Absence of Kondo effect in $CeNiGe_3$ revealed by coherent phonon dynamics

Longyu Wang,[1,2,*] Yadong Han,[1,2,*] Junhong Yu,[1] Fang Xu,[2] Hang Zhang,[1,2] Chunsheng Gong,[3] Hechang Lei,[3,†] and Jianbo Hu[1,2,‡]

[1]*Laboratory for Shock Wave and Detonation Physics, Institute of Fluid Physics, China Academy of Engineering Physics, Mianyang 621900, China*

[2]*State Key Laboratory for Environment-Friendly Energy Materials, Southwest University of Science and Technology, Mianyang 621010, China*

[3]*Department of Physics and Beijing Key Laboratory of Opto-electronic Functional Materials & Micro-nano Devices, Renmin University of China, Beijing 100872, China*

(Received 10 July 2021; revised 14 November 2021; accepted 15 November 2021; published 29 November 2021)

Cerium-based intermetallic $CeNiGe_3$ has been generally believed to be a heavy-fermion material with Kondo behavior at low temperatures. Using femtosecond-resolved coherent phonon spectroscopy, we present a temperature-dependent dynamic investigation of the bosonic quasiparticles in $CeNiGe_3$. Our data do not agree with the heavy-fermion expectation and instead show that the phonon stiffening from room temperature down to 5 K can be well explained by the anharmonic effect in the absence of a Kondo mechanism. Furthermore, the coherent lattice vibration located at ~7.9 THz exhibits a mode splitting at $T^+ \approx 105$ K, which is close to the energy scale of the first excited crystal field splitting of the Ce $4f$ level. We argue that an orbital crossover may account for this intriguing observation.

DOI: 10.1103/PhysRevB.104.205133

I. INTRODUCTION

Investigation of cerium-based materials has been the research frontier of condensed matter physics since the strong electronic correlation in their $4f$ electrons can give rise to various exotic ground states [1–3]. Among these correlation-driven ground states, Kondo effect-caused insulators are well documented and can be characterized by the formation of a narrow band gap (i.e., the energy scale of several tens of meV) at low temperatures with the Fermi energy level in the gap [4–6]. Such a Kondo insulator is distinct from the typical band insulators (e.g., SiO_2 or diamond) and the energy gap opening is the result of a collective Kondo hybridization between localized f electrons and conduction electrons [7,8]. Recently, a cerium-based ternary intermetallic $CeNiGe_3$, has attracted much interest due to the predicted coexistence of the magnetic ordering and the Kondo effect at low temperature [9–11], a phenomenon by far only experimentally observed in some uranium compounds [12]. To confirm this expectation, on one hand, static transport characterizations (including magnetic susceptibility, electrical resistivity, and Hall effect measurements) have identified the existence of an antiferromagnetic ordering at $T_N = 5.5$ K [9], consistent with the predicted well-organized $4f$ magnetic moments [11]. On the other hand, the existence of Kondo behavior in $CeNiGe_3$, which is thought to be naturally guaranteed in materials with an unstable electronic $4f$ shell, still lacks experimental verifications.

As aforementioned, the Kondo effect in electronic correlation systems manifests as the emergence of collective hybridization and the formation of an energy gap at the coherent temperature T^*. In this respect, femtosecond-resolved coherent phonon spectroscopy is eminently suitable to verify the existence of the Kondo effect [13–18] since it provides a nonequilibrium way to study the dynamics of collective bosonic excitations in $CeNiGe_3$ whose response is directly associated with the emergence of an energy gap in the vicinity of the Fermi level [7,19]. Therefore, in this work, we report a comprehensive study of the temperature-dependent dynamics of bosonic quasiparticles in $CeNiGe_3$ utilizing coherent phonon spectroscopy. Our spectroscopic data show that the photoexcited bosonic quasiparticle dynamics is akin to the observation in typical semimetals [20,21], which can be well explained by an anharmonic phonon-phonon scattering process [22,23], and the temperature evolution of coherent phonon modes does not reveal any Kondo-like behavior. Furthermore, we have observed a peculiar coherent phonon mode splitting at $T^+ \approx 105$ K, which is in great agreement with the energy scale of the first excited level of the crystalline electric field (CEF) [9,10], suggesting an orbital crossover around this temperature [24,25].

