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Coherent Three-Photon Excitation of the Strontium Clock Transition

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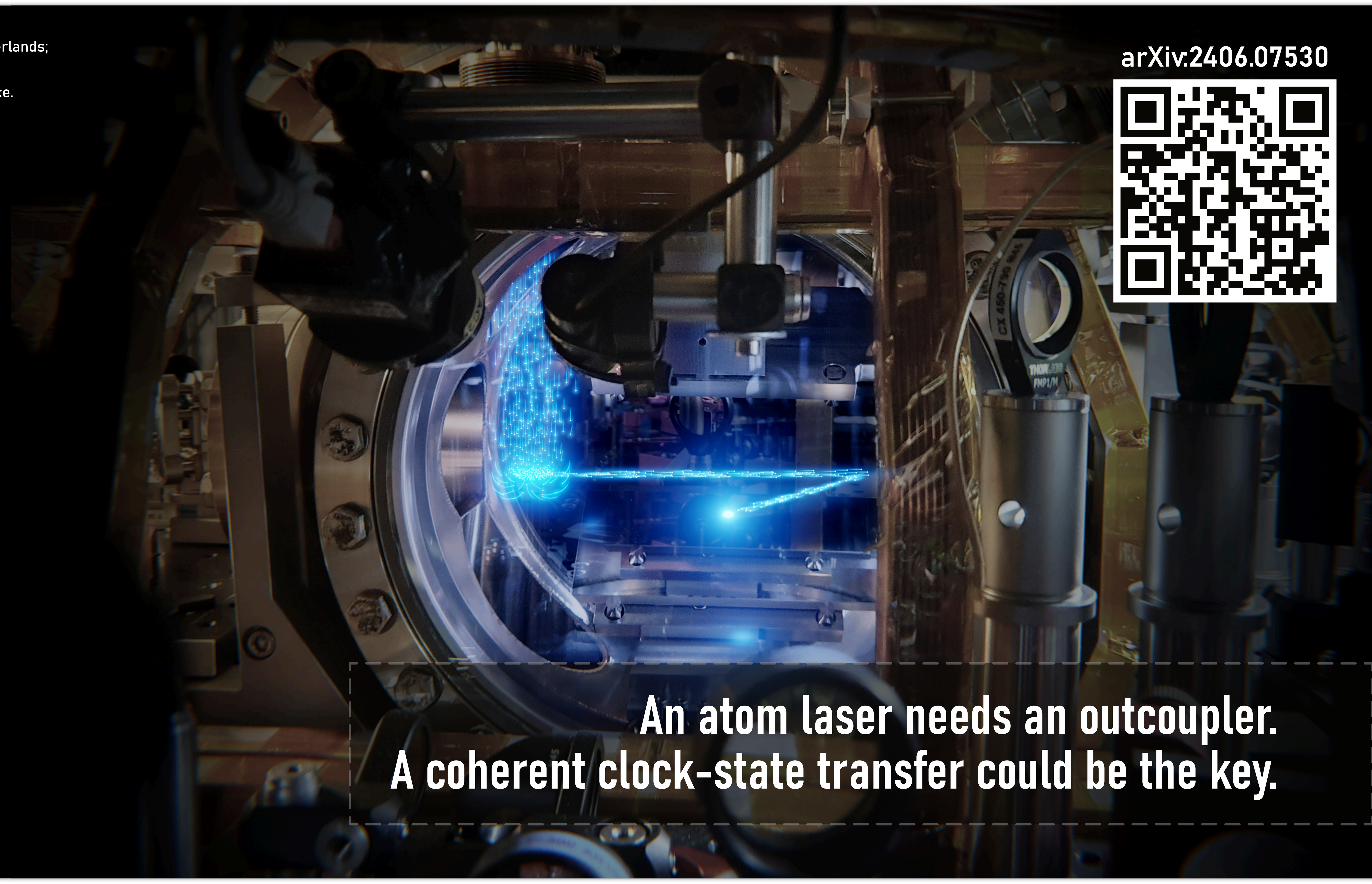
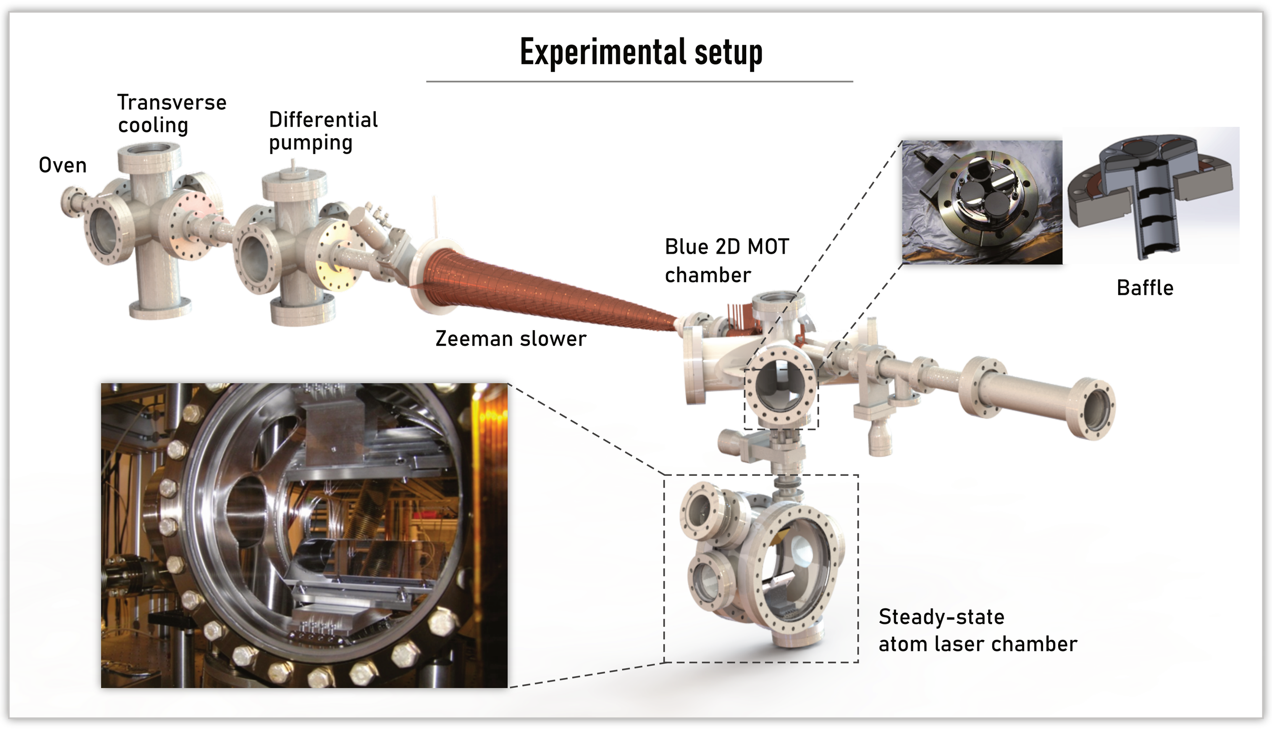
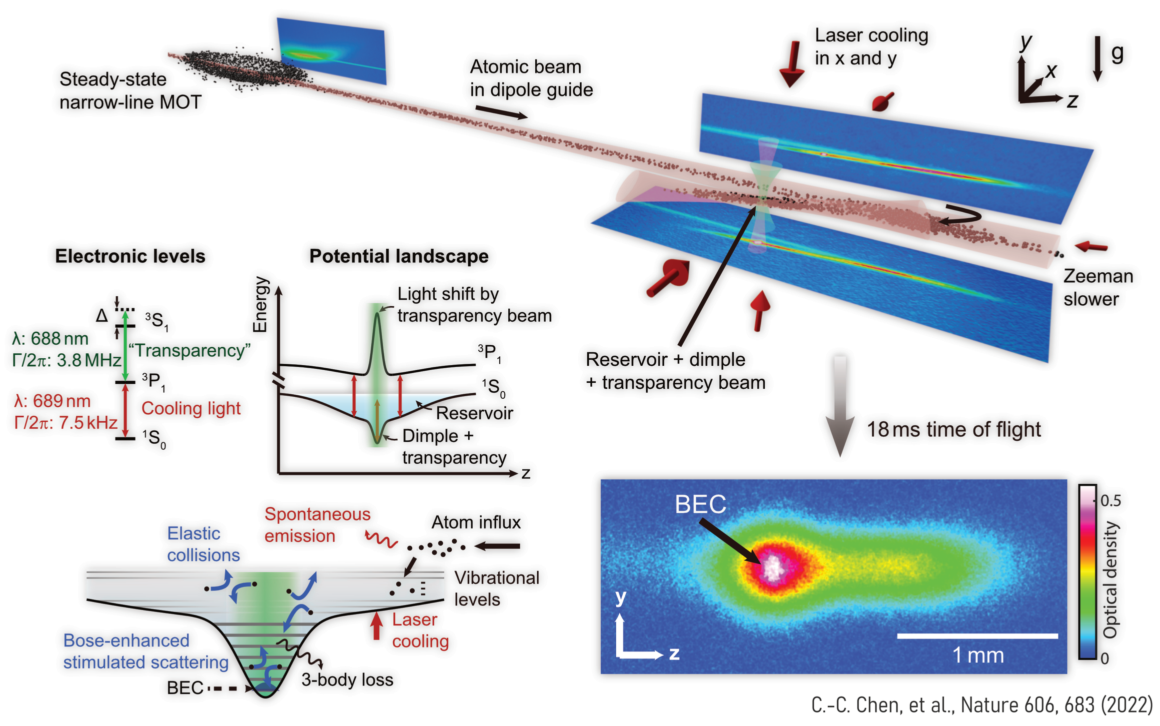
We recently demonstrated a continuous Bose-Einstein condensate of strontium atoms. We could turn this into a continuous-wave atom laser if an efficient outcoupling mechanism is found. Here we show a coherent three-photon excitation of the clock transition in a strontium BEC with contrast of 44.6(3.5)%. We follow it up with a demonstration of three-photon STIRAP-like transfer. Our work constitutes an essential step towards the outcoupling of a continuous atom laser beam and provides a robust excitation mechanism for quantum simulation.



