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Improving Trapped Ion Quantum Information Processing Through Parametric Amplification

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The main objective of this research program is to demonstrate an amplification of engineered spin-spin interactions in trapped-ion crystals by externally driving the motional degrees of freedom of the crystal. Amplifying optical dipole force induced spin-spin interactions without increasing laser power will mitigate decoherence due to off-resonant light scatter.

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Final Report
Improving Trapped Ion Quantum Information Processing Through Parametric Amplification

AFOSR Grant No: FA9550-20-1-0019
Principal Investigator: John Bollinger, Andrew Wilson
Institution: University of Colorado
AFOSR Program Manager(s): Dr. Grace Metcalfe
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Program Objective: The main objective of this research program is to demonstrate an amplification of engineered spin-spin interactions in trapped-ion crystals by externally driving the motional degrees of freedom of the crystal. Amplifying optical dipole force induced spin-spin interactions without increasing laser power will mitigate decoherence due to off-resonant light scatter.

Scientific Approach: With trapped-ion crystals, strong spin-spin (or qubit-qubit) interactions are generated by employing a spin-dependent force to couple the spin degree of freedom of the trapped-ions with the ion motional degrees of freedom. As discussed in many manuscripts [1-3], the motional modes act as a bus that mediates the spin-spin interactions. Recent theory work [4,5] has shown how these boson-mediated interactions can be strengthened or amplified by driving the modes of the trapped-ion crystal. The appropriate drive is a non-linear drive called parametric amplification. It consists of a simple modulation of the potential of the ion trap at a frequency close to twice that of a motional frequency of the ions. We will experimentally demonstrate and investigate parametric amplification (PA) of induced spin-spin interactions in two-dimensional trapped-ion crystals of a few hundred ions stored in a Penning trap. Our set-up employs a spin-dependent optical dipole force from a moving one-dimensional optical lattice to couple the spin and motional degrees of freedom of the trapped ion crystal [3]. Implementing parametric amplification of an engineered spin-spin interaction in the Penning trap set-up involves several challenges, which we will systematically undertake through the following steps.

1. The phase of the spin-dependent optical dipole force will be stabilized.
2. The large, several centimeter electrode structure of the NIST Penning trap dictates the design and construction of electronic circuitry capable of a low noise, tens of volt drive at 3.2 MHz (twice the trap frequency) with enough current to drive the capacitive 300 pF load of the trap.
3. We will initially demonstrate amplification of a geometric phase (that is, amplification of spin-dependent motion) in a weak force sensing protocol [6,7]. The protocol relies on single particle effects and will enable the most straightforward demonstration and characterization of the parametric amplification.
4. A main goal of this project will be to demonstrate an amplified Ising coupling strength J for a given spin-dependent optical dipole force that then results in a reduced decoherence due to spontaneous emission. We propose to utilize the amplified Ising coupling strength to investigate the generation of spin states with higher quantum Fisher information [8,9].

Summary of accomplishments in the past year (4/24/2023 – 12/31/2023): With the superconducting magnet coil replacement undergoing construction and testing, the accomplishments for this period focused on improving the experimental set-up for delivering laser beams and on a theory project investigating techniques for improved cooling of the in-plane ExB modes of single-plane ion crystals.

1. Improved laser beam delivery - We replaced the 313 nm source for generating the optical dipole force laser beams (ODF laser beams) used with $^9Be^+$ ions with a higher power, 313 nm source that has improved intensity stability. In addition, with the +/- 10-degree angles with

which the ODF beams cross to form a 1D optical lattice, it was possible to implement a cylindrical lens telescope that reduces the vertical (in the direction of the magnetic field) beam waist by a factor of 6. Both these steps greatly increase the laser intensity available for implementing a sin-dependent force. This will enable tuning the frequency of the spin-dependent force laser source outside the Zeeman manifold of excited P states, which reduces decoherence due to off-resonant light scatter compared to the coherent spin-spin interaction strength.

2. The normal modes of motion of a single-plane crystal on N ions consists of N so-called drumhead modes that describe motion parallel to the magnetic field (transverse to the plane) and N cyclotron modes and N ExB modes that describe motion in the plane of the ion crystal. Measuring the temperature of the ExB and cyclotron modes is challenging because of the requirement of measuring small thermal fluctuations that are superimposed on the large coherent rotation of the ion crystal. However, over the last few years new theory work has been applied to previous experimental measurements and indicated that the temperature of the ExB modes could be close to 10 mK. The ExB mode energies are characterized by potential energy fluctuations from ion positional fluctuations. They are not efficiently cooled by Doppler laser cooling. In collaborative theory work with Scott Parker, Univ. Colorado Physics and his student Wes Johnson, we show that the ExB modes can be efficiently cooled by resonantly coupling them to the drumhead modes, which are efficiently Doppler laser cooled. (See Ref. 2 under publications.)

   The development of a protocol for efficiently cooling the ExB modes with reduce the frequency fluctuations of the drumhead modes, which includes the axial center-of-mass mode. Mode frequency fluctuations are a form of motional decoherence that can limit the amount of parametric amplification that can be usefully applied. Improved cooling of the ExB modes can therefore further enhance the benefits of parametric amplification for strengthening the coherent spin-spin interaction induced through the application of a spin-dependent force.

Summary of major accomplishments during project (if final report):
Implementation of PA on single plane crystals of 100 – 200 ions: Before our work, parametric amplification or motional squeezing had been applied on single trapped ions or small ion crystals consisting of 2-3 ions. A major accomplishment of this project was a demonstration that parametric amplification can also be usefully applied to large ion crystals consisting of a few hundred ions. In Affolter, et al., Phys Rev A [10] we benchmarked the application of parametric amplification through the measurement of motional squeezing. In the same manuscript we simultaneously applied PA with the application of a spin-dependent force and demonstrated that we could modify the driven spin-dependent force in a manner consistent with theory.

