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Dynamic Thermal Management and Tunable Magnetic Phase Transitions via a Dynamic Chiral Thomson Effect on Rotating Conductors

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Abstract

In this work, we describe a new wavelike nonlinear heat conduction model aimed at implementing chiral thermal management and dynamic tunable chiral thermal emission on rotating conductors exposed to **a** chopped laser beam. We assume the existence of a rotational dynamical thermal Hall effect due to a self-induced out-of-equilibrium Barnett magnetic field, demonstrating that it allows for the transverse deviation of the harmonic heat flux and the modulation of the phase velocity of helical thermal waves propagating on the rotating metallic disks. We introduce a novel dynamic approach to thermoelectricity with complex valued thermal field dependent transport coefficients ,deducing then a new dynamic chiral Thomson effect. We show that it is proportional to the angular velocity vector of the rotating disk, providing an estimate of its average Thomson voltage coefficient in the case of a ferromagnetic sample. We exploit then the laser-induced chiral Thomson electric field associated with a time-dependent Barnett magnetic field to enhance dynamic magnetic phase transitions and to tune time dependent Curie temperature fluctuations. We introduce finally a dynamic tunable chiral thermal emissivity dependent on a gauge breaking thermal Poynting vector, outlining its relevance for a novel rotational approach to chiral nonreciprocal photonics.

Keywords: dynamic chiral thermal management; dynamic chiral Thomson effect; dynamic tunable magnetic phase transitions; dynamic tunable chiral thermal emissivity

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1. Introduction

Thermoelectric cooler is a research issue which solid state cooling technology is attracting a lot of attention in recent years due to the growing importance of solid state cooling technology for developing more efficient thermoelectric modules in electronics and medicine.

Thermoelectric effects consist in the mutual conversion of heat in electricity and were discovered in 1821 from T.J. Seebeck when he observed that two different metals at different temperatures generate an electric current at their two junctions. Few years later in 1834 J.C.A. Peltier discovered the inverse effect, that is a thermal gradient at the junction of two metal induced by an electric current. Based on these effects W.Thomson predicted in 1851 a third thermoelectric effect where the cooling-heating effect depends on the sign of the thermal gradient along a single conductor carrying electric current [1].

It was then understood empirically that a good thermoelectric device should have a low thermal conductivity k, a big electric conductivity σ and a big Seebeck coefficient S to minimize irreversible heat dissipation due to the Joule effect and to preserve a big temperature gradient. Till 1940's thermoelectricity have been investigated only on metals which had a high thermal conductivity and therefore had low electric performances and were not attractive for technological applications on thermoelectric coolers. In the late 1950's Joffe applied thermoelectricity to semiconductor samples and introduced the figure of merit $zT = \frac{\sigma S^2}{k}$ [2] to measure its electric performance, proving that the maximum temperature difference ΔT was proportional to the figure of merit

$$\Delta T_{max} = \frac{zT_C^2}{2}$$

with T_C the cold junction of a Peltier cooler module.

Despite the efforts of many researchers to improve the figure of merit , particularly at cryogenic temperatures the power generation and efficiency of the thermoelectric coolers were still very low for technological applications and thermoelectricity was nearly abandoned. In the 1990's green technology research issue stimulated renewed interest on thermoelectric coolers, due to its potential technological application to waste heat recycling. It was only in recent years that were investigated Thomson cooler devices abandoning the conventional temperature independent assumption so far exploited ,extending the working range of Peltier coolers to larger temperature gradients and higher electrical currents introducing Thomson cooler [2].

Then were realized thermal diodes with temperature dependent properties observing metal-insulator phase transitions when the electric conductivity and the Seebeck coefficient had sharp changes. In fact, due to the Thomson effect since the heat density Q is proportional to both the electric current $\vec{J}\cdot$ and the temperature gradient by

$$Q = -\tau\vec{J}\cdot\nabla T$$

with ∇T the thermal gradient and τ the Thomson coefficient given by

$$\tau = T\frac{dS}{dt}$$

This non linear contribution due to the temperature dependent Seebeck coefficient implies an extra Joule-Thomson current in the heat diffusion equation which modifies the efficiency of thermoelectric devices which was evaluated by most authors assuming a constant Thomson coefficient and exploiting for unidimensional thermoelectric modules the balance equation

$$k\frac{d^2T}{dx^2} + \frac{J^2}{\sigma} - \tau J\frac{dT}{dx} = 0 \quad .$$

Few years ago, in 2022 this new framework based on the hypothesis od a constant Thomson coefficient was applied successfully to magnetic phase transitions [3] and it was detected at T=305K ,using particular ferrite alloys, a giant Thomson coefficient $\tau \cong -906\mu V/K$. It was then proved experimentally in 2023 an enhanced Thomson effect with big temperature drops showed that measuring a steady temperature relative span $\Delta T/T \cong 5\,/38$ [4].This result improved greatly performances of conventional thermoelectric coolers and were then confirmed proving that Thomson effect enhances efficiency of thermoelectric cooling when it is implemented by phase transitions.

