Entropy-Decreasing Processes With ^{4}He Superflows

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Abstract. We argue microscopically that ^{4}He superflows carry heat unavoidably. We then show that a heterogeneous ^{4}He superflow loop can be used to realize an entropy-decreasing process, thus providing an exception to the second law of thermodynamics. This exception is a quantum effect for its essential dependence on the quantum phenomenon of superfluidity.

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The second law of thermodynamics (SLT), first formulated by Clausius in 1850s, rules out the decrease of the entropy in an isolated system. Despite more than one and a half century of studies, it remains elusive to find a solid principle behind SLT. This could suggest that SLT is almost universal rather than exactly universal, and that there are a few exceptions to SLT. On the other hand, an exception to SLT could open up the possibility of rendering usable the thermal energy of materials in the environment, thus bringing forth a potential solution to the energy issue faced by the world. In this note, we show that superfluid ^{4}He can realize an entropy-decreasing process, and that it is possible to build a ^{4}He-based system for extracting thermal energy from the environment in principle.

The phenomenological two-fluid model of superfluid ^{4}He postulates that a superflow carries no heat or entropy. This postulation is not corroborated by any microscopic understandings of superfluidity. On the contrary, a recently developed theory [1, 2, 3], built in the natural quantum mechanics terms of many-body quantum states and jumps among the states, suggests that a superflow carries heat. This microscopic theory reveals that the many-body spectrum of a superfluid has a characteristic feature [1, 2, 3].

Consider a superfluid composed of N particles in a limited geometry, the many-body Hamiltonian operator of the system can be written in the form of

$$\widehat{H} = -\sum_{i=1}^{N} \frac{\hbar^2}{2M} \frac{\partial^2}{\partial \boldsymbol{r}_i^2} + \sum_{i<j}^{N} V(\boldsymbol{r}_i - \boldsymbol{r}_j), \tag{1}$$

where M is the mass of a particle and $V(\boldsymbol{r})$ is the two-body interaction. Consider the eigenspectrum of the Hamiltonian operator, labelled by κ,

$$\widehat{H}\psi_\kappa(\boldsymbol{r}_1, \boldsymbol{r}_2, ..., \boldsymbol{r}_N) = E_\kappa \psi_\kappa(\boldsymbol{r}_1, \boldsymbol{r}_2, ..., \boldsymbol{r}_N), \tag{2}$$

where E_κ is eigenlevel and ψ_κ is the many-body eigenwavefunction. We shall consider also the momentum carried by eigenwavefunction ψ_κ,

$$P_\kappa = \langle \psi_\kappa(\boldsymbol{r}_1, \boldsymbol{r}_2, ..., \boldsymbol{r}_N) | \widehat{P} | \psi_\kappa(\boldsymbol{r}_1, \boldsymbol{r}_2, ..., \boldsymbol{r}_N) \rangle, \tag{3}$$

where $\widehat{P}$ is the total momentum operator along a superflow direction. Note that ψ_κ is not required to be an eigenwavefunction to the operator $\widehat{P}$.

If one schematically plots the energy levels of the system at the energy-momentum ($E-P$) plane (see Fig. 1), one then spots that the low-lying levels with various momenta form valley-like structures at the boundary region [1, 2, 3]. At low temperature, only those levels within the bottoms of the valleys are relevant in physics. A superflow state corresponds to some occupied levels at a valley at a non-zero momentum. The system is not allowed to jump from the occupied levels at this valley to some levels at the left-side neighboring valley, due to the energy barrier which separates the valleys. The prohibition of inter-valley jumps ensures that a superflow keeps its momentum, thus causing the phenomenon of superfluidity [4].

Under this microscopic description, a ^{4}He superflow shall always exchange quanta with its surroundings, as a result of the microscopic interactions between the ^{4}He atoms in the superflow and the particles in the surroundings. This exchange process promotes the superflow's intra-valley jumps among the occupied low-lying levels at the corresponding valley. It leads to a thermal equilibrium occupation probability of the levels, namely, the occupation probability of a level at the valley is proportional to $e^{-E/kT}$, where E is the energy of the level, k is the Boltzmann constant and T is the temperature of the superflow. This exchange process also establishes a thermal equilibrium between the superflow and its surroundings, in the sense that the temperature of the superflow is the same as the temperature of its surroundings.

Clearly, this natural framework shows not only that a superflow carries heat, but also that superfluidity doesn't require a superflow with zero entropy. One could also note that, from a general physics viewpoint, a macroscopic flow with zero entropy, immune from thermal influence of its surroundings, is rather too peculiar to be understood.

