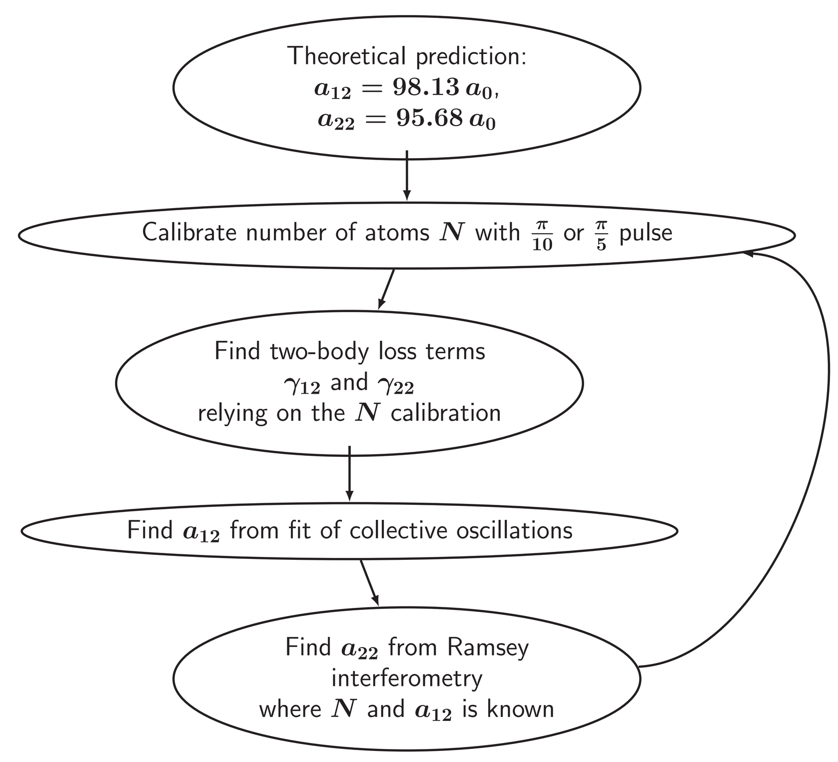
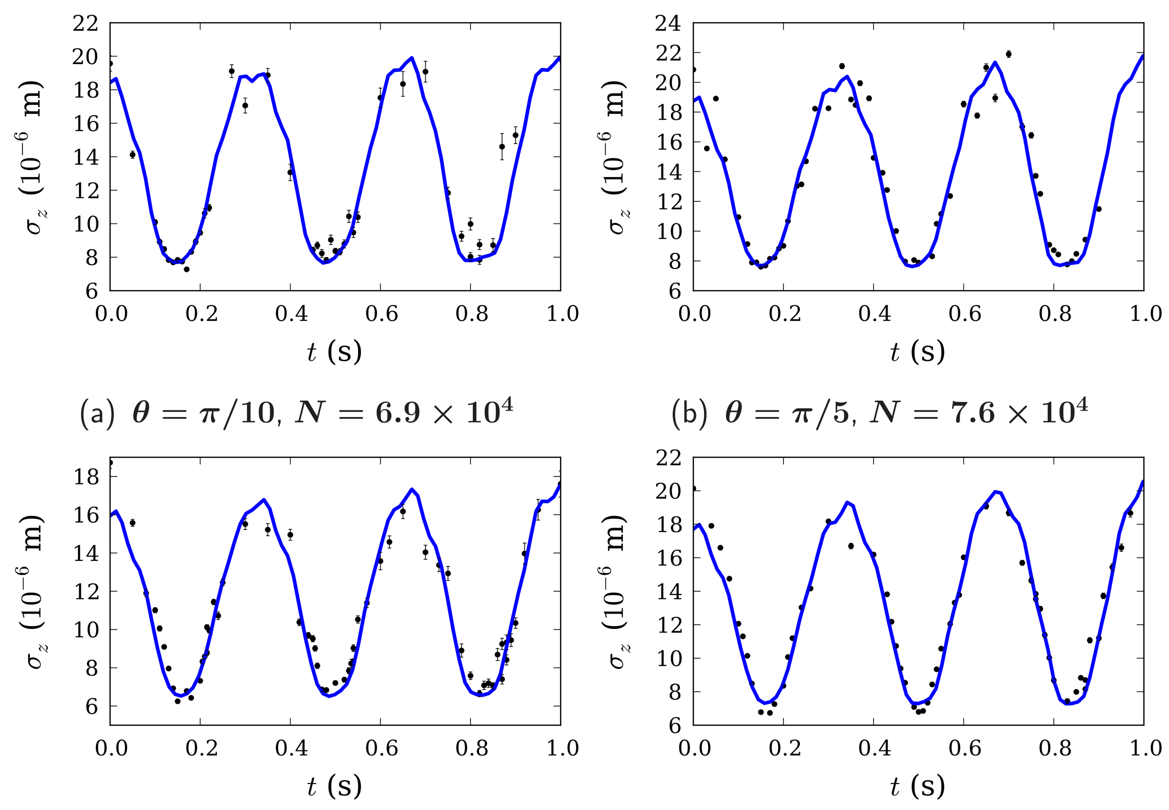