Despite these impressive results obtained in the last three years and the efforts to improve Thomson cooler efficiency the strategy to try to find materials to improve just the figure of merit by enhancing temperature gradients was not successful. In fact, these experimental investigations were not justified theoretically since they assumed the existence of a figure of merit for this non linear stationary framework . Anyway, differently from the conventional approach to thermoelectricity introduced by Joffe, it is not possible to define an equivalent definition of figure of merit zT and of power generators for Thomson cooler devices [2].

The main theoretical motivation that inspired our work stems from this open question and is aimed to stimulate a debate in the thermoelectricity community on the necessity to overcome the stationary unidimensional approach and abandon the hypothesis of a static Thomson coefficient τ.

We will illustrate therefore a new dynamic approach to Thomson thermoelectric coolers, which, differently from conventional ones so far investigated, will have a complex valued thermal field dependent Thomson coefficient $\tau(T)$.

The main result of the framework proposed in this work is the prediction of a new dynamic chiral magneto thermoelectric effect, which we called dynamic chiral Thomson effect, that consists in a pulsating Thomson voltage associated to chiral helicoidal thermal waves propagating on rotating conductors exposed to the harmonic heat source of the laser beam. We will show that the harmonic heat source of the chopped laser beam induces an out of equilibrium Barnett magnetic field which allows to control dynamically the direction and the intensity of the heat flux via a dynamic self-induced Righi-Leduc effect. The new dynamic chiral approach to thermoelectricity is non linear and non-stationary and therefore, differently from conventional stationary approaches, predicts complex valued time dependent transport coefficients such as thermal conductivity, electric conductivity and Seebeck coefficient.

Therefore, it is not possible to evaluate the electric performances of the new rotating Thomson coolers applying the conventional definition of the figure of merit zT since it cannot be extended to non stationary thermal gradients [5].

We will give some simple estimates of average Thomson voltages associated to the dynamic non linear Thomson cooling effect in accordance with recent experimental results measured on Thomson coolers associated to phase transitions [4].We will show that on rotating ferromagnetic conductors implement dynamic tunable local magnetic phase transitions associated to detectable Curie temperature fluctuations.

We remark that this new time dependent thermoelectric effect is caused by harmonic heat source induced on the rotating conductors by the chopped laser beam and is not a byproduct of equilibrium thermal noise. In fact, it cannot be applied in this dynamic framework the well-known Fluctuation-Dissipation theorem [6] lacking either the definition of a stationary local temperature and its generalization on rotating frames. Therefore, neither the Johnson-Nyquist theorem can be exploited to compare the harmonic temperature fluctuations induced on rotating metallic disks by the chopped laser beam with those due to thermal noise conversion.

More generally we expect that the dynamic thermal management due to the dynamic chiral Thomson effect predicted could be tested indirectly by observing macroscopic violations of the Fluctuation-Dissipation Theorem and therefore of the Johnson-Nyquist theorem on rotating conductors. Whenever confirmed experimentally this rotation induced violation of these Theorems could be interpreted as an indirect proof of the existence of dynamic tunable magnetic phase transitions associated to time dependent Curie temperature fluctuations. In fact, in accordance with recent investigations on the Fluctuation -Dissipation Theorem in the presence of external oscillating fields [7], we can interpret microscopically our non linear wavelike heat diffusion model as a non Markovian heat transport process associated to non-gaussian and non-stationary thermal noise on the rotating disks.

We remark the definition of a generalized Langevin equation is lacking even in quasi-stationary regime of low frequency of the laser chopper. Therefore, the local thermomagnetic phases transition associated to local maximum of the specific magnetic entropy exploiting an analogy with similar local equilibrium states of spin glass systems [8].

It is missing in the modern literature on thermoelectric coolers a discussion on the possible generalization of the Johnson-Nyquist Theorem on accelerated samples [9],although a covariant generalization of this theorem could help to implement nano Thomson coolers and to improve some experimental results on giant spin Thomson effect on semimetals with strong spin-orbit coupling as bismuth.

In fact, although in the last ten years, the search for more efficient spintronic devices has stimulated some authors to investigate electric-field-induced orbital angular momentum in metals, a discussion on the relevance of a generalized Fluctuation-Dissipation Theorem is missing in the nascent research issue of non-equilibrium orbital physics called orbitronics [10]. One important research direction that has been explored very recently, using a stationary approach and disregarding non Gaussian thermal noise effects, is how to convert orbital currents to charge currents to enhance the spin Seebeck effect and improve electric performance of thermoelectric devices. This new research issue of orbital physics, although currently lacking a solid experimental verification of the predicted orbital currents, might explain new phenomena such as the orbital Hall effect and anomalous Hall effect in ferromagnets and semimetals [1]. These studies have not previously investigated the effects of out-of-equilibrium orbital currents on enhancing the efficiency of junction less thermoelectric devices which, conventionally, exploit the classical stationary Thomson effect or its phase-transition-induced enhancement [11–13].

