Keeping atoms synchronized for better timekeeping

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In a new regime for atomic clocks, strong interactions between atoms dramatically increase the clock’s coherence time.

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Atomic clocks often have a limited coherence time due to the interactions between the constituent atoms. While it is usually very easy to use fewer atoms to reduce the interactions, this leads to lower signal-to-noise and less precise measurements. This tension between strong interactions and noise seems unavoidable and limits the accuracy of the world’s best cesium clocks, the keepers of international atomic time [1, 2]. As reported in a paper in Physical Review Letters, Christian Deutsch and coworkers at three laboratories in Paris, France, have circumvented this seemingly unavoidable compromise by showing that a clock’s coherence can actually be enhanced by strong atomic interactions [3]. Even better, strong atomic interactions might also reduce the clock’s systematic frequency shifts. The authors demonstrated long coherence times with an “atom chip,” but their key requirements can also be satisfied in optical lattice clocks [4].

The tick rate or frequency $\nu$ of an atomic clock is given by the energy difference between two atomic eigenstates, $\nu = \Delta E/\hbar$. Clocks based on trapped atoms can suffer from a lack of coherence if the trap strength is different for the two atomic eigenstates. The tick rate of atoms in higher energy trap states can be faster than for those in lower energy trap states, limiting the coherence time. Researchers in this field often represent the coherence of a system of two-level atoms with a geometric tool called the Bloch sphere: vectors pointing to the north and south poles represent the pure states $|\uparrow\rangle$ and $|\downarrow\rangle$, while vectors on the equator represent equal superpositions of $|\uparrow\rangle$ and $|\downarrow\rangle$. In Fig. 1(a), the dephasing of the atomic coherences is depicted as the red and blue arrows precessing in opposite directions on the equator of the Bloch sphere. Dephasing is a torque $D$ acting in opposite directions on the fictitious spin vectors that represent the superposition of the two atomic eigenstates. The dephasing broadens the linewidth of the clock and often degrades the clock’s stability. Although there are techniques for some clocks that make the trap strengths nearly equal for the two eigenstates, such as magic wavelengths for optical lattice clocks [4], other effects, including atomic interactions, also limit the maximum coherence time. Even when traps are delicately tuned [5], the coherence times are still limited, as this tuning is not very robust.

The essential trick of Deutsch et al. is to increase

FIG. 1: (a) Bloch sphere representation of two atomic coherences that are described by fictitious red and blue spins. The spins dephase by precessing in the horizontal plane with opposite dephasing torques $D$. (b) Triplet and singlet energy eigenstates for two interacting spins. In this picture, dephasing is a precession between the triplet state $|\uparrow\rangle$ and the singlet $|\downarrow\rangle$. The precession is inhibited when the spins interact strongly, $\omega_{\text{ex}} \gg D$, shifting the energy of the singlet state. (c) The interactions exert a torque $\omega_{\text{ex}}$ on the spins about their mean spin. When $\omega_{\text{ex}} \gg D$, the precession of the spins about the vector sum of the two torques $\omega_{\text{ex}}$ and $D$, so they no longer precess about the equator, giving extraordinarily long coherence times for a clock.
the atomic interactions so that they are much greater than the dephasing rates in their trap. However, while
the interactions have to be strong enough to overcome
dephasing, they also have to be weak enough so that
the atoms do not rapidly scatter between different trap
states. This is the Knudsen gas regime, accessible at
low energies where the de Broglie wavelength is much
longer than the atomic scattering length. A second es-
sential feature is to use fermions, or “fermionic-like”
atoms. The mechanism can already be seen when there
are as few as two particles in the trap. The energy eigen-
states of a two-particle system are shown in Fig. 1(b). At
low temperatures, the Pauli principle ensures that ident-
tical fermions have no interactions, a desirable regime
for making good clocks. In Fig. 1(b), there are no inter-
actions for the three states with spin wave function that
are symmetric under particle exchange—both fermions
in the lower or upper states, or the symmetric combi-
nation of both spin states, |t⟩. On the other hand, the
antisymmetric spin combination, the pseudo spin sin-
glet state |s⟩, has a symmetric spatial wave function and
therefore can have strong interactions at low tempera-
ture. Deutsch et al., in fact, use a boson, ⁸⁷Rb—it has the
unique property that all three of the relevant scattering
lengths, a∥, a⊥, and a∥∥, are very nearly identical. This
shifts all of the spin-symmetric triplet states by the same
energy, but not the singlet state. Thus this special boson
has the same energy spectrum as fermions [6, 7].

In the singlet-triplet basis of Fig. 1(b), dephasing is a
precession of the atoms between the singlet state |s⟩ and
the triplet state |t⟩. The different tick rates of the two
atoms is precisely a different phase evolution of the two
coherences, giving a precession from the triplet state |t⟩
to |s⟩, back to |t⟩, and so on. When strong interactions
split the energy levels of singlet and triplet states by
much more than the dephasing rate, the precession from
|t⟩ to |s⟩ becomes energetically forbidden. In this way,
Deutsch et al. robustly inhibit dephasing and observe
long coherence times. Pairs of atoms do populate both
the singlet and the triplet states, but the coupling D be-
tween them becomes negligible for strong interactions
ω_ex. When the interactions are weak, the atoms rapidly
dephase in 100 ms, but for strong interactions, the co-
herence decays negligibly in 5 s, suggesting coherence
times as long as a minute!

