Journal of Thermodynamics & Catalysis

Shukla, J Thermodyn Catal 2018, 9:1
DOI: 10.4172/2157-7544.1000198

Review Article Open Access

Impossibility of the Continuous Persistent-Current in a Superconductor

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Received date: September 10, 2018; **Accepted date:** October 01, 2018; **Published date:** October 06, 2018

Abstract

The presence of a "persistent", "directional-current" in superconducting states is a direct "threat" to the 2nd law of thermodynamics. In this paper, we will show that there will never be a directional, (either clockwise, or anti-clockwise) "persistent-current" for "infinite-time" in any superconductor (or in any material at any pressure and temperature), otherwise the 2nd law of thermodynamics will be break down. We will show that the presence of very small, non-zero, finite, electrical-resistance below the critical temperature and critical magnetic field in a superconductor is a clear "signature" of the finite life-time of circulating-current, and thus, direct experimental "validation" of the 2nd law of thermodynamics at quantum-mechanical level.

Keywords: Superconductor; Persistent-current; Thermodynamics

Introduction

Materials can be classified into insulator, semiconductor, conductor and superconductor, based on their electrical response to the applied voltage. Superconductivity has been discovered by Heike Kamerlingh Onnes in 1911, when he was working with solid mercury wire at 4.2 K [1-5]. He found that resistivity of solid mercy wire drops 10^{-5} ohm at 4.2 K. For this discovery, he was awarded Nobel prize in physics in 1913. After that, several attempts have been made to realize the superconductivity at room temperature [2]. There is a general belief in the scientific community that, "once the material reaches into superconducting states, then, no further power is required to maintain the electrical current (direct-current, (DC)) in a superconducting material" [5-7]. And, thus, one can use superconducting material electrical property (in principle) and can run any electrical appliances (based on direct-current) which is made from the superconducting material, without any electrical-cost persistently. Some research group [8-14] claims that the continuation of a persist-current in any experiment breaks the essence of the 2nd law of thermodynamics. They claim that the 2nd law of thermodynamics require a serious modification at-least at the quantum mechanical level [9-12]. In this paper, we will resolve this controversy and will show that the 2nd law of thermodynamics is still valid in superconducting materials at the quantum mechanical level.

Superconducting $YBa_2Cu_3O_7$–δ, I-V Data

Material transform into a superconducting state at a very precise temperature known as the critical temperature, and below very precise magnetic field known as the critical magnetic field. There are three type of superconductor namely: type-I, type-II, and type 1.5 [15], depending upon that whether superconducting material reject/allows magnetic lines to pass through, or, whether there is any static/moving, attractive/repelling magnetic vortices' (fluxons) under the presence of an external magnetic field below the critical magnetic field [4,15-19]. We will not cover this topic in great details, because, our purpose is not to write another review article on superconductor, but to analyze the persistent current, which present in superconducting states. And whether this persistent-current violates the 2nd law of thermodynamics or not. We will use $YBa_2Cu_3O_{7-\delta}$ superconductor as our test case (without losing any generality). One can use another superconductor for analysis [20,22], but, conclusion will remain the same. If one sees $YBa_2Cu_3O_7$-δ film resistance versus temperature curve at zero external magnetic field shown in Figure 1, then, one notice that there is a transition in magnitude of resistance from 20 ohm to nearly 0 ohm, between 92-90 K. The main key point here is that $YBa_2Cu_3O_7$-δ film behaves like normal material above 92 K, while turns into superconducting states below the 90 K with effectively zero-resistance. Why we are saying "effectively- zero-resistance", because, if one plot the same resistance versus temperature curve on logarithmic scale, then, one notice that resistance is not "exactly" zero below the 90 K. There is a "non-zero", finite resistance at any temperature, even at 0-K. The origin of this resistance is due to pure quantum mechanical effect. It has nothing to do phonon scattering with electrons. However, phonon does contribute in finite resistivity or finite conductivity at any non-zero temperature. The net resistance at any temperature is the sum of resistance arises due to quantum mechanical effect, resistance due to phonon scattering, and contribution due to other impurity scattering. The net resistance will never be zero at any temperature and pressure. Only net resistance value can be minimized, but this value will never become "absolute-zero". If one see $YBa_2Cu_3O_7$-δ film I-V curve shown in Figure 2, then, one notice that the below the transition temperature (90K), there is a finite voltage drop at any current value. Finite "potential drop" shown in Figure 2 at any applied current suggest that there is a "finite-resistance" in superconducting state in $YBa_2Cu_3O_7$-δ films. This resistance is the sum of quantum mechanical and temperature dependent resistance (phonon contribution). The value of this resistance can be minimized, but it will "never" become "absolute-zero". The reason that the net resistance will never become absolute-zero at any temperature (even at 0-K), because, resistance arises due to quantum mechanical effect will always contribute. This quantum part of resistance is immortal at any temperature. The presence of very small, non-zero, finite resistance during superconducting states will guarantee that no current in superconducting material will survive forever. This current will never become "immortal" in the presence of very small, finite, non-zero resistance. Thus, we are concluding that the circulating current in superconducting states will "vanish" in finite

