

Casimir radiation with Weyl semimetals

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When Casimir friction torque acts upon a rotated nanoparticle (NP), mechanical energy can be transformed into thermal energy, known as Casimir radiation, which significantly affects the thermal performance of nano-electromechanical systems. In this work, we investigate Casimir radiation with nonreciprocal Weyl semimetal (WSM) NP levitated on a plate. WSM NP with inherent nonreciprocity has a radiative heat flux 27 times higher than NP with degenerate modes. The underlying physics is elucidated by the coupling and decoupling of the electromagnetic local density of states between nonreciprocal WSM NP and the plate in the near-field. The threefold localized plasmon modes of WSM NP split into localized circular modes with strong gyrotropic response, which opens up channels for Casimir radiation. This work provides a method for nanoscale energy conversion in NP systems.

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I. INTRODUCTION

In 1948, Casimir proposed the “Casimir effect” based on quantum fluctuation of electromagnetic waves. Nanoparticles (NPs) accelerated by Casimir friction torque emit heat to surroundings due to changes in the boundary conditions of the electromagnetic field, known as Casimir radiation [1,2]. Pioneering work by Manjavacas and García de Abajo studied frictional torque acting on NPs rotating in a vacuum, demonstrating that Casimir friction transforms mechanical energy into thermal energy and produces NP heating [3,4]. Recently, Deop-Ruano and Manjavacas investigated the near-field radiative heat transfer (NFRHT) and Casimir interactions between nanostructures, where the near-field radiative heat flux (NFRHF) can be increased, decreased, or even reversed due to rotation, making an important step toward the simultaneous exploration of energy conversion and angular momentum [5]. Previous studies have focused on the Casimir radiation of graphite NPs, which are abundant in interstellar dust. However, nonreciprocity—a fundamental property of our universe characterized by direction-dependent behavior—has not been considered in these investigations of Casimir radiation [6,7].

In recent years, advances in material science and physics have sparked a revival of research on Casimir radiation. Weyl semimetals (WSMs) are a distinctive class of anisotropic materials that have garnered significant attention in thermal photonics owing to their unique electronic band structure and intriguing topological properties [8–10]. Hu, *et al.* designed a high-performance thermal diode using the nonreciprocity of WSM, allowing NFRHT in a prior direction while being blocked in a reverse direction [11]. Guo, *et al.* designed a thermal router that utilizes optical gyrotropy of WSM, which directs an NFRHF to a drain of choice by adjusting the momentum separation of Weyl nodes [12]. Ott, *et al.* predict an anomalous thermal Hall effect mediated by photons in networks of WSM [13]. The inherent nonreciprocity and gyrotropy of WSM NP could promote the light-matter interaction and are expected to enhance and regulate Casimir radiation.

In this work, we investigate the Casimir radiation with rotated WSM NP in close vicinity to a plate with the same temperature. Inspired by previous works [14–17], a plate is placed in proximity to the NP to provide a huge local density of states (LDOS). We will analyze the case where the flat plates are hexagonal boron nitride (hBN) and WSM, respectively, and expect to observe an enhancement of Casimir radiation due to the coupling between NP and plate in the near-field.

II. MODELING AND CALCULATION

The configuration of the Casimir radiation based on WSM NP is shown in Fig. 1(a). This work will provide two Casimir radiation enhancement schemes corresponding to the cases of

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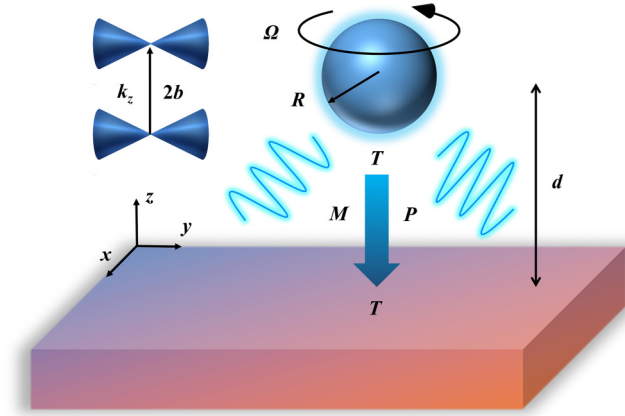


FIG. 1. The configuration of the proposed system. The WSM NP with radius R is levitated above the plate along the z axis with a gap distance of d . The WSM NP is rotated around the z axis. The temperatures of NP and plate are both T . The NFRHT and Casimir torque are along the z axis.