Our work, on the contrary, is aimed at developing an out-of-equilibrium generalization of the Thomson effect on macroscopic rotating metals and semimetals with Thomson coefficient dependent on the thermal waves propagating on moving samples [14,15], which might be exploited to implement dynamic rotational Thomson thermoelectric coolers. The principal motivation that inspired our proposal is to elaborate a new unified framework of heat diffusion and thermal emission based on orbital physics which might implement chiral thermal management and tunable magnetic phase transitions via a dynamic chiral Thomson effect.

The theoretical proposal we will illustrate develops a novel dynamic rotational approach to thermoelectricity and thermal emission and predicts a new generalized magneto-chiral Thomson effect which might be exploited for technological applications such as thermal management once confirmed experimentally.

The main result of our model is the prediction of a generalized dynamic rotation-induced chiral magneto Thomson cooling-heating effect, in accordance with recent experiments confirming the existence of the magneto-Thomson effect and of the transverse Thomson effect [16,17], due to an out-of-equilibrium, temperature-dependent Barnett magnetic field $\Delta B(T)$ applied orthogonally to both the temperature gradient and to the Thomson electric current. We will show that the harmonic heat source due to a chopped laser beam induces a dynamic enhancement of the Thomson coefficient, giving an estimate of this giant enhancement on iron samples. Finally, we deduce the existence of a chiral tunable thermal emissivity associated to the gauge breaking dynamic Thomson voltages, discussing its relevance for a future nonlinear approach to thermal harvesting[18], polarized control of thermal radiation, and nonreciprocal photonics [19,20] on rotating conductors.

2. Out of Equilibrium Barnett Effect and Dynamic Chiral Thermal Management

The theoretical proposal we will illustrate in this section develops a novel dynamic rotational approach to thermal management based on out of equilibrium generalization of the Barnett effect associated to an effective magnetic field $\overrightarrow{\Delta B(T)}$ dependent on helical thermal fields generated on rotating metallic disks.

We will assume that the harmonic heat source due to the chopped laser beam on the rotating disk induces an effective temperature-dependent Barnett magnetic field $\overrightarrow{\Delta B(T)}$ parallel to the angular velocity vector of the body $\vec{\Omega}$ [21,22], that is, an out-of-equilibrium thermomagnetic effect:

$$\overrightarrow{\Delta B(T)} = \frac{\vec{\Omega}}{g(T)} = \frac{2m(T)}{e}\,\vec{\Omega} = b(T)\vec{\Omega}\ , \tag{1}$$

with $\overrightarrow{\Delta B(T)}$ the Barnett effective magnetic field measured with respect to the average magnetic thermal noise, b(T)=2m(T)/e a new coefficient inverse to the gyromagnetic ratio g(T), e the electron charge and m(T) a new unknown thermal field dependent effective electron mass m(T).

We will introduce, in accordance with a similar approach used to study the performance of thermoelectric devices, an empirical coefficient A defined as a temperature average of the Righi-Leduc number A(T)

$$A = \int_{T_0}^{T_c} \frac{A(T)dT}{T_c - T_0} = kA_{R-L} = k\int_{T_0}^{T_c} \frac{A(T)dT}{T_c - T_0} = k\int_{T_0}^{T_c} \frac{\frac{\nabla_y T}{B\nabla_x T}dT}{T_c - T_0}\ , \tag{2}$$

with

$$A_{R-L}(T) = \frac{\nabla_y T}{B\nabla_x T} = \frac{\partial_y T}{B\partial_x T}\ , \tag{3}$$

so that the equation (1) can be rewritten as

$$\overrightarrow{\Delta B(T)} = \frac{2m(T)A\vec{\Omega}}{e} = \frac{b(T)\vec{\Omega}}{A}\ . \tag{4}$$

It can be deduced using the classical Drude theory of electron conduction in metals that this coefficient A, associated with the Righi-Leduc transverse heat flux, is proportional to the Hall coefficient $R_H = 1/ne$ and to the electron relaxation and the electron relaxation time τ_0 by the relation [9]

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$$A = \sigma R_H = \frac{\tau_0 e^2 n}{m_{eff}} R_H \ , \tag{5}$$

with A the average coefficient of (2) dependent on the metal sample considered and was originally measured on bismuth .