II. RESULTS AND DISCUSSION

$CeNiGe_3$ has recently been predicted as a Kondo system with the antiferromagnetic ordering at low temperature [9,10]. As shown in Fig. 1(a), $CeNiGe_3$ crystallizes in the orthorhombic $SmNiGe_3$-type structure (*Cmmm*, No. 65) with a sequence of Ge_2Ni-$CeGe_2Ce$-$NiGe_2$ layers along the b axis [26]. In this lattice structure, Ce^{3+} occupies a single $4j$ site and the well-localized $4f$ magnetic moments

*These authors contributed equally to this work.
†hlei@ruc.edu.cn
‡jianbo.hu@caep.cn

 ©2021 American Physical Society

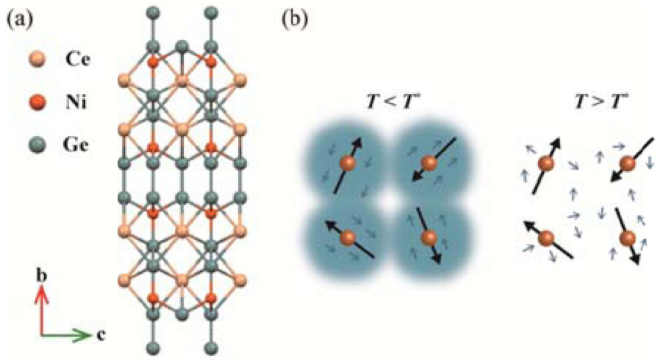

FIG. 1. Crystal structure of $CeNiGe_3$ and the Kondo effect concepts. (a) The ball-and-stick model oriented to the *bc* plane. Ce: yellow; Ni: red; Ge: green. (b) A schematic illustration of 4*f* electrons below and above the coherence temperature T^*.

permit the emergence of antiferromagnetism below $T_N = 5.5$ K, which has been revealed by the transport measurements of the thermal, magnetic, and electrical properties [10,27,28]. While the Kondo behavior in $CeNiGe_3$, which manifests as the collective hybridization between the localized *f* and free conduction electrons below the coherence temperature T^* [see the schematic in Fig. 1(b)] still lacks experimental verifications [7,8,29]. To confirm the existence of the Kondo effect, we have performed an ultrafast time-resolved coherent phonon spectroscopy measurements on high-quality single-crystal $CeNiGe_3$ at a center wavelength of 789 nm (∼1.57 eV) using a Ti: sapphire femtosecond laser with a pulse width of ∼20 fs, taken from room temperature down to 5 K. More details about the experimental setup can be found in previous publications [15,30–35].

Figure 2(a) shows the measured $\Delta R/R_0$ signals at three representative temperatures with pump polarization perpendicular to the *b* axis. Upon photoexcitation with a pump fluence of 4.1 μJ/cm^2, the transient reflectivity trace can be decomposed into an electronic part (i.e., a non-oscillatory response due to the excitation and relaxation of nonequilibrium carriers) which has been subtracted by exponential fittings [14,15,34], and a coherent oscillating part which is normally attributed to the generation of optical phonons at the center of the Brillouin zone via the displacive excitation mechanism [36] or a photoexcitation induced Raman process [37]. Please note that with such a low excitation fluence, we have estimated the temperature increase induced by laser heating is less than 2 K. The frequencies of coherent phonon modes in $CeNiGe_3$ can be clarified from the Fourier transform (FT) of the time domain signal. As shown in Figs. 2(b) and 2(c), four coherent phonon modes with the frequencies of ∼3.6, ∼5.2, ∼7.9, and ∼8.8 THz can be identified from the temperature dependence of the corresponding FT spectrum. It is noteworthy that all these four modes can be clearly resolved in our measured temperature range, indicating that photoinduced phase transition or point-group symmetry change can be ruled out in the following observations [38,39].

To glean insights into whether there exists an energy gap induced by the Kondo effect below a critical temperature (T^*) in $CeNiGe_3$, we have extracted the *T*-dependent amplitudes and frequencies of all coherent phonon modes. As