Citation: Shukla G (2018) Impossibility of the Continuous Persistent-Current in a Superconductor. J Thermodyn Catal 9: 198. doi: 10.4172/2157-7544.1000198

time. Finite time may be one second, one minute, one hour, one day, one year, 100 year, or 10,000 year. 10,000 year is also a finite time. If current persist long, then there is a great chance and greater certainty that some electronic device can be made based on the superconducting material, which can be used to improve the human living standard. The existence of very small, non-zero, finite-resistance at any temperature (even at 0-K) below the transition temperature will "guarantee" that the superconducting-current will "die" its own natural death in a finite-time, and thus, 2nd law of thermodynamics will "win" this battle with full certainty. The same superconducting device can be modeled using the inductance and resistance of the superconducting $YBa_2Cu_3O_7$-δ film shown in Figure 3. The total quantized magnetic flux associated with the superconductor in a superconducting state with inductance L, and supper current I, can be written as,

$$\phi = L \times I \qquad (1)$$

Since the supper-conducting film has a very small, non-zero, finite resistance shown in Figure 2. therefore, current in an inductor will decreases as a function of time and dictated by the mathematical relation,

$$I = I_0 e^{\frac{-RT}{L}} \qquad (2)$$

where I_0 is the maximum amplitude of the superconducting current that will exist during superconducting states in a superconductor [3], R, is resistance, L, is the self-inductance of the superconductor, and t, is the time (in second). As time progress, then this superconducting current will start decreasing, and after 5-6 time constant [23].

$\frac{L}{R}$, it will decrease very significantly [23]. However, in principle, infinite time will elapse to turn it perfectly "zero". If one sees the time constant equation, $\frac{L}{R}$, then one notice that it is inversely proportional to magnitude of the superconducting film resistance. So, if resistance is small (as in superconducting case), then time constant will be large. Still, current will be almost dead within the 5-6-time constant [23]. If one knows the total magnetic flux associated with the superconductor in a superconducting state, then one can get the inductance (L) of the film using the relation, $L = \frac{\phi}{I}$ (3)

Where ϕ is the total magnetic flux associated with the superconductor in a superconducting state.

One can also approach the same problem from conservation of energy perspective. The magnetic energy stores in the superconductor in a superconducting state can be written as,

