様　式　C－１９、F－１９－１、Z－１９　（共通）

科学研究費助成事業　　研究成果報告書

令和　３ 年　 ５ 月 ２５ 日現在

機関番号： ３８００５
研究種目： 若手研究
研究期間： 2018～2020
課題番号： １８Ｋ１３５０７
研究課題名（和文） Exploiting quantum phase transitions to improve the efficiency of quantum thermodynamic processes

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交付決定額（研究期間全体）：（直接経費）　　1,700,000円

研究成果の概要（和文）：この研究で、多体系の集団効果は量子熱エンジンの動作を向上させることを示した。1次元の強く相互作用した冷却原子の超流動相や絶縁相を駆動させ、エンジンサイクルを回す。これらの相は、調節可能なエネルギーギャップに特徴付けられる、別個のエネルギースペクトラムをもつ。このエネルギーギャップ近くで、エンジンを作動させることで、相互作用しない系に比べ、動力の出力や効率が向上する。
このサイクルを短い時間で回そうとすると、臨界点で、不必要な不可逆的励起が生成してしまう。しかし、この研究で、近似的shortcut to adiabaticityにより、素早くかつ摩擦のないサイクルの構成が可能であることを示した。

研究成果の学術的意義や社会的意義
While quantum thermal machines are well described for single particle and discrete systems, there is a lack of works addressing continuous many-body states. This work addressed this issue in a complex yet experimentally realizable setup, paving the way for experiments on many-body cold atom engines.

研究成果の概要（英文）：This project showed that many-body cooperative effects can improve the operation of a quantum heat engine near a critical point. The engine cycle was driven between the superfluid and insulating phases of a strongly correlated 1D cold atomic gas. These different phases have distinct energy spectra which are differentiated by a tunable energy gap. Operating the engine cycle near this gap can improve the efficiency and power output when compared to a non-interacting single particle engine, showing that many-body effects can be exploited in such systems.
Driving this cycle on short timescales can be difficult due to the creation of unwanted irreversible excitations at the critical point. These can harm the efficiency of the cycle and are a consequence of using complex many-body states. However, I showed that an approximate shortcut to adiabaticity can be designed to ensure fast and frictionless cycles on short times.

研究分野： Quantum thermodynamics

キーワード： heat engines　quantum control　correlations　speed limits

１．研究開始当初の背景

The control and precision of current experiments on quantum systems opens up exciting applications of quantum devices which can take advantage of wholly quantum effects such as entanglement and coherence. Quantum thermal machines are one such example, devices which use quantum systems as the active medium and require a new description of quantum thermodynamics for concepts such as work and heat, and how these are related to concepts already well established in quantum information theory. For example it was shown in [Klatzow *et* al, Phys. Rev. Lett.122, 110601 (2019)] that coherence can allow a quantum heat engine to outperform a classic counterpart, while in [Klaers *et al,* Phys. Rev.X7, 031044 (2017)] they showed that using non-classical heat baths allows one to exceed the Carnot limit.

While quantum thermal machines are well described for single particle and discrete systems, there is a lack of works addressing continuous many-body states which are ubiquitous in the cold-atoms community. Of course, describing continuous many-body interacting systems is no easy task, however, by restricting the motion of the particles to 1D and assuming strong repulsive interactions allows one to map these systems to non-interacting fermions which can be efficiently calculated. Nowadays experiments are regularly performed in this regime and they offer the perfect testbed to study the thermodynamics of strongly correlated many-body quantum states.

２．研究の目的

The purpose of the project was an extensive study of the thermodynamics of many-body quantum systems and their role in quantum thermal machines and under quantum control. The main work of this project was to explore the effect of quantum criticality on the operation of a quantum heat engine using a 1D gas of trapped atoms. The particles are confined to a tunable lattice potential which exhibits a superfluid-to-insulator phase transition when the number of a lattice sites is equal to the number of particles. This transition is signaled by the opening of an energy gap in the energy spectrum which depends on the lattice depth. By driving the system between the superfluid and insulator phases through modulations of the lattice depth, this energy gap is opened and closed. When the many-body state is near the critical point the energy spectrum therefore drastically changes during this driving and should have a large effect on the operation of the heat engine.

Since we are using a many-body state as the working medium, it is also interesting to investigate if there was an advantage to using strongly correlated many-body states over non-interacting single particle states in such an engine. Such many-body cooperative effects have been previously seen in the charging of quantum batteries due to the correlations between the particles [Uzdin, Phys. Rev. Applied 6(2) 024004] and therefore shows the advantage of using larger and more complex systems.