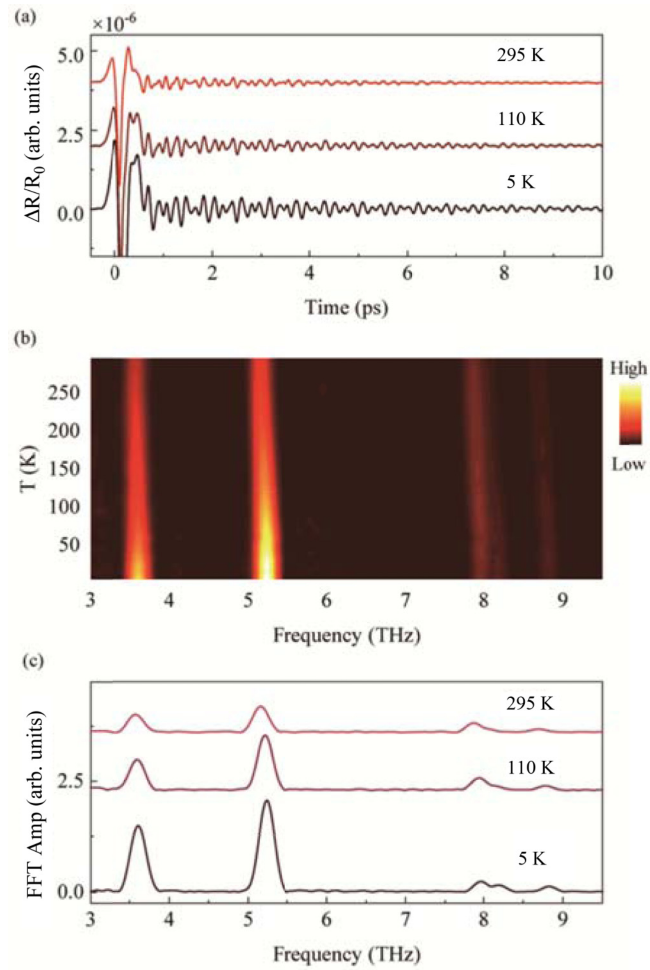

FIG. 2. Temperature-dependent coherent phonon spectra in $CeNiGe_3$ with the pump fluence of ∼4.1 μJ/cm^2. (a) Three representative time traces of coherent lattice oscillations at the temperature of 295, 110, and 5 K. (b) The pseudocolor photograph of frequency- and temperature-dependent photoinduced coherent phonon modes at all the measured temperatures. (c) The FT spectra at 295, 110, and 5 K.

demonstrated in various reports [7,19,40], if the collective hybridization and the consequent gap opening in the density of states (DOS) appears, a sharp downturn of mode frequency should be expected at low temperatures since the gap in the DOS constrains the electron-lattice scattering in the vicinity of the Fermi energy and as a consequence reduces the energy of coherent phonons. Such a frequency change can be related to the density of Kondo singlets $\langle b_i \rangle$, which is proportional to the population of quasiparticles (N) excited across the narrow gap in the form of $[1–N(T)/N(T^*)]$ [40]. However, in our spectroscopic data, frequencies of all coherent phonon modes [see Fig. 3(a)] display a hardening trend with decreasing temperature and become saturated in the even lower temperature range, which is highly inconsistent with the Kondo effect. Indeed, this temperature-dependent phonon frequency change in $CeNiGe_3$ agrees well with the anharmonic effect observed in numerous other materials [41–44], in which the optical phonon can decay into acoustic modes of lower energy and cause a renormalization of its self-energy. To test this

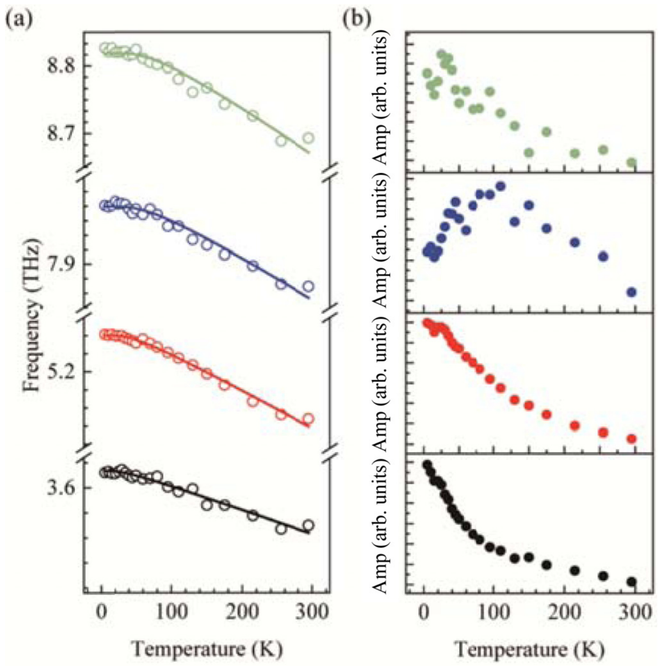

FIG. 3. Temperature-dependent mode analysis of coherent phonons in $CeNiGe_3$. (a) The mode frequency as a function of temperature. The solid lines represent the fit using the anharmonic phonon model. (b) The temperature-dependent mode amplitude. A peculiar kind at ∼105 K for the mode located around ∼7.8 THz is resolved.

