Sci. Bull. (2016) 61(14):1097–1106
DOI 10.1007/s11434-016-1123-x

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Review

Physics & Astronomy

Magnetic lattices for ultracold atoms and degenerate quantum gases

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Received: 16 April 2016 / Revised: 6 June 2016 / Accepted: 8 June 2016 / Published online: 27 June 2016

Abstract We review recent developments in the use of magnetic lattices as a complementary tool to optical lattices for trapping periodic arrays of ultracold atoms and degenerate quantum gases. Recent advances include the realisation of Bose–Einstein condensation in multiple sites of a magnetic lattice of one-dimensional microtraps, the trapping of ultracold atoms in square and triangular magnetic lattices, and the fabrication of magnetic lattice structures with submicron period suitable for quantum tunnelling experiments. Finally, we describe a proposal to utilise long-range interacting Rydberg atoms in a large spacing magnetic lattice to create interactions between atoms on neighbouring sites.

Keywords Magnetic lattices · Ultracold atoms · Degenerate quantum gases · Quantum simulation

1 Introduction

Since the advent of laser cooling and trapping techniques in the 1980s and 1990s [1–3], optical lattices produced by interfering laser beams have become an indispensable tool for trapping periodic arrays of ultracold atoms and degenerate quantum gases (see, e.g., Refs. [4–6] for reviews). Applications include quantum simulations of condensed matter phenomena [6], trapping of atom arrays in high precision atomic clocks [7] and quantum gas microscopes [8], and the realisation of quantum gates for quantum information processing [9, 10]. These "artificial crystals" allow precise control over system parameters, such as the lattice geometry, inter-particle interaction and lattice perfection, and, in principle, provide an ideal platform to achieve almost perfect realisations of a variety of condensed matter phenomena (e.g., Refs. [5, 6]). Examples include the superfluid to Mott insulator transition [11], the metal to insulator crossover in honeycomb lattices [12], the Ising spin model for a 1D spin chain [13], the Hubbard model involving antiferromagnetic correlations [14], low-dimensional quantum systems [15, 16], disordered systems involving Anderson localisation [17, 18], topological edge states and the quantum Hall effect [19], and arrays of Josephson junctions [20].

An alternative approach for producing periodic lattices for trapping ultracold atoms involves the use of arrays of magnetic microtraps created by patterned magnetic films [21–36], current-carrying conductors [37–40], nano-magnetic domain walls [41], vortex arrays in super-conducting films [42] or pulsed gradient magnetic fields [43, 44]. In the present mini-review, we focus on recent developments in the trapping of ultracold atoms in magnetic lattices of microtraps based on patterned magnetic films. These magnetic lattices have a high degree of design flexibility and may, in principle, be tailored with nearly arbitrary configurations and lattice spacing [29] without restrictions imposed by optical wavelengths. In addition, magnetic lattices do not require (intense) laser beams, they are free of spontaneous emission, they have relatively little technical noise or heating, and they involve state-selective

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atom trapping allowing radio-frequency (RF) evaporative cooling to be performed in the lattice and RF spectroscopy to be used to characterise the trapped atoms in situ [45, 46]. Finally, magnetic lattices are well suited for mounting on atom chips and incorporating into devices such as "atomtronic" circuits [47]. However, magnetic lattices are still in their infancy compared with optical lattices, due largely to the difficulty of fabricating suitable magnetic microstructures with well controlled potentials, especially lattices with sub-micron periods suitable for quantum tunnelling.

In this article we review recent progress in the development of magnetic lattices based on patterned magnetic films for trapping periodic arrays of ultracold atoms and degenerate quantum gases, and discuss future prospects for the application of magnetic lattices.

2 One-dimensional magnetic lattices

Magnetic lattices consisting of arrays of one-dimensional microtraps are a useful testing ground prior to progressing to more complex two-dimensional geometries. They are a natural extension of the magnetic mirrors [48] proposed by Opat et al. [49] and subsequently realised using arrays of permanent magnets [50–52] and current-carrying conductors [53–55]. A magnetic mirror may be turned into a magnetic lattice of 1D microtraps by applying a uniform bias field to interfere with the rotating magnetic field of the periodic array (Fig. 1a), as described by Eq. (1) below.

