Physics Letters A 379 (2015) 327–332

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Precision measurement of a trapping potential for an ultracold gas

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ARTICLE INFO

Article history:
Received 24 July 2014
Received in revised form 18 October 2014
Accepted 27 October 2014
Available online 29 November 2014
Communicated by P.R. Holland

ABSTRACT

Parametric excitation of ultracold atomic gases in optical dipole traps strongly depends on the trap anharmonicity. For non-interacting gases, the anharmonicity prevents energy input beyond certain level. We use this as a basis for precision measurement of trap parameters. The frequencies and depth are derived from comparison of the excitation spectrum to models, where the anharmonicity is treated non-perturbatively. Measurements are done for both quantum and classical motion of trapped atoms. For the classical motion, the validity of the model is crosschecked in an independent experiment.

1. Introduction

Several paradigmatic quantum models for the first time have been realized in experiments with ultracold atoms. These models include Bogoliubov's weakly-interacting Bose gas [1], Bertsch's Fermi matter with resonantly-strong interactions [2], crossover between the Bardeen–Cooper–Schrieffer superfluidity and Bose condensation [3], Tonks–Girardeau fermionization of one-dimensional Bose gas [4], and Efimov trimer bound states [5]. Owing to purity of atomic systems and control of parameters, ultracold atoms are used for quantitative tests of many-body quantum theories including those applicable to solid-state, high-energy, and nuclear physics [6–8].

Quantitative comparison of data to theory requires precision knowledge of external potentials, which are used for holding the ultracold atoms. These potentials are formed by magnetic or optical fields. Optical dipole traps [9] are particularly popular: In such traps, the magnetic field is a free parameter and may be used for tuning the interactions by means of the magnetic Fano–Feshbach resonances [10]. An optical dipole trap may be formed by a focus of a traveling wave or by a standing-wave antinode [Fig. 1(a)]. The shape of the optical dipole potential is the same as the intensity distribution of the optical field. Close to the potential minimum, such traps are nearly harmonic with the frequencies ω_x, ω_y, and ω_z, which may be measured by parametric heating of the atoms: When the laser power is modulated as

$$P(t) \propto 1 + \alpha \sin \omega t, \quad \text{with } |\alpha| \ll 1, \tag{1}$$

the trap depth and values of ω_i^2 (i stands for x, y, or z) vary at the same rate; whenever ω is near $2\omega_i$, the modulation pumps energy into the gas and may deplete the atoms from the trap [11]. In the atom loss spectrum, the peak is always shifted to ω values somewhat below $2\omega_i$ because the traps actually deviate from the harmonic shape. The shift is strongly affected by the soft edges of the real potentials, such as the one of Fig. 1(d). Calculation of this shift and hence the measurement of the trap frequencies in a real experiment is prone to errors: The exact shape of the potential edge may be unknown because of admixture of laser modes beyond TE_{00} as well as the influence of the gravity [12] and magnetic-field gradients. Avoiding excitation to the top of the trap reduces the anharmonic effects: Small addition of energy may be measured [13] instead of monitoring the atom loss. Experimentally it was later found that the maximal loss and the minimal number of low-energy atoms occur at different ω values [14]. Alternatively, edge effects may be avoided when various oscillatory modes of a trapped gas are measured [13,15–17]. Methods based on these collective modes impose a technical limit: The frequency of oscillations along the observation direction is not measurable.

The anharmonicity is an unwanted effect in all methods available to date. In precision measurements, anharmonic effects are minimized whenever possible. Then to derive the trap parameters from the measurements, the anharmonicity effects are treated perturbatively. The analysis in many cases is complicated by the atom–atom interactions, e.g. in Refs. [16,17].

