Thermodynamics

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A supercharged photonic quantum heat engine

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A photonic quantum heat engine based on superradiance — many-atom quantum coherence — is shown to deliver enhanced operation, with an efficiency no longer bounded by the Carnot limit.

The field of thermodynamics largely sprang from the attempt to make better heat engines. Early steam engines were very inefficient, and it was hoped that a better fuel might make a better engine; for example, perhaps if alcohol was used instead of coal, then maybe the efficiency would be higher. Unfortunately, this was not to be. Only the temperature of the hot energy source T_h and the low-temperature cooling water T_c mattered. As the nineteenth-century French physicist Nicolas Carnot famously showed, the limiting efficiency η of a heat engine is always given by $\eta = 1 - T_c/T_h$. It doesn't matter if you have a mini motor burning ethanol or a nuclear reactor burning U^{235}, the limiting efficiency is always η.

But what about the idea of making an engine that runs on a cheap energy source by simply using the heat in the atmosphere or in ocean water to provide locomotion. For example, running a car by just extracting energy from the atmosphere. Or an ocean liner by taking in warm ocean water and ejecting ice cubes; there is a lot of energy in the ocean and such a ship would never need to refuel. Such a device has been dubbed a perpetuum mobile (perpetual motion machine) of the second kind.

Such an engine seems to be ruled out by Carnot. Recall that real ships cool their heat engine by using ocean water. Thus, the temperature of the cooling water, T_c, is the same as the temperature of the heat source, T_h, and so the Carnot engine efficiency is $\eta = 1 - 1 = 0$. That is, an engine in which the temperature of the energy source equals the temperature of the coolant is not possible.

But maybe this two-temperature motor is too simple. Perhaps, if we consider more complicated systems, we can achieve perpetuum mobile of the second kind. Despite years of searching nobody has ever found a way to make such an engine and this 'no go' theorem is the essence of the second law of thermodynamics. To quote[1] the acclaimed English physicist Arthur Eddington: "If someone points out to you that your pet theory of the Universe is in disagreement with Maxwell's equations — then so much the worse for Maxwell's equations. If it is found to be contradicted by observation — well, these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics, I can give you no hope; there is nothing for it but to collapse in deepest humiliation."

But then came quantum mechanics and cracks in the 'second law barrier' began to appear. For example, physics Nobel Laureate Norman Ramsey said:[2] "During this process [of preparing an article on negative temperatures] I was shocked to find I was writing a paper contrary to one of the most popular statements of the second law of thermodynamics. My paper is consistent with most statements of the second law, like the principle of increasing entropy, but it is contrary to the Kelvin–Planck statement [of the second law]."

Of course, Ramsey is not claiming to have an ice-cube-generating ocean liner or any other type of perpetuum mobile of the second kind. However, now experiments by Kim et al., as reported in *Nature Photonics*, have shown how to make a quantum heat engine that can operate with supra-Carnot efficiency (Fig. 1c)[3].

In previous theoretical work in 2003, a photonic quantum Carnot engine (Fig. 1a) was proposed and analysed in which radiation pressure drives the piston[4]. That is, radiation is the working fluid (analogous to steam), which is heated by a beam of hot atoms (analogous to coal). When the temperature of the radiation working fluid, T_{rad}, is governed by hot two-level atoms, the engine efficiency is given by the Carnot limit (Fig. 1a). However, when the atoms in the heat bath have a small amount of coherence between the two lower levels, the use of quantum coherence fundamentally alters quantum heat engine (QHE) operation. In such a photon-Carnot QHE (Fig. 1b), T_h, T_c and the atomic phase ϕ are control parameters, and the efficiency of converting heat to work is given by $\eta_\phi = 1 - T_c/(T_h + \delta T_\phi)$ where δT_ϕ is small compared with T_h (Fig. 1b). By the proper choice of ϕ, work is obtained even when effectively $T_h = T_c$, that is, even when there is only one thermal bath. However, the underlying physics behind the second law of thermodynamics is not violated because work is required to produce atomic coherence.

Now the team of Kim et al. has shown how to use superradiance to make a sort of 'supercharged' photonic QHE. Their experiment provides a proof-of-principle demonstration of a quantum heat engine driven by N atom quantum coherence, that is, superradiance. In this experiment, atoms prepared in a coherent superposition state traversed a cavity to supply quantum coherence into the engine composed of a photon gas (working fluid) and cavity mirrors as a piston (Fig. 1c). The atoms in Fig. 1c have both an effective temperature (associated with the population inversion) and coherence (associated with the phase of the off-diagonal elements of the atomic density matrix). By controlling the phase of atoms, it is possible to turn the coherence on and off. A reservoir with coherence serves as a hot reservoir, while one without coherence serves as a cold reservoir. Owing to coherence among atoms[3], superradiance occurs. This strong collective emission considerably enhances the radiation pressure and the engine's output mechanical power. It has been noted[3] that this permits work extraction with substantially greater efficiency than the standard Carnot bound; in particular, that the efficiency can be enhanced up to 98%. It is also of interest to note that the efficiency of a nanobeam photon Carnot heat engine fuelled by squeezed thermal noise is also not bounded by the standard Carnot limit[5].

