Manuscript entitled:

Number-resolved imaging of 88Sr atoms in a long working distance optical tweezer

Jackson *et al.*

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In this work, Jackson et al. study strontium (Sr) atom(s) in a large-mode-volume optical tweezer. In an effort to differentiate their work from recent papers with alkaline-earth atoms (AEAs) in tightly-focused tweezers (cited in [15,16,17,19]), the authors build their story around the use of a single tweezer generated by a low-numerical aperture lens with a long working distance. They try to sell this approach as a feature, but the reader wonders if instead their experimental system was just not compatible with a proper optical tweezer set-up.

They claim that their avoidance of parity projection is due to the larger size of their tweezer; however, this claim was not fully substantiated. A carefully study of references [15,16] shows that parity projection can be avoided during imaging *and cooling* in tightly-focused tweezers if desired. In fact, inducing parity projection was an effort in these works, as described in their appendices. The authors do not fully describe the mechanism by which their tweezer avoids parity projection, nor do they provide any quantitative analysis to support their claim that parity projection is related to the trap volume (or as they say it: NA of their lens).

The authors acknowledge that heating of the atoms during imaging leads to a reduction in the fluorescence signal for longer exposures, but they do not discuss the possible connection between this observation and their claim of observing atom-resolved loss. According to the histograms in (a) and (b) of Fig 5, the detection fidelity is very poor, and the presence of 1 vs 2 vs 3 atoms cannot be determined with high accuracy (note that the fidelity is never given, as far as I am aware). The count traces in (c) and (d) in Fig 5 show that there is significant noise compared to the separation between 1 and 2 atoms (clearly shown also in (b)). The authors work in a deep tweezer that has a large differential polarizability on the 1S0-1P1 transition, thus the detuning of the imaging beam from the atomic resonance depends strongly on the position of the atom in the trap, and therefore its temperature. Hence, it is possible that as the atoms heat up from scattering photons (no cooling is applied), their scattering rate from the probe beam decreases which creates the appearance of atom loss. Even if this is not the case, this effect will certainly complicate the analysis of the fluorescence counts and should be considered.

Generally, the manuscript lacks quantitative detail. For example, the tweezer depth is often described as “shallow”, or “deep”, or “very deep”. I understand that the maximum depth used is 7.5 mK, presumably for the 1S0 state. The trap depths of the 1P1 state are only mentioned in reference to a differential Stark shift. Also, Fig 4 should have a horizontal axis of trap depth in mK or MHz. Power in mW is very empirical and is usually not appropriate for publication. Perhaps a double horizontal axis (top and bottom) could be used. Further, the authors do not say anything about the axial direction of the tweezer, to my knowledge. The Rayleigh length and an estimate of the axial trap frequency should be stated. Also, it would be helpful if an estimate of the trap frequency for the radial direction could be given earlier, even before it is carefully measured. It is helpful for understand “shallow” vs “deep”.

Finally, I believe the overall story of this paper is unclear. The “new” features are: 1. Longer working distance lens, 2. SPAD detection, and 3. Claimed novel ability to operate without parity projection and the claimed atom-resolved loss during imaging. The advantages of 1 are far oversold, 2 is interesting but not utilized since there is only one tweezer, and 3 is partially wrong and not entirely convincing. The authors should decide what point they are really trying to make and make it thoroughly.

On these grounds, I cannot recommend acceptance of this manuscript until my comments are addressed. Specifically, the claims about parity projection and atom-resolved detection need further justification and analysis. Moreover, there are other statements in this manuscript which are incorrect or misleading, which I now list:

1. The authors choose to cite references [15] and [16] individually in several cases, even though these papers were published together and are very similar. For example, the authors cite [15] for a statement about in-vacuo lenses. A quick glance at the website of this group shows that this is clearly wrong. Moreover, the authors only cite [16] when discussing cooling to the motional ground state. Since sideband cooling was performed in [15], the authors’ statement is either ignorant or aggressive. This applies also to a statement about measuring the trap frequencies using motional sidebands, in which only [16] is cited.
2. Since the working distance of the objective used in this work is only ~2x longer than in other recent works with tweezers, it seems that the authors oversell their potential advantage regarding dielectric surfaces and charging problems. Such problems are not significant in recent experiments with Rb Rydberg atoms in tweezers at Harvard, for instance. Also, why does the use of a longer working distance preclude a large NA? Presumably, only limited optical access is available to the authors. They may choose instead to motivate their work on the grounds that tweezers can be generated in systems with limited optical access.
3. The authors should address the implied scalability of their system. Large tweezers require more power. What is the power/tweezer that is required for ~0.5 mK traps, and how many can be generated with realistic optical powers? Further, large tweezers allow larger variation in the interatomic separations which will give rise to a spread of Rydberg interaction strengths, for instance. This problem is particularly severe in the axial direction. Do the authors plan to apply an optical lattice along the axial direction to enhance the confinement on this axis? What is the field of view of the lens system? How large of an array could be created, and how large of a Rydberg or clock beam would be needed to uniformly illuminate the array?