Our proposal is similar to an approach recently published [23] and is based on the introduction of a transverse gauge breaking heat flux current vector, similar to due to a self-induced nonlinear rotational thermal Hall effect generated on rotating disks by a chopped laser beam based on [16], caused by the effective Barnett magnetic field of (1)

$$\overrightarrow{q(t+\tau)} = -k\nabla T + b(T)\vec{\Omega} \times \nabla T \ , \tag{6}$$

with τ a local electron relaxation time of the rotating conductor to be determined and k the standard thermal conductivity of the conductor at rest.

This new wavelike heat diffusion model is a chiral nonlinear generalization of the Cattaneo-Vernotte model [24,25], since the transverse heat flux added at second member of (6) is proportional via the function b(T) to the angular velocity $\vec{\Omega}$ vector of the rotating disk. We will show that (6) implements a dynamic chiral thermal management since the effective out of equilibrium Barnett magnetic field of (1) allows to control the direction of heat flux by tuning the shifted pulsation of the thermal field T due to a thermal rotational Doppler effect.

We remark that unlike the conventional analysis of the thermal Hall effect the deflection angle of the transverse heat flux is a dynamic deflection angle dependent on the thermal field T that, in polar coordinates [15], is given by

$$\theta_{R-L}(T,\Omega) = Re\frac{k_\theta(T)\nabla_\theta T}{k_r(T)\nabla_r T} \ , \tag{7}$$

where on the right-hand side we have the real part of the complex valued functions, and with the polar and azimuthal gradients given by

$$\nabla_r T = \frac{dT}{dr}; \ ; \ \nabla_\theta T = \frac{dT}{rd\theta} \ . \tag{8}$$

We will assume in the following a frequency shift due to a rotational Doppler effect of the thermal field due T to a thermal analogue of the Zel'dovich effect [26,27].

$$\frac{dT}{dt} = D_t T = -i\omega' T, \tag{9}$$

with the shifted pulsation

$$\omega' = \omega - m\Omega \ , \tag{10}$$

and m the topological index of the structured thermal field T, associated with angular momentum transfer, whose chirality depends on the sign of this integer number. We note that the time derivative of (8) is a convective time derivative comoving with the rotating disk

$$D_t = \frac{\partial}{\partial t} + \Omega \cdot \frac{\partial}{\partial \theta} \ . \tag{11}$$

Therefore using (9) and (10) it is possible to introduce a thermal Hall angular velocity $\Omega_{R-L}(T,\Omega)$ proportional to this shifted pulsation ω'

$$\Omega_{R-L}(T,\Omega) = \frac{d\theta_{R-H}(T,\Omega)}{dt} \ , \tag{12}$$

with

$$\frac{d\theta_{R-H}(T,\Omega)}{dt} = Re\frac{d\theta_{R-H}(T,\Omega)}{dT}\frac{dT}{dt} = \frac{d\theta_{R-H}(T,\Omega)}{dT}\omega' Re(iT) \ , \tag{13}$$

which changes sign when the shifted pulsation ω' does and is zero if the resonant condition of Zel'dovich rotational superradiance is satisfied

$\omega' = 0$, that is if

$$\omega = m\Omega \ . \tag{14}$$

We note that this rotation induced chiral thermal control can be tuned changing the angular velocity Ω of the disk is associated, as we will see in the next paragraph, to peaks of the Thomson coefficient and to symmetry breaking chiral magnetic phase transitions .

In fact, it is possible to show [15] that the new thermal fields T satisfy, far from the focus of the laser beam incident on an ultrathin disk, a homogeneous generalized telegraphist wave equation, that using the convective time derivative of (9) can be written as

$$D_t{}^2 T + \frac{D_t T}{\tau(r,\omega')} - v_T{}^2 \nabla^2 T = 0 \ . \tag{15}$$

We will find the local relaxation time $\tau(r,\omega')$ looking for particular solutions temporally periodic and spatially attenuated (SATP solutions) given in polar coordinates (r,θ) by

$$T(r,\theta,t) = T_0 e^{i[\beta(r)r + m\theta - \omega' t]} \ , \tag{16}$$

with T_0 the average environment temperature and $\beta(r)$ a local complex valued wave vector whose real part is a solution of the differential equation in the r variable

$$Re\,\frac{d(\beta(r)r)}{dr} = \frac{R\omega'}{r v_T} - \frac{\gamma\omega' r}{2k}, \tag{17}$$

with k the thermal conductivity and γ the specific heat at constant pressure of the disk at rest.

