Dr. Nam Nguyen

Editor, Journal of Visualized Experiments

Dear Dr. Nguyen,

We would appreciate the opportunity to resubmit our paper, “Cooling an optically-trapped ultracold Fermi gas by periodical driving”, in response to the editorial comments and comments from reviewer #1, which have been addressed individually as follows.

Editorial comments:

1.Additional detail is required in numerous steps:

“If locking a laser is a multistep process, please provide a citation for the method used.”

Response: Locking the ECDL frequency is indeed a multistep process, so in Section 3 Note. We have included “A digital laser current modulation method (DLCM) is applied for laser frequency stabilization10”. Ref 10 is our previous publication *Appl. Opt.* 54 (13), 3913-3917, which provides the details of locking procedure.

“Is the camera used at earlier steps in the protocol? It would be better to incorporate instructions for use of the camera when it is first used. We won’t film this separately as written.”

Response: The camera is used in an earlier step in the protocol. We accepted the editor’s suggestion to move the camera section to section 2 so that camera usage instructions are described before any steps that require the camera.

2. Formatting: Make sure that narrative descriptions of what is happening occur as notes and are not included with the action in the step.

Response: We have removed the narrative descriptions and have kept the narrative as notes so that they contain important information about what to expect from the steps.

3. Visualization: Make sure to provide labeled, photographic images of the setup/equipment. These can be provided as supplemental files.

Response: we provide labeled photographic images of the equipment in the supplemental files, including 1. apparatus, 2.laser locking, 3.mot optics, 4.Fiber laser, 5. Offset locking.

Reviewers' comments:

Reviewer #1:

The reviewer #1 suggested us to provide more details so that the reader can follow the experimental procedure. We accepted the reviewer’s suggestion and made the following improvements.

1.“the current of the slower and crossover coils in section 2.2.2 and the photodetector voltage in 2.4.1 were given, but the coil design and the MOT fluorescence intensity were not explained.”

Response: The Zeeman slower coil is shown in Figure 5, and we added Reference 13 in section 5.3.1 note “The fluorescence of the MOT is collected by a lens with spatial angle of about 10-4 rad. The loading phase atom number can be calculated by the method in Reference 13.”. Ref.13 describes how to estimate the atom number from the photodetector signal.

2. “Section 3.2.2 discussed channels 2 and 3 of bias field coils and Table 1 listed the temperature settings of Channels 1-5 of their lithium oven, but the bias field direction generated by each coil channel and the location of each oven channel were not provided.”

Response: A picture of the oven with labeled coil positions is included in Figure 4 and the direction of the bias field is now included in the note in 6.2 “In order to generate an interacting Fermi gas, a bias magnetic field in the vertical direction is applied to tune the s-wave scattering length.”

3. “The information of the optical dipole trap beams (e.g., their beam waists and the polarizations) should also be pretty useful, but was not listed.”

Response: The beam waist and polarization of each beam is now included in the caption of Figure 8.

4. In the introduction section, it is stated that "the lowering scheme also decreases the collision rate of the atoms" and this method can evaporatively cool Fermi gases without a lowering scheme. Does it imply that this method leads to a higher collision rate and can thus cool Fermi gases more effectively than a lowering scheme? Some widely-used methods, e.g., magnetic field tilting trap (Phys. Rev. A 78, 011604 (2008)), can also provide a high collision rate. Therefore, it will be very helpful to compare this parametric modulation method with some widely-used methods, and clearly list the advantages of this modulation method in the introduction section of the manuscript.

Response: We will address this question from two perspectives. First, without requiring lowering the trap depth, parametric driving provides a possibility to enhance the collision rate. As shown in Equation 10 of reference 6, the collision rate is reduced as the power law of the trapping potential for a Fermi gas (which is also true for a Bose gas). By keeping the trap depth, the collision rate will be maintained. Second, in this paper as well as in the previous publication Reference 7, we did not implement the parametric cooling scheme to interacting (collisional) Fermi gas because it has some nontrivial thermalization effects observed. Instead, we demonstrate this protocol for cooling a noninteracting Fermi gas. The noninteracting Fermi gases have zero collision rate, it is impossible to show a higher collision rate effect for a noninteracting Fermi gas. For our current experiment, we cannot make a comparison with Phys. Rev. A 78, 011604 (2008), which works for interacting quantum gas and shows a good way to maintain the high collision rate by titling the trap with magnetic gradient. We agree with the referee that it is rather interesting to compare the parametric cooling scheme with other schemes if we could apply this method to the interacting gases in the future. However, this comparison is beyond the scope of the current protocol paper. For the current protocol paper, we want to emphasize the basic idea and effectiveness of the parametric cooling that by using the anhamornicity of the trap, we can selective remove the high-energy atoms even for a noninteracting Fermi gas.