$$\frac{1}{2}LI^2 \qquad (4)$$

$$\frac{\phi^2}{2L} \qquad (5)$$

where ϕ, is equal to the total magnetic flux associated with the superconductor in a superconducting state, L is self-inductance of superconductor which depends upon the geometry of the superconductor, and I is the persistent-superconducting-current that flow in superconductor in a superconducting state. If there is no any finite resistance in a superconducting state then the magnetic flux ϕ, the persistent-current I, and the total magnetic energy $\frac{\phi^2}{2L}$, will persist forever, and thus, these quantities will behave like an immortal in time. However, if there is any small, non-zero, finite resistance exists in the system, then, these quantities will turn from immortal into mortal. Now, how long these quantity will survives under the non-zero, finite resistance in a system is depends upon the how fast resistance drains energy from the magnetic field and convert it into heat, which finally flows out from the system, using the relation, I2R, where I is the superconducting current at any time t, and R is the resistance of the superconductor in a superconducting state. As the time progress, the total magnetic energy, $\frac{\phi^2}{2L}$, the total magnetic energy associated with the superconductor in a superconducting state will be dissipated, until or unless there is an external agency (such as external magnetic field) which supply the magnetic energy with the same rate as the resistor drains the energy from the superconductor and dissipate it into heat. Under the absence of external magnetic field, the total magnetic energy associated with the superconductor, $\frac{1}{2}LI^2$, will be drained by the resistor into heat, and thus, the final total magnetic energy, $\frac{1}{2}LI^2$, will be zero, which implies that final superconducting current I, will be zero.Shortcoming in Alexey Nikulov and Daniel Sheehan Paper

Nikulov and Sheehan in their editorial paper [24] at page 4, vehemently argued against the second law of thermodynamics. They even indirectly suggested that no conclusion should be made on any physical process using the second law of thermodynamics. There are many shortcomings in their argument. We will go one by one and will clear each doubt surround the second law of thermodynamics, and then we will show that the second law of thermodynamics is supreme, and it cannot be violated in any process on any scale (length, and time). Let go one by one.

Alexey nikulov and Daniel sheehan wrote,

- "*Circular arguments about impossibility of second law violation abound. For a modern case in point, consider the quantum mesoscopic phenomenon of persistent current, i.e., direct current observed under equilibrium conditions investigated by one of the editorial authors (A.N.). It has been known for over forty years that persistent currents can be observed at non-zero resistance. Based on quantum theory and as corroborated in numerous experiments, a direct current in the equilibrium state can be maintained at non-zero power dissipation [15]. This is a clear threat to the second law, however, when confronted with this persistent current observed at non-zero resistance, the author found that most scientists simply stated that such an equilibrium phenomenon could not threaten the second law since no work can be extracted from the equilibrium state [16]. Clearly, the defending statement is itself a formulation of the second law, rendering the argument circular*" [24].

The first key point in above argument is that, Nikulov has measured the persistent direct-current under equilibrium condition. Question arise that in what direction? Clockwise or anticlockwise? Who provide this unique direction to the net current in an equilibrium condition? Is this not contradicting itself that there is a net directional process under equilibrium condition? How can a system has attained the equilibrium if any directional process is still operating and dragging the system forward? Also, Nikulov should have shown his experimental set-up and experimented current data as a function of time to the scientific community, because we want to know each detail about his experiment, that whether there is any small, non-zero, finite resistance exists in his I-V data or not.

The second key point in their argument is that "It has been known for over forty years that persistent currents can be observed at non-zero resistance". Nikulov and Sheehan should have provided a clear, unambiguous information about the amplitude of the persistent current, that whether it has decreased with time or not. We have no doubt that amplitude of persistent current will be decreased as a function of time under nonzero resistance states to Figure 3. It must decrease and follows the relation, $I = I_0 e^{\frac{-RT}{L}}$, where R is the small, non-zero, finite resistance that exist in superconductor during superconducting state, and it can be inferred from I-V data at any temperature (Figure 2). Also, one can find inductance L, of the superconductor, once the total magnetic flux ϕ, and superconducting current I, is known, after using the relation, L=ϕI. Also, one should not be surprised that persistent-current exist in non-zero resistance superconducting circuit. Because, how long current will persist in such states depends on the time constant $\frac{L}{R}$ of the electrical circuit, which is made from the superconductor. Generally, current does persist till 5-6 time-constant with decreasing amplitude in any L-R circuit [3,23].