WSM and hBN plates, respectively. The plate is semi-infinite, and therefore, we neglect the piezoelectric effects as a first approximation [18,19]. The WSM NP is rotated around the z axis with a frequency $\Omega = 10^9$ rad/s. The momentum separation $\mathbf{b}$ of WSM NP is along the z axis. The temperature T of both the NP and the plate is 300 K. In our calculations, the smallest gap separation considered is 50 nm. Additionally, the NP radius is 10 nm, which is significantly smaller than the gap distance. Such parameter settings are widely adopted in the study of NP-plate structures in NFRHT and the Casimir interactions. When the thermal wavelength and particle-plate distance are much larger than the radius of nanoparticle, the NP can be regarded as pointlike source and the dipole approximation is valid [20,21].

Casimir radiation is determined by the electric response of the material. Regarding the WSM, the time-reversal symmetry can be broken by splitting a Dirac point into a pair of Weyl nodes with opposite chirality separated by wave vector $2\mathbf{b}$ in momentum space. Furthermore, Weyl nodes alter the electro-

magnetic response, and the displacement electric field $\mathbf{D}$ can be expressed as [22,23]

$$\mathbf{D} = \varepsilon_d \mathbf{E} + \frac{ie^2}{4\pi^2 \hbar \omega} (-2b_0 \mathbf{B} + 2\mathbf{b} \times \mathbf{E}). \quad (1)$$

The specific meanings of parameters are provided in the Supplemental Material [24]. Dirac semimetals are typically considered isotropic when there are no external magnetic fields. Therefore, the diagonal elements of the permittivity tensor are all assumed to be ε_d . The terms $-2b_0 \mathbf{B}$ and $2\mathbf{b} \times \mathbf{E}$ represent the chiral magnetic effect and optical gyrotropic response, respectively. We only consider $b_0 = 0$ where the Weyl nodes have the identical energy. The momentum separation $\mathbf{b}$ of the Weyl nodes is an axial vector, similar to an internal magnetic field. We align the coordinates with $\mathbf{b}$ along the positive z direction for NP ($\mathbf{b} = b\mathbf{z}$), resulting in the permittivity tensor of the WSM [24]:

$$\varepsilon = \begin{bmatrix} \varepsilon_d & i\varepsilon_a & 0 \\ -i\varepsilon_a & \varepsilon_d & 0 \\ 0 & 0 & \varepsilon_d \end{bmatrix}. \quad (2)$$

The off-diagonal element

$$\varepsilon_a = \frac{be^2}{2\pi^2 \varepsilon_0 \hbar \omega}. \quad (3)$$

When $b \neq 0$, ε_a is nonzero, resulting in an asymmetric ε , potentially breaking Lorentz reciprocity. The value of ε_a is comparable to ε_d in the infrared region, indicating an exceptionally large and highly unusual gyrotropic response. The specific calculation parameters and the variation of dielectric constant with frequency are included in the Supplemental Material [24]. WSM is a very attractive and intricate material, and we focus here on the effect of its nonreciprocity on the Casimir radiation; for other material properties, i.e., tilted Dirac cone, bandwidth, axion field, surface states, and Weyl nodes, etc., refer to the detailed discussion in Refs. [25–27].

The Casimir torque M (integrate M_ω in frequency space) and NFRHT P (integrate P_ω in frequency space) between NP and plate are calculated by the fluctuation-dissipation theorem [3,4,16,24].

$$\begin{aligned} M_\omega(\omega) = & \frac{\hbar}{2\pi} [n_{np}(\omega - \Omega) - n_{pl}(\omega)] \text{Im}[\alpha_{xx}(\omega - \Omega) + \alpha_{yy}(\omega - \Omega)] \text{Im}[G_{xx}(\omega) + G_{yy}(\omega)] \\ & + \frac{\hbar}{2\pi} [n_{np}(\omega - \Omega) - n_{pl}(\omega)] \text{Im}[\alpha_{xx}(\omega - \Omega) - \alpha_{yy}(\omega - \Omega)] \text{Re}[G_{xy}(\omega) - G_{yx}(\omega)] \\ & + \frac{\hbar}{2\pi} [n_{np}(\omega - \Omega) - n_{pl}(\omega)] \text{Re}[\alpha_{xy}(\omega - \Omega) - \alpha_{yx}(\omega - \Omega)] \text{Im}[G_{xx}(\omega) - G_{yy}(\omega)], \end{aligned} \quad (4)$$