5. The authors stated that "We find that the cloud energy in the axial direction is significantly reduced by parametric modulation, preparing an ultracold Fermi gas with anisotropic energy distribution" in the abstract. However, this statement is not supported by the data in Fig. 5: i.e., Fig. 5 shows that E\_x and E\_z were very different when no modulation (t\_m = 0) was applied, but the difference between E\_x and E\_z decreased after a parametric cooling (e.g., at t\_m ~ 600 ms). Therefore, Fig. 5 indicates that the traditional lowering scheme could also generate energy anisotropy, and the parametric modulation partially diminished the energy anisotropy. This contradiction should be clarified.

Response: The referee is right. We realized this inconsistency. In our previous publication of Reference 7, the parametric process increases/generates the energy anisotropy. However, in this paper, as shown in Fig.9 (old version Fig.5), the anisotropy decreases from 1.8/1.2 to 0.9/1.2. This shows the parametric cooling is not only able to generate anisotropy (Ref 7) but also can diminish the anisotropy (this paper) depending on the initial condition. So we changed our abstract to “We observe that the cloud energy is changed in an anisotropic way, where the energy of the axial direction is significantly reduced by parametric driving”. This statement emphasizes the change is anisotropic instead of saying the final effect is anisotropy. We also provide more discussion in the “REPRESENTATIVE RESULTS” section. We write “We find that parametric cooling changes the atomic cloud energy in an anisotropic way, in which the energy in the axial direction is below the Fermi energy while the radial one is still above the Fermi energy. It is noted that the initial unequal energies in axial and radial directions (Figure 9b) are generated by the fast trap lowering applied in section 6.3. After the parametric cooling, the axial direction energy is significantly reduced while the radial energy is barely changed. This result indicates the way that parametric cooling changes the cloud energy is anisotropic.”

6. To make a clear comparison of the author's parametric modulation method to the lowering scheme, data taken after further lowering the trap depth to a value small than 0.01 U₀ without a modulation should be present. These new data will be helpful to compare the lowering scheme and the parametric modulation method when the system is kept at a similar energy, which can better show the advantage of the parametric modulation method.

Response: Same as the 4th point, we should emphasize that parametric cooling in this paper is implemented for a noninteracting Fermi gas, while the lowering the trap depth is implemented in the interacting regime. It does not make sense to make such a comparison. If we lowered the trap depth in the noninteracting regime, we did not see any cooling effect, the atoms lost and the absolute temperature decreased, but the E/E\_F are unchanged.

7. A sentence in section 3.3.2, "start the second stage of evaporative cooling 30 ms after 2.3.1", is confusing.

Response: In the current version, section 6.3.2 is the old section 3.3.2. We changed the sentence to “After the first state evaporative cooling is finished, we wait 30 ms, and then start the second stage of evaporative cooling”. The first and second stage of evaporative cooling explained in the first note in 6.3. We write “A standard evaporative cooling is used to cool the fermionic atoms of 6Li near the degenerate regime. The first stage of evaporative cooling is controlled by the pulse of the fiber laser and the second is controlled by the ODT AOM.”

8. Figure 4 indicates that the dipole trap remains at 0.01 U₀ during the imaging stage. However, Section 5.1.7 states that "Program the APG to release the atoms from the ODT by abruptly turning off the trapping beams". These two appear to be contradictory and confusing.

Response: The old step 5.1.7 now is step 7.1.2. "Program the APG to release the atoms from the ODT by abruptly turning off the trapping beams" is the correct description of the required action. The old Figure is wrong, which is corrected by our new timing figure (Figure 2).

9. It will be useful for the reader if all important equipments are listed in Table-of-Materials/Equipment, e.g., multiplexer circuit used in Section 2.4, photodetector used in Section 2.4.1, and the beam reducer shown in Fig. 3. In addition, some of the equipment listed in the table are not mentioned in the manuscript, e.g., Faraday isolator.

Response: We accepted the referee’s suggestion. The Table of Materials now includes more equipment, such as the photodetector, Faraday (optical) isolator, multiplexer, and the lenses used for the beam reducer.

Reviewer # 2:

No Comments

Best,

Le Luo

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