Improved understanding of the trade-offs in strengthening the coherent spin-spin interaction induced by a spin-dependent force vs amplifying motional decoherence: Before the work of this project, the trade-offs between employing PA to strengthen an engineered spin-spin interaction vs amplifying decoherence due to motional dephasing were not well understood. While the trade-offs will depend on the details of the system, our work showed that motional dephasing such as mode frequency fluctuations can provide a significant limit to the potential gain obtained with parametric amplification. (See Affolter, et al., Phys Rev A [10], Fig. 6.) This motivates further experimental work on improving the stability of the motional degrees of freedom of trapped ion crystals and theoretical work on protocols for the application of PA that can dynamically decouple PA from motional decoherence.

Changes to originally proposed work (if applicable): Because the NIST superconducting magnet failed approximately halfway through the term of this research program, we did not get sufficient time in the lab to directly demonstrate an amplification of engineered spin-spin interactions in trapped-ion crystals through parametric driving of the motional degrees of freedom of the crystal. While waiting for the magnet to be repaired, we carried out theoretical investigations of different laser beam frequencies and polarizations for generating a spin-dependent force [11], investigated how to improve the cooling of the low-frequency ExB modes through a collaboration with the group of Scott Parker [Publications, Ref. 2], and improved the overall laser delivery set-up of the experiment.

Next steps: Prepare for the return of the repaired NIST superconducting magnet. After the magnet is returned, rebuild the apparatus, and make the set-up operational as rapidly as possible. We have a long list of investigations to pursue, but, with an improved experimental set-up, plan to return to further demonstrations of the utility of parametric amplification.

Team Members, Institutions (if applicable):
Jennifer Lilieholm, Univ. Colorado and NIST, postdoc
Bryce Bullock, Univ. Colorado, graduate student
Allison Carter, NIST Ion Storage group staff

Accomplishments for each team member (if applicable):

References (if applicable):

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Publications: 04/24/2023 through 12/31/2023. Publication 4 is closely related to the subject of this proposal.

1.“Bilayer crystals of trapped ions for quantum information processing,” Samarth Hawaldar, Prakriti Shahi, Allison L. Carter, Ana Maria Rey, John J. Bollinger, Athreya Shankar, https://arxiv.org/abs/2312.10681 .

2.“Rapid cooling of the in-plane motion of two-dimensional ion crystals in a Penning trap to millikelvin temperatures,” Wes Johnson, Athreya Shankar, John Zaris, John Bollinger, Scott E. Parker, https://arxiv.org/abs/2311.11906, accepted by Phys. Rev. A.
3.“Robustness of the projected squeezed state protocol,” B. J. Alexander, J. J. Bollinger, M. S. Tame, https://arxiv.org/abs/2310.11948 .
4.“Experimental speedup of quantum dynamics through squeezing,” S. C. Burd, H. M. Knaack, R. Srinivas, C. Arenz, A. L. Collopy, L. J. Stephenson, A. C. Wilson, D. J. Wineland, D. Leibfried, J. J. Bollinger, D. T. C. Allcock, D. H. Slichter, https://arxiv.org/abs/2304.05529 .

Presentations: 4/24/2023 through 12/31/2023
1. University of Amsterdam, Institute of Physics colloquium, 11/2/2023, “Quantum dynamics and sensing with a 200-ion crystal stored in a Penning trap,” (John Bollinger, invited).
2. Pursuing Quantum Sensing for reliable Roadmaps, Advance Research Workshop, 5-7 December 2023, Frascati, Italy, “Quantum sensing with trapped ions,” (John Bollinger, invited).
3. 65th APS Division of Plasma Physics meeting, October 30–November 3, 2023, “Penning trap ExB mode temperature considerations for quantum information science,” (Bryce Bullock, oral contributed).
4. 65th APS Division of Plasma Physics meeting, October 30–November 3, 2023, “Multi-qubit gate configurations for quantum sensing and simulation in a Penning ion trap with three-dimensional crystals,” (Allison Carter, poster contributed).
5. 65th APS Division of Plasma Physics meeting, October 30–November 3, 2023, “Towards single site addressing of ions in a Penning ion trap,” (Jennifer Lilieholm, poster contributed).
6. European Conference on Trapped Ions, September 25-September 29, 2023, “Spontaneous emission error characterization and improvements for quantum simulation and sensing in a Penning trap,” (Allison Carter, poster contributed).
7. Gordon Research Seminar, GRC on Atomic Physics, June 9,10, 2023, “Towards Enhanced Quantum Sensing and Simulation using Parametric Amplification on 2D Crystals of over 100 Ions in a Penning Trap,” (Bryce Bullock, oral, invited).
8. GRC on Atomic Physics, June 11-16, 2023, “Towards Enhanced Quantum Sensing and Simulation using Parametric Amplification on 2D Crystals of over 100 Ions in a Penning Trap,” (Bryce Bullock, poster, contributed).
9. 54th APS Division of Atomic, Molecular and Optical Physics meeting, June 5-9, 2023, “Towards single site addressing of ions in a Penning trap,” (Jennifer Lilieholm, poster, contributed).
10. 54th APS Division of Atomic, Molecular and Optical Physics meeting, June 5-9, 2023, “Laser Cooling Planar Motion of a 2D Ion Crystal with a Strong Rotating Wall,” (Wes Johnson, oral, contributed).

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