Bouncing Bose-Einstein Condensates: A Novel Path to Discrete Time Crystals

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In recent years, the idea of time crystals-states in which a periodically driven many-body system spontaneously breaks time-translation symmetry-has gained considerable attention. These systems exhibit ultra-stable, subharmonic oscillations that lock to the external drive and remain robust against external disturbances, promising new avenues for quantum technology. Our work is dedicated to the experimental realization of a discrete time crystal using a Bose-Einstein condensate of potassium-39 atoms. By employing a periodically modulated atomic mirror, we induce a resonant bouncing behaviour in the weakly interacting condensate. This bouncing motion stabilizes into long-lived orbits with periods that are integer multiples of the driving period, effectively creating a temporal lattice comprising many distinct sites [1]. We utilize potassium-39 atoms due to their advantageous interaction properties, which include several broad Feshbach resonances [2]. These resonances allow for precise tuning of the attractive interactions near the zero crossing. Initially, we cool approximately 8×10^8 atoms using a two-dimensional magneto-optical trap (MOT) that loads into a three-dimensional MOT at a temperature of 2.6 mK. Given the small hyperfine splitting in the excited state, conventional laser cooling does not reach the Doppler limit. Therefore, we implement a hybrid D2/D1 MOT scheme along with grey molasses on the D1 line, successfully cooling the atoms to 6 μK. The cold ensemble is then transferred into a 1064 nm crossed-beam dipole trap, where we have identified four broad Feshbach resonances at 32.6, 59, 163, and 403 G. The 32.6 G resonance is exploited for evaporative cooling, moving us closer to achieving quantum degeneracy. In the final phase, the Bose-condensed atoms are dropped from a height of about 150 μm onto an atomic mirror generated by a 532 nm fibre laser beam modulated at 2.8 kHz. When the mirror's modulation frequency is synchronized with the atoms' bouncing period, a sequence of 30 stable wavepackets emerges-each acting as a site in a temporal lattice. By tuning the scattering length to a slightly negative value (approximately -1.6a_0), tunnelling between adjacent sites is suppressed, stabilizing a large-scale discrete time crystal (s = 30). This experimental platform not only demonstrates the creation of time crystals over many temporal lattice sites but also paves the way for exploring condensed matter phenomena in the time domain, including the development of "time-tronics" [3] as a time-based analogue to conventional electronics or atomtronics.

[1] K. Sacha, Physical Review A 98, 013613 (2015).
[2] K. Giergiel et al., New Journal of Physics 22, 085004 (2020).
[3] K. Giergiel, P. Hannaford and K. Sacha, arXiv: 2406.06387 (2024).