An atom laser needs an outcoupler. A coherent clock-state transfer could be the key.

Continuous Bose-Einstein condensate

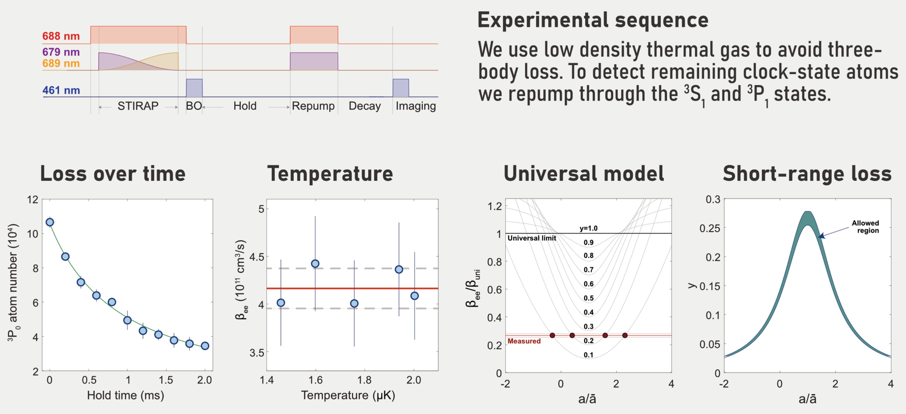




C.-C. Chen, et al., Nature 606, 683 (2022)

By coherently transferring to the clock state, we could outcouple an atom laser beam from the steady-state BEC.

Collisional loss



Experimental sequence
We use low density thermal gas to avoid three-body loss. To detect remaining clock-state atoms we repump through the $^3S_1$ and $^3P_1$ states.

We fit atom loss data with a two-body loss model. It explains the data fully.