However, this comes with a drawback as larger systems are also harder to control in time-dependent processes. The operation of any quantum device relies on short timescales to beat the decoherence rate of the system, while for heat engines shorter cycles translate into more power. Effects such as the orthogonality catastrophe mean that the fidelity of large quantum states are very sensitive to perturbations making their control problematic. Similarly, dynamics around quantum critical points are notoriously irreversible leading to the creation of large non-equilibrium excitations which hamper the performance of quantum heat engines. One way to mitigate these effects during finite time control is the use of shortcuts to adiabaticity which allow one to mimic adiabatic dynamics on finite timescales. The final part of the project was to derive shortcut protocols for the many-body system and compare these to more stable single particle control to see if the advantage gained from the many-body state can be preserved for short cycle times.

３．研究の方法

I focused on the limit of infinite repulsive interactions between bosons trapped in quasi-one-dimensional trapping potentials. This is known as the Tonks-Girardeau (TG) limit, and with the use of the celebrated Fermi-Bose mapping theorem can be described in terms of spinless non-interacting fermions. The many-body state of the fermions can be constructed from single particle states which are easily calculatable once the potential is known. Local properties of the TG gas, such as density and energy, are equivalent the spinless Fermi gas, but quantities that describe correlations such as the reduced single particle density matrix and momentum distribution are vastly different. However, for the latter their description can be written in terms of the fermionic correlation functions while taking into account the symmetrization of the bosonic wavefunction. This allows for efficient calculation in terms of the aforementioned single particle states allowing one to describe systems containing hundreds of particles.

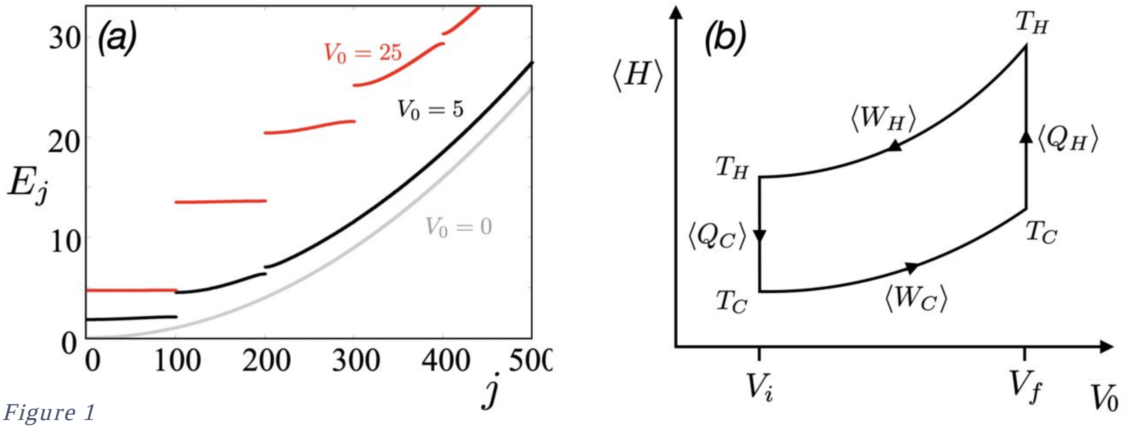

Figure 1

The superfluid-insulator is realized by trapping the TG gas in an optical lattice potential that is commensurate with its density. In this scenario each particle of the TG gas occupies a single lattice site, and due to the infinite repulsive interactions between them, tunnelling is restricted between neighboring sites. In the energy spectrum a gap opens and it scales with the lattice depth V_0, see Fig.1(a). In the groundstate at commensurability the particles then fully occupy this lowest energy band, while thermal excitations at finite temperature give the particles some probability to partially occupy the bands above the gap. The temperature and the filling fraction therefore determine if the gap plays any role in the thermodynamics of the system. The Hamiltonian of the system is solved numerically using exact diagonalization, while approximate analytic results were found through perturbation theory for atoms localized to single sites.

In this work I consider a quantum Otto cycle (see Fig.1(b)) where work is done on the gas by changing the lattice depth at constant temperature (isentropic compression and expansion). These strokes are connected by heating and cooling strokes which change the temperature of the gas. The temperature of the compression adiabat is fixed at T=0 to ensure the system begins in its groundstate. The initial and final lattice depths, the temperature of the hot adiabat and the filling fraction can then be used as free parameters to explore the performance of the cycle. Dynamics of the single particle states were performed using the Crank-Nicolson in a time dependent Hamiltonian whereby the lattice depth was dynamically changed. The shortcut to adiabaticity was derived using a variational wavefunction to describe each single particle state in the lattice [Fogarty *et al,* SciPost Phys. 6(2) 21]. Individual optimization of these states could then be performed yielding different optimal ramps of the lattice potential.