Deutsch et al. analyze the precession of individual
spins due to the interactions, whereas the basis set in
Fig. 1(b) is comprised of the eigenstates of the atomic
interactions [7]. Both basis sets offer insight. In Fig.
1(c), the individual spins precess about one another at
a frequency given by the atomic interaction energy ω_ex,
and the dephasing is a torque in the z direction, op-
posite for each spin. If the precession of each spin about
the other is much larger than the dephasing rate, the smaller
dephasing torque does not deflect the spin significantly
throughout the cycle. They offer an analogy to rephasing
in a spin-echo. For those familiar with detuned Rabi
flopping, it is a mathematically exact analogy, as can be
seen from Fig. 1(b). Rotating Fig. 1(c) so that ω_ex points
downward gives the usual Bloch sphere representation
for detuned Rabi flopping. The Rabi frequency of the
electromagnetic field Ω is analogous to the dephasing
torque D, and the detuning for Rabi flopping is analo-
gous to ω_ex. The total torque on each spin is given by
the vector sum of ω_ex and D for each spin. Thus, when
ω_ex > D, the total torque is nearly along ω_ex and the
spins precess about it, never dephasing significantly.

In addition to long coherences times, Deutsch et al. al-
so observe revivals of the coherence when the interactions
are more moderate and allow some dephasing. At first,
the transition contrast goes down as the spins precess
for a fraction of a cycle because the light that excited
the atoms no longer couples to them in the same way.
But, waiting a little longer, the spins precess through
one full cycle and are back to where they started. If a
second pulse of light is applied at this time, the transi-
tion can be observed with a large contrast, giving the
revival. Indeed, Deutsch et al. convincingly observe the
oscillation of the contrast, seeing that the spin precession
rate is proportional to the interactions. In the singlet-
triplet basis, the revival occurs when the singlet state ac-
quires phase factors exp(−iω_ex t) where the phase ω_ex
is a multiple of 2π. Subsequent revivals are smaller
since they may be washed out by scattering to other
trap states and also by the distribution of interaction
strengths when the atoms populate many trap states.

This suppression of dephasing is fairly general. It
should be directly applicable to optical lattice clocks.
Rapid spin exchange for room-temperature atoms be-
hoes similarly and has also yielded long coherence
times, leading to more sensitive atomic magnetometers
[8]. Further, recent work suggests that strong interac-
tions might also eliminate the systematic clock error due
to collisional frequency shifts [9]. Thus, with strong in-
teractions, chip and lattice clocks might be able to have
both long coherence times, giving higher stability, and
potentially improved accuracy. However, an impor-
tant future question is how can we establish the accu-
ricy of a clock with strong interactions? Conven-
tionally, the clock’s frequency is linearly proportional
to the atomic density, allowing an extrapolation of the clock’s
frequency to that of a single atom. But here, reducing
the density will degrade the clock’s stability and its ac-
curacy, so some new understanding or tricks may be
needed to prove the accuracy of such a clock. Nonethe-
less, many important clock applications require only sta-
bility and not accuracy. Deutsch et al. have shown ex-
traordinarily long coherence times with a robust mech-
anism that should be highly immune to small drifts of
the clock’s parameters. They realize an important step
towards miniature atomic chip clocks with high stabil-
ity.
References

[1] K. Gibble and S. Chu, Phys. Rev. Lett. 70, 1771 (1993).
[2] See R. Wynands and S. Weyers, Metrologia 42, S64 (2005) and references therein.
[3] C. Deutsch, F. Ramirez-Martinez, C. Lacroûte, F. Reinhard, T. Schneider, J. N. Fuchs, F. Piéchon, F. Laloe, J. Reichel, and P. Rosenbusch, Phys. Rev. Lett. 105, 020401 (2010).
[4] H. Katori et al., Phys. Rev. Lett. 91, 173005 (2003).
[5] D. M. Harber, H. J. Lewandowski, J. M. McGuirk, and E. A. Cornell, Phys. Rev. A 66, 053616 (2002).
[6] J. N. Fuchs, D. M. Gangardt, and F. Laloe, Phys. Rev. Lett. 88, 230404 (2002).
[7] K. Gibble, Phys. Rev. Lett. 103, 113202 (2009).
[8] W. Happer and H. Tang, Phys. Rev. Lett. 31, 273 (1973); M. P. Lederbetter and M. V. Romalis, Phys. Rev. Lett. 89, 287601 (2002).
[9] M. D. Swallows, Michael Bishop, Yi Ge Lin, Sebastian Blatt, Michael J. Martin, Ana Maria Rey, and Jun Ye, arXiv:1007.0059; A. M. Rey, A. V. Gershkoy, and C. Rubbo, Phys. Rev. Lett. 103, 260402 (2009); K. Gibble, Proc. 2010 IEEE Int. Freq. Control Symp. (to be published).

About the Author

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