- "*Clearly, the defending statement is itself a formulation of the second law, rendering the argument circular. The free energy F=E-ST has minimum value in the equilibrium state and it is impossible to decrease in value below its minimum. But the internal energy E can be decrease without any decrease of the free energy at nonzero temperature T>0 if the entropy S decreases at the same time. As this anecdote shows, in defending the second law, one must be careful not to implicitly assume it, but this is often not as easy as it looks"* [24].

There are two type of free energy in thermodynamics. One is Gibb's free energy and other is called Helmholtz free energy [25,26]. We guess that they are talking about Gibb's free energy. Let see how Josiah Willard Gibbs has defined this energy in 1873: "*the greatest amount of mechanical work which can be obtained from a given quantity of a certain substance in a given initial state, without increasing its total volume or allowing heat to pass to or from external bodies, except such as at the close of the processes are left in their initial condition"* [27].

Now, take any thermodynamics system with total free energy or total maximum available energy for reversible work is equal to,

$$G=E-ST \qquad (6)$$

Question is whether this, G=E-ST, is the maximum amount of "*non-expansion work*" that can be extracted from a thermodynamically closed system, or one can extract more than G=E-ST? Nikulov and Sheehan [24] are arguing that they can extract more than G=E-ST. Let critically analyze this problem. If we take Gibb's free energy, G=E-ST, then the first term corresponds to the total internal energy (H) equal to chemical energy (U) and pressure-volume energy (PV), whereas the second term ST corresponds to the thermal energy. Let take an exothermic reaction in which the total chemical energy decreases after reaction. Thus, E term decreases, because, we are dealing "non-expansion work", so no expansion is allowed. Now, lookup the second term ST. If process is exothermic, then the temperature of the system will increase, which indirectly increases the entropy. Or, the other possibility is that the entropy S, increases at the constant temperature, T, under volume expansion. But, volume expansion is not allowed. So, only first scenario can happen. In first scenario, the first term, E, decreases, whereas the second, ST, increases. The net ΔG=ΔE −Δ(ST)<0, (7) term decreases and thus ΔG turns negative. Turning ΔG negative at equilibrium contradict the essence of "*thermodynamics equilibrium*" which says that the change in Gibb's free energy at the equilibrium must be zero. Thus, this process will be "*impossible*" in nature. If one analyzes the endothermic case, then, one notice that change in first term, E, will be positive (because process is endothermic. In endothermic process, the change in total internal energy is always positive). The second term ST, will decreases, because, process is endothermic and energy reshuffle has taken place from term (ST) to the first term (E). In this process the net change in Gibb's free energy ΔG=ΔE−Δ(TS)>0, (8) at equilibrium will be positive. Again, this contradict the essence of the thermodynamic equilibrium, which says that the change in Gibb's free energy at thermodynamic equilibrium must be zero. So, endothermic process is also not allowed. So, neither exothermic nor endothermic process is allowed for extracting further reversible work greater than, G=E-ST. Let see if the process is neither exothermic nor endothermic. If the process is neither exothermic, nor endothermic, then, the change in first term (ΔE) will be zero, and thus the change in second term (Δ(ST)) will also be zero. In other words,

$$ΔG=ΔE=Δ(ST)=0 \qquad (9)$$

Because, there is no way through which reshuffling between the coherence energy (E) and non-coherence energy (ST) can take place in this case. What we are concluding in this section is that, we don't know on what "*fundamental-ground*", Alexey Nikulov and Daniel Sheehan have argued to extract further reversible work greater than G=E-TS. Alexey Nikulov and Daniel Sheehan should have explained their unique process through which they will extract maximum amount of non-expansion work greater than, G=E-TS, at any temperature and pressure, without breaking any thermodynamics fundamentals. What seems to this author is that, if one defines,

$$G=E+ST \qquad (10)$$

instead of G=E-TS, only then, Nikulov and Sheehan thought process can work. But, then, every thermodynamics rules and fundamentals will break down.