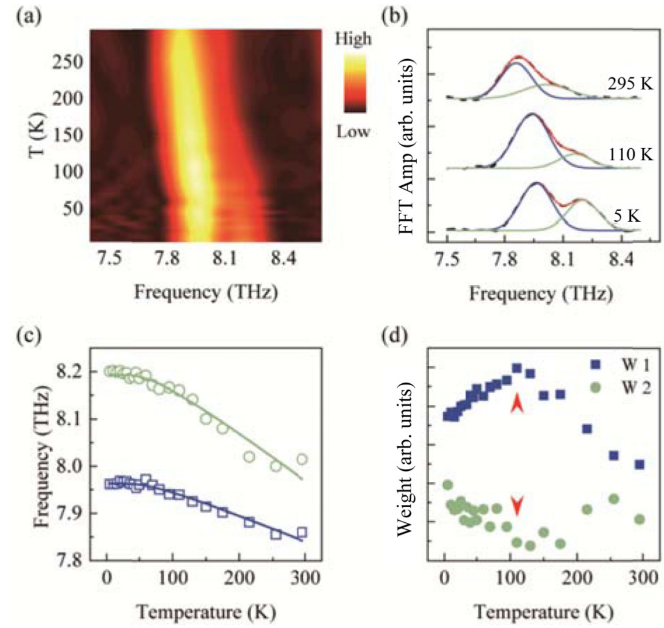

FIG. 4. The splitting behavior of the ∼7.8 THz coherent phonon mode. (a) A zoomed-in pseudocolor photograph around the frequency of 8.0 THz. (b) Gaussian line shaping fitting to the FT spectra at 295, 110, and 5 K. (c) Absence of frequency anticrossing for these two splitting modes. The solid lines represent the fit using the anharmonic phonon model. (d) The temperature-dependent amplitude of these two splitting modes.

argument, we fit the frequency change using the anharmonic expression, which assumes the coherent phonon decays into two modes of frequency $\omega_0/2$ or three modes of frequency $\omega_0/3$ [22,23]:

$$\omega(T) = \omega_{\rm int} + m\left[1 + 2n\left(\frac{\omega_{\rm int}}{2}, T\right)\right] + n\left[1 + 3n\left(\frac{\omega_{\rm int}}{3}, T\right) + 3n^2\left(\frac{\omega_{\rm int}}{3}, T\right)\right], \quad (1)$$

where $n(\omega, T) = \frac{1}{\exp(\hbar\omega/k_B T)-1}$ is the Bose-Einstein distribution, $\omega_{\rm int}$ is the intrinsic harmonic angular frequency, and m and n are fitting parameters.

As shown in Fig. 3(a), the quality of the fit (the solid lines) is quite satisfactory, suggesting that the anharmonic effect should account for the observed phonon energy change in $CeNiGe_3$. It is worth mentioning that we have also estimated the size of the phonon softening caused by the Kondo effect using the density of Kondo singlets [7,19]. The calculated results reveal that fitting root mean square deviation (RMSE) for the Kondo singlet density model is as large as $(3–9)\times10^{-3}$ (RMSE for the anharmonic phonon model is smaller than 4×10^{-5}) which rules out the possibility that phonon frequency down-turning caused by the Kondo effect may embed in the fitting uncertainties. Moreover, the monotonical increase of phonon amplitudes (except the mode at ∼7.9 THz, which will be discussed later) with decreasing temperature in Fig. 3(b) also confirms the absence of energy gap formation in $CeNiGe_3$ since the temperature dependence of a coherent phonon amplitude in absorbing media is often dominated by the photoexcited carrier density and a gap opening will change the population of excited carriers [20].

Now we discuss the peculiar amplitude behavior of the coherent phonon mode at ∼7.9 THz which displays a kink at $T^+ = \sim$105 K. As shown in the zoomed-in pseudocolor map of temperature-dependent FT spectra [see Fig. 4(a)], a “side lobe” is gradually developed with decreasing temperature and leads to the amplitude kink observed in Fig. 3(b). Here, we exclude the Fano effect [45–47] to account for the occurrence of the coherent phonon mode splitting since two symmetric Gaussian line shapes can describe the measured phonon profile reasonably well at all temperatures, as shown in Fig. 4(b). Moreover, although T^+ is close to the first excitation crystalline electric field (CEF) level in $CeNiGe_3$ (the measured energy scale is at around 100 K) [9,10], it is unlikely that the mode splitting is coming from a strong coupling between the coherent phonon mode and the crystal field excitations of the Ce^{3+} $4f$ electrons [48–50] because such coupling should result in the frequency anticrossing (i.e., when the temperature increases, the higher mode shifts to lower frequencies while the lower peak shifts to higher frequencies), which is inconsistent with the similar frequency shifting trend observed in our measurements [Fig. 4(c)]. Therefore, we propose that the mode splitting may originate from an orbital crossover [24,25]: With increased temperature, the conduction band hybridizes with the first excitation CEF level in $CeNiGe_3$ and the electron occupancy will be changed. As suggested by a series of experimental and theoretical works [51,52], once the CEF states become thermally occupied, electron-lattice scattering and the energy scale of lattice vibrations are affected, leading to the phonon mode splitting at $T^+ = \sim 105\,\mathrm{K}$ observed in Fig. 4(d).