$$\begin{aligned} P_\omega(\omega) = & \frac{\omega \hbar}{2\pi} [n_{np}(\omega - \Omega) - n_{pl}(\omega)] \text{Im}[\alpha_{xx}(\omega - \Omega) + \alpha_{yy}(\omega - \Omega)] \text{Im}[G_{xx}(\omega) + G_{yy}(\omega)] \\ & + \frac{\omega \hbar}{2\pi} [n_{np}(\omega - \Omega) - n_{pl}(\omega)] \text{Im}[\alpha_{xx}(\omega - \Omega) - \alpha_{yy}(\omega - \Omega)] \text{Re}[G_{xy}(\omega) - G_{yx}(\omega)] \\ & + \frac{\omega \hbar}{2\pi} [n_{np}(\omega - \Omega) - n_{pl}(\omega)] \text{Re}[\alpha_{xy}(\omega - \Omega) - \alpha_{yx}(\omega - \Omega)] \text{Im}[G_{xx}(\omega) - G_{yy}(\omega)] \\ & + \frac{\omega \hbar}{\pi} [n_{np}(\omega) - n_{pl}(\omega)] \text{Im}[\alpha_{zz}(\omega)] \text{Im}[G_{zz}(\omega)], \end{aligned} \quad (5)$$

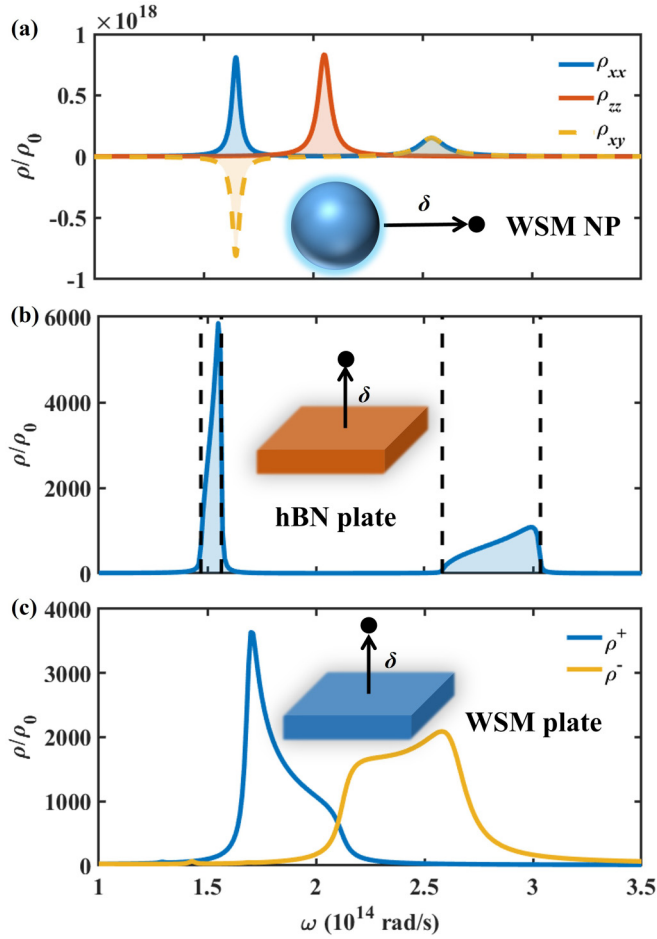


FIG. 2. (a) The LDOS of WSM NP when $b = 1 \times 10^9 \text{ m}^{-1}$. (b) The LDOS of a semi-infinite hBN plate. The black dashed lines present the transverse and longitudinal phonon frequencies. (c) The LDOS of a semi-infinite WSM plate for positive and negative directions of the wave vector when $b = 1 \times 10^9 \text{ m}^{-1}$.

where $n_{np}(\omega)$ and $n_{pl}(\omega)$ are the Bose-Einstein distributions of NP and plate. $\alpha = 4\pi R^{2l+1} \frac{l(\epsilon-1)\mathbf{I}}{l\epsilon+(l+1)\mathbf{I}}$ is the polarizability of WSM NP and $\mathbf{G}$ is the Green's function in the dipole-plate geometry. The detailed derivations and discussions are provided in the Supplemental Material [24].

III. RESULTS AND DISCUSSION

The Casimir torque and NFRHT are significantly affected by the LDOS [14,28,29]. We try to couple the LDOS of the NP with the plate to enhance the Casimir torque and near-field radiative heat flux. The orientation-averaged LDOS of WSM NP is shown in Fig. 2(a), which can be obtained by the following equation [29,30]:

$$\frac{\rho}{\rho_0} = 1 + \frac{1}{8\pi k_0^3} \sum_{l=1}^{\infty} (l+1)(2l+1) \frac{(\alpha - \alpha^*)/2i}{(R + \delta)^{2(l+2)}}. \quad (6)$$

The LDOS are proportional to the imaginary part of the polarizability. Through exploring the polarizability α ($l=1$), the analytical equation for mainly resonance modes can be

expressed as

$$\det(\epsilon + 2\mathbf{I}) = (\epsilon_d + 2)[(\epsilon_d + 2)^2 - \epsilon_a^2] = 0. \quad (7)$$

