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COMMENT OPEN

Atom-level electronic physicists are needed to develop practical engines with a quantum advantage

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Theoretical research into quantum information engines that surpass the classical Carnot limit has exploded these past 10 years, but experiments so far have almost exclusively been the realm of the optics community. To help advance the field, and to develop solutions that might help our energy-dependent global society navigate the planetary crises, it’s high time that physicists working on atom-level electronics join the game.

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INTRODUCTION

The industrial revolution was propelled by the discovery of combustion engines that obey the laws of thermodynamics. A recent revolution is underway to extend and rewrite these laws to take into account quantum mechanics, using engines that are downscaled to the electronic levels of mere atoms.

ENGINES WITH A QUANTUM ADVANTAGE

In a typical quantum information engine, the working substance is made of discrete, quantum-entangled electronic states. When describing how it operates, the field of quantum thermodynamics, which has matured theoretically[1,2] within the past 10 years, underlines the advantages of quantum interactions between this working substance and the outside world. Several concepts can constitute a quantum asset in such an engine. For example, an excited quantum state of this working substance can, upon returning to the ground state, provide an additional source of work of quantum origin[3]. This is an example of so-called ergotropy[4]. Furthermore, the working substance is made to selectively interact with the engine’s hot and cold baths. These interactions, if they are coherent and are electronically/energetically tailored, can amount to quantum information measurements/setting of the working substance, which also generates ergotropy[5]. In general, ergotropy allows a quantum engine to outperform its classical counterpart[3–7].

Within the past 3 years, several experimental demonstrations of this quantum advantage in an engine have been reported[3,6–8]. So far, achieving an engine cycle of setting and measuring the quantum state of electronic levels on atoms (e.g., the nitrogen vacancy center diamond with an unpaired electron spin[3,6]) has almost exclusively been the realm of optical experiments. The engine strokes are typically performed using visible light and microwave excitations, and the engine state readout occurs using luminescence.

By crafting every stroke through an explicit external input, scientists are able to study these engines’ inner workings and the role of quantum assets. However, this fundamental approach precludes any practical applications due to the substantial auxiliary equipment needed to operate the engine.

GOING ELECTRONIC: PITFALLS, SUCCESSES AND CHALLENGES

From an applicative standpoint, a natural direction is to develop quantum engines that are electronic in nature. One major advantage over an optical route is that electronic interactions can be several orders of magnitude faster than optical ones, so that quantum coherence throughout the engine parts can in principle be better preserved. In the context of exploding (some would add, unrealistic) energy needs to fuel our booming information society, an electronic engine could be affixed to existing electronic gear to harvest the waste heat that is generated. Although this is already done using classical concepts such as the thermoelectric effect, a quantum engine would perform the harvesting much more efficiently.

From a materials standpoint, a historically logical workhorse has been to harness semiconductor physics. Here, the typical working substance is an electrostatically confined 2-dimensional electron gas that occurs at heterointerfaces. The engine’s electronic operation then occurs between the n and $n+1$ electronic levels of this so-called ‘quantum dot’[9]. However the large n~100 precludes a quantum advantage in this mesoscopic system, while the minute energy difference between levels requires deep cryogenic operation.

Superconducting quantum engines operating in a mesoscopic regime have also been reported[10]. It may be possible[11] for a superconducting implementation to exhibit a quantum advantage, but this track requires cryogenic temperatures, which essentially precludes mass-market applications.

We recently reported[7,12] that an alternate route may be to harness spintronics[13], a green nanotechnology in which information is encoded and transmitted using the electrons’ quantum spin property, in addition or in lieu of its charge. In our concept (see Fig. 1) and experiments, the spin-split electronic levels of a paramagnetic atom form the engine’s working substance, which interact with spin-selecting electrodes. The resulting spintronic quantum engine is thought to harvest the thermal fluctuations of the atomic paramagnet, and rectify the resulting flow of electrical charge using spintronics to generate useable power. In this sense, this concept isn’t subsumed within spin caloritronics[14], which implements a classical/mesoscopic view of spintronics.

