Response to referee report for manuscript LF16722/Anderson

December 22, 2017

Dear Dr. Wang,

Thank you for considering our manuscript LF16722 for publication in *Physical Review A* without further review.

Below we respond to the comments made by the referees, and outline associated changes to the manuscript.

Kind regards,

R. P. Anderson, M. J. Kewming, and L. D. Turner

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Second Report of Referee A -- LF16722/Anderson
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In their reply to my comments the authors boil down my comments to the fact "that our results lack novelty, because they essentially replicate the work of Baumgart et al".
First, I want to clarify that I did neither write this in my report nor did I intend to. Baumgart et al. is just one example out of a host of papers on dynamical decoupling that I used to stress my point that this field has been worked on for long. The work of the authors does add something new, but this in my opinion is just an add-on to existing work on dynamical decoupling.

In October 2013 Pierre Meystre posted an editorial (10.1103/PhysRevLett.111.180001), where referees are asked to address the following points:

"We will ask both authors and referees to address more explicitly than in the past how the paper (i) substantially advances a particular field; or (ii) opens a significant new area of research; or (iii) solves a critical outstanding problem, or makes a significant step toward solving such a problem; or (iv) is of great general interest, based, for example, on scientific aesthetics."

Authors' response—We apologize for giving the impression that we mis-characterized Referee A's first report, and thank them for the helpful explanation of their review in terms of *Physical Review Letters* policies.

Judged the present manuscripts, I get to the following conclusions: i) Advancing a particular field: Dynamical decoupling is a quite mature field, and many robust schemes have been developed especially in the field of NMR and cold ions. To show advancement of another field (e.g. atomic clocks), the authors would have to prove that their method allows to surpass the present state-of-the-art. Considering e.g. the 10^-16 sensitivity of state-of-the-art clocks, this is definitely hard. Considering the example of artificial gauge fields or spinor dynamics, typical cold atoms experiments currently are limited by decoherence due to scattering of light, as for state-selective lattice potentials the detuning can not be larger than the fine-structure splitting, and not by the residual noise. Actually, the experiments I know of do not involve dynamical decoupling at all, as this would not change their results.

Authors' response—We thank Referee A for their detailed example and clear interpretation of the PRL guidelines. Despite the reviewers comments, we do believe our result advances our field by producing the first continuous weak measurement of a dynamically-decoupled state; and further showing a cyclically-coupled band-tunable system that is dynamically decoupled from environmental noise.

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ii) Open a new area: This is clearly not the case, as dynamical
decoupling is quite mature and routinely used in e.g. NMR.

iii) The present manuscripts do not solve an outstanding problem, it
is clearly a subproblem existing in the dynamical decoupling
community. The authors mention "Typical noise levels in
unshielded environments are often comparable to these
Rabi frequency", but unshieded environments can be simply shielded
by mu-metal shieldings, or by using existing pulse sequences (which
admittedly requires control of the pulses, but as e.g. the ion trap
community has shown this is doable to a high precision).
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Authors' response—There is a compromise between the efficacy of mu-metal shielding and high numerical aperture optical access required in a wide range of vacuum-based experiments; in practice such shielding has been very little used due to these serious technical impediments. The situation is only made more complex by, for example, introducing a white-light microscope which would be needed to align with biomedical targets. Shielding the entire apparatus is then prohibitively difficult.

The advantages of continuous decoupling over existing pulse sequences are rehearsed in our manuscript and elsewhere in the literature cited: maximal utilization of available Rabi frequency (i.e. continuous decoupling as the limit of long pulses), obviation of hard pulse shaping errors, congruence with weak measurement as we demonstrate here, and the conceptual advantages of the simple quantum geometry of the bare-to-dressed transform.

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iv) "is of great general interest": This is of course always a
debatable issue, as "general interest" is a rather unclear definition.
Nevertheless, I doubt that the majority of readers of PRL cares about
the fact that dynamical decoupling now has yet another twist to make
it yet a little better. Thus, I personally would deny the fact that
this is of general interest.
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Authors' response—We agree with the reviewer that this is a subjective criterion.

What is now referred to as 'dynamical decoupling' commenced somewhat before PRL did (Carr & Purcell, Physical Review **94**, 630 (1954)), and the development of this major subfield through NMR and ESR applications, to atom interferometry, quantum information and more recently quantum sensing has resulted in many Letters.

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In their reply, the authors state "the transition matrix
elements between dressed states enable the design of
new Hamiltonians with non-trivial topological
characteristics." This is obviously true, but this is not the focus
of both manuscripts. Thus, if the authors find an interesting
Hamiltonian with non-trivial features I am happy to hear about it, but
the present manuscripts do not provide any insight here. The reply by
the authors did not provide any material that would change my previous
opinion, and correspondingly I still can not recommend publication in
PRL.
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Authors' response—This comment pertains to the co-submission of manuscript LF16721 by Trypogeorgos *et al.*.