４．研究成果

Research outcomes

Firstly, it was found that when the filling fraction is unity the best performance is achieved. This is due to the effect of the energy gap being maximal in this case as the system was driven between essentially gapless and gapped spectra. Away from commensurability the effect of the gap was diminished and therefore performance suffered. Secondly, the role of the lattice depth was explored, finding that driving between finite lattice depths gives the best performance (see Fig.2(a)). Here the efficiency of the many-body cycle is compared to a comparable one-body cycle. Values of this ratio larger than 1 indicate a many-body advantage is present, with the maximum of the efficiency being about 1.5 times that of the one-body engine. Finite lattice depths are crucial to ensure the particles still overlap and interact in the lattice, which yields a non-trivial energy spectrum. On the contrary, in deep lattices the particles are completely isolated from one another and any many-body characteristics of the system are lost. In this regime the performance becomes comparable to the one-body engine.

The many-body efficiency boost in a finite time cycle is shown in Fig.2(b). The dashed dotted line shows the efficiency of the cycle when using unoptimized sinusoidal ramps of the lattice potentials. At short time the efficiency is poor and drops below 1, indicating that it performs worse than a one-body engine. This is due to many-body excitations induced by the fast ramp of the potential. For slower ramps the efficiency slowly approaches the adiabatic limit (dashed lines). Two shortcuts to adiabaticity were used to improve the performance. One based on an average over all the states in the gas (red line) shows a small increase in the efficiency. However, by designing the shortcut to only optimize the dynamics of states near the energy gap (black line) the performance could be significantly increased over intermediate timescales.

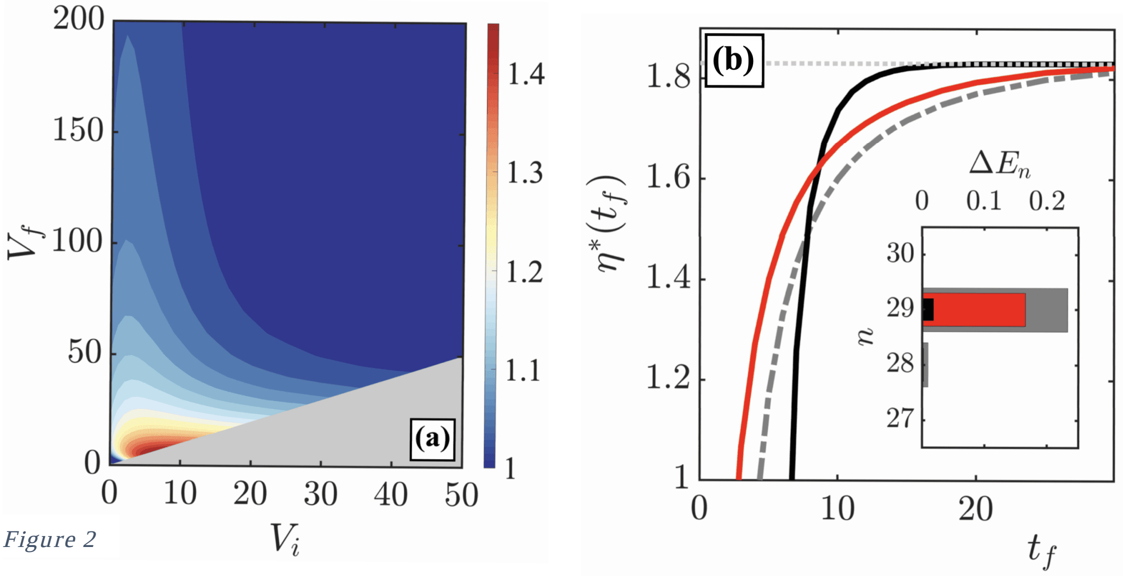

Figure 2

Impact of the result and unexpected findings

This work, which appeared in the journal *Quantum Science and Technology* [Fogarty & Busch, Quantum Sci. Technol. 6 (1), 015003] showed that many-body effects could be used to enhance quantum heat engines and showed this in a strongly interacting many-particle system. This is due to the subtle interplay between the interactions and the lattice trapping potential which can result in a nontrivial energy spectrum which possesses a tunable energy gap. While the gap is problematic when driving the system quickly as it creates irreversible excitations, approximate shortcuts can be successfully used to reduce them. While not many works on shortcuts or heat engines consider interacting many-body states, this work has shown that a careful examination of the spectrum can yield improved engine cycles and shortcuts for these experimentally realizable systems. This will hopefully encourage experimental groups to create many-body engines in future as this system also possesses good scalability due to the ubiquity of lattice potentials in quantum engineering and the inherent strong interactions between the particles.