Please note that the magnetic ground state and a large magnetic anisotropy in $CeNiGe_3$ are assumed to be associated with the CEF splitting of the Ce Hund's rule ground state multiplet [10]. Splitting of the sixfold degeneracy of the $J = 5/2$ multiplet of Ce^{3+} is expected to develop a long-range magnetic order, which results in a fairly weak Kondo coupling strength between conduction carriers and the local moments of the f electrons (i.e., $CeNiGe_3$ is expected to locate at the left side of the Doniach diagram with large Ruderman Kittel Kasuya Yosida (RKKY) interactions) [25]. This may be the main reason that explains why the expected Kondo behavior is absent in our coherent phonon dynamics. More importantly, our experimental results have established that thermal energy can change the energy hybridization between the conduction band in $CeNiGe_3$ and the first excitation CEF level to form an orbital crossover and change the electronic occupation, which manifests as the phonon energy modulation. This observation suggests that future studies can take the crystal field splitting into consideration as a tuning knob for the Kondo effect in $CeNiGe_3$ since it has been demonstrated that the Kondo energy scale is highly dependent on the orientations and occupations of different CEF orbitals [25,51].

III. CONCLUSION

In summary, by using femtosecond-resolved coherent phonon spectroscopy, we show that unlike other cerium-based intermetallics, the nonequilibrium dynamics of bosonic quasiparticles in $CeNiGe_3$ does not exhibit any features which can be associated with the emergence of collective hybridization induced by the Kondo effect at low temperature. Instead, the temperature-dependent coherent phonon behavior can be well described by the common anharmonic effect. Moreover, we have also indicated that the appearance of the crystal field effect can affect the lattice vibrations in $CeNiGe_3$. Our results may provide a supplementary perspective on the understanding of heavy-fermion physics in cerium-based materials.

The data that support the plots of this paper are available from the corresponding authors upon reasonable request.

ACKNOWLEDGMENTS

This work was supported by the Science Challenge Project (Grant No. TZ2018001), the National Natural Science Foundation of China (Grants No. 12072331, No. 11822412, and No. 11774423), the Ministry of Science and Technology of China (Grants No. 2018YFE0202600 and No. 2016YFA0300504), and the Beijing Natural Science Foundation (Grant No. Z200005).

The authors declare no competing financial interests.

[1] P. S. Riseborough, Heavy fermion semiconductors, Adv. Phys. **49**, 257 (2000).

[2] Q. Y. Chen, D. F. Xu, X. H. Niu, J. Jiang, R. Peng, H. C. Xu, C. H. P. Wen, Z. F. Ding, K. Huang, L. Shu, Y. J. Zhang, H. Lee, V. N. Strocov, M. Shi, F. Bisti, T. Schmitt, Y. B. Huang, P. Dudin, X. C. Lai, S. Kirchner *et al.*, Direct observation of how the heavy-fermion state develops in $CeCoIn_5$, Phys. Rev. B **96**, 045107 (2017).

[3] T. Willers, F. Strigari, Z. Hu, V. Sessi, N. B. Brookes, E. D. Bauer, J. L. Sarrao, J. D. Thompson, A. Tanaka, S. Wirth, L. H. Tjeng, and A. Severing, Correlation between ground state and orbital anisotropy in heavy fermion materials, Proc. Natl. Acad. Sci. USA **112**, 2384 (2015).

[4] T. Kasuya, Physical mechanism in Kondo insulator, J. Phys. Soc. Jpn. **65**, 2548 (1996).

[5] X. Zhang, N. P. Butch, P. Syers, S. Ziemak, R. L. Greene, and J. Paglione, Hybridization, Inter-Ion Correlation, and Surface States in the Kondo Insulator SmB_6, Phys. Rev. X **3**, 011011 (2013).