This spintronic quantum engine appears to operate autonomously, at room temperature, and already benefits[12] from the

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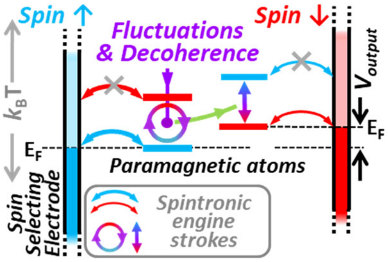

Fig. 1 A spintronic quantum information engine. Spin↑/↓ is in blue/red. The spin degeneracy of the paramagnetic atom's unpaired electron is dynamically lifted by transport fluctuations (blue on left) with spin-selecting electrodes. Interactions of different strength on either side (thinner red arrow on right), along with spin selection (gray crosses) break the detailed balance of transport. Thermal fluctuations (circular purple arrows) provide the energy to promote the electron to an excited quantum state. The quantum passivation of this excited state, and the spin measurement by the electrodes, effectively generate ergotropy, leading to a dc voltage V_{output}. Additional quantum assets, such as entanglement between spin states (green arrow), are described in ref. [7].

industrialization vector developed for next-generation magnetic memories[13]. These constitute paramount advantages over optical and semiconducting/superconducting approaches. However, there remain challenges to flesh out the concept and develop the technology. A major challenge is that, so far, these spintronic quantum engines are very poorly characterized. Indeed, these nanodevices operate using the laws of quantum physics by funneling current across a nanotransport path[15] within a micro- or nano-pillar, while the remainder of the device's atoms aren't at all involved. Materials science experiments on the heterostructure that was used to craft the device are therefore only of limited relevance. Conversely, isolating the properties of the atoms along this nanotransport path is arduous because it requires so-called *in operando* techniques in which the device is stimulated using the materials science technique (soft X-ray absorption[15], nuclear spin resonance[16]…) and the readout is electrical. This device-relevant approach is not widespread because it is arduous to implement. Furthermore, the quantum spintronic engine strokes are thought to occur in the 10^2–10^5 GHz range[7]. To explicitly drive the engine strokes will require THz electronics that are still maturing.

ATOM-LEVEL ELECTRONICS: PRESENT & FUTURE STRATEGIES

The electronics community working at the atomic level could crack this black box open by harnessing its experimental toolbox to flesh out this engine's electronic strokes. Recent reports have shown how to electrically and optically address the quantum states of individual atoms using a scanning tunneling microscope[17] (STM) or a lateral junction[16]. An important conceptual hurdle to overcome was to electronically decouple the target atom from the metallic substrate (e.g., a Ho atom on MgO[17]). Recent efforts have focused precisely on developing in operando electron spin resonance (ESR)-STM[17] and nuclear magnetic resonance[16] experiments on single atom/molecule junctions

I propose that atom-level electronic researchers can help the quantum thermodynamics field to greatly progress along this spintronic route with mass-market application potential[13] by using model spin-polarized transport experiments to explicitly open the black box that is this spintronic quantum engine. According to our present understanding[7] (see Fig. 1), ferromagnetic leads not only constitute an entropy sink, but the spin-polarized electronic interactions they generate constitute the engine's transport fluctuation stroke. This dynamically generates a spin splitting of the paramagnetic atom's energy levels that can not only be tuned through the electronic coupling thanks to a suitable quantum spacer, but can also be directly measured. Transport spectroscopy on the engine's atoms used as the working substance can also be used to measure the effective electronic bandwidth of this engine stroke. The interaction between this stroke and the spin swap stroke that occurs on the paramagnetic atom (this is where the harvesting of thermal energy takes place) can be studied using device operando ESR techniques. It may even be possible to assemble a full-fledged model quantum spintronic engine using STM and lateral junction techniques, if the electrodes and their interactions with the target atom(s) are spin-tailored. Multi-terminal STM/lateral junctions could also help monitor heat flow around the engine's atomic parts.

CONCLUSION

This subtle nudge in the research scope of the atom-level electronics community would help to better understand how real-world solid-state quantum spintronic engines operate, so as to bring it on par with the elegant experiments into engines that display a quantum advantage reported by the quantum optics community[3,6]. It would also confer a dual use to atom-level electronics research that has, so far, seen quantum information/communication technologies as its only finality—one that will become irrelevant if radical alternatives for our fossil-energy-driven global society are not found soon. By studying facets of the quantum spintronic engine, this community can keep on tinkering with the fascinating quantum world as it helps to develop energy-efficient quantum technologies[18] with a realistic short-term industrialization path[13]. This would help address the unlimited-energy-in-a-closed-ecosystem societal contradiction that is entrapping humanity, along a technological solution track that realistically may have to be balanced with a more precautionary track based on frugality[19].

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AUTHOR CONTRIBUTIONS

M.B. wrote this comment.

COMPETING INTERESTS

The author declares no competing interests.

ADDITIONAL INFORMATION

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