Fig. 5: We use $a_{11} = 100.40\,a_0$ as an established value. We post-process the results of measurements in a cycle. Three iterations are enough for convergence.

Measurement of a_{12}

Absorption images of the component $|2\rangle$ are post-processed using "eigenface" fringe-removal algorithm [5]. Axial widths are measured by fitting $2D$ Gaussian functions. The results are fitted with the GPE simulations.

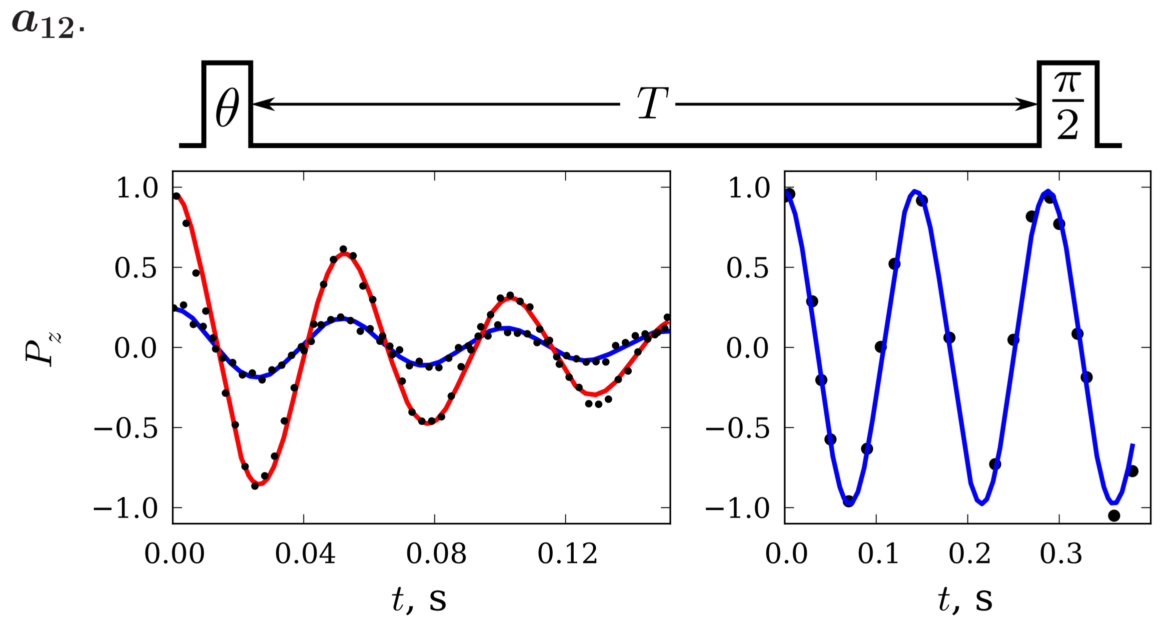


(a) $\theta = \pi/10$, $N = 6.9 \times 10^4$ (b) $\theta = \pi/5$, $N = 7.6 \times 10^4$ (c) $\theta = \pi/10$, $N = 1.1 \times 10^5$ (d) $\theta = \pi/5$, $N = 1.1 \times 10^5$

Fig. 6: Periodic dynamics of axial widths for a range of parameters (a-d).

Measurements of a_{22}

Approximate theory of collisional shift in BEC assumes that collisional shift $\Delta\nu \propto (a_{11} - a_{22})$ when $\theta = \pi/2$ and $\Delta\nu \propto 2(a_{11} - a_{12})$ when $\theta \ll \pi/2$ [6]. Therefore, we can perform measurement of a_{22} relying on our measurement of a_{12}.