[6] M. Neupane, S.-Y. Xu, N. Alidoust, G. Bian, D.-J. Kim, C. Liu, I. Belopolski, T.-R. Chang, H.-T. Jeng, T. Durakiewicz, H. Lin, A. Bansil, Z. Fisk, and M. Z. Hasan, Non-Kondo-like Electronic Structure in the Correlated Rare-Earth Hexaboride YbB_6, Phys. Rev. Lett. **114**, 016403 (2014).

[7] Y. P. Liu, Y. J. Zhang, J. J. Dong, H. Lee, Z. X. Wei, W. L. Zhang, C. Y. Chen, H. Q. Yuan, Y.-F. Yang, and J. Qi, Hybridization Dynamics in $CeCoIn_5$ Revealed by Ultrafast Optical Spectroscopy, Phys. Rev. Lett. **124**, 057404 (2019).

[8] Y. Yang, Two-fluid model for heavy electron physics, Rep. Prog. Phys. **79**, 074501 (2016).

[9] A. P. Pikul, D. Kaczorowski, T. Plackowski, A. Czopnik, H. Michor, E. Bauer, G. Hilscher, P. Rogl, and Y. Grin, Kondo behavior in antiferromagnetic $CeNiGe_3$, Phys. Rev. B **67**, 224417 (2003).

[10] E. D. Mun, S. L. Bud'ko, A. Kreyssig, and P. C. Canfield, Tuning low-temperature physical properties of $CeNiGe_3$ by magnetic field, Phys. Rev. B **82**, 054424 (2010).

[11] M. J. Winiarski and M. Samsel-Czekała, The electronic structure of $CeNiGe_3$ and $YNiGe_3$ superconductors by *ab initio* calculations, Solid State Commun. **179**, 6 (2014).

[12] N. B. Perkins, J. R. Iglesias, M. D. Núñez-Regueiro, and B. Coqblin, Coexistence of ferromagnetism and Kondo effect in the underscreened Kondo lattice, Europhys. Lett. **79**, 57006 (2007).

[13] H. Martinho, P. G. Pagliuso, V. Fritsch, N. O. Moreno, J. L. Sarrao, and C. Rettori, Vibrational and electronic excitations in the (Ce, La) $M\mathrm{In}_5$ (M = Co, Rh) heavy-fermion family, Phys. Rev. B **75**, 045108 (2007).

[14] J. Yu, Y. Han, L. Wang, F. Xu, H. Zhang, Y. Yu, Q. Wu, and J. Hu, Visualizing nonlinear phononics in layered $ReSe_2$, J. Phys. Chem. Lett. **12**, 5178 (2021).

[15] J. Hu, O. V. Misochko, and K. G. Nakamura, Direct observation of two-phonon bound states in ZnTe, Phys. Rev. B **84**, 224304 (2011).

[16] R. V. Yusupov, T. Mertelj, J.-H. Chu, I. R. Fisher, and D. Mihailovic, Single-Particle and Collective Mode Couplings Associated with 1- and 2-Directional Electronic Ordering in

Metallic $R\mathrm{Te}_3$ (R = Ho, Dy, Tb), Phys. Rev. Lett. **101**, 246402 (2008).

[17] R. Y. Chen, S. J. Zhang, E. D. Bauer, J. D. Thompson, and N. L. Wang, Optical spectroscopy and ultrafast pump-probe studies on the heavy-fermion compound $\mathrm{CePt_2In_7}$, Phys. Rev. B **94**, 035161 (2016).

[18] J. Qi, T. Durakiewicz, S. A. Trugman, J.-X. Zhu, P. S. Riseborough, R. Baumbach, E. D. Bauer, K. Gofryk, J.-Q. Meng, J. J. Joyce, A. J. Taylor, and R. P. Prasankumar, Measurement of Two Low-Temperature Energy Gaps in the Electronic Structure of Antiferromagnetic $\mathrm{USb_2}$ Using Ultrafast Optical Spectroscopy, Phys. Rev. Lett. **111**, 057402 (2013).

[19] Y. H. Pei, Y. J. Zhang, Z. X. Wei, Y. X. Chen, K. Hu, Y. Yang, H. Q. Yuan, and J. Qi, Unveiling the hybridization process in a quantum critical ferromagnet by ultrafast optical spectroscopy, Phys. Rev. B **103**, L180409 (2021).

[20] K. Ishioka, M. Kitajima, and O. V. Misochko, Temperature dependence of coherent A_{1g} and E_g phonons of bismuth, J. Appl. Phys. **100**, 093501 (2006).

