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Accessing Phonon Polaritons in Hyperbolic Crystals by Angle-Resolved Photoemission Spectroscopy

Andrea Tomadin,1 Alessandro Principi,2 Justin C. W. Song,3 Leonid S. Levitov,4,† and Marco Polini5,1,†

1NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, I-56126 Pisa, Italy
2Department of Physics and Astronomy, University of Missouri, Columbia, Missouri 65211, USA
3Walter Burke Institute for Theoretical Physics and Institute for Quantum Information and Matter, California Institute of Technology, Pasadena, California 91125, USA
4Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
5Instituto Italiano di Tecnologia, Graphene Labs, Via Morego 30, I-16163 Genova, Italy

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Recently studied hyperbolic materials host unique phonon-polariton (PP) modes. The ultrashort wavelengths of these modes, as well as their low damping, hold promise for extreme subdiffraction nanophotonics schemes. Polar hyperbolic materials such as hexagonal boron nitride can be used to realize long-range coupling between PP modes and extraneous charge degrees of freedom. The latter, in turn, can be used to control and probe PP modes. Here we analyze coupling between PP modes and plasmons in an adjacent graphene sheet, which opens the door to accessing PP modes by angle-resolved photoemission spectroscopy (ARPES). A rich structure in the graphene ARPES spectrum due to PP modes is predicted, providing a new probe of PP modes and their coupling to graphene plasmons.

Introduction.—The intrinsic hyperbolic character [1] of hexagonal boron nitride (hBN) grants a unique platform for realizing deep-subwavelength nanophotonic schemes. Key to these developments are phonon-polariton (PP) modes that exist within reststrahlen frequency bands [2,3], characterized by wavelengths that can be as small as 1–100 nm. Highly directional, these modes exhibit deep subdiffraction confinement of light with wavelengths far shorter than those of exciton-polaritons in semiconductor microcavities [4]. PPs have been shown to propagate with low losses [2,3] besting artificial metallic-resonator metamaterial schemes, and holding promise for transformation optics applications [5,6].

Harnessing PP modes depends on gaining access to their response over a wide wave number and energy bandwidths. However, to date these modes have only been studied within a small frequency range limited by laser choice (e.g., 170 meV ≲ ω ≲ 200 meV via the scattering-type near-field optical spectroscopy technique [2]), or at specific wavelengths fixed by the sample geometry [3]. New approaches allowing researchers to resolve the PP modes at short wavelengths and over a broad range of energies are therefore highly desirable.

Here we describe an angle-resolved photoemission spectroscopy (ARPES) [7] scheme to achieve broadband energy-resolved access to ultrashort wavelength PPs in hBN. At first glance, ARPES access to PPs in a wide-bandgap insulator (hBN) where no free carriers are available may seem counterintuitive. To circumvent this difficulty, we employ coupling to charge degrees of freedom in graphene monolayer placed atop a hBN slab. Strong coupling [8–13] between hBN Fabry-Pérot PP modes and the collective charge oscillations in a doped graphene sheet [14] gives rise to hybrid excitations—plasmon-phonon polaritons—which from now on we will refer to as hybrid plasmons. This opens up new channels for quasiparticle decay yielding a rich structure of dispersive satellite features in the graphene ARPES spectrum, marked by red arrows in Fig. 1. The Fabry-Pérot resonances and the associated structure in ARPES spectrum are tunable by hBN slab thickness.

As discussed below, a one-atom-thick conducting material like graphene, placed atop an insulating hyperbolic crystal, fully enables ARPES studies of PP modes. The advantage of this approach is that ARPES achieves extreme resolution over a wide range of wave vectors k (from the corners K, K′ of the graphene Brillouin zone to the Fermi wave number kF in graphene) and energies ω, with all energies below the Fermi energy being probed simultaneously. This gives an additional benefit, besides tunability, in that the entire range of frequencies and wave numbers can be covered within a single experiment.

From a more fundamental perspective, ARPES will also be an ideal tool to investigate whether effective electron-electron (e-e) interactions mediated by the exchange of PPs are capable of driving electronic systems towards correlated states. We also note that the tunable coupling between graphene quasiparticles and the complex excitations of its supporting substrate can be used to achieve control over the spectral properties of graphene carriers, including their decay rates, renormalized velocities, etc.
Standing PP modes [2] correspond to poles of the interaction in Eq. (1) inside the reststrahlen bands. Changing \( \tan \) to \( \tan \) in Eq. (1) we obtain Fabry-Pérot PP modes which from now on will be referred to simply as PP modes. Illustrative numerical results for \( d = 10 \) and \( d = 60 \text{ nm} \) and analytical expressions, which are valid for \( qd \ll 1 \) and \( qd \gg 1 \), can be found in [15].