(a) BEC ($\theta = \pi/2$ and $\theta = \pi/10$) (b) 10^4 non-condensed atoms

Fig. 7: We perform Ramsey interferometry of BEC ($N = 1.5 \times 10^5$) with $\theta = \pi/10$ (blue line, smaller amplitude) and $\theta = \pi/2$ (red line, larger amplitude) (a) and find the detuning in Ramsey interferometry of 10^4 non-condensed atoms (b).

Measurements of two-body loss coefficients

Previous measurements of two-body loss coefficients at $B = 8.32$ G has shown $\gamma_{12} = 7.8 \times 10^{-20}\ {\rm m^3/s}$ and $\gamma_{22} = 11.94 \times 10^{-20}\ {\rm m^3/s}$ [7]. This is not consistent with our rephasing experiments [2], therefore we perform our measurements of γ_{ij}.

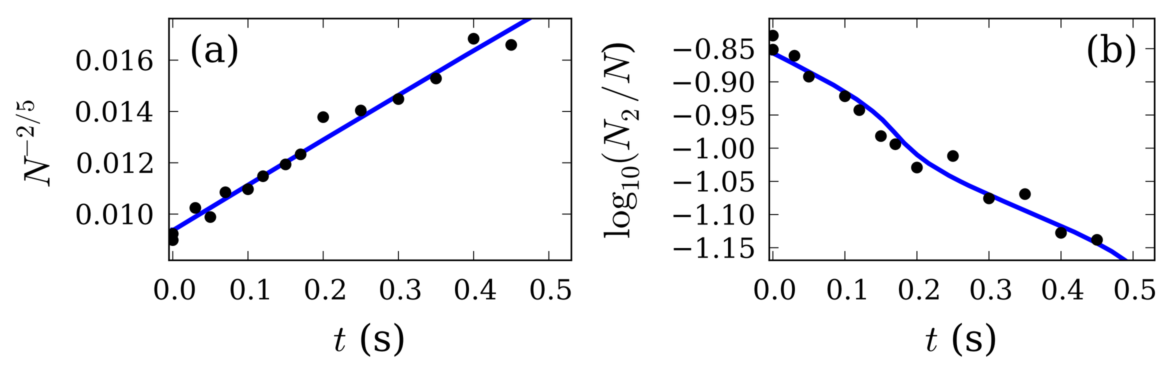


Fig. 8: Measurements of two-body loss coefficients γ_{22} (a) and γ_{12} (b)

For the measurement of γ_{22}, we apply π-pulse and measure population N of the state $|2\rangle$. When BEC adiabatically follows the trapping potential during the loss process, it decays as:

$$N_2^{-\frac{2}{5}}(t) = N_2^{-\frac{2}{5}}(0) + \left[\frac{2}{5}\frac{(2\pi)^{\frac{1}{5}}15^{\frac{2}{5}}}{7a_{22}^{\frac{3}{5}}}\left(\frac{m\bar{f}}{\hbar}\right)^{\frac{6}{5}}\gamma_{22}\right] t, \qquad (5)$$

where $\bar{f}$ is mean trap frequency, therefore we make a plot $N^{-2/5}(t)$ (a) but fit the data with GPE simulations in order to obtain γ_{22}. Knowing that, we measure γ_{12} fitting population decay of state $|2\rangle$ in a two-component BEC prepared by a $\pi/5$-pulse (b).

Interferometric atom number calibration

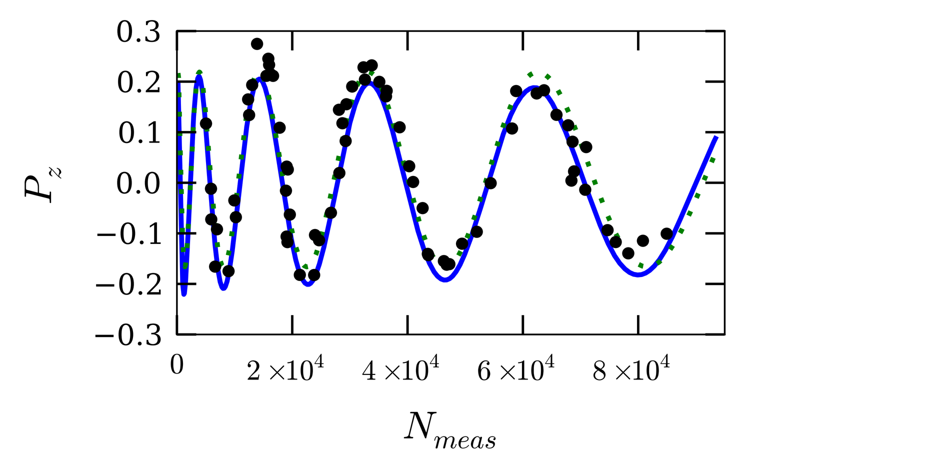


Fig. 9: Fitting of experimental data (black dots) with GPE simulations (solid line) and analytics (dotted line), calibration coefficent k is a free parameter