[21] M. Hase, K. Mizoguchi, H. Harima, S. ichi Nakashima, and K. Sakai, Dynamics of coherent phonons in bismuth generated by ultrashort laser pulses, Phys. Rev. B **58**, 5448 (1998).

[22] M. Balkanski, R. F. Wallis, and E. Haro, Anharmonic effects in light scattering due to optical phonons in silicon, Phys. Rev. B **28**, 1928 (1983).

[23] J. Menéndez and M. Cardona, Temperature dependence of the first-order Raman scattering by phonons in Si, Ge, and α-Sn: Anharmonic effects, Phys. Rev. B **29**, 2051 (1984).

[24] R. Y. Chen, J. L. Liu, L. Y. Shi, C. N. Wang, S. J. Zhang, and N. L. Wang, Possible orbital crossover in the ferromagnetic Kondo lattice compound $\mathrm{CeAgSb_2}$, Phys. Rev. B **99**, 205107 (2019).

[25] Q. Y. Chen, C. H. P. Wen, Q. Yao, K. Huang, Z. F. Ding, L. Shu, X. H. Niu, Y. Zhang, X. C. Lai, Y. B. Huang, G. B. Zhang, S. Kirchner, and D. L. Feng, Tracing crystal-field splittings in the rare-earth-based intermetallic $\mathrm{CeIrIn_5}$, Phys. Rev. B **97**, 075149 (2018).

[26] P. Salamakha, M. Konyk, O. Sologub, and O. Bodak, Ce-Ni-Ge and Nd-Ni-Ge phase diagrams: Systematics of rare earth-nickel-germanium compounds, J. Alloys Compd. **236**, 206 (1996).

[27] A. Harada, H. Mukuda, Y. Kitaoka, A. Thamizhavel, Y. Okuda, R. Settai, Y. Onuki, K. M. Itoh, E. E. Haller, and H. Harima, Intimate interplay between superconductivity and antiferromagnetism in $\mathrm{CeNiGe_3}$: A ^{73}Ge-NQR study under pressure, Phys. B (Amsterdam, Neth.) **403**, 1020 (2008).

[28] N. Tateiwa, Y. Haga, T. D. Matsuda, S. Ikeda, M. Nakashima, A. Thamizhavel, R. Settai, and Y. Ōnuki, Thermodynamics investigation on pressure-induced superconductor $\mathrm{CeNiGe_3}$ by ac calorimetry, J. Phys. Soc. Jpn. **75**, 174 (2006).

[29] S. Jang, J. D. Denlinger, J. W. Allen, V. S. Zapf, M. B. Maple, J. N. Kim, B. G. Jang, and J. H. Shim, Evolution of the Kondo lattice electronic structure above the transport coherence temperature, Proc. Natl. Acad. Sci. USA **117**, 23467 (2020).

[30] J. Hu, O. V. Misochko, A. Goto, and K. G. Nakamura, Delayed formation of coherent LO phonon-plasmon coupled modes in n- and p-type GaAs measured using a femtosecond coherent control technique, Phys. Rev. B **86**, 235145 (2012).

[31] J. Yu, S. Shendre, W.-K. Koh, B. Liu, M. Li, S. Hou, C. Hettiarachchi, S. Delikanli, P. Hernández-Martínez, M. D. Birowosuto, H. Wang, T. C. Sum, H. V. Demir, and C. Dang, Electrically control amplified spontaneous emission in colloidal quantum dots, Sci. Adv. **5**, eaav3140 (2019).

[32] M. Hase, M. Katsuragawa, A. M. Constantinescu, and H. Petek, Frequency comb generation at terahertz frequencies by coherent phonon excitation in silicon, Nat. Photon. **6**, 243 (2012).

[33] J. Yu, M. Sharma, A. Sharma, S. Delikanli, H. V. Demir, and C. Dang, All-optical control of exciton flow in a colloidal quantum well complex, Light Sci. Appl. **9**, 27 (2020).

[34] O. V. Misochko, M. Hase, K. Ishioka, and M. Kitajima, Observation of an Amplitude Collapse and Revival of Chirped Coherent Phonons in Bismuth, Phys. Rev. Lett. **92**, 197401 (2004).

[35] J. Hu, K. Igarashi, T. Sasagawa, K. G. Nakamura, and O. V. Misochko, Femtosecond study of A_{1g} phonons in the strong 3D topological insulators: From pump-probe to coherent control, Appl. Phys. Lett. **112**, 031901 (2018).