The coupling of PP modes in a hBN slab to plasmons in a nearby graphene sheet is well captured by the random phase approximation (RPA) [19]. In the RPA the interacting electron system is taken to respond as an ideal Fermi gas to the Hartree potential determined by the external charges and by the polarization charges, while local field effects due to exchange and correlations are neglected [19]. This gives

\[
W_{q,\omega} = \frac{V_{q,\omega}}{\epsilon(q, \omega)} = \frac{V_{q,\omega}}{1 - V_{q,\omega} \chi_0(q, \omega)},
\]

Here \( \epsilon(q, \omega) \) is the RPA dielectric function and \( \chi_0(q, \omega) \) is the density-density response function of a 2D massless Dirac fermion fluid [20]. In addition to the poles of \( V_{q,\omega} \) which describe the slab PP modes, new poles of \( W_{q,\omega} \) emerge, given by weakly damped solutions \( \omega = \Omega_q - i0 \) of the equation \( \epsilon(q, \omega) = 0 \).

Interestingly, out of many PP modes only a few are strongly hybridized with plasmons. Illustrative numerical results for \( \epsilon_F = 400 \text{ meV} \) and \( d = 60 \text{ nm} \) are shown in Fig. 2(a). Solid lines represent the hybrid modes originating from graphene plasmons (dashed line) and standing PP modes in the hBN slab. Three strongly hybridized modes are marked by red lines; the majority of PP modes, however, remain essentially unhybridized with plasmons (such modes are marked by black lines). We also see that there are special \( q \) values (green circles) where group velocity equals \( v_F \), a feature that will be crucial for our analysis below. The corresponding modes couple strongly to quasiparticles in graphene, as we now proceed to demonstrate.

**Quasiparticle decay rates.**—An excited quasiparticle with momentum \( k \) and energy \( h\omega_0 \), created in graphene in an ARPES experiment [21–25], can decay through scattering processes involving electron-hole pairs or collective modes. The decay rate \( h/\tau_{\lambda}(k, \omega) \) for these processes can be calculated [19] from the imaginary part of the retarded quasiparticle self-energy \( \Sigma_{\lambda}(k, \omega) \), i.e. \( h/\tau_{\lambda}(k, \omega) = -2\text{Im}[\Sigma_{\lambda}(k, \omega)] \). In the RPA and at zero temperature we have [26,27]

\[
\text{Im}[\Sigma_{\lambda}(k, \omega)] = \int \frac{d^2q}{(2\pi)^2} \text{Im}[W_{q,\omega} - \xi_{\lambda,k+q}] F_{\lambda\lambda'} \times \left[ \Theta(h\omega_0 - \xi_{\lambda,k+q}) - \Theta(-\xi_{\lambda,k+q}) \right].
\]

Here, \( F_{\lambda\lambda'} \equiv 1 + 2\lambda\lambda' \cos(\theta_{kk+q})/2 \) is the chirality factor [26,27], \( \xi_{\lambda,k} = \hbar v_F k - \epsilon_F \) is the Dirac band energy measured from the Fermi energy \( \epsilon_F \) (\( \lambda, \lambda' = \pm 1 \), and

**Phonon-polaritons and hybrid plasmons.**—We consider a vertical heterostructure—see inset in Fig. 2(b)—comprised of a graphene sheet located at \( z = 0 \), placed atop an anisotropic insulator of thickness \( d \) with dielectric tensor \( \epsilon_a = \epsilon_b \). The two half-spaces \( z > 0 \) and \( z < -d \) are treated as homogeneous isotropic media with dielectric constants \( \epsilon_a \) and \( \epsilon_b \). For a *uniaxial* \( \epsilon_b = \epsilon_c \) dielectric, the Fourier transform of the Coulomb interaction potential in the graphene plane is given by

\[
V_{q,\omega} = \frac{q}{(q\varepsilon_a + \epsilon_b)\tan(qd\varepsilon_a/\varepsilon_b)\sqrt{\varepsilon_a^2 + \epsilon_b^2}} \tan(qd\varepsilon_a/\varepsilon_b),
\]

where \( q = 4\pi e^2/(q\varepsilon_a + \epsilon_b) \) and \( \tilde{e} = (\varepsilon_c, \varepsilon_c, \varepsilon_c) / (\varepsilon_a + \epsilon_b) \). A more general result, which is valid in the case \( \varepsilon_c \neq \varepsilon_c \), can also be derived [15]. In the case of hBN, the components \( \epsilon_c \) and \( \varepsilon_c \) of the dielectric tensor have resonant dependence on frequency \( \omega \) in the midinfrared [18]. Here we use a simple parametrization for \( \varepsilon_{x,c}(\omega) \) [15]; a more realistic parametrization can be found in the Supplemental Material of Ref. [11].
properties of holes produced in the Fermi sea by photo-
ejection, only \( \omega < 0 \) is relevant for this experimental probe in an \( n \)-doped graphene sheet.