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I would also like to mention that for the general audience the
terminology is rather confusing (which is not the authors fault, as
the terms are around already quite some time). The term "continuous
dynamical decoupling" would have been called "dressed state physics" a
decade or two ago, and there is no dynamics required, the pulses are
static. In the end, by adding a control field new eigenstates are
prepared in the system, which have different properties from the bare
states.I fully agree with the authors that the dressed states have
sometimes useful properties (as the quartic decoupling), but this
deviates strongly from the "classical" field of dynamical decoupling,
where a sequence of tailored rephasing pulses was used to battle
decoherence.
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Authors' response—We agree that the relatively new interest in 'continuous dynamical decoupling' falls in the broad category of the well-established area of 'dressed state physics'; if a distinction needs to be made, much of the historical work concerned spatial variation of dressed energy eigenstates for e.g. rf trapping, while our work and other recent work focus on protection from temporal variations in the eigenspectrum. Nevertheless referring to our work as continuous dynamical decoupling is wholly consistent with the broader literature cited, and we maintain consistency to avoid adding any further confusion. The term is now widely used when pulse sequences are replaced with an uninterrupted coupling of bare spin states yielding dressed spin eigenstates. Indeed, we agree with the referee that our work does 'deviate' strongly from the field of classical dynamical decoupling. The novelty of our work lies in exploiting the multilevel spin structure of our spin-1 system (applicable to other quantum platforms with more than two levels), rather than embroidering ever more elaborate pulse sequences.

Report of Referee B -- LF16722/Anderson

The manuscript describes the generation of dressed states in a spin 1 quantum gas using continuous dynamical decoupling and shows how carefully choosing experimental parameters can lead to additional protection against magnetic field noise. The manuscript also demonstrates a very nice and fast technique for measuring the dressed state spectrum as well as the state coherences and coupling strengths. This may be particularly interesting for magnetometry. The data is well presented, and sufficient error analysis has been performed.

Authors' response—We thank Referee B for their review.

The use of continuous dynamical decoupling for the protection against ambient magnetic field noise is well established and has led to a number of publications especially in the fields of NV centres and trapped ions and beyond (see references in the manuscript and within). I particularly note the work of Timoney et al Nature 476, 185 (2011) which covers pioneering work in this area, presenting a system which is protected against magnetic field fluctuations as well as Rabi frequency fluctuations of the dressing fields. I recommend including this reference in the manuscript. The work of Baumgart et al PRL 116, 240801 (2016) is based on the underlying concept of this work and very nicely makes use of the protected subspace (against magnetic field and Rabi frequency fluctuations) to demonstrate the suitability of continuous dynamical decoupling for magnetometry.

Authors' response—We have added a reference to Timoney *et al.*, Nature **476**, 185 (2011).

The work presented in this manuscript makes a nice addition to the broad range of continuous dynamical decoupling work and I believe it may find useful applications. However, I do not believe that in its current form it is of sufficiently broad interest to warrant publication in PRL. While it is of course very interesting to utilize magic experimental parameters to increase the protection against magnetic field noise and combine this with a very efficient measurement technique, given previous work in the area of continuous dynamical decoupling which appears to share many similarities with this work and in some cases has some advantages such as inherent protection against dressing field amplitude noise I believe the advances in this manuscript are not sufficient and more is needed to warrant publication in PRL. As stated in the introduction and conclusion, one of the prime potential applications is magnetometry. To be of broader interest I believe significantly more work is required to show the suitability of this work for magnetometry and beyond as it is not clear at all from the manuscript how well this system will perform in this and other potential application areas.

Authors' response—We thank Referee B for recognizing the potential utility of our work and taking the time to carefully review the manuscript. We note that previous work to our knowledge did not measure the higher-order decoupling at the 'magic' parameter that we demonstrated. As we have clearly demonstrated continuous measurement of the Rabi frequency, the absence of 'inherent protection' against dressing field amplitude noise is no great disadvantage: should this actually be a limitation of an ac magnetometer or other application, then a synchronous demodulator and PID controller could provide closed-loop Rabi frequency control ('atoms in the loop'). Our tabulation of transition matrix elements makes plain the potential for ac magnetometry. While this is one motivation, our aim was to show the broad utility of the quartically-decoupled system rather than to explore one particular application.

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I do believe the work in its current form is of interest and in my
opinion, would fit well with the requirements of NJP or PRA for
example.
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Authors' response—We thank Referee B for their recommendation.