We note that this new structured thermal fields have, differently from conventional one local tunable phase velocity v_T given by

$$v'_T = \sqrt{\frac{k}{\gamma\tau(r,\omega')}} = \frac{v_T}{n(r,\omega')} \ , \tag{18}$$

with the phase velocity at rest v_T on the border of the disk and the effective index of refraction of thermal waves defined respectively $n(r,\omega^{'})$ as

$$v_T = \frac{2k}{\gamma R} \ , \tag{19}$$

and

$$\tau(r,\omega') = n^2\tau_0. \tag{20}$$

Taking in account (17), (18), (19) it is possible to write the local electron relaxation time $\tau(r,\omega')$ as

$$\tau(r,\omega') = \frac{k}{\gamma\omega'^2}\left[\omega'^2\left(\frac{R}{r v_T} - \frac{\gamma}{2k}r\right)^2 + \frac{m^2}{r^2}\right] \ , \tag{21}$$

We note that the tunable thermal phase velocity of (16) becomes linear dependent on the rotational Doppler frequency shift ω' on the border of the disk

$$v'_T(R) = \frac{R\omega'}{m} = \frac{R(\omega - m\Omega)}{m} \ , \tag{22}$$

which, going to zero when $\omega^{'} = 0$, can be exploited to prove existence of thermal rotational super radiant effect by measuring heat transport arrest on the border of the disk.

In fact, the thermal wave phase velocity (16), depending on the local relaxation time $\tau(r,\omega')$,depending on the effective local thermal refractive index n, makes the disk an effective dispersive medium in a similar way to what has recently been proposed in a study on the hyperbolic propagation of heat on metamaterials [28].

It is possible to show [9] that the nonlinear telegraphist equation with particular solutions (16), singular at the center of the disk, have chiral isothermal helical wavefront profiles

$$\theta(r) = \frac{R\omega'}{m v_T}\ln\frac{r}{R} - \frac{\gamma\omega'}{4km}r^2, \tag{23}$$

with R the disk radius and v_T the phase velocity of the conductor at rest and with m associated to the angular momentum of the polarized laser beam and transported by the helical thermal wave considered.

It is possible to test experimentally the rotation induced thermal control predicted by our model introducing a new parameter given by the difference between the angle of the isothermal profile on the border R of thin rotating disks and those one of identical disks at rest given by

$$\Delta\theta(R,\Omega) = \frac{\gamma R^2 \Omega}{4k} \ . \tag{24}$$

For example, assuming that the rotating disk is iron, inserting the values of its thermal conductivity and specific heat and choosing angular velocity Ω=100Hz and R=1dm, from (19) we have an estimate of the detectable relative angle of deviation induced by rotation given by

$$\Delta\theta \cong \frac{45000}{320} 10^{-2} \cong \frac{4{,}5}{320} \cong 1{,}4 rad \ , \tag{25}$$

This theoretical prediction could be easily tested in laboratories by using IR thermal cameras with lock in thermography technique to map isothermal profiles of the helical thermal waves and, whenever confirmed, could pave the way to dynamic chiral thermal management.

On the contrary to compare the isothermal angle deviation respectively when the laser is switched on rand when it is switched off it can be used on the border of the disk the following quadratic relation in R

$$\Delta\theta(R, \omega' = \Omega) = \frac{\gamma[(1+m)\Omega - \omega]}{4k} R^2, \tag{26}$$

which, when the thermal wave has m equal to zero becomes the simple relation

$$\Delta\theta(R, \omega' = \Omega) = \frac{\gamma(\Omega - \omega)}{4k} R^2. \tag{27}$$

We will see in the next paragraph that this rotational induced chiral control of heat transport can be exploited to enhance magnetic phase transitions via a self induced dynamic chiral Thomson effect.

3. Dynamic Chiral Thomson Effect and Tunable Magnetic Phase Transitions

We will show now that the Barnett magnetic field self-induced by rotation B(T,Ω) of (1), will generate a dynamic Thomson voltage $\Delta V(T,\Omega)$ [15], whose radial pulsating electric field will tend to counteract the dissipative heating process due to the Joule effect .

In fact, according to Faraday's law, a temperature dependent electromotive force is induced on the rotating disk $\Delta V(T,\Omega)$ proportional to the angular velocity Ω of the rotating conductor

$$\Delta V(T,\Omega) = -\int_0^r \Omega \frac{db(T)}{dt} \Omega 2\pi r dr = -\int_0^r \frac{db(T)}{dT}\frac{dT}{dt} \Omega 2\pi r dr, \tag{28}$$

which by using the Zel’dovich condition (9) and the function b(T) introduced in (4), it can be shown to be proportional to the angular velocity of the rotating disk Ω

$$\Delta V(T,\Omega) = i \frac{\omega\prime\Omega}{A} \int_0^r \frac{db(T)}{dT} T 2\pi r dr. \tag{29}$$

This dynamic Thomson voltage is associated with an oscillating conservative chiral radial Thomson electric field $\vec{E}$ tuned by Ω with a radial component given by

$$E_r(T,\Omega) = -\nabla \Delta V(T,\Omega) = -\frac{d\Delta V(T,\Omega)}{dr} = i 2\pi r \frac{\omega\prime\Omega}{e}\frac{dm(T)}{dT} T. \tag{30}$$

We note that this new dynamic chiral Thomson cooling-heating effect might be used as a signature of magneto thermal phase transitions since the radial component of the Thomson electric field E changes electron conduction bands, pushing electrons harmonically outward and inward, in accordance with an out of equilibrium generalization of the Stewart-Tolman effect recently investigated for its relevance in out of equilibrium thermodynamics of neutron stars [29–31].

