Note on "Collective Excitations of a Degenerate Gas at the BEC-BCS Crossover", Phys. Rev. Lett. 92, 203201 (2004)

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We present a reinterpretation of our previous results on the radial compression mode of a degenerate quantum gas in the BEC-BCS crossover in [1]. We show that our former data are consistent with other experimental and theoretical work, when the ellipticity of the optical trapping potential in [1] is properly taken into account .

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The radial compression mode of an optically trapped, ultracold ^{6}Li Fermi gas in the BEC-BCS crossover regime has been a focus of study of experimental work performed at Innsbruck University [1, 2] and at Duke University [3, 4, 5]. In our most recent work [2], we reached a level of control which allows us to identify systematic effects in our measurements. With our new knowledge of the system, we can reinterpret the previous data and resolve the apparent discrepancy between [1] and [2, 3, 4].

The atoms are trapped by a single focused laser beam resulting in a cigar-shaped trap geometry. In [1], we assumed cylindrical symmetry along the z-axis of the trapping potential, where the trap frequencies ω_x and ω_y in x- and y-direction are equal. With this assumption we used ω_y as the relevant radial trap frequency ω_r.

The experimental setup of [1] was only capable to resolve oscillations in y- and z-direction. With a new imaging system along the z-axis we now get full access to the x- and y-directions and are able to determine the two transverse trapping frequencies individually. In contrast to the assumption of cylindrical symmetry in [1], we found significant ellipticity of the trap, being characterized by an aspect ratio $\zeta = \omega_x/\omega_y$. For the experimental trap setup of [1] we found an aspect ratio of $\zeta \approx 0.8$ [7].

To calculate the frequency ω_c of the compression mode in the elliptic trap, we start from the triaxial eigenfrequency equation (e.g. [6]) and neglect the weak confinement in z-direction. This gives the collective mode frequencies ω (compression mode and surface mode)

$$\omega^4 - (2+\Gamma)(\omega_x^2+\omega_y^2)\omega^2 + 4(\Gamma+1)\omega_x^2\omega_y^2 = 0, \tag{1}$$

where Γ is the polytropic interaction index. From equation (1) the frequency of the radial compression mode ω_c can be calculated [6]. This results in

$$\left(\frac{\omega_c}{\omega_y}\right)^2 = \frac{1}{2}\left(2+\Gamma\right)\left(1+\zeta^2\right) + \sqrt{\left(\frac{1}{2}\left(2+\Gamma\right)\left(1+\zeta^2\right)\right)^2 - 4\left(\Gamma+1\right)\zeta^2}, \tag{2}$$

where ω_c is normalized to ω_y, corresponding to the way we presented our data in [1].

In Fig. 1 the experimental data of [1] and theoretical data [8] corresponding to a mean-field BCS model (lower curve) and a quantum Monte-Carlo model (upper curve), both models assuming $\zeta = 0.8$, are shown. The same data set is plotted versus the magnetic field (left-hand side) and the interaction parameter $1/k_Fa$ (right-hand side), where a represents the atom-atom scattering length and k_F is the Fermi wave number.

In the BEC limit ($\Gamma = 2$) the data fit well with the theoretically expected value of 1.85. In the unitarity regime at resonance ($\Gamma = \frac{2}{3}$), the experimental data also fit well if one includes a small anharmonicity shift, which corrects $\omega_c/\omega_y = 1.62(2)$ to $\omega_c/\omega_y = 1.67(3)$ [1]. In the strongly interacting BEC regime the data can be compared with the theoretical models using equation (2). Above resonance, we see a larger downshift in frequency until a jump to $\omega_c/\omega_y \approx 2$ happens and the frequency remains constant.

In the strongly interacting BEC regime, at magnetic fields just below the Feshbach resonance or $2 > 1/k_Fa > 0.5$, the experimental data points lie between both theoretical curves. In our latest precision measurements [2], the data clearly support the quantum Monte-Carlo model and they also show a downshift in frequency for increased temperatures. This is consistent with the data presented in Fig. 1, taking into account the relatively high temperature of the sample. Note that the temperatures in [1] are higher than in [2] as the evaporation ramp was not optimized to achieve deepest temperatures and the timing sequence was not optimized to minimize heating.