Here the anharmonicity is turned into an advantage. Anharmonic effects in parametric excitation are used for precision measurements of the trap frequencies. Experimentally and numerically we find that for small excitation amplitude, the energy input into an ideal gas saturates at levels much below the trap depth. This

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http://dx.doi.org/10.1016/j.physleta.2014.10.049
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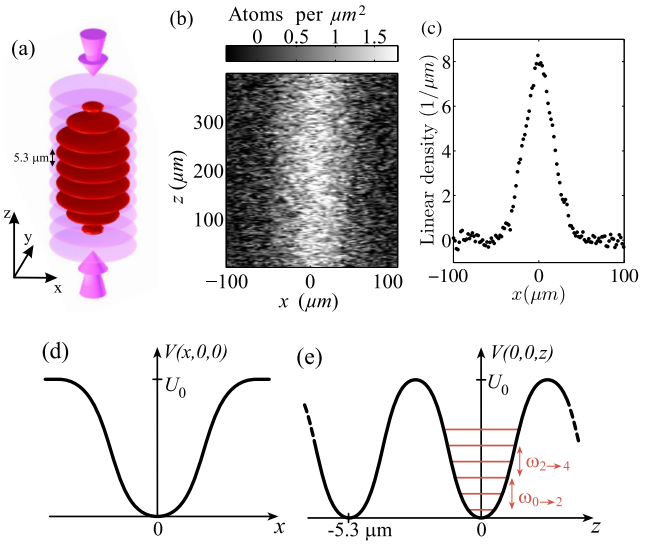

Fig. 1. (a) Trapping ultracold atoms in antinodes of a standing optical wave. The isolated clouds of atoms are shown in dark red, the standing-wave intensity is shown in light purple. (b) An image of the series of the clouds taken along the y direction after short expansion that makes adjacent clouds overlap but leaves the density distribution along x nearly unchanged. (c) Linear profile $n_1(x)$ obtained by integrating Fig. 1(b) along z. (d) Potential in direction x. (e) Periodic potential along z. Few lowest Bloch bands schematically shown in red. Band separation is unequal, even for the lowest bands: $\omega_{0\to2} > \omega_{2\to4}$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

precludes excitation to the top of the potential and removes uncertainties related to the trap edges.

Trap parameters are measured for both possible situations: for quantized motion in the trap and for classical motion. Measured dependence of the energy input on the drive frequency ω is compared to *ab initio* non-perturbative calculation of particle dynamics and excitation spectrum. Such *ab initio* calculation is possible because a non-interacting gas is used in the experiment: Interactions, such as in Ref. [11], would complicate the dynamics and excitation spectrum. The comparison between our non-perturbative model and experiment gives trap frequencies and depth, with no systematic errors related to trap anharmonicity. Also the measured dependence of the energy input on the pump time is used for checking the validity of the models. The focus is on characterizing a pancake-shaped potential [Fig. 1(a)] recently used in precision measurements on quasi-two-dimensional Fermi and Bose gases [18]. The same approach may be applied for finding parameters of cigar-shaped dipole traps as well.

In Section 2, the optical dipole potential and the gas preparation are described. Section 3 is devoted to measuring the trap depth U_0 and frequency ω_z for the tight direction, where the motion is quantized. In Section 4, the classical motion along the x and y is considered; measurement of ω_x and ω_y is described; the saturation of energy input is demonstrated qualitatively within a simplified analytic model and observed in an experiment and a quantitative numerical model.

2. The trapping potential and gas preparation

A series of pancake-shaped potentials is created by a standing electromagnetic wave formed by two counterpropagating TE_{00} beams with fully overlapping foci, identical power and polarization, and the wavelength of 10.6 μm [19]. The potential felt by each atom is

$$V(\vec{\rho}, z) = U_0\left[1 - \exp\left(-\frac{x^2}{\rho_x^2} - \frac{y^2}{\rho_y^2}\right)\cos^2 kz\right], \tag{2}$$

where $\vec{\rho} = (x, y)$, ρ_x and ρ_y are the radii of the potential along the x and y direction respectively, $k = 2\pi/(10.6\ \mu\text{m})$ is the wave vector, and U_0 is the trap depth. In Eq. (2), we neglect the beam divergence, because the Rayleigh length $\simeq$3.1 mm is much bigger than the $\simeq$340 μm long region used for measurements. At the bottom of each well, the potential is close to the harmonic shape with $\omega_x^2 = 2U_0/m\rho_x^2$, $\omega_y^2 = 2U_0/m\rho_y^2$, and $\omega_z = 2\sqrt{U_0 E_{\text{rec}}}/\hbar$, where m is the mass of the lithium-6 atom used in experiments and $E_{\text{rec}} = \hbar^2k^2/2m$ is the recoil energy of the periodic potential.