The new oscillating thermoelectric field can be associated to an out of equilibrium thermodynamic process with specific entropy production in a rotating frame which generalizes the conventional one on sample at rest [7]

$$\partial_t s(T,\Omega) = Re\,\frac{div\vec{q}}{T}, \tag{31}$$

$$D_t s(T,\Omega) = Re(\frac{\vec{q}^{\,2}T}{\sigma} + k(\nabla T^2) - i\omega'\gamma T), \tag{32}$$

with σ the electric conductivity.

We note that our model, differently from a similar wavelike nonlinear heat diffusion model recently investigated [32], depends on the dynamic chiral Thomson effect previously discussed by

$$\overrightarrow{q(t+\tau)} = S(T)T\vec{J} - k\nabla T, \tag{33}$$

with S(T) a dynamic generalization of the magneto Seebeck coefficient recently investigated [33].

From (6) we deduce

$$S(T)T\vec{J} = A\left[\overrightarrow{\Delta B(T,\vec{\Omega})} \times \nabla T) = b(T)\vec{\Omega} \times \nabla T\right], \tag{34}$$

with the orbital electric current density $\vec{J}$ given by

$$\vec{J} = \sigma(\overrightarrow{E -} S\nabla T). \tag{35}$$

We note that the specific entropy production of (31) can be negative whenever the gradient term due to the Thomson effect is bigger than the first term due to the Joule effect. Moreover equation (31) can be exploited to tune dynamically magnetic phase transitions, assuming that they are associated to maxima or minima of the entropy flux rate comoving with the rotating disks, that is

$$D_t s(T,\Omega) = \frac{\partial}{\partial t} s(T,\Omega) + \Omega \cdot \frac{\partial}{\partial \theta} s(T,\Omega) = 0\ , \tag{36}$$

using the time convective derivative D_t solidal to the rotating disks of (11).

From (35) we can generalize the stationary local conservation law of energy density and the conventional specific entropy flux rate of a system at rest [13], taking in account that it depends on helical thermal fields solutions of telegraphist equation introduced in (16)

$$D_t s = \frac{\vec{E}\cdot\vec{J}}{T} - \frac{div\vec{q}}{T} = \frac{\vec{J}^2}{\sigma T} + k\,\frac{(\nabla T)^2}{T^2} = \gamma D_t T = -i\gamma\omega' T, \tag{37}$$

by (31) and (35) it follows that the electric current density on the thermal field T satisfies the relation

$$\vec{J}^2 = -\sigma(k\nabla lnT^2 + i\gamma\omega' T). \tag{38}$$

This equation allows to deduce the explicit dependence on the thermal field T of the magneto Seebeck coefficient S(T), once is known by experiments for a specific metallic sample the effective electron mass m(T) introduced in (1), and inserting in the equation (33).

As a case study of the rotation induced thermoelectric effect associated to magnetic phase transitions we illustrate some simple estimates of the average dynamic Thomson voltage $\Delta V(T,\Omega)$ of (28) in the simple case of ferromagnetic disks. We will assume a generalized Curie-Weiss like magnetization law of the out of equilibrium Barnett magnetic field of (1),

$$ReB(T,\Omega) = Re\,\frac{\chi}{T} = \frac{\chi'}{T_0(1-cos\omega' t)} \cong \frac{2\chi}{T_0(\omega'\tau_{laser})^2}\ , \tag{39}$$

with the χ the complex valued average magnetic susceptivity and χ' the real part of the average magnetic susceptivity .

Taking as t the time scale of the chopper $\tau_{laser} \cong \frac{2\pi}{\omega}$ we get an approximation of the average Barnett magnetic field induced by rotation given by $ReB(T(\tau_{laser},\Omega) \cong \frac{2\chi}{T_0(\omega'\tau_{laser})^2} 3{,}7\,T$, easy to detect experimentally.

Inserting the equation (39) in equation (28) we deduce the oscillating self induced chiral Thomson voltage,

$$\Delta V(T,\Omega) \cong -i\omega' \int_0^r \frac{\chi}{T}(1+\tau_0\omega')\, 2\pi r dr = \frac{i\pi\omega'\chi(1+\tau_0\omega')r^2}{T}, \tag{40}$$

becoming on the border a detectable minimum of the oscillating electric voltage given by

$$Re\Delta V(T_0,\Omega) \cong \frac{i\pi\omega'\chi(1+\tau_0\omega')R^2}{T_0\,(1-cos\omega' t)} \geq 0{,}1\, mV, \tag{41}$$

taking R=0,1m, $\chi = 10^6$ and $T_0 = 300K$.