The heat content (specific enthalpy) of a superflow is in principle determined by its physical settings, such as its geometry, its temperature and its flow velocity. Let us consider a ^{4}He superflow passing through a channel where second half of the channel is empty but the first half is packed with a medium such as fine powders. If one keeps the temperature of the superflow the same when it exits the medium, one could expect

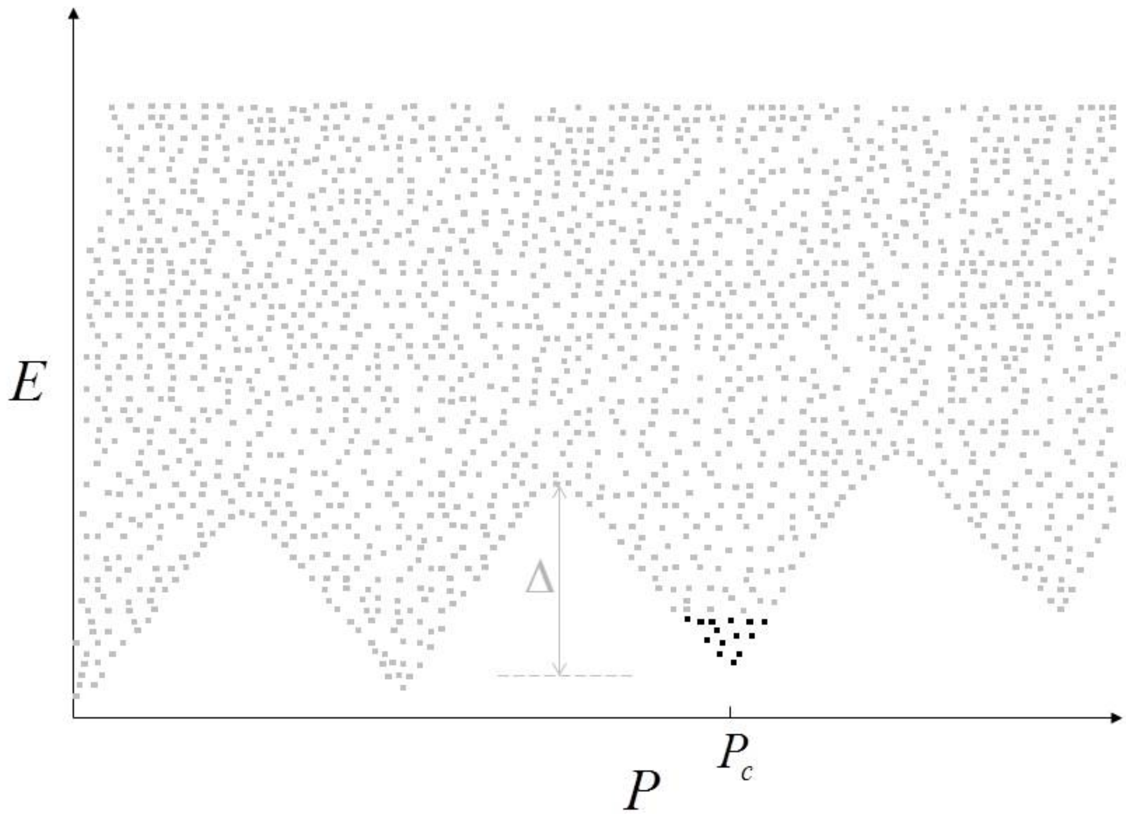

Figure 1. A schematic plot of many-body eigen levels of a superfluid in the $E - P$ Plane. Dots (in gray and in black) represent levels. The horizontal and vertical coordinate of a dot correspond to the momentum and the energy of the level, respectively. Δ denotes the height of an energy barrier between two "valleys". Dots in black are the occupied levels of the system (at low temperature), corresponding to a superflow state with a momentum of P_c.

that the heat content of the superflow shall change due to the change of its physical settings. If the change of heat content is negative, for the conservation of energy, one should provide heating to the superflow to maintain its temperature. Without such a heating, the temperature of the superflow shall drop when it enters the second half of the channel.

Shortly after the discovery of superfluidity [5], the temperature drops of ^{4}He superflows, when passing from media to rather free space, were reported [6]. Some observations involved superflows in capillaries. For convenience, we enhance the meaning of media so that superflows in various media also cover a superflow in a capillary. Free space is referred to as a medium of vacuum. Then one would expect a change of the temperature of a superflow going from a medium to a different medium, for the reasons

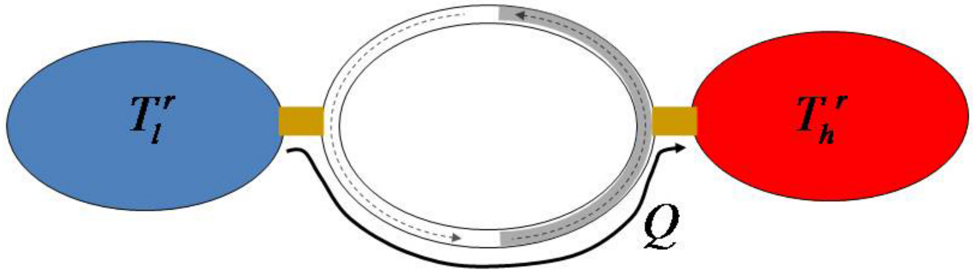

Figure 2. An counterexample to SLT. The superflow in the loop transfers heat flow from the heat reservoir at $T^r{}_l$ to another heat reservoir at a higher temperature.

illustrated above. This is analogous to Peltier effect, in which the heat content of an electric current shall change when it passes from one wire to another wire made of a different kind of metal, causing a cooling or heating at the junction of two wires.