For measuring the frequencies we prepare a nearly ideal Fermi gas and monitor parametric excitations. For the gas preparation, the techniques initially developed for cigar-shaped traps [20,21] are adapted to pancake-shaped potentials [22]. During the first 8 s of preparation, 10^8–10^9 atoms are collected in a magneto-optical trap (MOT) from an atomic beam. After the MOT fields are turned off, $\sim 10^6$ atoms remain trapped in the standing-wave dipole-trap potential (2), which spatially overlaps with the MOT and whose depth is $U_0 \simeq 280$ μK. The lithium-6 atoms are equally populating internal states with the lowest energy, $|1\rangle$ and $|2\rangle$ [19], which are respectively identical to $|F = 1/2, F_z = \pm 1/2\rangle$ at magnetic field $B = 0$. Immediately after the MOT is off, a nearly uniform magnetic field along the $-y$ direction is raised from $B = 0$ to 300 G. At this field, the s-wave scattering length $a = -300$ Bohr, which is a local maximum of $|a|$. The high scattering rate allows to perform evaporative cooling. At the end of the 21-second evaporation, B is adiabatically tuned to 528 G where $a = 0$ and the gas is nearly non-interacting [23]. By the end of the gas preparation, the potential is raised to the final value where the frequencies are measured. A typical set of measured frequencies of potential (2) is $\omega_x/2\pi = 201.7 \pm 0.5$ Hz, $\omega_y/2\pi = 312.6 \pm 2.2$ Hz, and $\omega_z/2\pi = 13\,090 \pm 90$ Hz ($\omega_\perp \equiv \sqrt{\omega_x\omega_y} = \omega_z/52.1$, $\omega_y/\omega_x = 1.55 \pm 0.01$). The values drift on the scale of $\simeq$0.2% per hour possibly due to changes in the laser power and alignment of the beams forming potential (2).

The gas occupies about 160 potential wells. For the analysis, we use about 60 central cells with nearly the same occupation of N atoms per spin state, which is in the range $N = 200$–400 depending on particular experiment. The respective Fermi energy is $E_F = \hbar\omega_\perp\sqrt{2N} = (0.4\text{–}0.5)\hbar\omega_z$. The temperature of the gas is measured as in Ref. [19] and found in the range $T = (0.5\text{–}0.7)E_F$. On average, $T = 0.6E_F$ and $N = 330$, which corresponds to 96% of atoms occupying the lowest state of motion along z.

3. Measurement of the trap depth and frequency for quantized motion

For the parametric drive at frequencies near $\omega = 2\omega_z$, the dynamics is quantum because the majority of atoms occupies the lowest Bloch band prior to the excitation. The separation of the Bloch bands is that of the simpler potential

$$V_\parallel(z) = U_0 \sin^2 kz. \tag{3}$$

The bands are schematically shown in Fig. 1(e). The atoms are excited from the 0th to the 2nd band when $\omega = \omega_{0\to2}$, where $\omega_{i\to j}$ designates separation between the ith and jth band. The anharmonicity prevents further energy input: Since $\omega_{2\to4} < \omega_{0\to2}$, the atoms may not be excited to the 4th band by the drive at $\omega = \omega_{0\to2}$. Termination of the energy input justifies the use of simplified potential (3), as opposed to (2), because the atoms do not progress to the trap top, where all three directions of motion are coupled.

The images are taken along the y direction, i.e. along the plane of the flat clouds as may be noted from Fig. 1(a). Individual clouds may be easily resolved [19], however, the resolution is not sufficient to see the thickening of the clouds along z as the atoms progress to the 2nd excited band.