We find no temperature dependence, as expected for s-wave collisions.

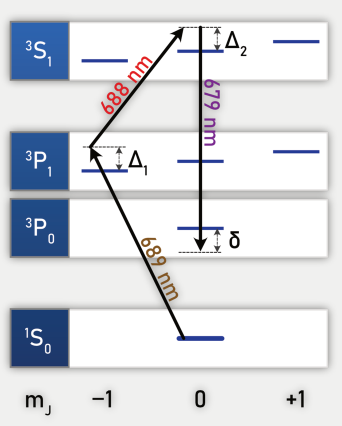
We measure a loss coefficient of $4.2(2)\times10^{-11}$ cm^3s^{-1}, four times below the universal limit.

We determine an upper limit on the short range loss probability, $y < 0.268(13)$.

Clock-state-atom collisions are inherently lossy. We measure a loss coefficient a quarter of the universal limit.

M. Bishof, et al., Phys. Rev. A 84, 052716 (2011)
A. Traverso, et al., Phys. Rev. A 79, 060702 (2009)
C. Lisdat, et al., Phys. Rev. Lett. 103, 090801 (2009)

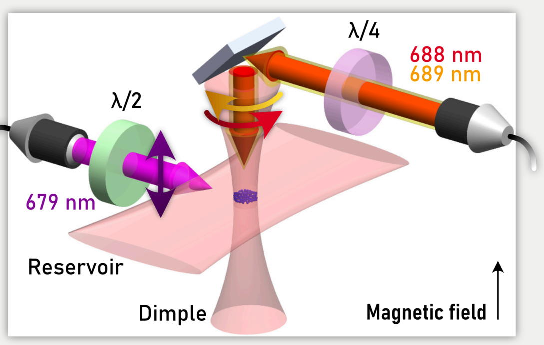
Three-photon transition



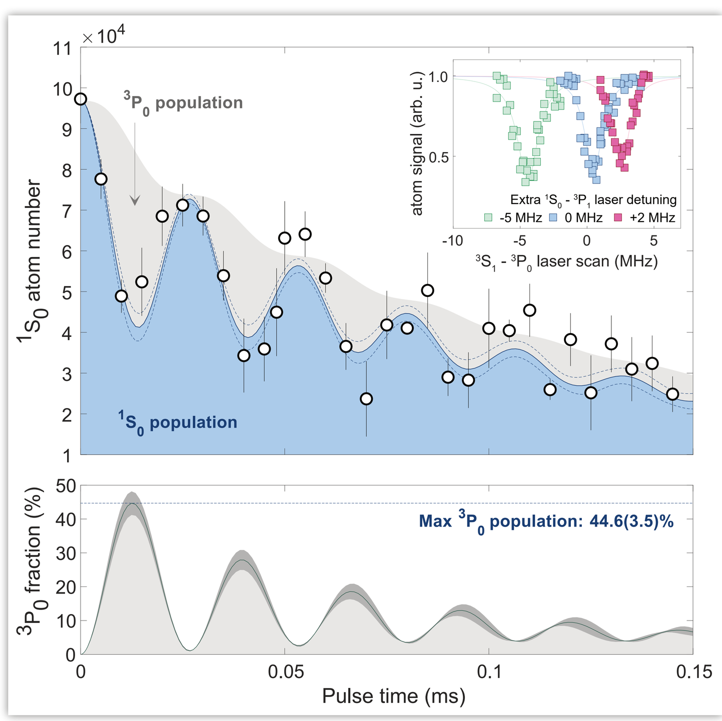
Directly driving the $^1S_0$-$^3P_0$ clock transition would require excessive magnetic or laser fields. Instead, we choose a three-photon Raman coupling via intermediate $^3P_1$ and $^3S_1$ states.

Z. W. Barber, et al., Phys. Rev. Lett. 96, 083002 (2006)
D. S. Barker, et al., Phys. Rev. A 93, 053417 (2016)
T. Hong, et al., Phys. Rev. Lett. 94, 050801 (2005)

To avoid destructive interference from the magnetic sublevels in the $^3P_1$ and $^3S_1$ states, we carefully choose our laser polarizations. We use a small magnetic field to setup the quantization axis.