To gain more insight into the behavior of \( \text{Im}[\Sigma_j(k, \omega)] \) we focus on the initial hole states with momentum \( k = 0 \). In this case, the 2D integral in Eq. (3) reduces to a simple 1D quadrature. The initial hole energy is \( E_i = \hbar \omega + \varepsilon_F \).

The dynamical screening due to e-e interactions is crucial for producing hybridized plasmons and resonances in Fig. 2(b). In contrast, for \( \varepsilon(k, \omega) = 1 \), the off-shell decay rate \( \text{Im}[\Sigma_j(0, \omega)] \) shows only a polaronic peak, due to the emission of a Fabry-Perot PP mode with group velocity equal to \( v_F \); see Fig. 1 in Ref. [15].

The features in the ARPES spectral function, described at \( k = 0 \) as outlined above, feature a characteristic \( k \) dependence. In particular, plasmon resonance splits into a doublet dispersing with \( k \) and giving rise to a blurred X-shaped feature in Fig. 1. In this case, splitting and
A representation and probes the quasiparticle spectral function graphene electrons and the PP modes. The character of the plasmons which mediate coupling between dispersion of PP modes and because of the off-shell the Dirac continuum. This is so because of a relatively weak approximately linear dispersion which closely tracks the edges of $G_k$.

The features of the spectral function originating from PP dispersion can be understood by noting that at small $k$ the relevant $k$ and $q$ are nearly parallel for the conduction-band states and nearly anti-parallel for the valence-band states. The features of the spectral function originating from PP modes (marked by red arrows in Fig. 1) show an approximately linear dispersion which closely tracks the edges of the Dirac continuum. This is so because of a relatively weak dispersion of PP modes and because of the off-shell character of the plasmons which mediate coupling between graphene electrons and the PP modes.

**Quasiparticle spectral function.**—An ARPES experiment [7] probes the quasiparticle spectral function $A(k, \omega) = -\pi^{-1} \sum_{j} \text{Im}[G_j(k, \omega)] = \sum_{j=\pm1} A_j(k, \omega)$. Here, $G_j(k, \omega)$ is the one-body Green’s function in the band representation and

$$A_j(k, \omega) = -\frac{1}{\pi} \frac{\text{Im}\Sigma_j}{(\omega - \xi_{j,k} / \hbar - \text{Re}\Sigma_j / \hbar)^2 + (\text{Im}\Sigma_j / \hbar)^2}.$$  \tag{6}$$

The real part Re[\Sigma_j(k, \omega)] of the quasiparticle self-energy can be calculated, at least in principle, from the Kramers-Kronig transform of Im[\Sigma_j(k, \omega)]. A more convenient way to handle the numerical evaluation of Re[\Sigma_j(k, \omega)] is to employ the Quinn-Ferrell line-residue decomposition [29].

Our main results for the quasiparticle spectral function $A(k, \omega)$ are summarized in Figs. 1 and 3. Notably, the presence of the hBN substrate is responsible for the appearance of a family of sharp dispersive satellite features associated with the PP modes and plasmon modes. This is particularly clear in the one-dimensional cut at $k = 0$ of $A(k, \omega)$ displayed in Fig. 3(a) for $d = 10$ nm. All the sharp features between the quasiparticle peak slightly below $\hbar \omega = -0.4$ eV and the peak at $\hbar \omega \approx -0.7$ eV, which is mostly plasmonic in nature, are sensitive to the detailed distribution and dispersion of PP modes in the hBN slab. The latter are tunable by varying the slab thickness $d$. As illustrated in Figs. 3(b) and 3(c), these peaks shift by several meV when $d$ is changed from 10 nm to 60 nm with $v_F$ kept constant.

In summary, the coupling between Fabry-Perot phonon-polariton modes in a hyperbolic crystal slab and plasmons in a nearby graphene sheet yields a complex spectrum of hybrid modes. The modes with group velocity equal to the graphene Fermi velocity couple strongly to graphene quasiparticles, enabling direct ARPES access to these modes. Our calculations indicate that the mode frequencies can be easily tuned by varying the slab thickness, as illustrated in Figs. 3(b) and 3(c), these peaks shift by several meV when $d$ is changed from 10 nm to 60 nm with $v_F$ kept constant.

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includes Refs. [16,17], where we present analytical details on the phonon-polariton dispersion and further numerical results on the quasiparticle decay rates and spectral function.


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