We shall consider a circling ^{4}He superflow filling a torus-shaped vessel, where half of the vessel is packed with one kind of medium and the other half is packed with a different medium [7]. We refer to this system as a heterogeneous superflow loop (HSL). If an isolated HSL is waited for a sufficient time, one can reach an interesting temperature configuration along the system. Away from the interfaces between two media, one part of the system has a temperature T_h higher than the temperature of the opposite part of the system (denoted by T_l). At this configuration, the heat content of superflow in one medium is (approximately) the same as the heat content of superflow in the other medium. To demonstrate an exception to SLT, consider to have two infinitely large heat reservoirs (besides a HSL), with one reservoir at a temperature T_h^r and the other at a temperature T_l^r. T_h^r and T_l^r is set to satisfy $T_h > T_h^r > T_l^r > T_l$. Consider making a good thermal contact between the high temperature part of the HSL and the reservoir at T_h^r, and making a good thermal contact between the low temperature part of HSL and the reservoir at T_l^r. Then, the superflow at the high temperature medium is cooled (by releasing heat to the reservoir at T_h^r), thus carrying less heat content while the superflow at the low temperature medium is warmed and carries more heat content. Therefore the superflow in the high temperature medium carries less heat content than the superflow in the low temperature medium. As a result, the (moving) superflow transfers energy from the low temperature part of the HSL to the high temperature part of the HSL, or equivalently, it transfers heat from the reservoir at T_l^r to the reservoir which has a higher temperature ($T_h^r > T_l^r$) (see Fig. 2). This is a process in which the entropy of the whole system decreases rather than increases. The entropy-decreasing process can run for a cosmologically long time, for that the decay of the superflow is prevented by some energy barriers [8].

It is rather straightforward to sketch out a primitive system for extracting thermal energy from the environment. It shall include a HSL, a cryogenic heat device (CHD), another heat device referred to as the major heat device (MHD). The operation of each heat device shall generate a net effect similar to that of a heat engine; it absorbs heat from a hot object, converts part of the heat into another form of energy and releases the rest to a cold object. The CHD operates between the high temperature part and the low temperature part of the HSL. It converts part of heat, absorbed from the high temperature part of the HSL, into another form of energy and releases this energy to the environment [9]. The CHD passes some heat to low temperature part of the HSL, and the superflow transfers this heat back to the high temperature part. The MHD operates between a room temperature material and the high temperature part of the HSL. It absorbs heat from the material and converts part of the heat into usable energy or works. It is clear that MHD is responsible for generating the bulk of useful energy or work while the CHD mainly plays the role of returning the heat received by the HSL back to the environment. To improve the operation conditions for the CHD, one could use a series of HSLs for generating a large temperate difference across the series. In the series, the low temperature part of the first HSL is in good thermal contact with the high temperature part of the second HSL, the low temperature part of the second HSL in contact with the high temperature part of the third HSL, and so on.

Vacuum systems shall be involved to prevent the direct heat transfer, mediated by air, from the environment to the HSL. Thermal radiation from the environment to the HSL can be technically reduced but can not be effectively eliminated. If the thermal radiation upsets the operation conditions for the HSL, one can add a layer to surround the HSL. The MHD then operates between the room temperature material and the layer, and an additional cryogenic heat device works between the layer and the HSL. This layer has an intermediate temperature so that thermal radiation received by HSL can be largely weakened. If needed or preferred, more layers can be implemented.

In conclusion, we show that there is a quantum exception to the second law of thermodynamics, and that it could lead to a solution to the energy issue.

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[4] More generally, a superflow state could corresponds to a number of valleys with each of these valleys being partially occupied (The occupation probability of one valley refers to the sum of the occupation probabilities of the levels at the valley). Since the occupation probability of each valley doesn't change (with time) due to the prohibition of inter-valley jumps, the superflow state will always keep its momentum.

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[6] see, e. g., J. G. Daunt and K. Mendelssohn, Nature, **143**, 719 (1939).
[7] Here a medium could also refer to vacuum, and to a specific geometric setting of a superflow.
[8] For experimental observations of persistent ^{4}He superflow, see, e. g., J. D. Reppy and D. Depatie, Phys. Rev. Lett. **12**, 187 (1964).
[9] For example, one can use a number of thermocouples between the high temperature part and the low temperature part of the HSL. these thermocouples, connected in series and in parallel, could generate a workable voltage and current. If preferred, the voltage and current can be passed without dissipation to a separate cryogenic device placed away, by using superconducting wires. This cryogenic device could work at a temperature of several tens of kelvins for the sake of its performance (The heat leak through the superconducting wires will be negligible if the wires were sufficient long). This device could be a number of light-emitting diodes to release energy in the form of photons, into the environment. Or it could convert the (direct) current to alternating current, which in turn drives a superconducting solenoid to generate an oscillating magnetic field. The magnetic energy then can be picked up by a room-temperature solenoid outside, which is physically not in touch with the cryogenic parts. One might also develop cryogenic thermomagnetic generators for this use.