We note that assuming an average magneto Seebeck coefficient of iron disk at rest $S_0 \cong 1{,}9 \times 10^{-5} V/K$ we can estimate the minimum average fluctuation of the Curie temperature $T_c \cong 1043K$ on the border of the disk of radius R=0,1m to be given by

$$\Delta T_c \cong \frac{1 \times 10^{-4}}{1{,}9 \times 10^{-5}} \geq \frac{10}{1{,}9} \cong 5{,}2K\ , \tag{42}$$

This not negligible effect shows that rotation and harmonic heat source of a laser beam with chopper can induce tunable magnetic phase transitions. Therefore, our new predicted Curie temperature fluctuations could be easily detected in Laboratories with modern infrared thermocamera lock in technique, proving the existence of dynamic chiral management and magnetic phase transitions associated to peaks of the average rotation induced chiral Thomson effect.

We note that the laser induced out of equilibrium thermodynamics on rotating metallic disks implies, taking in account the dynamic chiral Thomson effect, the following generalization of the Faraday law on the rotating metallic disk given by

$$rot(\overrightarrow{E} - S(T)\nabla T) = -D_t\overrightarrow{B(T)}\ , \tag{43}$$

with $\overrightarrow{B(T)}$ the out of equilibrium Barnett magnetic field of (1).This equation implies that there is a new dynamic transverse Thomson electric field with non-null rotor given by

$$rotS(T)\nabla T = \frac{d}{dT}\overrightarrow{B(T)}\,\frac{dT}{Dt} = i\omega' T\frac{d}{dT}\overrightarrow{B(T)}, \tag{44}$$

proving the existence of a dynamic transverse magneto Thomson effect, generalizing recently observed magneto and transverse Thomson effects [10,11], whenever the shifted pulsation ω' is non zero.

We remark that the predicted dynamic chiral magneto Thomson effect allows to deduce, once solved equation (43) the magneto Seebeck coefficient S(T),allows to deduce the thermal field dependence of the Thomson coefficient [13],

$$\tau_{TH}(T) = T\frac{dS(T)}{dT}, \tag{45}$$

Therefore, is it possible to compare the figure of merit of new rotating thermoelectric devices with respect to conventional ones at rest using the relation

$$ZT = \frac{\sigma S(T,\Omega)^2}{k} = \frac{L_0 S(T,\Omega)^2}{k^2 T}\ , \tag{46}$$

with L_0 the Lorenz number, having assumed the validity of the Weidermann-Franz law for rotating metallic disks. Due to the rotational super radiant effect it is possible to have giant Thomson effect, enhancing the oscillating electric field of (30) and reducing the relative magnitude of the Joule heating process, by tuning the thermal field pulsation ω'.

For example, in the case of iron disk using the chiral Thomson voltage of (40) and (41) we get the following naïve estimate

$$Re\, \tau_{TH}(T_0) \cong -\frac{2\pi\omega'\chi R^2}{{T_0}^2(1-cos\omega' t)} \geq -\frac{2\pi\omega'\chi R^2}{{T_0}^2} \cong -62{,}8\, V/K, \tag{47}$$

taking R=0,1m, and a ferromagnetic sample, that is an ideal peak of the Thomson coefficient whose absolute values is four orders of magnitude bigger than magnetic phase transitions induced giant Thomson effect observed recently [3]

More over since the transverse oscillating Thomson voltage depends on the sign of the thermal field pulsation ω' it is possible to control thermal emission by rotation, using the out of equilibrium effective Barnett magnetic field of (1) and the oscillating radial electric field of (30).

In fact, in accordance with new recent approach to non reciprocal photonics and tunable thermal emissivity on metamaterials [19,34], assuming Stefan-Boltzmann law it can be introduced a chiral dynamic tunable thermal emissivity

$$e(T,\Omega) \propto \frac{div\,\vec{P}_T(T,\Omega)}{(T^4-T_0^4)}\ , \tag{48}$$

with $\vec{P}_T(T,\Omega)$ an out of equilibrium electromagnetic chiral Poynting vector proportional to heat torque transfer and to the dynamic magneto Seebeck coefficient S(T)

$$\vec{P}_T(T,\Omega) = \frac{-S(T)\nabla T \times \Delta\overrightarrow{B(T)}}{\mu}. \tag{49}$$

Using equation (2) and (4) it can be rewritten making explicit the linear dependence on the angular velocity Ω of the Poynting vector

$$\vec{P}_T(T,\Omega) = \frac{b(T)S(T)\vec{\Omega}\times\nabla T}{\mu}, \tag{50}$$

which is a chiral vector since it depends on the sign of Ω.