Rabi oscillation



In a ^{84}Sr Bose-Einstein condensate we drive coherent Rabi oscillations. Several oscillations are visible.

Using an optical Bloch equations model we determine a Rabi frequency $\Omega = 2\pi \times 37.4(6)$ kHz. This agrees with a theoretical prediction of

$$\Omega = \frac{\Omega_1 \Omega_2 \Omega_3}{4\,\Delta_1(\Delta_2 - \Delta_1) - \Omega_2^2} = 2\pi \times 32.2(5.0)\ \text{kHz}.$$

From the optical Bloch equation model we also determine the maximum clock-state population of 44.6(3.5) %.

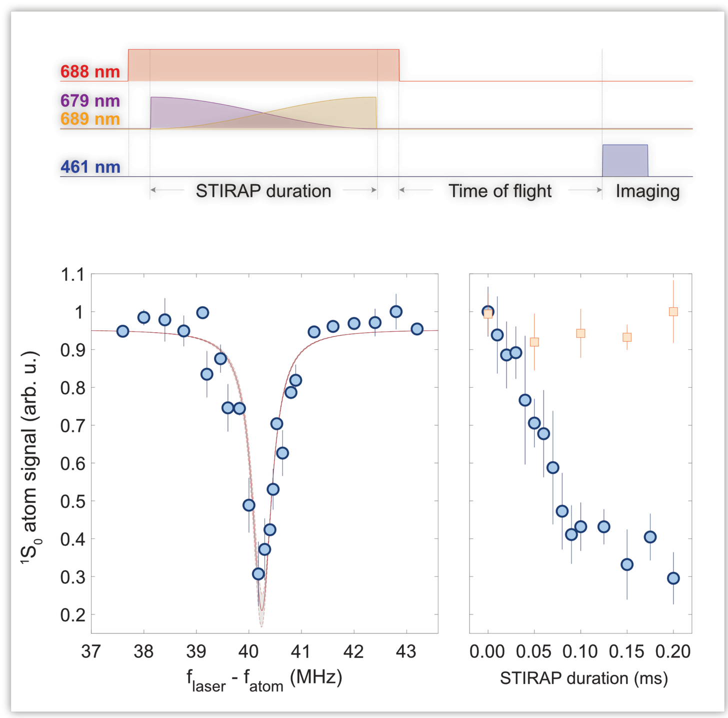
We observe several Rabi oscillations at a flipping frequency of 2π × 37.4(6) kHz

STIRAP

STIRAP is typically restricted to odd-level systems. We made it work for four levels.

N. V. Vitanov, et al., Rev. Mod. Phys. 89, 015006 (2017)

We couple the $^3P_1$ and $^3S_1$ states with a constant power 688-nm laser. This way we form an effective three-level system. Then, we execute STIRAP pulses on 679-nm and 689-nm.



We monitor transfer efficiency via loss of ground-state atoms. From a lorentzian fit we determine a 74(4)% transfer efficiency. The maximum clock state population, however, is much lower due to rapid two-body losses.

All three lasers are needed: shutting off the 688-nm laser disables the transfer.

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Author contributions. J.H. led the experimental effort, with support from R.G.E. and S.Z., performed the data analysis and wrote the manuscript. M.B. contributed the theoretical analysis and cowrote the paper. B.P. conceived the use of the 3-photon Raman scheme as an atom laser outcoupler. J.H., B.P. and F.S. guided the effort. J.H., B.P., M.B. and F.S. discussed the results and F.S. acquired the funding.

Parallel work. During the completion of this work, we became aware of concurrent work on the three-photon transition in ^{88}Sr [S. P. Carman, J. Rudolph, B. E. Garber, M. J. V. de Graaff, H. Swan, Y. Jiang, M. Nantel, M. Abe, R. L. Barcklay, and J. M. Hogan, Collinear three-photon excitation of a strongly forbidden optical clock transition (2024), arXiv:2406.07902].

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