For an infinite periodic array of long magnets in the x–y plane with perpendicular magnetisation M_z, periodicity a and bias fields B_{bx}, B_{by}, the magnetic field components at distances $z \gg a/2\pi$ from the bottom of the magnets are given approximately by [22]

$$\left[B_x; B_y; B_z\right] \approx \left[B_{bx}; B_0 \sin(ky)\mathrm{e}^{-kz} + B_{by}; B_0 \cos(ky)\mathrm{e}^{-kz}\right], \tag{1}$$

where $k = 2\pi/a$, $B_0 = 4M_z(\mathrm{e}^{kt} - 1)$ is a characteristic surface magnetic field (in Gaussian units), and t is the thickness of the magnets. The magnetic field minimum (or trap bottom) $B_{\min}$, trapping height $z_{\min}$, barrier heights $\Delta B_{y,z}$, and trap frequencies $\omega_{y,z}$ for an atom of mass m in a harmonic trapping potential are given by

$$B_{\min} = |B_{bx}|, \tag{2}$$

$$z_{\min} = \frac{a}{2\pi} \ln\left(\frac{B_0}{|B_{by}|}\right), \tag{3}$$

$$\Delta B_y = \left(B_{bx}^2 + 4B_{by}^2\right)^{1/2} - |B_{bx}|, \tag{4a}$$

$$\Delta B_z = \left(B_{bx}^2 + B_{by}^2\right)^{1/2} - |B_{bx}|, \tag{4b}$$

$$\omega_y = \omega_z = \omega_{\mathrm{rad}} = \frac{2\pi}{a}\left(\frac{m_F g_F \mu_{\mathrm{B}}}{m|B_{bx}|}\right)^{1/2} |B_{by}|, \tag{5}$$

where m_F is the magnetic quantum number, g_F is the Landé g-factor and μ_{B} is the Bohr magneton. $B_{\min}$, $z_{\min}$, $\Delta B_{y,z}$ and $\omega_{y,z}$ may all be controlled by adjusting the bias fields B_{bx} and B_{by}. Equations (1)–(5) illustrate how the characteristics of the magnetic lattice can be varied by varying the bias fields B_{bx}, B_{by} and how the magnetic lattice can be switched on or off by switching B_{by} on or off. Equations (2)–(5) are useful for providing scalings for the various parameters.

In 2005, Sinclair et al. [56] created a periodic array of 1D magnetic traps, or magnetic "waveguides", made from a sinusoidal magnetisation pattern of period 106 μm written on videotape plus bias fields, and successfully produced a single Bose–Einstein condensate (BEC) in one of the waveguides. In 2007, Boyd et al. [57] created an array of 1D traps produced by a hard disk platter written with a periodic pattern of period 100 μm plus bias fields, and produced a condensate in one of the traps.

In 2008, Singh et al. [26] produced a 10 μm-period magnetic lattice of 1000 1D traps formed from a perpendicularly magnetised 1 μm-thick TbGdFeCo film on a grooved silicon substrate on an atom chip plus bias fields (Fig. 1b). About 10^8 ^{87}Rb atoms were initially trapped in a mirror magneto-optical trap (MOT) and then confined in a compressed MOT using the quadrupole field from a current-carrying U-wire plus bias field. Atoms in the $|F = 2, m_F = +2\rangle$ low field-seeking state were then transferred to a Z-wire magnetic trap where they were RF evaporatively cooled to ~15 μK [60].

The atoms in the Z-wire trap were then brought close (~5 μm) to the chip surface by ramping down the Z-wire current (I_z) and ramping up the bias field B_{by} to 30 G to create the magnetic lattice microtraps. When the Z-wire trap merged with the magnetic lattice traps, I_z was reduced to zero with $B_{bx} = B_{\min} = 15$ G. In this way, typically 3×10^6 atoms were loaded into ~100 magnetic lattice traps in the central region of the lattice, with barrier heights ~1 mK and trap frequencies in the range $\omega_{\mathrm{rad}}/2\pi = 20$–$90$ kHz, $\omega_{ax}/2\pi \approx 1$ Hz. Radiofrequency spectroscopy measurements indicated temperatures >150 μK, which were limited largely by the weak axial confinement that prevented efficient evaporative cooling in the lattice.

3 Bose–Einstein condensation in multiple magnetic lattice sites

A significant breakthrough was made in recent experiments by Jose et al. [33] and Surendran et al. [35] using the above magnetic lattice chip. The ^{87}Rb atoms were optically