Dear Editor,

first, we like to thank both reviewers for their careful reading of the manuscript, and the constructive remarks to improve it. In particular, the suggestion to consider the CPMG protocol brought up by the second reviewer was extremely helpful. We implemented this in response to the comments on our manuscript, and observed a substantial increase in the coherence time in our experiment. A new figure accompanied by a complete paragraph on the CPMG protocol has been included in the manuscript.

In the following, we would like to address the points raised by the reviewers.

Comments from the first reviewer:

"i. Page 3, Sec.3, the 1st paragraph. The imperfect Rabi oscillation can be concluded by imperfect state preparation. The authors should estimate their efficient of state preparation. Upper figure in Fig. 3 is quite common and I don’t think it is needed."

Our reply: The state preparation efficiency is calculated and included in the text.

"ii. Page 5, the 1st paragraph. “We suspect that the fluctuations in dipole beam intensity gives rise to the differential light shift that limits our coherence time in the magnetic insensitive states.” Should here the ‘magnetic insensitive’ be ‘magnetic sensitive’?"

Our reply: 'magnetic insensitive' has been corrected to 'magnetically sensitive'.

"iii. The system uses a pair of log-periodic antennae to drive the states. What is the polarization after they synthesize? How well is the polarization? Can we characterize it?"

Our reply: The magnetic field synthesized at the location of the atom is estimated to be an equal superposition of left and right circularly polarized field, with respect to the bias magnetic field axis. While the left circularly polarized magnetic field is used to drive the qubit transition, the magnetic field components of other polarization have a negligible impact due to the large Zeeman detuning introduced by the bias magnetic field.

"iv. Page 10, the 1st paragraph. The 50Hz modulation may be induced by the power frequency alternating current."

Our reply: We agree that the 50 Hz modulation may be induced by the alternating current of the power line. We have included the argument in the text.

"v. Page 2, Sec. 2, the 2nd paragraph. ‘Theatomic’ should be ‘The atomic’."

Our reply: We have corrected 'Theatomic' to 'The atomic'.

Comments from the second reviewer:

"- Previous work is not sufficiently highlighted in the introduction. After introducing their motivation, the authors focus on the current work without demonstrating the gaps in previous work. For example, what are the state-of-the-art coherence times previously measured in this system (e.g. Ramsey)? Is this the first demonstration of dynamical decoupling on trapped Rubidium?"

Our reply: A short summary of previous work has been included in the introduction.

"- Timing of the DD pulses: the authors implement the PDD dynamical decoupling protocol, in which the free evolution time between all pulses is the same. It is well known in NMR, however, that such sequencing provides sub-optimal performance compared to protocols in which the free evolution time between pi-pulses is twice the free evolution time after the first (and before the last) pi/2-pulse . This fact is also nicely simulated by the authors in Fig. 9. However, I do not understand why the authors chose to study a protocol with equal spacings, which was well known to be inferior in the first place, instead of just implementing the standard CPMG protocol currently being used for prolonging the coherence times of solid-state qubits. Is there any technical limitation in realizing the CPMG protocol? I would assume that temporal resolution is not an issue in microwave controlled system that supports much more advanced Uhrig sequences. If experimental results cannot be shown, could the authors at least simulate the expected performance of CPMG?"

Our reply: While CPMG is commonly implemented with solid-state qubits, it was not completely clear that CPMG has a better performance for the particular noise environment of our single neutral atom system. Therefore, PDD with equal free evolution time is chosen in our preliminary study for its simplicity. Regarding to the CP and CPMG protocols, a new figure and a complete paragraph has been added in the text.

"- Pulse imperfections: the authors mention that the number of pulses was limited to 20 due to the accumulation of pulse imperfections, a well-known phenomenon for spins in the solid state. First, what is the quantitative behavior (i.e. a plot of signal contrast versus number of pulses could be helpful)? Second, what are the main (physical/technical) sources of imperfections in this atomic system? Could the authors provide a quantitative model for these imperfections and / or their impact on spin dynamics?"

Our reply: The discussion about the impact of pulse imperfections is added in the text.