According to Eq. (7), it can be seen that when $b \neq 0$, such a threefold degenerate mode splits into three singly degenerate modes. The resonance modes appear when $(\epsilon_d + 2) = 0$ or $(\epsilon_d + 2)^2 - \epsilon_a^2 = 0$ is satisfied. The former corresponds to the localized plasmon modes corresponding to the resonance of ρ_{zz} at $\omega = 2.05 \times 10^{14} \text{ rad/s}$, while the latter corresponds to the localized circular modes corresponding to the resonances of ρ_{xx} and ρ_{xy} , which distribute on both sides of the resonance of ρ_{zz} at $\omega_{m=+1} = 1.65 \times 10^{14} \text{ rad/s}$ and $\omega_{m=-1} = 2.55 \times 10^{14} \text{ rad/s}$. The localized circular modes are momentum separation dependent and related to the off-diagonal elements affected by gyrotropic optical responses. It is worth noting that the magnitude of ρ_{xy} has the opposite value of ρ_{xx} at lower frequency when the momentum separation is along the positive z axis.

The LDOS of the hBN and WSM plate is obtained by [24,31]

$$\begin{aligned} \frac{\rho}{\rho_0} = & \int_{-\infty}^{\infty} \frac{dk_x}{2\pi} \int_{-\infty}^{\infty} \frac{dk_y}{2\pi} \frac{\omega}{\pi c^2} \text{Im} \frac{i}{2\sqrt{k_0^2 - \kappa^2}} \\ & \times \left[4 + \frac{2\kappa^2}{k_0^2} \left((r_{ss} + r_{pp}) e^{2i\sqrt{k_0^2 - \kappa^2}z} \right) \right]. \end{aligned} \quad (8)$$

As a hyperbolic material, hBN can excite hyperbolic phonon polaritons over a wide frequency range. It can be observed from Fig. 2(b) that the LDOS of the hBN plate can be significantly enhanced within the hyperbolic bands. Broadband enhancement makes it easy to couple with NP modes. For the WSM plate, when the direction of momentum separation is in the plane, the LDOS exhibits nonreciprocity with resonances at different frequencies.

Due to the great tunability and nanoscale inhomogeneity of optical gyrotropy in WSM, the magnitude and direction of momentum separations $\mathbf{b}$ can be tuned easily by magnetization control [12,32–34]. To clearly show the difference between WSM NP ($b \neq 0$) and isotropic WSM NP ($b = 0$), the enhancement ratio $\eta = M_{b \neq 0}/M_{b=0}$ ($P_{b \neq 0}/P_{b=0}$) is defined here. The enhancement ratio varying with momentum separations is shown in Fig. 3(a) when the plate is hBN. The shaded area represents the strong coupling region where the resonance of localized circular modes within the hyperbolic band is present. It can be seen that the enhancement ratio first increases and then decreases with the momentum separations. The enhancement ratio can be up to 66 for Casimir torque and 27 for NFRHF when $b = 1.3 \times 10^9 \text{ m}^{-1}$, and 31 for Casimir torque and 14 for NFRHF when $b = 1.5 \times 10^9 \text{ m}^{-1}$, indicating that the coupling of the local circular modes in WSM NP and hyperbolic modes in hBN plate could enhance the Casimir radiation.

The localized circular modes are momentum separation dependent. We explore the polarizability varying with frequency with different momentum separations, as shown in Figs. 3(b)–3(d). When $b = 0$, the off-diagonal elements of WSM permittivity are zero, and the imaginary part of α_{xx} and α_{zz} coincide. The WSM NP degenerates as isotropic Dirac semimetal, and the localized circular modes could not appear.