[36] A. Cavalleri, T. Dekorsy, H. H. W. Chong, J. C. Kieffer, and R. W. Schoenlein, Evidence for a structurally-driven insulator-to-metal transition in $\mathrm{VO_2}$: A view from the ultrafast timescale, Phys. Rev. B **70**, 161102(R) (2004).

[37] R. Merlin, Generating coherent THz phonons with light pulses, Solid State Commun. **102**, 207 (1997).

[38] J. Hu, G. M. Vanacore, Z. Yang, X. Miao, and A. H. Zewail, Transient structures and possible limits of data recording in phase-change materials, ACS Nano **9**, 6728 (2015).

[39] M. Hase, P. Fons, K. Mitrofanov, A. V. Kolobov, and J. Tominaga, Femtosecond structural transformation of phase-change materials far from equilibrium monitored by coherent phonons, Nat. Commun. **6**, 8367 (2015).

[40] K. S. Burch, E. E. M. Chia, D. Talbayev, B. C. Sales, D. Mandrus, A. J. Taylor, and R. D. Averitt, Coupling between an Optical Phonon and the Kondo Effect, Phys. Rev. Lett. **100**, 026409 (2008).

[41] P. Verma, S. C. Abbi, and K. P. Jain, Raman-scattering probe of anharmonic effects in GaAs, Phys. Rev. B **51**, 16660 (1995).

[42] D. J. Late, S. N. Shirodkar, U. V. Waghmare, V. P. Dravid, and C. N. R. Rao, Thermal expansion, anharmonicity and temperature-dependent Raman spectra of single- and few-layer $\mathrm{MoSe_2}$ and $\mathrm{WSe_2}$, ChemPhysChem **15**, 1592 (2014).

[43] J. Lin, L. Guo, Q. Huang, Y. Jia, K. Li, X. Lai, and X. Chen, Anharmonic phonon effects in Raman spectra of unsupported vertical graphene sheets, Phys. Rev. B **83**, 125430 (2011).

[44] M. Hase, M. Kitajima, S. ichi Nakashima, and K. Mizoguchi, Dynamics of Coherent Anharmonic Phonons in Bismuth Using High Density Photoexcitation, Phys. Rev. Lett. **88**, 067401 (2002).

[45] B. Xu, Y. M. Dai, L. X. Zhao, K. Wang, R. Yang, W. Zhang, J. Y. Liu, H. Xiao, G. F. Chen, S. A. Trugman, J.-X. Zhu, A. J. Taylor, D. A. Yarotski, R. P. Prasankumar, and X. G. Qiu, Temperature-tunable Fano resonance induced by strong coupling between Weyl fermions and phonons in TaAs, Nat. Commun. **8**, 14933 (2017).

[46] J. Yu, S. Hou, M. Sharma, L. Y. M. Tobing, Z. Song, S. Delikanli, C. Hettiarachchi, D. Zhang, W. Fan, M. D. Birowosuto, H. Wang, H. V. Demir, and C. Dang, Strong plasmon-Wannier Mott exciton interaction with high aspect ratio colloidal quantum wells, Matter **2**, 1550 (2020).

[47] Y. Okuno, Y. Saito, S. Kawata, and P. Verma, Tip-Enhanced Raman Investigation of Extremely Localized Semiconductor-to-Metal Transition of a Carbon Nanotube, Phys. Rev. Lett. **111**, 216101 (2013).

[48] E. T. Heyen, R. Wegerer, and M. Cardona, Coupling of Phonons to Crystal-Field Excitations in $NdBa_2Cu_3O_7$, Phys. Rev. Lett. **67**, 144 (1991).

[49] P. Thalmeier and P. Fulde, Bound State between a Crystal-Field Excitation and a Phonon in $CeAl_2$, Phys. Rev. Lett. **49**, 1588 (1982).

[50] G. Güntherodt, A. Jayaraman, G. Batlogg, M. Croft, and E. Melczer, Raman Scattering from Coupled Phonon and Electronic Crystal-Field Excitations in $CeAl_2$, Phys. Rev. Lett. **51**, 2330 (1983).

[51] S. Pal, C. Wetli, F. Zamani, O. Stockert, H. v. Löhneysen, M. Fiebig, and J. Kroha, Fermi Volume Evolution and Crystal-Field Excitations in Heavy-Fermion Compounds Probed by Time-Domain Terahertz Spectroscopy, Phys. Rev. Lett. **122**, 096401 (2019).

[52] L. V. Pourovskii, P. Hansmann, M. Ferrero, and A. Georges, Theoretical Prediction and Spectroscopic Fingerprints of an Orbital Transition in $CeCu_2Si_2$, Phys. Rev. Lett. **112**, 106407 (2013).