This project also lead to related works on the control of many-body states. One of these works which appeared in Physical Review Letters [Fogarty *et al,* Phys. Rev. Lett. 124 (11), 110601] explored the effect of the orthogonality catastrophe on quantum speed limits, specifically how large systems are driven away from their initial state faster. While this effect had consequences for the control of the engine I considered, it also affects quantum devices which rely on the control of large interacting systems. We showed that the timescale for the driven system to be orthogonal with its initial states is described exactly by the quantum speed limit, which in turn is dependent on the energy variance of the system.

Further to this, I also worked on a similar project designing shortcuts for interacting systems in non-trivial traps [Xu *et* al, Physical Review Research 2 (2), 023125]. Here the role of particle statistics was explored, whether the many-body state was fermionic or bosonic. Spinless fermions were found to be easy to control as they possess interparticle interactions and therefore low many-body coherence. On the contrary, the bosonic system by possessing strong interactions and therefore coherence was more difficult to control. This was due to the presence of particle interactions during the control which can destroy the coherence of the state during the time evolution. Since coherence can't be successfully recovered at the end of the process the fidelity of this state could be vastly different from its fermionic counterpart. This further highlights the importance of interactions in the control of many-body systems and how effective approximate shortcut techniques can be.

５．主な発表論文等

〔雑誌論文〕　計10件（うち査読付論文　10件／うち国際共著　10件／うちオープンアクセス　10件）

１．著者名 Fogarty Thomas、Busch Thomas	４．巻 6
２．論文標題 A many-body heat engine at criticality	５．発行年 2020年
３．雑誌名 Quantum Science and Technology	６．最初と最後の頁 015003～015003
掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/2058-9565/abbc63	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Keller Tim、Fogarty Thomas、Li Jing、Busch Thomas	４．巻 2
２．論文標題 Feshbach engine in the Thomas-Fermi regime	５．発行年 2020年
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オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

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２．論文標題 In-Situ Thermometry of a Cold Fermi Gas via Dephasing Impurities	５．発行年 2020年
３．雑誌名 Physical Review Letters	６．最初と最後の頁 80402
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevLett.125.080402	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

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掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/universe5100207	査読の有無 有
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１．著者名 Garcia-March M.A.、Harshman N.L.、da Silva H.、Fogarty T.、Busch Th.、Lewenstein M.、Ferrando A.	４．巻 3
２．論文標題 Graded-index optical fiber emulator of an interacting three-atom system: illumination control of particle statistics and classical non-separability	５．発行年 2019年
３．雑誌名 Quantum	６．最初と最後の頁 210～210
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１．著者名 Usui Ayaka、Fogarty Thomas、Campbell Steve、Gardiner Simon A、Busch Thomas	４．巻 22
２．論文標題 Spin-orbit coupling in the presence of strong atomic correlations	５．発行年 2020年
３．雑誌名 New Journal of Physics	６．最初と最後の頁 013050～013050
掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1367-2630/ab6576	査読の有無 有
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１．著者名 Fogarty Thomas、Deffner Sebastian、Busch Thomas、Campbell Steve	４．巻 124
２．論文標題 Orthogonality Catastrophe as a Consequence of the Quantum Speed Limit	５．発行年 2020年
３．雑誌名 Physical Review Letters	６．最初と最後の頁 110601
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevLett.124.110601	査読の有無 有
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１．著者名 Xu Tian-Niu、Li Jing、Busch Thomas、Chen Xi、Fogarty Thomas	４．巻 2
２．論文標題 Effects of coherence on quantum speed limits and shortcuts to adiabaticity in many-particle systems	５．発行年 2020年
３．雑誌名 Physical Review Research	６．最初と最後の頁 23125
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevResearch.2.023125	査読の有無 有
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２．論文標題 Static and dynamic phases of a Tonks-Girardeau gas in an optical lattice	５．発行年 2018年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1367-2630/aae98e	査読の有無 有
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２．論文標題 Fast control of interactions in an ultracold two atom system: Managing correlations and irreversibility	５．発行年 2019年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.21468/SciPostPhys.6.2.021	査読の有無 有
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〔学会発表〕　計6件（うち招待講演　2件／うち国際学会　4件）

１．発表者名 Thomas Fogarty
２．発表標題 In situ thermometry of a cold Fermi gas via dephasing impurities
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3．学会等名
JPS Spring meeting, Fukuoka（国際学会）

4．発表年
2019年

1．発表者名
Thomas Fogarty

2．発表標題
Shortcuts to adiabaticity for interacting few body systems

3．学会等名
Small and medium sized cold atomic systems, Benasque, Spain（国際学会）

4．発表年
2018年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関