"- Phases of the DD pulses: as correctly pointed out by the authors, pulse imperfections can be mitigated toward the preservation of arbitrary states utilizing phase control (e.g. composite pulses in the KDD sequence). However, even to preserve a single state, as studied in this work , it is optimal to apply the pi-pulses with a phase perpendicular to that of the pi/2 pulses. This is the advantage of the CPMG compared to the CP protocol well studied in NMR. Such a simple phase modification could boost the number of pulses before the signal

contrast begins to drop. If I understand correctly, spin control in this work is performed utilizing microwave fields that can be modulated (e.g. I/Q mixing) to provide arbitrary phases. How challenging is the implementation of dynamical decoupling utilizing such a phase flip, and could the authors estimate the expected performance coherence time and signal contrast?
Finally, the authors should also mention the possible use of “concatenated” protocols (e.g. Phys. Rev. Lett. 95, 180501, Phys. Rev. B 92, 060301), in which phases are changed recursively, as another method of preserving arbitrary spin states."

Our reply: We agree that the phase shifting protocols can boost the number of pulses before the signal contrast begins to drop. Experimental results for CPMG, which is the phase shifted version of CP, have been included. References for concatenated protocols are included.

"- Energy level structure: If I understand correctly, the authors mostly work with the qubit {|2,-2>,|1,-1>} because the former state features an optical transition useful for quantum information processing (these states are referred to as “stretched states”, even though I could not find the term explicitly defined in the text). However, the contrast of Rabi oscillations seems to be limited due to the occupation of other states. What are these other states, and can they be pumped out by other methods (e.g. optically) to improve the spin initialization within the desired qubit?"

Our reply: In the experiment, the atom is prepared in the desired state by optical pumping. However, there is a non-zero probability that the atom will end up in some other Zeeman states in the F=2 level or even in the F=1 ground state. The efficiency of state preparation is inferred to be 88.3(8)% from the Rabi oscillation visibility and state detection efficiency.

"In addition, at some point the authors implement a spin-echo sequence on different, “magnetically insensitive”, states “to compare the coherence with other systems”. I did not understand this step. First, if these transitions are “magnetically insensitive”, how can they be coupled using microwave fields? Second, if only these transitions have been studied in previous work, and here they also exhibit longer coherence times than the stretched states, why aren’t they the main transitions studied here for multi-pulse dynamical decoupling? Is this because the lack of optical transitions from them? If so, and these states are not very useful, I do not understand the added value in presenting their spin-echo results. Could the authors clarify this point?"

Our Reply: The term 'magnetically insensitive' refers to the m_F=0 Zeeman state that does not experience energy shift due to magnetic field. The transition between |2,-2> and |1,-1> is a magnetic dipole allowed transition as such can be coupled using microwave fields.

The results for the magnetic insensitive states are presented because the coherence of the mentioned states for an optically trapped single atom has been widely studied. This has allowed us to check that our noise environment is similar to the other systems with an optically trapped single atom.
The coherence of the stretched states (Zeeman state with the maximal or minimal m_F value), which has the possibility to access a closed optical transition between |3,-3> and |2,-2>, remains relatively unexplored and is our main topic in the text.

"I believe that adding an energy level diagram and a paragraph explaining all the energy levels and transitions could shed light on all these points."

Our reply: An energy diagram has been included to clarify the discussion.

"- The readout fidelity 97.4% is very impressive. It is worth mentioning that such performance provides single-shot readout capabilities, i.e. individual states can be manipulated for quantum information processing and efficiently read without further averaging."

Our reply: The dark counts of the detector correspond to a mean photon number of 0.28. We attribute the remaining photon counts to the off resonant scattering of the dark state and background light.

The comment about the readout fidelity has been added in the text.

With this, we hope to have addressed all point indicated by the referees. We again like to thank the reviewers for their constructive comments. For convenience, we added a differential pdf version highlighting the changes of the revised manuscript compared to the original manuscript, and look forward to your reply.

With Best Regards on behalf of all authors,

Christian Kurtsiefer