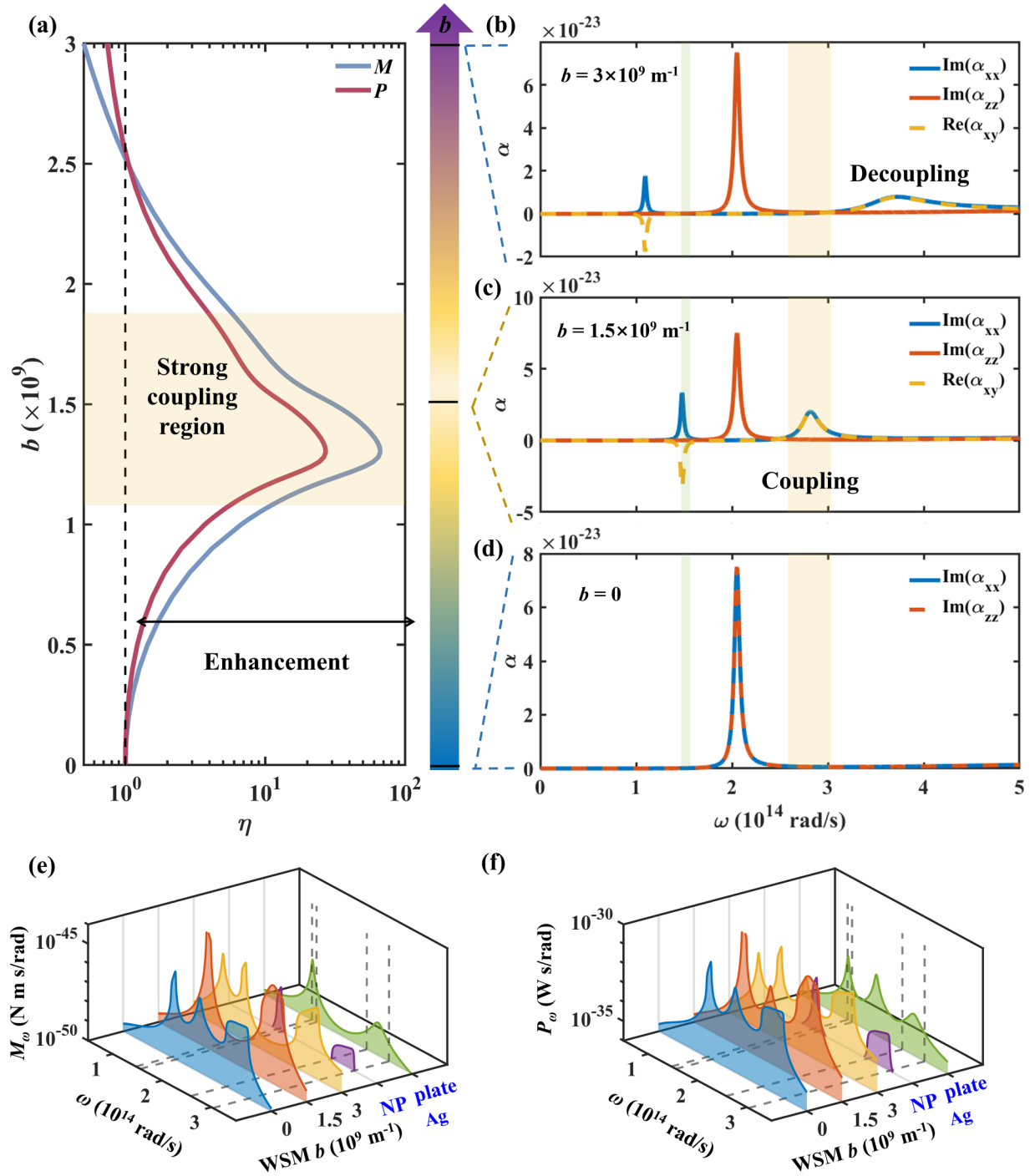


FIG. 3. (a) The enhancement ratio varying with momentum separation. The main and off-diagonal elements of the polarizability tensor varying with frequency: (b) $b = 0$, (c) $b = 1.5 \times 10^9 \text{ m}^{-1}$, and (d) $b = 3 \times 10^9 \text{ m}^{-1}$. The shaded areas represent the hyperbolic bands of hBN. The spectral distribution of (e) Casimir torque and (f) NFRHT. The black labels indicate the WSM NP and hBN plate structure. The blue labels indicate the Ag NP and hBN plate structure, and the WSM ($b = 1.5 \times 10^9 \text{ m}^{-1}$) NP and Ag plates for comparison.

When $b \neq 0$, the localized circular modes could be excited. The larger the value of momentum separation b , the further the localized circular mode resonance frequency is from the localized plasmon mode resonance frequency. The spin for quantum numbers $m = -1$ ($m = +1$) results in a blue (red) shift, making the splitting analogous to Zeeman splitting. When adjusting the value of momentum separations, the reso-

nance of polarizability could be located within the hyperbolic band, promising enhancement of Casimir torque and radiative heat transfer.

The Casimir torque and NFRHT varying with angular frequency are shown in Figs. 3(e) and 3(f). For Casimir torque, when $b = 0$, the resonance at $\omega = 2.05 \times 10^{14} \text{ rad/s}$ is attributed to the localized plasmon modes. The resonance within