Equation (50) implies that the thermal emissivity of (48) implements chiral polarized thermal radiation emitted by rotating conductors exposed to chopped laser beam which could be detected looking for a dynamic nonlinear magneto Kerr effect.

We note that the effective magnetic Barnett magnetic field of (1) can be associated to a gauge breaking out of equilibrium magnetic vector potential $\overrightarrow{A_T(T)}$, defined by

$$rot\overrightarrow{A_T(T)} = \overrightarrow{B(T)}\ , \tag{51}$$

and using the convective time derivative of equation (11)

$$c^2 div\overrightarrow{A_T(T)} + \partial_t \Delta V(T) = (\Omega\cdot\frac{\partial}{\partial\theta})\Delta V(T)\ , \tag{52}$$

in accordance with recent investigations on Extended Electrodynamics, thermal induced gauge breaking effects and dynamic thermal management through magnetic field control [35–39]. This new out of equilibrium gauge breaking electrodynamic framework might be useful, we hope, to investigate the role of thermoelectric effects on out of equilibrium electrodynamics of neutron stars [30,31] and to implement chiral control of polarized thermal emission of ferromagnetic rotating disks, enhancing performances of magnetic random access memory devices and magnetic storage technology.

4. Discussion

The main motivation that inspired our novel proposal of dynamic rotating thermolectric coolers is to elaborate a new unified framework of anomalous heat diffusion, tunable chiral thermal emission and dynamical orbital physics which might have innovative technological applications in the future such as chiral tunable thermal diodes and heat assisted dynamic magnetic recording.

We illustrated a new dynamic approach to Thomson electric coolers which, differently from conventional stationary approaches so far investigated, predicts complex valued time dependent Seeback coefficient and Thomson coefficient. Therefore, since in our dynamical non linear framework it is not possible to use standard notion of electric performance by the figure of merit zT we introduced its average real part in equation (46).

We deduced a naïve estimate of the average real part of the dynamic Thomson coefficient τ_{TH} in equation (47), in the particular case of a ferromagnetic rotating disk, showing its enhancement due to rotation.

We neglected the effect due the imaginary part χ'' of the average magnetic susceptivity, which could be associated, by the Fluctuation-Dissipation Theorem, to a thermal noise contribution to Thomson coefficient and Thomson voltage fluctuations.

Anyway ,as recently investigated [6] , as far as we know, it is not possible to extend the Johnson theorem and to give estimate of the Johnson noise in non-equilibrium framework with non-uniform bidimensional temperature profiles.

In fact all the time dependent measures of the variance of the squared voltage

$$< V^2 > \cong \frac{2Rk_BT}{\Delta t} \tag{53}$$

were detected so far just in the one dimensional case, assuming a stationary equilibrium temperature T [6]

We remark that the chiral symmetry breaking effect of our wavelike non linear heat diffusion model is a specific signature of the existence of a dynamic Thomson effect and cannot be associated neither to any equilibrium thermal noise nor to any disorder effect.

We think that to prove that our new dynamic rotational approach to thermoelectricity does not depend on stochastic fluctuations , differently from complex systems such as spin glass, it would be important to detect its chiral symmetry breaking effect by detecting indirectly either anisotropic optical activity due to a dynamic chiral magnetic effect [40]) that by observing , as recently confirmed with tellurium samples of a non linear chiral thermoelectric Hall effect [41].

We outline that the predicted chiral thermal radiation emitted given by equation (50) , due to the time derivative of the oscillating self induced Thomson voltages $\Delta V(T)$ introduced in equation (29), whenever confirmed experimentally would prove the existence of a dynamical heat torque transfer associated to polarized heat waves propagating on the out of equilibrium rotating disks

Finally, we hope that this prediction will stimulate to realize experiments to detect angular momentum transport on metallic disks at rest exposed to the near field chiral thermal radiation emitted by the rotating ones , which will prove indirectly the existence of dynamic chiral Thomson voltages and pave the way to polarized control of thermal emission.

5. Conclusions

We **have illustrated** in this work a new dynamic chiral Thomson effect **self-induced** on rotating conductors exposed to **a** chopped laser beam, assuming the existence of a rotational **nonlinear** thermal Hall effect due to an out-of-equilibrium Barnett magnetic field. We showed that this new framework allows **for implementing** a novel rotational chiral approach to thermal management associated **with** structured helical thermal waves transporting angular momentum. We proved the existence of a dynamic chiral Thomson voltage which can be used to enhance dynamically magnetic phase transitions and to improve the performance of rotating thermoelectric devices.

We showed that this novel dynamic chiral Thomson effect is associated **with** a gauge-breaking thermal Poynting vector, **leading** to a chiral dynamic tunable thermal emissivity which, we outlined, might be exploited to develop a new chiral approach to **nonreciprocal** photonics and, more generally, to **the** out-of-equilibrium electrodynamics associated to quantum heat transport of rotating nano disks.

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