At magnetic fields above the Feshbach resonance ($1/k_Fa \lesssim 0$), the data show a significant downshift compared to the theoretically expected values, which we cannot explain by the elliptical trap. Also other experiments show a similar trend [4, 10]. The proximity of the energy corresponding to the collective mode frequency to the pairing gap [11] and

thermal effects may be possible explanations for this downshift.
At a magnetic field of about 900G ($1/k_Fa \approx -0.5$), the normalized frequency shows a pronounced jump up to the value of approximately 2, which is expected in a collisionless Fermi gas. For the collisionless oscillation along the y-axis, the ellipticity of the trap is irrelevant. So the visibility of the jump is clearly enhanced in an elliptic trap, as the lower frequency side of the jump in an elliptic trap is downshifted compared to a cylindrically symmetric trap. This jump marks the transition from hydrodynamic to collisionless behavior.

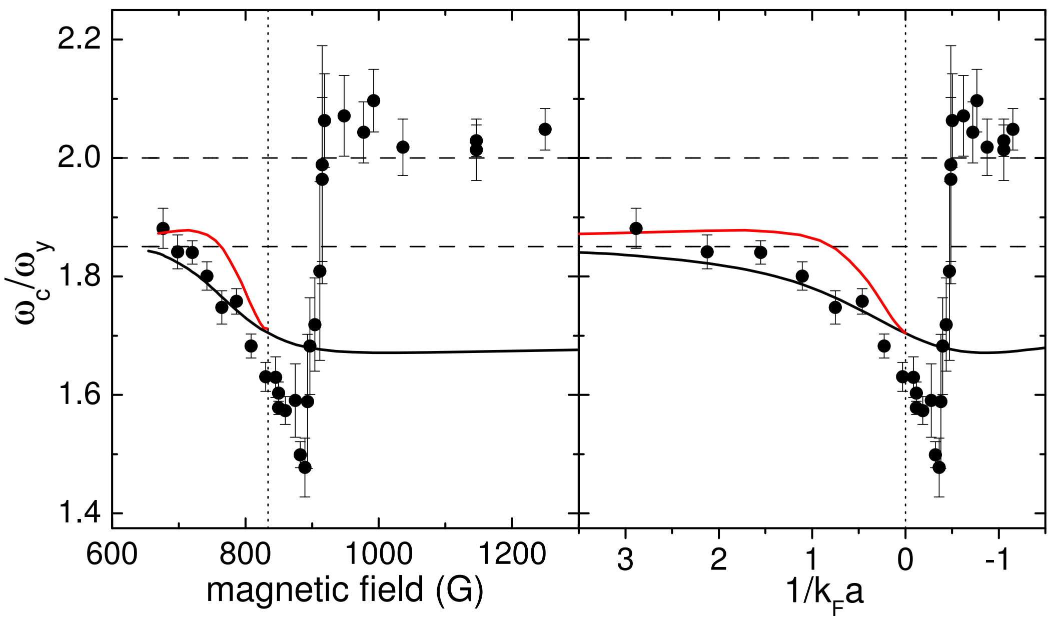

FIG. 1: Normalized compression mode frequency ω_c/ω_y in the BEC-BCS crossover regime versus magnetic field (left hand side) and interaction parameter $1/k_Fa$ (right hand side) [1]. The lower theory curve is based on a mean-field BCS model and the upper curve on a quantum Monte-Carlo model. Both curves correspond to the theoretical data presented in [8]. The horizontal dashed lines indicate the values for the BEC limit ($\omega_c/\omega_y = 1.851$ for $\zeta = 0.8$) and the collisionless limit ($\omega_c/\omega_y = 2$). The vertical dotted line marks the position of the Feshbach resonance at 834.1G [9].

In conclusion, by taking into account the ellipticity of the trapping potential, the results of [1] now essentially agree with other experimental results [2, 3, 4] and theoretical predictions [8].
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