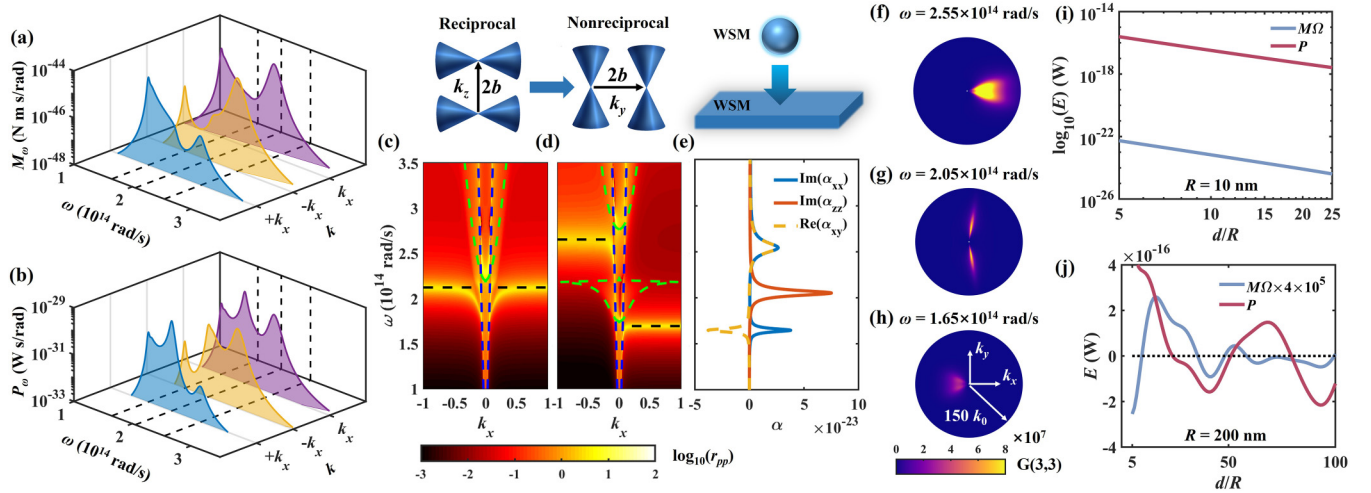


FIG. 4. The spectral distribution of (a) Casimir torque and (b) NFRHF. The reflection coefficient varying with angular frequency and wave vector when the momentum separation is along (c) z axis and (d) y axis. The black lines are the linear dispersion relation in air (or vacuum). The magenta lines are the dispersion of surface plasmon polaritons. The green lines are the dispersion of bulk plasmon. The blue dotted lines represent the resonance frequencies of WSM NP. (e) The polarizability of WSM NP varying with frequency. The Green's function varying with the dimensional wave vector when (f) $\omega = 2.55 \times 10^{14}$ rad/s, (g) $\omega = 2.05 \times 10^{14}$ rad/s, and (h) $\omega = 1.65 \times 10^{14}$ rad/s. $b = 1 \times 10^9 \text{ m}^{-1}$. The Casimir torque and NFRHF varying with gap distance ($b = 1 \times 10^9 \text{ m}^{-1}$ and along the z axis). The radius of NP is (i) 10 nm and (j) 200 nm.

the shaded areas is attributed to the hyperbolic modes of the plate. When $b = 1.5 \times 10^9 \text{ m}^{-1}$, the local circular modes couple with the hyperbolic modes in type II hyperbolic band, leading to the significant enhancement of the Casimir torque. While $b = 3 \times 10^9 \text{ m}^{-1}$, the resonant frequency of local circular modes is decoupling with hyperbolic bands, leading to the slight weakening of Casimir torque and NFRHF. The mechanism of NFRHT varying with frequency is similar to that of Casimir torque. We have performed additional calculations to benchmark the Casimir radiation for an isotropic NP made of a perfect metal (Ag) levitated above an hBN (depicted in purple). Similarly, we have also analyzed the Casimir radiation when a WSM NP (when $b = 1.5 \times 10^9 \text{ m}^{-1}$) is levitated above an Ag plate (depicted in green). The results show that both the Casimir torque and the NFRHT are significantly weaker when either the NP or the plate is made of Ag. This reduction is primarily due to the absence of resonant coupling between the NP and the plate, which plays a crucial role in enhancing Casimir radiation.

Next, we analyze the scenario where both NP and plate are WSM and the direction of momentum separation of WSM is along the y axis. The spectral Casimir torque and near-field radiative heat flux distribution are shown in Figs. 4(a) and 4(b). The spectral distribution for $+k_x$ and $-k_x$ is different, which can be understood by the reflection coefficient in Figs. 4(c) and 4(d). When momentum separation b is along the z axis, the distribution of reflection coefficients at negative and positive wave vector space is symmetrical. The narrow and bright band at around $\omega = 2.05 \times 10^{14}$ rad/s is attributed to the excitation of surface plasmon polaritons (SPPs). The resonance of SPP can well coincide with the resonance of localized plasmon modes of WSM NP. However, when momentum separation b is along the y axis, the distribution of the reflection coefficients at negative and positive space is asymmetric. The resonance of SPP split to a larger frequency at $-k_x$ space while to a smaller

frequency at $+k_x$ space can be regarded as nonreciprocal SPP (NSPP). The resonance of NSPP can well coincide with the resonance of localized circular modes of WSM NP, as shown in Fig. 4(e).