The realization of heat engines based on quantum coherent or squeezed thermal reservoirs could lead to important applications in nanotechnology and in the life sciences. It is possible such

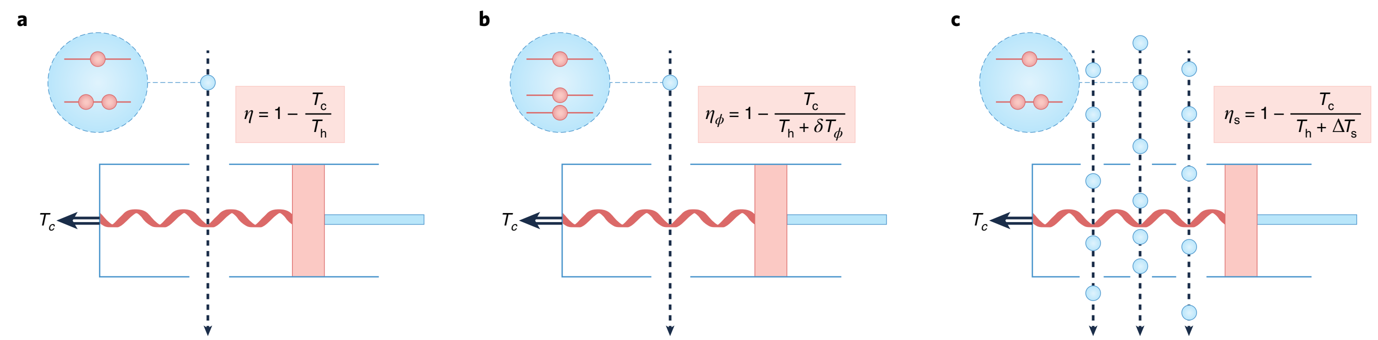

Fig. 1 | Photonic quantum engines. a, Photon-Carnot engine in which radiation pressure from a thermally excited single-mode field of a Fabry–Pérot cavity mode (red waves) drives a piston, which acts as one of the mirrors of the cavity. Atoms flow through the engine and keep the field at a constant temperature T_{rad} for the isothermal portion of the Carnot cycle. On exiting the engine, the bath atoms are cooler than when they entered, and are reheated to T_h by interactions with a heat source, which is not shown in the figure. A cold reservoir at T_c provides the entropy sink. Two-level atoms in a regular thermal distribution, determined by temperature T_h, heat the driving radiation to $T_{rad} = T_h$ such that the usual operating efficiency is given by the Carnot formula, limiting efficiency $\eta = 1 - T_c/T_h$. **b**, When the field is heated by atoms in which the ground-state doublet has a small amount of coherence and the populations of atomic levels are thermally distributed, the field temperature is $T_{rad} = T_h + \delta T_\phi$, where ϕ is the atomic phase, and the operating efficiency, η_ϕ, exceeds the Carnot bound η. **c**, Schematic of the superradiant quantum engine (SQE). The mirrors of a Fabry–Pérot cavity again act as a piston for the engine, but now the injection location of atoms is set at the antinodes of the cavity mode by a nanohole-array aperture. In this case $T_{rad} = T_h + \Delta T_s$ where ΔT_s, the temperature change in the SQE, can be larger than T_h.

engines might already be realized and exploited in the natural world to enhance biological processes, such as photosynthesis, a biochemical process converting the Sun's light energy into chemical energy. There is evidence that the photosynthetic conversion of solar energy to chemical fuel involves quantum coherence between exciton states, which implies a wave-like character of energy flow[6]. At low light levels, photosynthetic light harvesting operates at high quantum efficiency in delivering absorbed energy to the primary electron donor in the reaction centre[7].

In particular, the quantum nature of photosynthesis suggests that certain processes occurring in nature are effectively efficient heat engines developed to provide an evolutionary advantage[8]. Quantum coherence may arise in non-equilibrium environments[9] and could fuel such devices. It has been suggested that quantum mechanics might also be involved in brain functions, namely, quantum-mechanical superposition states of microtubules might produce brain activities[10].

An interesting phenomenon in open systems far from thermodynamic equilibrium is the emergence of collective behaviour and self-organization, which is the mechanism behind laser operation, noise-induced coherence[9], synchronization in collective nonlinear dynamics[11,12] and other processes. In biological systems, many theoretical works have suggested that the collective behaviour may have profound effects on the chemical and enzyme kinetics[13], and possibly even the cognitive function of the brain[10]. Among these works a widely used model is the Fröhlich condensation model[13,14], wherein energy of a driven set of oscillators would condense at the lowest vibrational mode once the external energy supply exceeds a threshold. It is very possible that such condensation[15] might yield an ordering of fluctuations in biological systems that could preserve coherence.

Of course, we can always discuss the extent to which devices of Fig. 1 are quantum engines and/or heat engines. For example, an electric motor is not a heat engine. It does not obey the Carnot bound. While we pay homage to Carnot at the power station, there is no doubt that the work of Kim et al. is a major step forward.

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Competing interests

The authors declare no competing interests.