Analytical predictions show that Ramsey fringe for fixed evolution time t when $\theta \ll \pi/2$ is:

$$P_z(t) = A\cos\left(\frac{t}{\hbar} \times \frac{4\mu}{3}\left(1 - \sqrt{\frac{a_{12}}{a_{11}}}\right) + \varphi_0\right), \qquad (6)$$

if t is proportional to collective oscillations period, while it can also be obtained in GPE simulations as:

$$P_z(N, t, \Delta) = {\rm Im}\left[e^{i(\varphi+\varphi_0)}\int 2\,\Psi_2^*\Psi_1\,d^3{\bf r}\right]/N, \qquad (7)$$

where φ_0 is defined by the radiation detuning. We obtain $k = N/N_{\rm meas} = 1.83(4)$ with $\theta = \pi/10$ and $\theta = \pi/5$.

Results

We report final results with errorbars:

$$a_{12} = 98.006(16)\,a_0, \quad a_{22} = 95.44(7)\,a_0, \qquad (8)$$

$$\gamma_{12} = 1.51(18), \quad \gamma_{22} = 8.1(3), \quad [\times 10^{-20}\ {\rm m^3/s}] \qquad (9)$$

Loss coefficient γ_{12} assumes ${\rm Im}\,(a_{12}) = -0.016\,a_0$, consistent with [8]. Scattering lengths are close to theoretical predictions $a_{12} = 98.13(10)\,a_0$, $a_{22} = 95.68(10)\,a_0$ [8, 9].

References

[1] R. P. Anderson, C. Ticknor, A. I. Sidorov, and B. V. Hall. Spatially inhomogeneous phase evolution of a two-component bose-einstein condensate. *Phys. Rev. A*, 80(2):023603, Aug 2009.

[2] M. Egorov, R. P. Anderson, V. Ivannikov, B. Opanchuk, P. Drummond, B. V. Hall, and A. I. Sidorov. Long-lived periodic revivals of coherence in an interacting Bose-Einstein condensate. *Phys. Rev. A*, 84(2):021605, Aug 2011.

[3] C. Chin and V. Flambaum. Enhanced sensitivity to fundamental constants in ultracold atomic and molecular systems near feshbach resonances. *Phys. Rev. Lett.*, 96(23):230801, 2006.

[4] L. Salasnich, A. Parola, and L. Reatto. Effective wave equations for the dynamics of cigar-shaped and disk-shaped bose condensates. *Phys. Rev. A*, 65(4):043614, 2002.

[5] C. F. Ockeloen, A. F. Tauschinsky, R. J. C. Spreeuw, and S. Whitlock. Improved detection of small atom numbers through image processing. *Phys. Rev. A*, 82(6):061606(R), 2010.

[6] D. Harber, H. Lewandowski, J. McGuirk, and E. Cornell. Effect of cold collisions on spin coherence and resonance shifts in a magnetically trapped ultracold gas. *Phys. Rev. A*, 66(5):053616, 2002.

[7] K. Mertes, J. Merrill, R. Carretero-González, D. Frantzeskakis, P. Kevrekidis, and D. Hall. Nonequilibrium Dynamics and Superfluid Ring Excitations in Binary Bose-Einstein Condensates. *Phys. Rev. Lett.*, 99(19):190402, 2007.

[8] E. G. M. van Kempen, S. J. J. M. F. Kokkelmans, D. J. Heinzen, and B. J. Verhaar. Interisotope determination of ultracold rubidium interactions from three high-precision experiments. *Phys. Rev. Lett.*, 88(9):093201, 2002.

[9] B. J. Verhaar, E. G. M. van Kempen, and S. J. J. M. F. Kokkelmans. Predicting scattering properties of ultracold atoms: Adiabatic accumulated phase method and mass scaling. *Phys. Rev. A*, 79(3):032711, 2009.