The contribution of the electromagnetic model of the plate is embodied by the Green's function. Therefore, Green's function distributions are delved in wave vector space. When the momentum separation is along the y direction, the reflection coefficients are unequal at the positive and negative x direction. Therefore, Green's function distribution is asymmetric in the x direction. When $\omega = 2.55 \times 10^{14}$ rad/s, Green's function is distributed at $-k_x$ wave vector, while at $+k_x$ wave vector when $\omega = 1.65 \times 10^{14}$ rad/s. The nonreciprocal distributions of Green's function lead to the nonreciprocal Casimir radiation property.

After analyzing the distribution of the reflection coefficients and Green's function, the mechanism of spectral heat flux resonance becomes clear. The resonances at $\omega = 1.65 \times 10^{14}$ and $\omega = 2.55 \times 10^{14}$ rad/s are attributed to the coupling of the localized circular modes of WSM NP and NSPP of the WSM plate. The resonances at $\omega = 1.65 \times 10^{14}$ rad/s are attributed to the coupling of the localized plasmon modes of WSM NP and bulk plasmon of the WSM plate. The Casimir radiation varying with gap distance is shown in Figs. 4(i) and 4(j) when the radius of WSM NP is 10 and 200 nm, respectively. For an NP with a 10 nm radius, Casimir radiation exhibits an expected exponential decay with increasing gap distance. However, for an NP with a 200 nm radius, the results reveal an oscillatory behavior. The observed sign oscillations in NFRHT and Casimir torque are related to NP resonances, suggesting that the direction and magnitude of heat flux and torque can be modulated by adjusting the NP-plate separation, and have a similar trend with the results in Ref. [16].

IV. CONCLUSION

In summary, we investigate the Casimir radiation based on WSM NP. The NFRHF can be transferred from NP to plate without a temperature gradient with the rotation of nonreciprocal NP. The Casimir radiation can be enhanced by one order of magnitude compared with isotropic NP due to the coupling of localized circular modes of WSM NP and hyperbolic modes of the hBN plate. When the plate is WSM, the Casimir radiation exhibits nonreciprocal properties and can be improved by the coupling of localized circular modes and NSPP of the WSM plate. This work provides an avenue to control the near-field energy based on nonreciprocity NP.

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The authors declare no competing financial interest.

DATA AVAILABILITY

The data are available from the authors upon reasonable request.