- "*In the second paper the deep physics behind the second law: Information and energy as independent forms of bookkeeping by T. L. Duncan and J. S. Semura discuss the possibility that the foundation of the second law may lie the finite capacity of nature to store information about its own state*" [24].

If one read Duncan et al. paper, "*The deep physics behind the second law*" [28], then one notice that Duncan et al. have not given any clear, unambiguous justification that "*why*" energy and information should be treated independently. In nature, both information and energy are perfectly connected. In-fact the flow of information is directly dictated by 2nd law of thermodynamics. Information can only flow if 2nd law of thermodynamics allows it after consulting with first law of thermodynamics. So, any bit of information can only be flown, when both first and second law of thermodynamics agree unequivocally. There are many shortcomings in Duncan et al. paper [28]. We will discuss these shortcomings once we finished Nikulov and Sheehan paper [24].

- "*Can order arise from disorder without an external influence? This is one of the deepest questions connecting Nature to the second law*" [24].

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Order cannot arise from disorder, because disorder happened due to the presence of chemical potential energy gradient. If system evolves under the presence of any kind of energy gradient (chemical/electrical/magnetic/gravitational/thermal), then it follows the irreversible path. The origin of disorder is the direct consequence of the irreversibility of the process. Order will never arise from disorder without any external influence. The day this happens, one can go back in past, time can flow back, dead man can alive again, and many more weirdness that one can think-of. This suggest that the breaking of the second law of thermodynamics have very serious consequences.

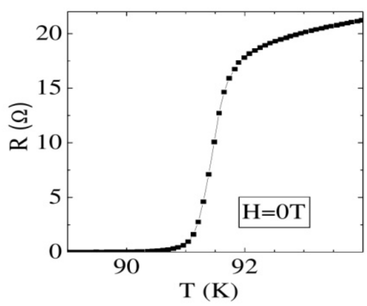

Figure 1: $YBa_2Cu_3O_7$-δ film resistive transition under zero magnetic field.

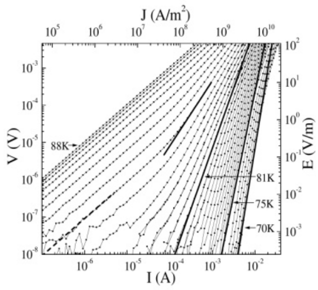

Figure 2: I-V curves for $YBa_2Cu_3O_7$-δ film, at constant temperature on log-log plot.

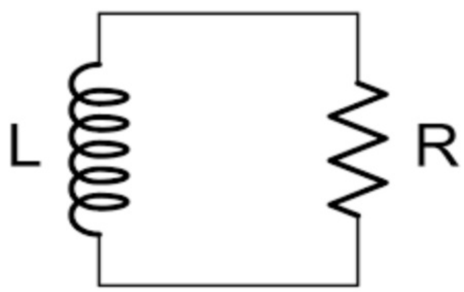

Figure 3: $YBa_2Cu_3O_7$-δ superconducting film electrically equivalent to L-R (inductance-resistance) circuit.

Shortcoming in Duncan et al. Paper

There are many short comings in this paper [28]. We will go one by one. Duncan et al. wrote:

- "*We pursue the notion that the second law is ultimately a restriction operating directly on the dynamics of information, so the existence of this law can be traced to the need for a system of "information bookkeeping" that is independent of the bookkeeping for energy. Energy and information are related but independent, so the dynamical restrictions for one cannot be derived from those for the other"* [28].

Energy and flow of any thermodynamical information are strongly coupled to each other. Thermodynamical system evolves under the presence of chemical/thermal/electrical/magnetic/gravitational potential energy gradient at any time-step. First, energy gradient-appear in the system, and then, any bit of information can flow. In nature, nothing can flow without gradient. The evolution of any thermodynamical system under any gradient produces irreversibility which increases overall entropy. We don't know which information can flow without energy gradient. And if there is any gradient, then it must be related to the energy (chemical/thermal/electrical/magnetic/gravitational potential energy). Duncan et al. should have provided at least one example in which thermodynamical information has been flown without any form of energy-gradient.