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- [1] O. Kenneth and S. Nussinov, Small object limit of the Casimir effect and the sign of the Casimir force, *Phys. Rev. D* **65**, 085014 (2002).
 - [2] M. Kardar and R. Golestanian, The “friction” of vacuum, and other fluctuation-induced forces, *Rev. Mod. Phys.* **71**, 1233 (1999).
 - [3] A. Manjavacas and F. J. García de Abajo, Vacuum friction in rotating particles, *Phys. Rev. Lett.* **105**, 113601 (2010).
 - [4] A. Manjavacas and F. J. García de Abajo, Thermal and vacuum friction acting on rotating particles, *Phys. Rev. A* **82**, 063827 (2010).
 - [5] J. R. Deop-Ruano and A. Manjavacas, Control of the radiative heat transfer in a pair of rotating nanostructures, *Phys. Rev. Lett.* **130**, 133605 (2023).
 - [6] B. A. Stickler, K. Hornberger, and M. S. Kim, Quantum rotations of nanoparticles, *Nat. Rev. Phys.* **3**, 589 (2021).
 - [7] A. K. Pearce, T. R. Wilks, M. C. Arno, and R. K. O'Reilly, Synthesis and applications of anisotropic nanoparticles with precisely defined dimensions, *Nat. Rev. Chem.* **5**, 21 (2021).
 - [8] S. H. Yang, M. Q. Liu, C. Y. Zhao, S. H. Fan, and C. W. Qiu, Nonreciprocal thermal photonics, *Nat. Photon.* **18**, 412 (2024).
 - [9] G. Cheng, V. S. Asadchy, B. Zhao, and S. H. Fan, Light control with Weyl semimetals, *elight* **3**, 2 (2023).
 - [10] N. Armitage, E. Mele, and A. Vishwanath, Weyl and Dirac semimetals in three-dimensional solids, *Rev. Mod. Phys.* **90**, 015001 (2018).
 - [11] Y. Hu, H. T. Liu, B. Yang, K. Z. Shi, M. Antezza, X. H. Wu, and Y. S. Sun, High-rectification near-field radiative thermal diode using Weyl semimetals, *Phys. Rev. Mater.* **7**, 035201 (2023).
 - [12] C. Guo, B. Zhao, D. Huang, and S. H. Fan, Radiative thermal router based on tunable magnetic Weyl semimetals, *ACS Photonics* **7**, 3257 (2020).
 - [13] A. Ott, S. A. Biehs, and P. Ben-Abdallah, Anomalous photon thermal Hall effect, *Phys. Rev. B* **101**, 241411 (2020).
 - [14] K. Joulain, J. P. Mulet, F. Marquier, R. Carminati, and J. J. Greffet, Surface electromagnetic waves thermally excited: Radiative heat transfer, coherence properties and Casimir forces revisited in the near field, *Surf. Sci. Rep.* **57**, 59 (2005).
 - [15] R. K. Zhao, A. Manjavacas, F. J. García de Abajo, and J. B. Pendry, Rotational quantum friction, *Phys. Rev. Lett.* **109**, 123604 (2012).
 - [16] A. Manjavacas, F. J. Rodríguez-Fortuño, F. J. García de Abajo, and A. V. Zayats, Lateral Casimir force on a rotating particle near a planar surface, *Phys. Rev. Lett.* **118**, 133605 (2017).
 - [17] Z. J. Xu, Z. Jacob, and T. C. Li, Enhancement of rotational vacuum friction by surface photon tunneling, *Nanophotonics* **10**, 537 (2020).
 - [18] K. H. Michel and B. Verberck, Phonon dispersions and piezoelectricity in bulk and multilayers of hexagonal boron nitride, *Phys. Rev. B* **83**, 115328 (2011).
 - [19] D. N. Le, P. Rodríguez-Lopez, and L. M. Woods, Phonon-assisted Casimir interactions between piezoelectric materials, *Commun. Mater.* **5**, 260 (2024).
 - [20] J. Dong, J. Zhao, and L. Liu, Long-distance near-field energy transport via propagating surface waves, *Phys. Rev. B* **97**, 075422 (2018).
 - [21] R. Messina, S. Biehs, and P. Ben-Abdallah, Surface-mode-assisted amplification of radiative heat transfer between nanoparticles, *Phys. Rev. B* **97**, 165437 (2018).
 - [22] B. Zhao, C. Guo, C. A. C. Garcia, P. Narang, and S. H. Fan, Axion-field-enabled nonreciprocal thermal radiation in Weyl semimetals, *Nano Lett.* **20**, 1923 (2020).
 - [23] V. Asadchy, C. Guo, B. Zhao, and S. H. Fan, Sub-wavelength passive optical isolators using photonic structures based on Weyl semimetals, *Adv. Opt. Mater.* **8**, 2000100 (2020).
 - [24] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/ldyf-753c> for dielectric function of WSM, the calculation of Casimir radiation using the fluctuation-dissipation theorem, and the reflection coefficient calculation.
 - [25] P. Rodríguez-Lopez, *et al.*, Signatures of complex optical response in Casimir interactions of type I and II Weyl semimetals, *Commun. Mater.* **1**, 14 (2020).
 - [26] D. N. Le, P. Rodríguez-Lopez, and L. M. Woods, Dispersive interactions between standard and Dirac materials and the role of dimensionality, *J. Phys. Mater.* **5**, 034001 (2022).
 - [27] Y. Ema, M. Hazumi, H. Iizuka, K. Mukaida, and K. Nakayama, Zero Casimir force in axion electrodynamics and the search for a new force, *Phys. Rev. D* **108**, 016009 (2023).
 - [28] Q. Li, Q. Chen, and B. Song, Giant radiative thermal rectification using an intrinsic semiconductor film, *Mater. Today Phys.* **23**, 100632 (2022).
 - [29] M. He, H. Qi, Y. Ren, Y. Zhao, and M. Antezza, Graphene-based thermal repeater, *Appl. Phys. Lett.* **115**, 263101 (2019).

- [30] T. Christensen, W. Yan, S. Raza, A.-P. Jauho, N. A. Mortensen, and M. Wubs, Nonlocal response of metallic nanospheres probed by light, electrons, and atoms, *ACS Nano* **8**, 1745 (2014).
- [31] K. Joulain, R. Carminati, J.-P. Mulet, and J. J. Greffet, Definition and measurement of the local density of electromagnetic states close to an interface, *Phys. Rev. B* **68**, 245405 (2003).
- [32] E. Cheng, *et al.*, Tunable positions of Weyl nodes via magnetism and pressure in the ferromagnetic Weyl semimetal CeAlSi, *Nat. Commun.* **15**, 1467 (2024).
- [33] J. Yuan, *et al.*, Magnetization tunable Weyl states in EuB₆, *Phys. Rev. B* **106**, 054411 (2022).
- [34] M. P. Ghimire, *et al.*, Creating Weyl nodes and controlling their energy by magnetization rotation, *Phys. Rev. Res.* **1**, 032044(R) (2019).