- "*The second law is a law about information-it operates at the level of information, not energy, and hence requires a separate bookkeeping system for information in order to impose the law*" [28].

The second law of thermodynamics is a law about thermodynamical irreversibility. Information must be related to the thermodynamical variables (such as pressure, temperature, entropy, internal energy, chemical potential). Information can only flow if there is any kind chemical/thermal/electrical/magnetic/gravitational/external) of energy gradient. So, both energy gradient and flow of information are coupled to each other. They are not independent.

- "*In terms of information, the second law says that information is truly and fundamentally erased by some processes, so that once erased, that information cannot be recovered"* [28].

Information cannot be recovered because system has been evolved under the presence of any kind (chemical/thermal/electrical/gravitational potential energy) of energy gradient, which inherently induce irreversibility in the system and thus increases entropy.

- "*We show that our statement contains the traditional statements of the second law; i.e., there is a clear link between the direction of heat flow and loss of information"* [28].

Heat can only flow if there is a thermal energy gradient (temperature gradient). No information can be lost if one investigates system and surrounding carefully. We don't know which thermodynamical information has lost during the heat flow under thermal energy gradient. Duncan et al should have provided it unambiguously.

- "*Since our basic argument is that the second law is most simply and fundamentally a law about information, we begin by suggesting a formulation in terms of information*" [28].

Second law of thermodynamics is all about irreversibility of any physical process. Because, every dynamical physical process evolves under the presence of chemical/thermal/electrical/magnetic/gravitational potential energy -gradient. The presence of any kind of gradient provide net direction in any process at any timestep, and thus induce irreversibility and increases entropy of the system.

- "*So, when energy is exchanged between two systems, information is also exchanged shown in Figure 1, but the dynamics of energy exchange does not uniquely determine the information exchanged. For the same amount of energy, different amounts of information that had been erased would have to be recovered*" [28].

Heat flow from hot to cold, because in hot side there is higher chemical potential energy compare to the cold side. System tries to equalize the chemical potential energy in both sides. The presence of chemical potential energy gradient drives the system to evolves, and thus heat flow from hotter side to the colder side. The evolution of any system under any kind of gradient will follows the ir-reversible path, and thus entropy increases.

- "*The dynamics of energy exchange does not always pin down which states are gaining or giving up the energy. Of course, the energy and information bookkeeping must be consistent with each other, but the dynamics of information is independent and equally necessary to describe the world, and the information description cannot be reduced to the energy description*" [28].

Energy can only flow if there is any spatial/temporal energy-gradient. So, one can indeed pin down which states are gaining, and which states are giving up energy. Thermodynamical information can only flows if there is any type of energy-gradient. Both energy-gradient and thermodynamical information are coupled to each other.

Conclusion

In this paper, we have tried to resolve the conflicting issue between the 2nd law of thermodynamics and persistent-current, which arises during superconducting states in a superconductor. We have shown that the presence of very small, finite, non-zero, electrical resistance below the critical temperature and critical magnetic field is the clear evidence of finite life-time of circulating current in a superconductor. Since, according to laws of thermodynamics, every directional process in nature is irreversible and has finite lifetime, therefore, circulating current will not persist continuously infinite time in a superconductor. We have shown that the presence of non-zero, finite, resistance in superconducting states is a direct evidence of validation of the 2nd law of thermodynamics at quantum mechanical level.

We hope that this paper will clear the controversy surrounding the 2nd law of thermodynamics at quantum mechanical level and will stimulate the scientific community to explore a new area with certain responsibility towards some very fundamental laws of nature, such as 2nd law of thermodynamics.

Now, we can quote Arthur Eddington again: "*The second law of thermodynamics holds, I think the supreme position among the laws of Nature. If someone points out to you that your pet theory of the universe disagrees 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*" [24].

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